# Assessing operational silviculture and modeling juvenile growth in Saskatchewan white spruce (*Picea glauca* (Moench) Voss) plantations

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Forest Biology and Management

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**Abstract**

White spruce (*Picea glauca* (Moench) Voss) plantations are often established with mechanical site preparation and tending. These silvicultural treatments encourage plantation survival and can influence growth, composition, and yield. To assess operational silviculture and model managed stand growth, 16 white spruce plantations (13-18 years old) and 18 white spruce Permanent Sample Plots (20-29 years old) (PSP's) were sampled across the Prince Albert Forest Management Agreement in Saskatchewan between 2011 and 2012.

Analysis of Covariance (ANCOVA) with soil moisture regime indicated that white spruce height was not significantly different between Bracke mounding, v-plow scarification, disc trenching, and disc trenching/tended treatments. However, v-plow scarification appeared to increase the DBH of young white spruce relative to Bracke mounding. This DBH difference was linked with a significant change in grass competition but could not be linked with changes in overstory vegetation. Site differences complicated analysis and may have obscured silvicultural effects. In addition, the effectiveness of each silvicultural treatment could not be explored, since a 'raw planted' control could not be located.

To estimate subsampled heights, generalized mixed-effects height-diameter models were developed for the PSP dataset. Generalized models containing top height and density often explained the most variation. Small sample sizes prevented validation of the PSP height-diameter models, limiting their use to the fitted PSP data.

Using repeated measurements in the PSP dataset, short-term Mixedwood Growth Model (MGM) projections (1996-2011) were compared to observed growth between 1996 and 2011. Site index assumptions (i.e. height-age site indices or ecosite-based site indices) largely dictated MGM performance. However, given accurate site indices, modeled white spruce height and DBH tracked observed growth in most spruce-aspen mixedwoods. Modeled white spruce height and DBH were overestimated in juvenile stands (<15 years-old) initialized with small trees (<1.3m height) and heavy conifer or deciduous competition. Since many factors influence young white spruce (e.g. browsing, frost damage, leader whip, woody/herbaceous competition), and juvenile site indices (<30 to 35 years breast height age) are difficult to define, initializing MGM with small trees (<1.3m height) or data from young stands (<15 years old) may be problematic.

Finally, long-term growth (120-year rotation) was modeled in MGM using the 16 white spruce plantations and 18 white spruce PSP's. Juvenile mixedwood stands with a strong white spruce component (~2000 trees/hectare) generally became white spruce-leading mixedwoods (>50% basal area) by age 60 and white spruce dominant (>75% basal area) by age 120. Increasing deciduous competition slowed succession but did not prevent hardwood-leading stands from becoming mixedwoods by age 120. Site index assumptions (i.e. ecosite-based site indices) strongly influenced modeled succession and long-term outcomes.

**Acknowledgements**

I would like to thank my supervisors Dr. Phil Comeau and Dr. Mike Bokalo for their continued guidance, insight, patience, and support. I would also like to thank Dr. Scott Chang, Dr. Barbara Thomas, and Dr. Victor Lieffers for serving on my committee.

I am grateful for the funding provided by the Saskatchewan Ministry of Environment, and I would like to thank Lane Gelhorn, Phil Loseth, and Vicki Gauthier for their input and generous support. I also appreciate Lane, Phil L., and Deb Desrosiers for their help in the field, regardless of the weather, difficult access, and road conditions.

From the University of Alberta, I would like to thank Dan Jensen, Kazi Hossain, Hongan Yan, Nicole Luchanski, Julie Steinke, Olivier Auge, Elise Pares, and Ludovic Lejour for their help with fieldwork. I would also like to thank Dr. Ken Stadt for his help with field equipment and lab materials. Finally, I would like to thank Gabriel Oltean for his thoughtful feedback and technical support.

Special thanks to Hyejin Hwang for her love, confidence, and encouragement.

Foremost, I would like to thank my family: Dean, Jean, and Mark Johnson. My success depends on their love and perpetual support.

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## Chapter 1. Introduction

Saskatchewan's Provincial Forest is sustainably managed to "*balance the use of the forests for various economic, social, and cultural purposes*" while maintaining long-term ecosystem health (SME 2009). Under these concurrent objectives, the forest is harvested to support employment and economic activity (SME 2009). This harvesting is regulated to maintain sustainable harvest levels, retain all forest age-classes (e.g. young, mature, and 'old-growth'), and ensure long-term forest productivity (SME 2009; SME 2012). Forest management in Saskatchewan also strives to assure adequate reforestation, emulate natural disturbances, and preserve biological, structural, and genetic diversity (SME 2009; SME 2012).

To support sustainable decision-making, modern forest management requires quantified silvicultural outcomes and reliable estimates of growth, yield, and succession (Messier et al. 2003; Comeau et al. 2005; Hawkins et al. 2006; Boateng et al. 2009; Cortini et al. 2010; Comeau 2014). Many retrospective studies have characterized growth in 'natural' boreal forests (e.g. Kirby et al. 1957; Kirby 1962; Kabzems 1971; Beckingham et al. 1996; Chen and Popadiouk 2002; Epp et al. 2009; McLaughlan et al. 2010; LeBlanc 2014). However, in managed stands, silvicultural treatments can alter crop tree growth (Boateng et al. 2006; Hawkins et al. 2006; Boateng et al. 2009; Youngblood et al. 2011) and/or produce growth trajectories that differ from natural forests (Huang et al. 2004). Unfortunately, the long-term impact of these silvicultural treatments is unclear (Cortini et al. 2010) since most silvicultural trials in western Canada are under 35 years old (e.g. Sutton et al. 2001; Boateng et al. 2006; Hawkins et al. 2006; Boateng et al. 2009). As a result, forest growth models have been used to estimate long-term growth (Huang et al. 2004; Comeau et al. 2005; Hawkins et al. 2006; Boateng et al. 2009; Cortini et al. 2010; Comeau 2014).

In Saskatchewan's Provincial Forest, white spruce plantations often receive site preparation and/or stand tending (CCFM 2015; Archibold et al. 2000; Lieffers and Beck 1994). The purpose of this study is to explore operational white spruce silviculture in the Prince Albert Forest Management Agreement and examine long-term ‘managed stand’ simulations with the Mixedwood Growth Model (MGM) (Bokalo et al. 2013).

*Thesis Structure*

This thesis includes 5 chapters: An introductory chapter, 3 independent data chapters, and a general conclusion. Chapter 1 briefly describes mixedwood succession and the Prince Albert Forest Management Agreement (PAFMA). Chapter 2 investigates operational silviculture’s influence on juvenile white spruce growth and competition across the PAFMA. In addition, Chapter 2 also discusses the design and implementation of robust silvicultural experiments. Chapter 3 explores generalized mixed-effects modeling and develops height-diameter models to initialize MGM in the PAFMA. Chapter 3 also evaluates generalized mixed-model construction, reviews mixed-model calibration, and discusses sampling protocols that encourage mixed-model deployment. Chapter 4 validates MGM’s juvenile white spruce functions in the PAFMA and examines MGM forecasts across a range of stand densities, species compositions, and site productivities. Chapter 4 also discusses protocols to optimize MGM performance, explores alternative data sources for MGM projections, and highlights sampling protocols that support forest growth modeling. Finally, Chapter 5 provides a summary of main findings.

*Mixedwood Succession*

Mixed stands of trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca*), jack pine (*Pinus banksiana* Lamb.), white birch (*Betula papyrifera* Marsh.), balsam poplar (*Populus balsamifera* L.), and balsam fir (*Abies balsamea* (L.) Mill.) dominate upland sites in the boreal forests of west-central Canada (Rowe 1972; Chen and Popadiouk 2002). These ‘mixedwoods’ are often characterized by deciduous or jack pine dominance at stand initiation, mixedwood codominance during mid-succession, and spruce/fir dominance in late-succession (Chen and Popadiouk 2002). Following disturbance, trembling aspen, jack pine, and/or white birch vigorously re-establish (Chen and Popadiouk 2002). Then, given a seed source, shade tolerant white spruce and balsam fir gradually establish in the deciduous or jack pine understory (Lieffers et al. 1996; Chen and Popadiouk 2002). Over time, trembling aspen, jack pine, and/or white birch undergo stem exclusion, intermediate disturbance (e.g. insect defoliation), and age-related mortality (e.g. stem decay/windthrow) (Chen and Popadiouk 2002). Afterward, white spruce emerge into the overstory, producing spruce dominated stands with an understory of balsam fir (Lieffers et al. 1996; Chen and Popadiouk 2002). Under a 'cyclic' pathway, light or intermediate disturbances (e.g. windthrow or insect outbreaks) may revert mixedwood stands to a previous stage of development, or stand-replacing disturbances (e.g. fire or clearcutting) may re-initiate the mixedwood and restart succession (Chen and Popadiouk 2002). Mixedwood stands may also persist through 'parallel succession'. For example, repeated stand-replacing disturbances can favour trembling aspen or white birch communities, given these species' ability to sucker and stump sprout (Chen and Popadiouk 2002). Periodic fire may also favour jack pine, assuming serotinous cones are mature and viable (Rowe and Scotter 1973; Chen and Popadiouk 2002). In the absence of stand-replacing disturbance, mature white spruce, trembling aspen, or mixedwood stands may persist through gap dynamics (Lieffers et al. 1996; Chen and Popadiouk 2002; LeBlanc 2014). In some cases, mixedwood succession can follow a 'divergent' pathway. For example, deep-burning fires may expose mineral soil, impair aspen suckering, and establish early-successional white spruce stands, provided a white spruce seed source (Lieffers et al. 1996). Deep-burning fires may also create meadows containing fireweed (*Chamerion angustifolium* (L.) Holub) and other herbaceous species (Lieffers et al. 1996). On moist sites, clearcutting or low severity fire can also facilitate bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) P. Beauv.) or shrub communities, particularly when trembling aspen fails to re-establish (Lieffers et al. 1996; Chen and Popadiouk 2002).

*Study Area*

The PAFMA of north-central Saskatchewan encompasses a 3.3 million hectare landbase (53°30′ N to 55°20′ N; 103°50′ to 108°10′), containing 2.6 million hectares of forests and 1.6 million hectares of forests suitable for intensive management (Sakaw Askiy Management 2014). Ecologically, the PAFMA occupies the Mid-Boreal Ecoregion, an area north of the Boreal Transition/Aspen Parkland, south of the Canadian Shield, east of the Alberta border, and west of the Mid-Boreal Lowland (Beckingham et al. 1996). Topography within the Mid-Boreal Upland was smoothed by glaciers and varies from elevated hills, rolling uplands, and level lowlands (Beckingham et al. 1996). The region's climate is characterized as cool and continental with "*long cold winters and warm summers*" (Beckingham et al. 1996). Mean seasonal temperatures fluctuate between 16°C in the summer and -19°C in the winter (Beckingham et al. 1996). Annual precipitation ranges from 400 to 500mm with the majority (~70%) falling as rain in midsummer. Annual evapotranspiration in the Mid-Boreal Upland often exceeds precipitation, yielding a water deficit of 180mm. Luvisolic and Brunisolic soil orders dominate most stable, well-drained sites (Beckingham et al. 1996).

Eight tree species are native to the Mid-Boreal Upland: balsam fir, balsam poplar, black spruce (*Picea mariana* (Mill.) B. S. P.), jack pine, tamarack (*Larix laricina* (Du Roi) K. Koch), trembling aspen, white birch, and white spruce (Beckingham et al. 1996). Well-drained sites are characterized by mixtures of trembling aspen, white birch, white spruce, and balsam fir (Rowe 1972). Poorly drained sites with shallow water tables, significant subsurface flow, or seasonal flooding are often associated with balsam poplar, black spruce, and tamarack (Beckingham et al. 1996). Alternately, jack pine tends to dominate dry or sandy sites (Beckingham et al. 1996) and mixes black or white spruce on hills and plateaus (Rowe 1972; McLaughlan et al. 2010).

## Chapter 2. Exploring operational silviculture and juvenile white spruce growth in the Prince Albert Forest Management Agreement

### 2.1 Introduction

In the mixedwood boreal forest, establishing white spruce during early succession often requires site preparation and stand tending (Lieffers and Beck 1994; Pitt and Bell 2005). These silvicultural techniques encourage white spruce growth and survival by reducing competition and allocating light, soil moisture, soil nutrients, and growing space to desired crop trees (Long et al. 2004; Balandier et al. 2006; Orlander et al. 1990). Site preparation and stand tending can also help create favourable planting environments by modifying light, soil moisture, soil nutrient, soil bulk density, and temperature conditions (Orlander et al. 1990; Long et al. 2004; Sutton 1993). Finally, when combined with plantation forestry, site preparation and stand tending can expedite forest succession and moderate environmental stresses linked with planting (Hawkins et al. 2006; Boateng et al. 2009; Orlander et al. 1990). Given the role of these silvicultural treatments and their associated costs, there is a need to understand how silviculture influences juvenile white spruce growth and competing vegetation in the PAFMA.

*Site Preparation*

Site preparation describes "*treatments applied to slash, groundstory vegetation, forest floor, and soil in order to make a site suitable for natural or planted regeneration*" (Smith et al. 1997). In Saskatchewan, mechanical site preparation is the dominant site preparation technique (CCFM 2015). Mechanical site preparation uses machinery to expose, blend, elevate and/or depress mineral soils (McMinn and Hedin 1990). Mechanical site preparation also strives to redistribute surface organic layers and remove, kill, cut, uproot, or bury unwanted vegetation (Smith et al. 1997). Depending on the treatment type, mechanical site preparation can also increase soil temperatures (Brand 1991; Archibold et al. 2000), loosen compacted soils, improve soil nutrient availability, enhance soil moisture availability, and/or establish a drained microsite (Sutton 1993; McMinn and Hedin 1990). As a result, mechanical site preparation can positively influence crop tree growth (Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006; Boateng et al. 2009).

Mechanical site preparation can be classified into 3 conceptual groups: scalping, mixing, and inverting (McMinn and Hedin 1990). Scalping removes local vegetation, creates mineral soil depressions, and displaces the roots and rhizomes of competing species (McMinn and Hedin 1990; Von der Gonna 1992; Landhausser and Lieffers 1999). Scalping can also increase soil temperature during the growing season by exposing mineral soil; however, scalping may remove nutrient-rich soil horizons and collect water within scalped depressions (McMinn and Hedin 1990). Mixing homogenizes surface organic layers and mineral soil (McMinn and Hedin 1990). By combining upper soil horizons, mixing reduces soil bulk density, increases soil moisture-holding capacity, and incorporates nutrient-rich organic layers into the seedbed (Von der Gonna 1992; McMinn and Hedin 1990). Mixing can also control competing vegetation by pulverizing roots and stems; however, intense mixing is often required to suppress competition (McMinn and Hedin 1990). Mixing also exposes mineral soil, increases soil temperatures, and may encourage nutrient leaching (McMinn and Hedin 1990). Inverting overturns upper soil horizons and buries surface organic layers under a 'mineral soil cap' (McMinn and Hedin 1990). As a result, inverting exposes mineral soil, increases soil temperatures, and retains nutrient-rich organic layers within the seedbed (McMinn and Hedin 1990). Inverting may also control competing vegetation by burying roots and seeds; however, a thick 'mineral soil cap' is often required to suppress competition (McMinn and Hedin 1990; Landhausser and Lieffers 1999). Finally, scalping, mixing, or inverting treatments that elevate the soil can create well-drained seedbeds (McMinn and Hedin 1990; Sutton 1993).

In the PAFMA, common mechanical site preparation treatments include Bracke mounding, disc trenching, and v-plow scarification (Leblanc and Sutherland 1987; Archibold et al. 2000). Bracke mounding overturns discrete patches of soil onto the adjacent forest floor, yielding shallow scalped depressions and small coarsely-mixed mounds (McMinn and Hedin 1990; Sutton 1993). Disc trenching overturns rows of soil onto the adjacent forest floor, creating shallow scalped furrows and small coarsely-mixed berms (McMinn and Hedin 1990; Boateng et al. 2012). Finally, v-plow scarification pushes aside the forest floor, producing wide scalped furrows and large coarsely-mixed berms (McMinn and Hedin 1990). Each of these treatments provides scalped, 'hinge', or elevated microsites, depending on the silvicultural requirements of the site (McMinn and Hedin 1990; Boateng et al. 2012; Lof et al. 2012). In terms of soil disturbance, Bracke mounding disturbs 10 to 30% of the site (Von der Gonna 1992). Disc trenching disturbs 25 to 50% of the site, and v-plow scarification disturbs 30 to 60% of the site (Von der Gonna 1992). However, the intensity of blade scarification (e.g. V-plow) can vary, depending on the equipment, operator, and season of treatment (Youngblood et al. 2011). In general, crop tree growth often increases with increasing mechanical site preparation disturbance (Lof et al. 2012).

*Stand Tending*

Stand tending strives to control growth by manipulating stand density and species composition (Smith et al. 1997, pg 14). In Saskatchewan, juvenile stands may be tended with manual 'cleaning' treatments (Lieffers and Beck 1994; CCFM 2015). Cleaning is an early-rotation cutting that removes overtopping vegetation around desirable crop trees (Smith et al. 1997, pg 147). Since competing vegetation influences light, soil moisture, soil nutrient, and temperature conditions (Brand and Janas 1988; Spittlehouse and Stathers 1990; Brand 1991; Munson et al. 1993), cleaning may improve crop tree growth (Pitt et al. 2005; Kabzems et al. 2011).

*Objectives*

To assess silvicultural effects within the PAFMA, this chapter has 3 objectives: 1) Evaluate juvenile white spruce growth under operational silvicultural treatments in upland boreal mixedwoods; 2) Explore the influence of silviculture on plot-level competition; and 3) Discuss the design and implementation of robust silvicultural experiments.

## 2.2 Methods

*TSP Plantations and Treatments*

In 2011-2012, Temporary Sample Plots (TSP's) were established in 16 white spruce plantations across the PAFMA (Figure 2-1; Table 2-1). All plantations were identified in the PAFMA geospatial database. Target sites were established between 1989-1999, planted with 1-0 containerized stock, and larger than 10 hectares in size. After initial filtering and site inspection, 4 plantations were selected across 4 silvicultural treatments: Bracke Mounding / Untended (BM-U), V-Plow Scarification / Untended (VP-U), Disc Trenching / Untended (DT-U), and Disc Trenching / Tended (DT-T) (Figure 2-1). Wildfire damage, flooded roads, and decommissioned bridges severely hindered plantation selection. If possible, plantations were randomly distributed across the PAFMA and/or separated by at least 500m. However, mechanical site preparation treatments were frequently clustered (e.g. Bracke mounding) (Figure 2-1), making minimum separation distances impossible. Plantations without tending and/or mechanical site preparation (i.e. untreated control) could not be located.

On selected plantations, harvesting occurred between 1991 and 1996 (Table 2-1). Site preparation typically followed within 1 year of harvesting, and planting occurred within 1 year of site preparation. All plantations were established between 1993 and 1998 in early summer (Table 2-1), and white spruce seedlings were planted in the 'hinge' microsite (McMinn and Hedin 1990; Boateng et al. 2012). In the Disc Trenching / Tended treatment, plantations were operationally cleaned between 2002 and 2005 (Table 2-1). Cleaning treatments were applied at the stand-level and removed deciduous competition within a 1 to 2m radius of planted white spruce. Stand-level cleaning prescriptions were not recorded, and post-cleaning stand densities were not measured.

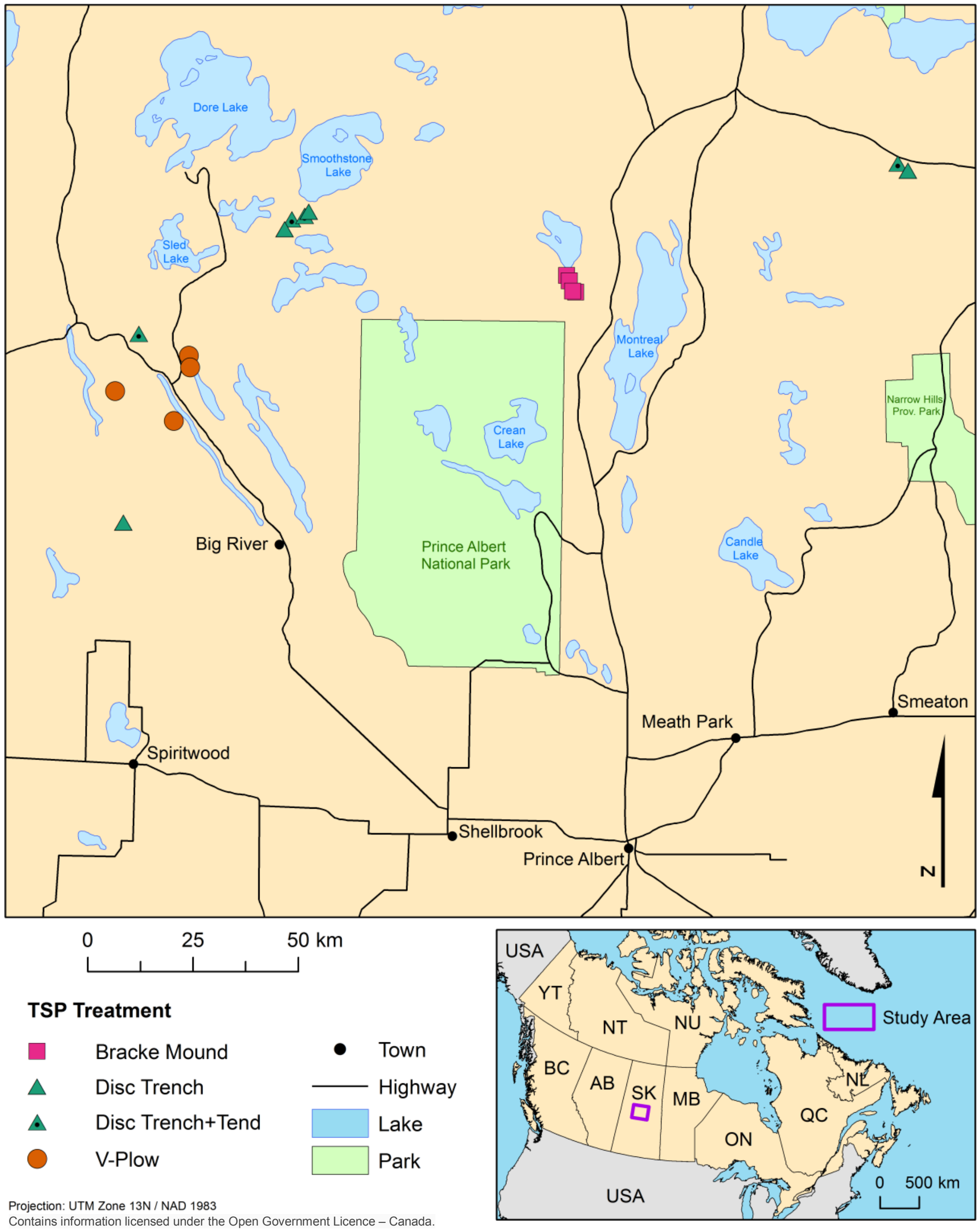


Figure 2-1. TSP stand locations and mechanical site preparation treatments.

Table 2-1. TSP plantation treatment regime, plantation information, and establishment events.

| Plantation | Name | **Area** (ha) | MSP | Spp | Stock | Harv Yr | **MSP Date** (dd/mm/yyyy) | **Plant Date** (dd/mm/yyyy) | **Tend Date** (dd/mm/yyyy) |
|---|---|---|---|---|---|---|---|---|---|
| 96_CCAMP_94.04 | Central Camp #2 | 16.0 | DT | WS | 1+0 C (410) | 1996 | 27/06/1997 | 13/05/1998 | . |
| 96_CCAMP_94.10 | Central Camp #1 | 39.5 | DT | WS | 1+0 C (410) | 1996 | 27/06/1997 | 21/05/1998 | 12/08/2005 |
| 96_NORT_95.11.2 | Norton Lake | 22.5 | DT | WS | 1+0 C (410) | 1996 | 21/08/1997 | 13/05/1998 | 16/09/2005 |
| 96_VIMYT_96.17 | Vimy Tower | 42.8 | DT | WS | 1+0 C (410) | 1996 | 25/07/1997 | 06/05/1998 | . |
| U07_23 | Weyakwin Lake #1 | 34.8 | BM | WS | 1+0 C (313B) | 1994 | 31/10/1995 | 10/06/1996 | . |
| U07_41 | Weyakwin Lake #2 | 26.0 | BM | WS | 1+0 C (313B) | 1994 | 31/10/1995 | 10/06/1996 | . |
| U07_77.2 | Wanner Lake #1 | 12.9 | BM | WS | 1+0 C (313B) | 1995 | 31/10/1995 | 06/07/1996 | . |
| U07_103 | Wanner Lake #2 | 38.9 | BM | WS | 1+0 C (313B) | 1994 | 31/10/1995 | 06/07/1996 | . |
| U14_273.1 | Clarke Tower #1 | 25.1 | DT | WS | 1+0 C (313B) | 1994 | 30/08/1995 | 29/06/1996 | 03/08/2002 |
| U14_337.1 | Clarke Tower #2 | 19.9 | DT | WS | 1+0 C (313B) | 1994 | 30/08/1995 | 05/07/1996 | . |
| U23_15 | Roberts Lake | 55.8 | VP | WS | 1+0 C (410B) | 1994 | 19/03/1996 | 15/05/1996 | . |
| U23_93 | Cowan North | 96.5 | VP | WS | 1+0 C (313B) | 1992 | - / - /1994 | 27/06/1994 | . |
| U23_158 | Taggart Creek | 20.2 | VP | WS | 1+0 C (313B) | 1991 | 02/10/1992 | 24/06/1993 | . |
| U23_299 | Taggart Lake | 11.0 | VP | WS | 1+0 C (313B) | 1991 | 02/10/1992 | 24/06/1993 | . |
| U24_413 | Smoothstone Lake #2 | 41.9 | DT | WS | 1+0 C (313B) | 1995 | 02/08/1995 | 07/07/1996 | 28/01/2005 |
| U24_425 | Smoothstone Lake #1 | 23.2 | DT | WS | 1+0 C (313B) | 1995 | 02/08/1995 | 07/07/1996 | . |

**Note:** ha = hectares; MSP = mechanical site preparation; DT = disc trenching; BM = Bracke mounding; VP = v-plow scarification; Spp = planted tree species; WS = white spruce; C = Container; Harv Yr = Harvest Year; dd/mm/yyyy = day/month/year; Plant Date = Planting Date; Tend Date = Tending Date; '-' = data unavailable; '.' = not applicable

Table 2-2. TSP plantation site information. Ecosite classes, topographic positions, moisture regimes, nutrient regimes, drainage classes, and effective soil textures are defined in Beckingham et al. (1996).

| **Plantation** | **Name** | **Elev.** (m) | **Aspect** (°) | **Slope** (%) | **Ecosite** | **Topo. Position** | **Moisture Regime** | **Nutrient Regime** | **Drainage Class** |
|---|---|---|---|---|---|---|---|---|---|
| 96_CCAMP_94.04 | Central Camp #2 | 514 - 521 | 90 - 270 | 2 - 10 | d - e | MS - LS | 5 - 6 | C - C | MW - I |
| 96_CCAMP_94.10 | Central Camp #1 | 502 - 527 | 0 - 0 | 0 - 0 | d - d | L - L | 6 - 6 | C - C | MW - I |
| 96_NORT_95.11.2 | Norton Lake | 489 - 495 | 0 - 0 | 2 - 2 | e - h | LS - L | 6 - 7 | C - D | I - I |
| 96_VIMYT_96.17 | Vimy Tower | 580 - 583 | 23 - 337 | 4 - 16 | d - e | MS - L | 5 - 6 | C - C | W - I |
| U07_23 | Weyakwin Lake #1 | 622 - 634 | 45 - 270 | 2 - 6 | d - e | MS - L | 5 - 6 | C - C | W - I |
| U07_41 | Weyakwin Lake #2 | 606 - 642 | 0 - 180 | 2 - 10 | d - d | MS - MS | 5 - 6 | C - C | MW - I |
| U07_77.2 | Wanner Lake #1 | 632 - 645 | 135 - 180 | 2 - 4 | g - g | MS - L | 7 - 7 | C - C | I - I |
| U07_103 | Wanner Lake #2 | 624 - 631 | 180 - 180 | 7 - 7 | d - d | MS - L | 6 - 6 | C - C | MW - I |
| U14_273.1 | Clarke Tower #1 | 559 - 575 | 90 - 270 | 2 - 10 | d - d | MS - MS | 5 - 6 | C - C | MW - I |
| U14_337.1 | Clarke Tower #2 | 512 - 533 | 7 - 90 | 0 - 8 | d - h | MS - LS | 5 - 6 | C - C | MW - I |
| U23_15 | Roberts Lake | 488 - 505 | 90 - 225 | 1 - 2 | e - e | MS - L | 6 - 6 | C - D | MW - I |
| U23_93 | Cowan North | 500 - 508 | 0 - 180 | 6 - 6 | d - e | MS - LS | 5 - 6 | C - C | W - I |
| U23_158 | Taggart Creek | 484 - 491 | 0 - 0 | 0 - 0 | e - h | L - L | 6 - 7 | C - D | I - I |
| U23_299 | Taggart Lake | 491 - 521 | 0 - 0 | 10 - 10 | d - h | MS - L | 5 - 7 | C - D | MW - I |
| U24_413 | Smoothstone Lake #2 | 513 - 518 | 0 - 180 | 2 - 2 | d - e | MS - L | 5 - 6 | C - C | MW - I |
| U24_425 | Smoothstone Lake #1 | 509 - 522 | 0 - 270 | 1 - 10 | d - e | MS - LS | 5 - 6 | C - C | MW - I |

**Note:** Elev. = elevation; Ecosite: d = mesic/medium, e = subhygric/rich, g = hygric/poor; h = hygric/rich; Topographic Position: L = level, MS = middle slope, LS = lower slope; Mositure Regime: 5 = mesic; 6 = subhygric; 7 = hygric; Nutrient Regime: C = medium, D = rich; Drainage Class: W = well, MW = moderately well, I = imperfect.

*TSP Plantation Characteristics*

TSP plantations occupied mesic to hygric soil moisture regimes, medium to rich soil nutrient regimes, and well-drained to imperfectly drained soil profiles (Table 2-2). Most plantations occured on intermediate relief sites (0 to 16%) across mid-slope, lower-slope, and level topographic positions. Plantation elevations ranged from 484 to 645m above sea level. Given these site characteristics, TSP's were classified under ecosites 'd' (mesic/medium), 'e' (subhygric/rich), 'g' (hygric/poor), and 'h' (hygric/rich) (Beckingham et al. 1996; Table 2-2).

*TSP Measurement Protocol*

Within each treated white spruce plantation, 4 circular 100m$^2$ TSP's were established on upland sites (Figure 2-2). All TSP locations were determined *a priori* with a random point generator in ArcGIS. To limit edge-effects and unusual treatment responses, TSP's were not located within 25m of roads, landings, or stand boundaries. TSP's were also screened to avoid saturated soils (e.g. subhydric or hydric ecosites), advance regeneration, slash piles, or glacial erratics. If necessary, rejected TSP's were substituted with other random locations within the same plantation. Ultimately, 64 TSP's were sampled across 16 white spruce plantations.

Height, DBH, and defect were measured on spruce (>1.3m height) within the 100m$^2$ primary plot (Figure 2-2). For spruce between 0.3m and 1.3m, height was tallied into 2 discrete classes (Class 1: 0.3m-0.8m; Class 2: 0.81m-1.3m) within the 100m$^2$ primary plot. Height and DBH were also measured on competing tree species (>1.3m height) within 1 to 4 circular 10m$^2$ subplots. For competing trees between 0.3m and 1.3m, height was tallied into 2 discrete classes (Class 1: 0.3m-0.8m; Class 2: 0.81m-1.3m) within 1 to 4 circular 10m$^2$ subplots. Competition subplots were added incrementally until approximately 20 trees were sampled (Figure 2-2). All trees within the primary plot were also tallied to indicate cumulative plot-level competition.

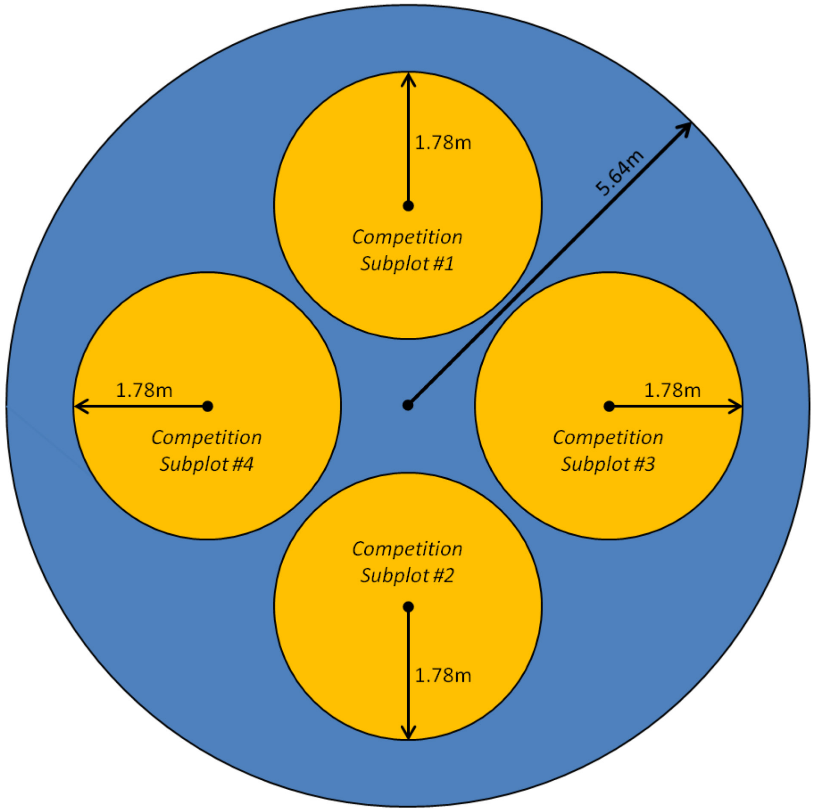


Figure 2-2. Basic TSP design. The circular 100m$^2$ primary plot (5.64m radius) is represented in blue. The circular 10m$^2$ 'competition subplots' (1.78m radius) are identified in orange. Plot radii are identified with black arrows.

Outside each TSP, a soil pit was excavated in a site prepared depression to determine effective texture, soil drainage class, and soil moisture regime. Pit depth ranged from 0.5m to 1.0m; however, bedrock or other impenetrable layers occasionally prevented excavation to 0.5m. Since site preparation disturbed humus layers and upper soil horizons, soil nutrient regime was approximated using effective texture, soil depth, seepage, and indicator vegetation (e.g. *Ledum groenlandicum*). Slope, aspect, topographic position, and understory species were also assessed. Finally, vegetation cover was visually estimated for grasses, herbs, tall shrubs, and low shrubs within the primary plot. After soil, site, and floristic evaluation, each TSP was assigned an ecosite under Beckingham et al. (1996).

*Data Management*

Across the TSP dataset, most plantations occupied mixedwood ecosites 'd' (mesic/medium), 'e' (subhygric/rich), and 'h' (hygric/rich); these ecosites are characterized by mixedwood stands with relatively vigorous white spruce growth (i.e. Site Index: 18.1m-19.7m) (Table 2-2; Beckingham et al. 1996). However, TSP plantation U07_77.2 occupied ecosite 'g' (hygric/poor), a conifer-dominated ecosite with poor white spruce growth (i.e. Site Index: 10.9m) (Table 2-2; Figure 2-3; Beckingham et al. 1996). Given U07_77.2's unusual ecosite and poor white spruce growth, U07_77.2 was excluded from silvicultural analysis.

Figure 2-3. Fifteen-year-old TSP plantation U07_77.2. Chlorotic and stunted white spruce located among vigorous black spruce and jack pine. White spruce are identified with pink ribbons. Deciduous trees are infrequent and stunted (i.e. right background).

For white spruce silvicultural analysis, trees under 1.3m were excluded, and white spruce with extensive lean were not considered (Table 2-3). However, white spruce with forking, sweep, or moderate stem damage (e.g. abrasion) were retained; these trees were considered representative of early-successional growth.

Table 2-3. TSP white spruce tree-level variables.

| Species | N | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| WS | 738 | Height (m) | 2.7 | 1.3 | 6.4 | 0.9 |
| | | DBH (cm) | 2.3 | 0.2 | 8.6 | 1.5 |

**Note:** WS = white spruce; N = number of observations; SD = standard deviation; DBH = diameter at breast height (1.3m).

Table 2-4. TSP plot-level competition variables.

| Species | Plots | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Total Basal Area ($m^2$/ha) | 16.7 | 4.9 | 34.3 | 8.1 |
| | | Conifer Basal Area ($m^2$/ha) | 2.1 | 0.0 | 16.3 | 3.3 |
| | | Deciduous Basal Area ($m^2$/ha) | 14.6 | 0.0 | 34.2 | 8.8 |
| | | Total Density #1 (trees/ha) | 15802 | 1900 | 49200 | 10291 |
| | | Conifer Density #1 (trees/ha) | 4139 | 100 | 47700 | 6832 |
| | | Deciduous Density #1 (trees/ha) | 11663 | 1000 | 38000 | 7583 |
| | | Total Density #2 (trees/ha) | 12715 | 2900 | 33000 | 7367 |
| | | Conifer Density #2 (trees/ha) | 3728 | 100 | 17400 | 4042 |
| | | Deciduous Density #2 (trees/ha) | 8987 | 300 | 28400 | 5637 |
| | | Grass Cover (%) | 29.0 | 0.0 | 95.0 | 33.7 |
| | | Herb Cover (%) | 19.9 | 1.0 | 70.0 | 14.4 |
| | | Low Shrub Cover (%) | 19.5 | 0.0 | 60.0 | 15.4 |
| | | Tall Shrub Cover (%) | 19.0 | 0.0 | 70.0 | 16.3 |

**Note:** ALL = all species; Plots = number of plots; SD = standard deviation; Density #1 = subplot density; Density #2 = primary plot density.

*Silvicultural Analysis in Operationally Treated Plantations*

After data filtering, 60 TSP's were randomly sampled in 15 random plantations[1] across the PAFMA. Four TSP's were sampled in each plantation, and 3 to 4 plantations were evaluated in each silvicultural treatment. This sampling design represents a randomized sample with plantations nested in silvicultural treatments and TSP's nested in plantations.

Since all plantations were operationally established, each plantation only contained 1 silvicultural treatment. Therefore, all 4 silvicultural treatments could not be assessed at the stand-level, and plantation×treatment interactions could not

[1] When possible, target plantations 1) established between 1989-1999, 2) planted with 1-0 containerized stock, and 3) larger than 10 hectares were randomly distributed across the PAFMA. However, plantations in the Bracke mounding treatment were clustered, since these plantations were established under operational objectives (e.g. equipment availability, contractor availability, season of treatment, etc).

be evaluated. In addition, plantations representing a 'raw planted' control could not be located within the PAFMA. TSP silvicultural analysis proceeded without blocked treatments, treatment×plantation interactions, or a 'raw planted' control; I wholly acknowledge these problems and all subsequent limitations to statistical or silvicultural inference.

*Evaluating White Spruce Growth by Silvicultural Treatment*

White spruce height and DBH were evaluated using mixed-effects Analysis of Variance (ANOVA) and Analysis of Covariance (ANCOVA) (Equations 2-1, 2-2, and 2-3). Preliminary ANOVAs were fit with Maximum Likelihood (ML) to allow Bayesian Information Criterion (BIC) comparisons between models with different fixed-effects (Equation 2-1; Pinheiro and Bates 2000, pgs 10, 19, 76). Then, if normality or homoscedasticity assumptions were not satisfied, preliminary ANOVAs were re-fit with natural logarithm and square root transformations of height and DBH. Finally, ANOVAs with normal and homoscedastic residuals were re-fit with Restricted Maximum Likelihood (REML) to accurately estimate model variance (Pinheiro and Bates 2000, pg 37). Then, treatment effects were evaluated with marginal F-tests (p-value ≤ 0.05), and significant treatments were compared using Tukey's Honestly Significant Difference Test (p-value ≤ 0.05).

$$Y_{ijkl} = \mu + \tau_i + b_j + b_{jk} + \varepsilon_{ijkl} \qquad \text{(Equation 2-1)}$$

where $Y_{ijkl}$ is height, ln(height), sqrt(height), DBH, ln(DBH+1), or sqrt(DBH+1) for tree $l$ in plot $k$ in stand $j$, and silvicultural treatment $i$, $\mu$ is the overall mean, $\tau_i$ is the silvicultural treatment ($i$ = BM-U, DT-T, DT-U, VP-U), $b_j$ is the stand-level random-effect, $b_{jk}$ is the plot-level random-effect, and $\varepsilon_{ijkl}$ is the residual error.

Preliminary ANCOVAs were fit with a treatment/covariate interaction to assure homogenous covariate slopes (Equation 2-2). Then, interaction significance was evaluated with marginal F-tests (p-value ≤ 0.05), and

ANCOVAs with a common covariate slope were re-fit without the treatment/covariate interaction (Equation 2-3). If normality or homoscedasticity assumptions were not satisfied, preliminary ANCOVAs were re-evaluated with natural logarithm and square root transformations of height and DBH. All preliminary ANCOVAs were fit with ML for BIC comparisons. Finally, ANCOVAs with normal and homoscedastic residuals were fit with Restricted Maximum Likelihood (REML) to accurately estimate model variance (Pinheiro and Bates 2000, pg 37). Then, treatment and covariate effects were evaluated with marginal F-tests (p-value ≤ 0.05), and significant treatments were compared with Tukey's Honestly Significant Difference Test (p-value ≤ 0.05).

$$Y_{ijkl} = \mu + \tau_i + \beta_i x_{ijk} + b_j + b_{jk} + \varepsilon_{ijkl} \qquad \text{(Equation 2-2)}$$

where $Y_{ijkl}$ is height, ln(height), sqrt(height), DBH, ln(DBH+1), or sqrt(DBH+1) for tree $l$ in plot $k$ in stand $j$, and silvicultural treatment $i$, $\mu$ is the overall mean, $\tau_i$ is the silvicultural treatment ($i$ = BM-U, DT-T, DT-U, VP-U), $\beta_i$ is the heterogeneous covariate slope, $x_{ijk}$ is the plot-level covariate, $b_j$ is the stand-level random-effect, $b_{jk}$ is the plot-level random-effect, and $\varepsilon_{ijkl}$ is the residual error.

$$Y_{ijkl} = \mu + \tau_i + \beta x_{ijk} + b_j + b_{jk} + \varepsilon_{ijkl} \qquad \text{(Equation 2-3)}$$

where $Y_{ijkl}$ is height, ln(height), sqrt(height), DBH, ln(DBH+1), or sqrt(DBH+1) for tree $l$ in plot $k$ in stand $j$, and silvicultural treatment $i$, $\mu$ is the overall mean, $\tau_i$ is the silvicultural treatment ($i$ = BM-U, DT-T, DT-U, VP-U), $\beta$ is the common covariate slope, $x_{ijk}$ is the plot-level covariate, $b_j$ is the stand-level random-effect, $b_{jk}$ is the plot-level random-effect, and $\varepsilon_{ijkl}$ is the residual error.

ANCOVA covariates included planting year, drainage class, soil moisture regime, and soil nutrient regime. All covariates were expressed as continuous integers (e.g. 4, 5, 6); however, soil moisture regime and soil nutrient regime were also expressed as continuous rational numbers (e.g. 4.0, 4.5, 5.0). Covariates were incorporated into each ANCOVA model individually to prevent over-parameterization and complex interactions. Planting year was used to compensate for age differences between TSP plantations (Table 2-1), and drainage class, soil moisture regime, and nutrient regime were used to compensate for productivity differences between TSP's (Table 2-2). In other studies, drainage class, soil moisture regime, and soil nutrient regime have been linked with white spruce productivity (Kabzems 1971; Beckingham et al. 1996; Wang and Klinka 1996).

*Exploring Silviculture's Influence on Plot-level Competition*

Plot-level competition was evaluated using mixed-effects ANOVAs under REML estimation (Equation 2-4). All plot-level competition variables were log-transformed to stabilize variance and/or model 'density variables' under a parametric framework (Equation 2-4; Zuur et al. 2009, pg 205). Treatment effects were evaluated with marginal F-tests (p-value ≤ 0.05), and significant treatments were compared using Tukey's Honestly Significant Difference Test (p-value ≤ 0.05). Plot-level competition variables included total basal area, conifer basal area, deciduous basal area, grass cover, herb cover, low shrub cover, and tall shrub cover. Total density, conifer density, and deciduous density were also modeled using subplot observations and primary plot observations (Figure 2-2).

$$ln(Y_{ijk} + 1) = \mu + \tau_i + b_j + \varepsilon_{ijk} \quad \text{(Equation 2-4)}$$

where $ln(Y_{ijk}+1)$ is the natural logarithm of plot-level competition for plot $k$ in stand $j$, and silvicultural treatment $i$, $\mu$ is the overall mean, $\tau_i$ is the silvicultural treatment ($i$ = BM-U, DT-T, DT-U, VP-U), $b_j$ is the stand-level random-effect, and $\varepsilon_{ijk}$ is the residual error.

*Analytical Software*

All mixed-effects models were fit using the *nlme* package in *R* (Pinheiro et al. 2015; Pinheiro and Bates 2000). All *nlme* models must meet 2 primary assumptions:

1. "*The within group errors are independent and identically normally distributed, with mean zero and variance $\sigma^2$, and they are independent of the random-effects*" (Pinheiro and Bates 2000, pgs 174, 360).
2. "*The random-effects are normally distributed, with mean zero and covariance matrix Ψ (not depending on the group) and are independent for different groups*" (Pinheiro and Bates 2000, pgs 174, 361).

Assumptions '1' and '2' were assessed using residual variance plots, residual histograms, and random-effect histograms. For each analytical graph, residuals were expressed as "standardized residuals" (i.e. raw residuals / estimated standard deviation) (Pinheiro and Bates 2000, pg 149). Shapiro-Wilk normality tests were performed on each model's standardized residuals and estimated random-effects. To assess significant treatment effects, paired comparisons were performed using the *R* package *lsmeans* (Lenth and Hervac 2015). This package produces 'predicted marginal' or 'least-squares' means similar to the SAS procedure 'LSMEANS' (Lenth 2015).

**2.3 Results**

*White Spruce Height by Silvicultural Treatment*

Preliminary ANOVA and ANCOVA models for white spruce height produced heteroscedastic and non-normal residuals (Appendix 1: Table A-1-1). As a result, all preliminary ANOVAs and ANCOVAs were re-fit with natural logarithm and square root transformations (Tables A-1-2 and A-1-3). Log-transformation largely eliminated ANOVA and ANCOVA heteroscedasticity but failed to generate normally distributed residuals (Table A-1-2). Alternately, square root transformation reduced ANOVA and ANCOVA heteroscedasticity and produced normally distributed residuals (Table A-1-3). Therefore, final ANOVA and ANCOVA models for white spruce height were fit using a square root transformation (Table 2-5).

Regardless of the height transformation, preliminary ANCOVAs that included planting year and 'integer soil nutrient regime' failed to converge with a covariate/treatment interaction (Equation 2-2; Tables A-1-1, A-1-2, and A-1-3). The remaining ANCOVAs under Equation 2-2 did not contain significant covariate/treatment interactions, allowing preliminary analysis to use 'common slope' ANCOVA models (Equation 2-3). Preliminary ANCOVAs containing 'integer soil moisture regime' (Equation 2-3) produced the lowest BIC's, followed by the preliminary ANOVAs (Equation 2-1; Tables A-1-1, A-1-2, and A-1-3).

Among the final models for white spruce height, ANCOVAs that included planting year and 'integer soil nutrient regime' failed to converge with a covariate/treatment interaction (Equation 2-2; Table 2-5). The remaining ANCOVAs under Equation 2-2 did not contain significant covariate/treatment interactions, allowing final analysis to use 'common slope' ANCOVAs (Equation 2-3; Table 2-5). Overall, silvicultural treatment failed to explain differences in white spruce height. However, the covariates drainage class and 'integer soil moisture regime' were significant in ANCOVAs 2.1.48 and 2.1.49 (Equation 2-3; Table 2-5). Diagnostic graphs for final ANOVA 2.1.40 and 'integer soil moisture regime' ANCOVA 2.1.49 are provided in Figures 2-4 and 2-5.

Table 2-5. Final ANOVA and ANCOVA summary statistics for sqrt(white spruce height). All models were fit using stand-level random-effects, plot-level random-effects, and REML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05. Model numbers 2.1.1 through 2.1.39 are found in Appendix 1: Tables A-1-1, A-1-2, and A-1-3.

| | | Parameters | | | | | | | | | | | | F-Test p-values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.1.40 | sqrt(HT)=ST | *1.54* | 0.10 | 0.03 | 0.12 | . | 0.24 | 132.15 | ◒ | ◒ | ● | ● | ● | 0.53 | . | . |
| 2.1.41 | sqrt(HT)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.42 | sqrt(HT)=ST×DC | 1.76 | 0.50 | 0.36 | -0.06 | -0.05 | 0.24 | 166.02 | ◒ | ◒ | ● | ● | ● | 0.54 | 0.52 | 0.46 |
| 2.1.43 | sqrt(HT)=ST×MR1 | 2.16 | 0.33 | 0.25 | -0.42 | -0.11 | 0.24 | 162.74 | ◒ | ◒ | ● | ● | ● | 0.56 | 0.27 | 0.44 |
| 2.1.44 | sqrt(HT)=ST×MR2 | 1.97 | 0.57 | 0.73 | -0.30 | -0.08 | 0.24 | 163.01 | ◒ | ◒ | ● | ● | ● | 0.42 | 0.45 | 0.32 |
| 2.1.45 | sqrt(HT)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.46 | sqrt(HT)=ST×NR2 | *1.26* | 0.73 | 1.26 | 0.51 | 0.10 | 0.24 | 159.96 | ◒ | ◒ | ● | ● | ● | 0.27 | 0.58 | 0.21 |
| 2.1.47 | sqrt(HT)=ST+PY | 64.09 | 0.13 | 0.07 | 0.06 | -0.03 | 0.24 | 142.82 | ◒ | ◒ | ● | ● | ● | 0.63 | 0.36 | . |
| 2.1.48 | sqrt(HT)=ST+DC | *1.83* | 0.12 | 0.04 | 0.13 | *-0.07* | 0.24 | 139.70 | ◒ | ◒ | ● | ● | ● | 0.42 | 0.05 | . |
| 2.1.49 | sqrt(HT)=ST+MR1 | *2.07* | 0.12 | 0.03 | 0.17 | *-0.10* | 0.24 | 137.31 | ◒ | ◒ | ● | ● | ● | 0.20 | 0.01 | . |
| 2.1.50 | sqrt(HT)=ST+MR2 | *1.99* | 0.11 | 0.02 | 0.15 | -0.08 | 0.24 | 139.57 | ◒ | ◒ | ● | ● | ● | 0.29 | 0.06 | . |
| 2.1.51 | sqrt(HT)=ST+NR1 | *1.35* | 0.09 | 0.03 | 0.11 | 0.06 | 0.24 | 141.38 | ◒ | ◒ | ● | ● | ○ | 0.68 | 0.45 | . |
| 2.1.52 | sqrt(HT)=ST+NR2 | *1.86* | 0.10 | 0.06 | 0.18 | -0.11 | 0.24 | 139.47 | ◒ | ◒ | ● | ● | ● | 0.31 | 0.09 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; sqrt(HT) = square root of height; "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

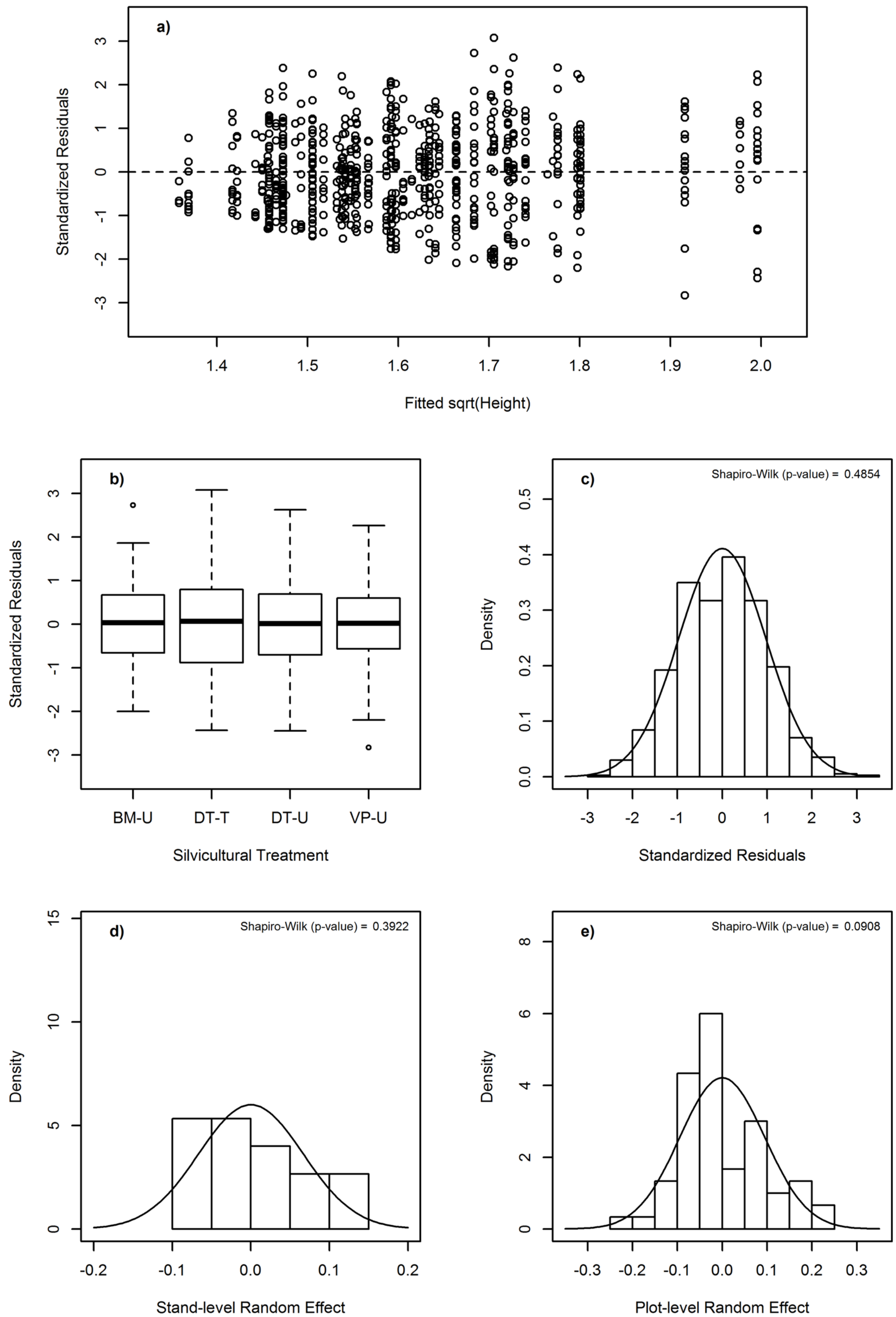


Figure 2-4. ANOVA residuals and random-effects for sqrt(white spruce height) (Table 2-5: Model 2.1.40): a) standardized residuals versus fitted height, b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

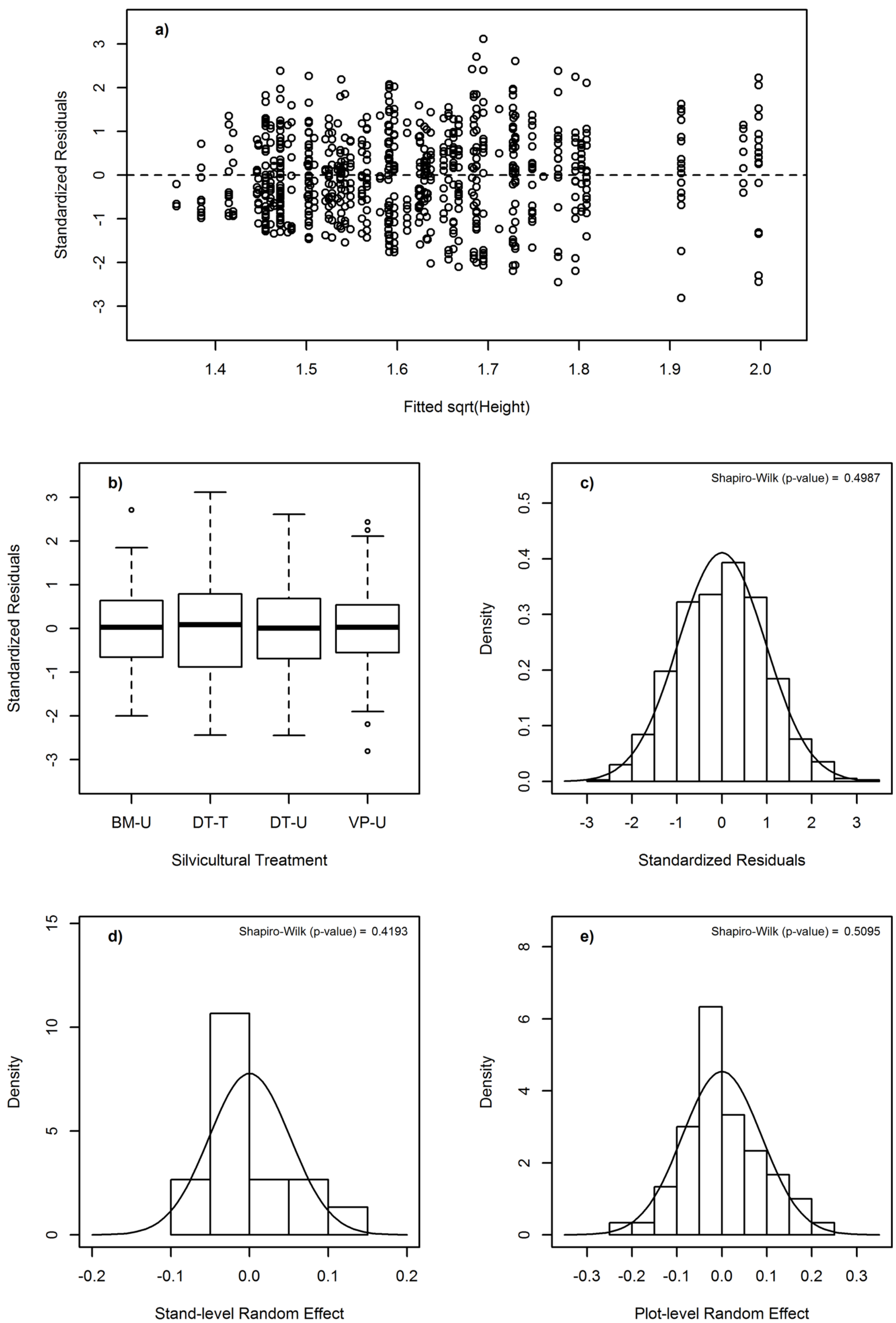


Figure 2-5. ANCOVA residuals and random-effects for sqrt(white spruce height) adjusted by 'integer soil moisture regime' (Table 2-5: Model 2.1.49): a) standardized residuals versus fitted height, b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

*White Spruce DBH by Silvicultural Treatment*

Preliminary ANOVA and ANCOVA models for white spruce DBH produced heteroscedastic and non-normal residuals (Table A-1-4). As a result, all preliminary ANOVAs and ANCOVAs were re-fit with natural logarithm and square root transformations (Tables A-1-5 and A-1-6). Log-transformation largely eliminated ANOVA and ANCOVA heteroscedasticity but failed to generate normally distributed residuals (Table A-1-5). Alternately, square root transformation reduced ANOVA and ANCOVA heteroscedasticity and produced normally distributed residuals (Table A-1-6). Therefore, final ANOVA and ANCOVA models for white spruce DBH were fit using a square root transformation (Table 2-6).

Regardless of the DBH transformation, preliminary ANCOVAs that included planting year and 'integer soil nutrient regime' failed to converge with a covariate/treatment interaction (Equation 2-2; Tables A-1-4, A-1-5, and A-1-6). The remaining ANCOVAs under Equation 2-2 did not contain significant covariate/treatment interactions, allowing preliminary analysis to use 'common slope' ANCOVA models (Equation 2-3). Preliminary ANOVAS produced the lowest BIC's (Equation 2-1), followed by ANCOVAs containing 'integer soil moisture regime' (Equation 2-3; Tables A-1-4, A-1-5, and A-1-6).

Among the final models for white spruce DBH, ANCOVAs that included planting year and 'integer soil nutrient regime' failed to converge with a covariate/treatment interaction (Equation 2-2; Table 2-6). The remaining ANCOVAs under Equation 2-2 did not contain significant covariate/treatment interactions, allowing final analysis to use 'common slope' ANCOVAs (Equation 2-3; Table 2-6). Silvicultural treatment significantly influenced white spruce DBH under the 'integer soil moisture regime' ANCOVA (Equation 2-3; Model 2.2.49). However, silvicultural treatment did not significantly influence any other DBH models. The covariates drainage class and 'integer soil moisture regime' were also significant in ANCOVAs 2.2.48 and 2.2.49 (Equation 2-3; Table 2-6). Diagnostic graphs for final ANOVA model 2.2.40 and 'integer soil moisture regime' ANCOVA 2.2.49 are provided in Figures 2-6 and 2-7.

Table 2-6. Final ANOVA and ANCOVA summary statistics for sqrt(white spruce DBH+1). All models were fit using stand-level random-effects, plot-level random-effects, and REML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05. Model numbers 2.2.1 through 2.2.39 are found in Appendix 1: Tables A-1-4, A-1-5, and A-1-6.

| | | Parameters | | | | | | | | | | | | | F-Test p-values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.2.40 | sqrt(DBH)=ST | *1.60* | 0.23 | 0.12 | *0.31* | . | 0.33 | 600.72 | ◒ | ◒ | ● | ● | ● | 0.14 | . | . |
| 2.2.41 | sqrt(DBH)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.42 | sqrt(DBH)=ST×DC | 1.82 | 0.81 | 0.67 | 0.26 | -0.05 | 0.33 | 632.25 | ◒ | ◒ | ● | ● | ● | 0.62 | 0.64 | 0.60 |
| 2.2.43 | sqrt(DBH)=ST×SMR1 | 2.31 | 0.42 | 0.68 | -0.31 | -0.13 | 0.33 | 630.04 | ◒ | ◒ | ● | ● | ● | 0.66 | 0.37 | 0.49 |
| 2.2.44 | sqrt(DBH)=ST×SMR2 | 1.97 | 0.69 | 1.49 | 0.03 | -0.07 | 0.33 | 630.87 | ◒ | ◒ | ● | ● | ● | 0.57 | 0.66 | 0.47 |
| 2.2.45 | sqrt(DBH)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.46 | sqrt(DBH)=ST×NR2 | 1.20 | 0.91 | *1.96* | 0.75 | 0.14 | 0.33 | 625.63 | ◒ | ◒ | ● | ● | ● | 0.19 | 0.57 | 0.14 |
| 2.2.47 | sqrt(DBH)=ST+PY | 45.18 | 0.25 | 0.14 | 0.27 | -0.02 | 0.33 | 611.44 | ◒ | ◒ | ● | ● | ● | 0.24 | 0.64 | . |
| 2.2.48 | sqrt(DBH)=ST+DC | *2.03* | 0.26 | 0.12 | *0.32* | *-0.10* | 0.33 | 607.32 | ◒ | ◒ | ● | ● | ● | 0.08 | 0.04 | . |
| 2.2.49 | sqrt(DBH)=ST+SMR1 | *2.26* | *0.26* | 0.11 | *0.37* | *-0.12* | 0.33 | 606.46 | ◒ | ◒ | ● | ● | ● | 0.04 | 0.03 | . |
| 2.2.50 | sqrt(DBH)=ST+SMR2 | *2.11* | 0.25 | 0.11 | *0.34* | -0.10 | 0.33 | 608.65 | ◒ | ◒ | ● | ● | ● | 0.08 | 0.12 | . |
| 2.2.51 | sqrt(DBH)=ST+NR1 | *1.15* | 0.22 | 0.12 | 0.27 | 0.15 | 0.33 | 608.19 | ◒ | ◒ | ● | ● | ● | 0.28 | 0.20 | . |
| 2.2.52 | sqrt(DBH)=ST+NR2 | *1.97* | 0.24 | 0.15 | *0.38* | -0.13 | 0.33 | 608.29 | ◒ | ◒ | ● | ● | ● | 0.09 | 0.16 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; sqrt(DBH+1) = square root of diameter at breast height (1.3m); "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

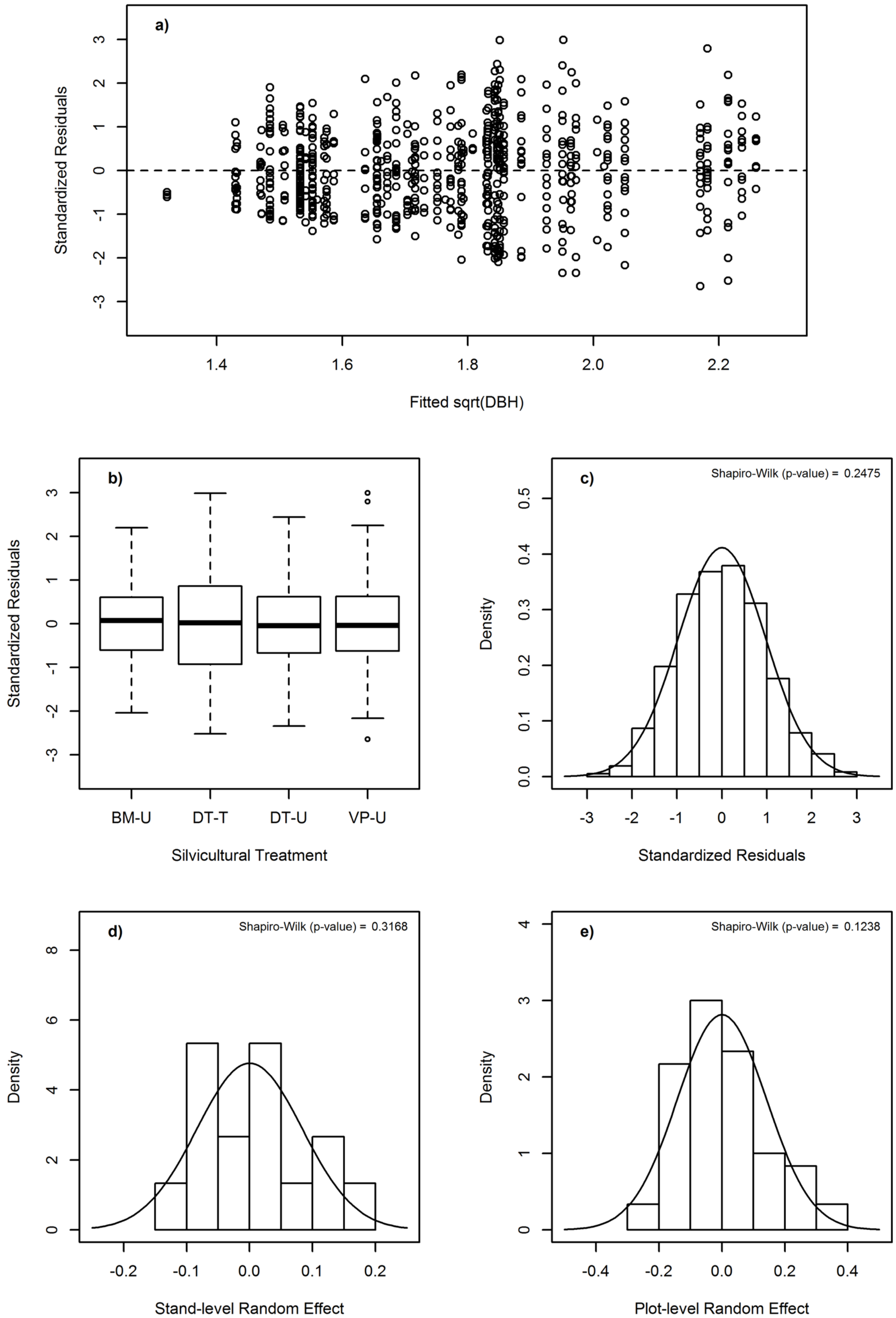


Figure 2-6. ANOVA residuals and random-effects for sqrt(white spruce DBH+1) (Table 2-6: Model 2.2.40): a) standardized residuals versus fitted DBH, b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

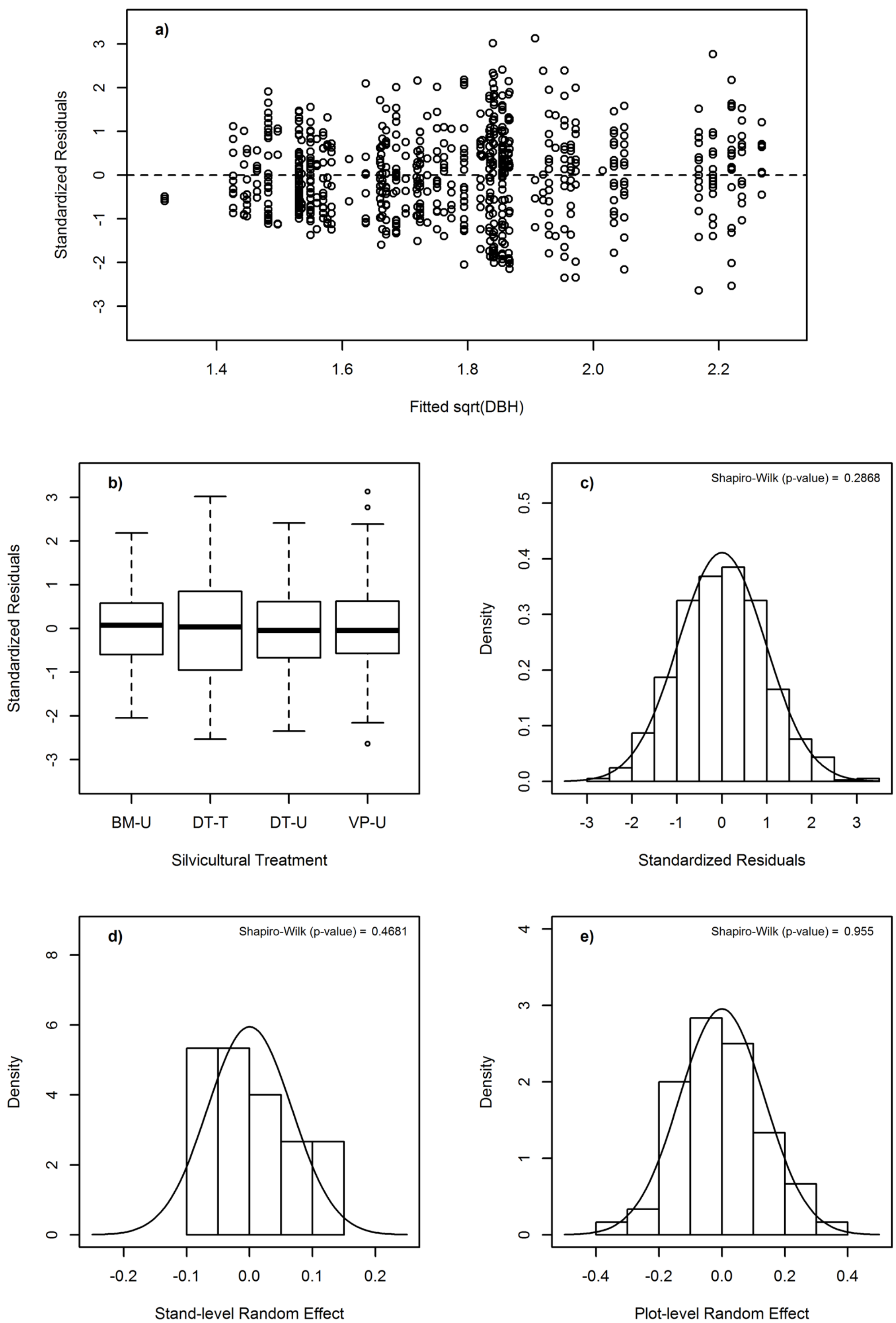


Figure 2-7. ANCOVA residuals and random-effects for sqrt(white spruce DBH+1) adjusted by 'integer soil moisture regime' (Table 2-6: Model 2.2.49): a) standardized residuals versus fitted DBH, b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

In ANCOVA 2.2.49, silvicultural treatment influenced the square root of white spruce DBH after adjusting for TSP soil moisture differences (Equation 2-3; Table 2-6). This model produced slightly heteroscedastic residuals with a normal distribution (Figure 2-7). Overall, residual variance was similar between treatments; however, the disc trenching/tended treatment appeared to have a slightly larger residual distribution (Figure 2-7). Stand-level and plot-level random-effects also passed Shapiro-Wilk normality tests. Under paired comparisons, DBH was significantly different between bracke mounding/untended and v-plow/untended treatments (Tables 2-7 and 2-8). All remaining DBH comparisons were not significant (Tables 2-7 and 2-8).

Table 2-7. ANCOVA 'least squares means' for sqrt(white spruce DBH+1) (Table 2-6: Model 2.2.49). All statistical inferences were performed using sqrt(white spruce DBH+1). Values within brackets represent DBH in centimetres.

| Treatment | LSMEAN | SE | $d_f$ | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|
| BM-U | 1.58 (1.49) | 0.09 | 14 | 1.39 (0.93) | 1.77 (2.12) |
| DT-T | 1.84 (2.39) | 0.07 | 11 | 1.68 (1.81) | 2.01 (3.02) |
| DT-U | 1.69 (1.86) | 0.08 | 11 | 1.53 (1.33) | 1.86 (2.45) |
| VP-U | 1.94 (2.78) | 0.08 | 11 | 1.77 (2.14) | 2.12 (3.48) |

**Note:** LSMEAN = least squares mean; SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; CI = confidence interval.

Table 2-8. ANCOVA contrasts for sqrt(white spruce DBH+1) (Table 2-6: Model 2.2.49). All statistical inferences were performed using sqrt(white spruce DBH+1) and Tukey's Honestly Significant Difference Test. Gray cells indicate p-values ≤ 0.05.

| Contrast | Estimate | SE | $d_f$ | t-ratio | p-value |
|---|---|---|---|---|---|
| BM-U vs. DT-T | -0.26 | 0.12 | 11 | -2.27 | 0.16 |
| BM-U vs. DT-U | -0.11 | 0.12 | 11 | -0.98 | 0.76 |
| BM-U vs. VP-U | -0.37 | 0.12 | 11 | -3.08 | 0.04 |
| DT-T vs. DT-U | 0.15 | 0.11 | 11 | 1.41 | 0.52 |
| DT-T vs. VP-U | -0.10 | 0.11 | 11 | -0.97 | 0.77 |
| DT-U vs. VP-U | -0.25 | 0.11 | 11 | -2.31 | 0.15 |

**Note:** SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

*Plot-level Competition by Silvicultural Treatment*

The residual variance of plot-level competition differed between silvicultural treatments and often failed to meet ANOVA variance equality assumptions (Table 2-9). Although competition variables were log-transformed, only the deciduous basal area and ‘primary plot deciduous density’ ANOVAs achieved partial variance equality between treatments (Table 2-9). In addition, all competition ANOVAs produced partially homoscedastic residuals (Table 2-9).

Among 13 competition variables, silvicultural treatment significantly influenced total basal area and grass cover (Equation 2-4; Models 2.3.1 and 2.3.10). The total basal area ANOVA produced slightly heteroscedastic residuals with a non-normal distribution (Figure 2-8). Residual variance differed between treatments, and stand-level random-effects passed a Shapiro-Wilk normality test (Figure 2-8). Under paired comparisons, total basal area was significantly different between disc trenching/tended and disc trenching/untended treatments (Tables 2-10 and 2-11). All remaining total basal area comparisons were not significant (Tables 2-10 and 2-11).

The grass cover ANOVA produced relatively homoscedastic residuals with a normal distribution (Figure 2-9). Residual variance differed between treatments, and stand-level random-effects passed a Shapiro-Wilk normality test (Figure 2-9). Under paired comparisons, grass cover was significantly different between 1) bracke mounding/untended and v-plow/untended treatments; 2) disc trenching/tended and disc trenching/untended treatments; and 3) disc trenching/untended and v-plow/untended treatments (Tables 2-12 and 2-13). All remaining grass cover comparisons were not significant (Tables 2-12 and 2-13). Given poor fit statistics, these ‘significant’ total basal area and grass cover effects should be considered ‘weak trends’.

Table 2-9. ANOVA summary statistics for log-transformed competition variables. All models were fit using stand-level random-effects and REML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | Parameters | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **F-Test p-value** |
| 2.3.1 | ln(TBA)=ST | *2.89* | *-0.49* | 0.04 | -0.04 | 0.46 | 106.32 | ◒ | ○ | ○ | ● | 0.03 |
| 2.3.2 | ln(CBA)=ST | *1.28* | -0.38 | -0.64 | -0.65 | 0.59 | 145.40 | ◒ | ○ | ● | ○ | 0.31 |
| 2.3.3 | ln(DBA)=ST | *2.58* | -0.49 | 0.27 | 0.04 | 0.61 | 149.02 | ◒ | ◒ | ○ | ○ | 0.21 |
| 2.3.4 | ln(TD1)=ST | *9.86* | -0.49 | -0.20 | *-0.75* | 0.52 | 131.85 | ◒ | ○ | ● | ● | 0.15 |
| 2.3.5 | ln(CD1)=ST | *8.45* | -0.82 | -0.66 | *-1.32* | 0.82 | 184.51 | ◒ | ○ | ○ | ○ | 0.21 |
| 2.3.6 | ln(DD1)=ST | *9.38* | -0.26 | 0.08 | -0.70 | 0.63 | 148.09 | ◒ | ○ | ● | ● | 0.10 |
| 2.3.7 | ln(TD2)=ST | *9.75* | -0.48 | -0.35 | *-0.91* | 0.29 | 84.29 | ◒ | ○ | ● | ● | 0.21 |
| 2.3.8 | ln(CD2)=ST | *8.48* | -0.73 | -0.67 | *-1.48* | 0.75 | 176.69 | ◒ | ○ | ● | ○ | 0.15 |
| 2.3.9 | ln(DD2)=ST | *9.20* | -0.25 | -0.12 | -0.82 | 0.52 | 138.75 | ◒ | ◒ | ○ | ● | 0.28 |
| 2.3.10 | ln(GC)=ST | *1.38* | *2.05* | 0.11 | *2.11* | 0.85 | 193.12 | ◒ | ○ | ● | ● | 0.01 |
| 2.3.11 | ln(HC)=ST | *2.42* | 0.53 | 0.58 | 0.16 | 0.75 | 169.38 | ◒ | ○ | ● | ○ | 0.44 |
| 2.3.12 | ln(LSC)=ST | *2.11* | *0.98* | 0.59 | 0.64 | 0.79 | 173.74 | ◒ | ○ | ○ | ● | 0.16 |
| 2.3.13 | ln(TSC)=ST | *2.77* | 0.17 | -0.72 | 0.07 | 0.67 | 165.37 | ◒ | ○ | ● | ● | 0.31 |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; ln() = natural logarithm; TBA = total basal area; ST = silvicultural treatment; CBA = conifer basal area; DBA = deciduous basal area; TD1 = subplot total density (trees/hectare); CD1 = subplot conifer density (trees/hectare); DD1 = subplot deciduous density (trees/hectare); TD2 = primary plot total density (trees/hectare); CD2 = primary plot conifer density (trees/hectare); DD2 = primary plot deciduous density (trees/hectare); GC = grass cover; HC = herb cover; LSC = low shrub cover; TSC = tall shrub cover; "●" = yes; "○" = no; "◒" = partial.

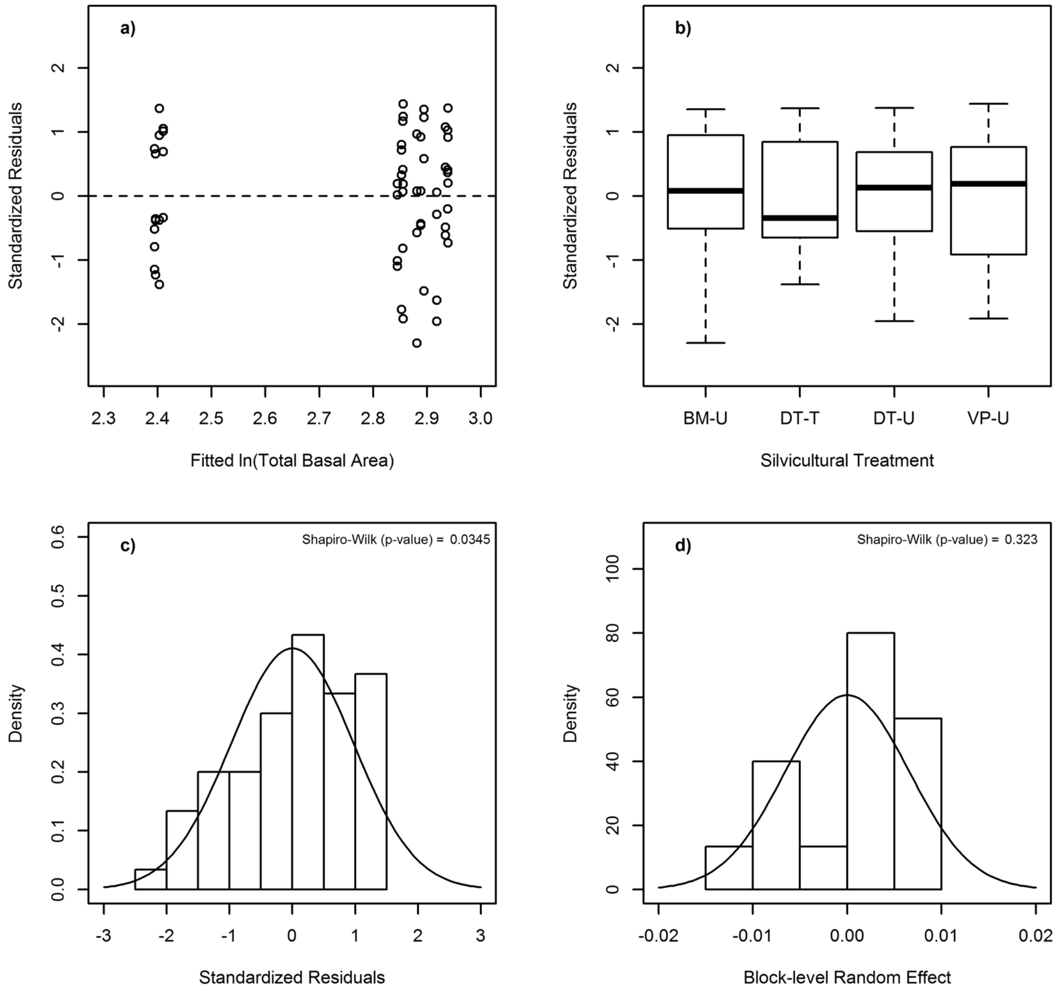


Figure 2-8. ANOVA residuals and random-effects for ln(total basal area) (Table 2-9: Model 2.3.1): a) standardized residuals versus fitted total basal area, b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

Table 2-10. ANOVA 'least squares means' for ln(total basal area) (Table 2-9: Model 2.3.1). All statistical inferences occurred using ln(total basal area). Values within brackets represent total basal area in $m^2$/hectare.

| Treatment | LSMEAN | SE | $d_f$ | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|
| BM-U | 2.89 (16.95) | 0.13 | 14 | 2.60 (12.47) | 3.17 (22.92) |
| DT-T | 2.40 (10.03) | 0.12 | 11 | 2.15 ( 7.55) | 2.66 (13.24) |
| DT-U | 2.93 (17.77) | 0.12 | 11 | 2.68 (13.54) | 3.19 (23.22) |
| VP-U | 2.85 (16.32) | 0.12 | 11 | 2.60 (12.42) | 3.11 (21.35) |

**Note:** LSMEAN = least squares mean; SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; CI = confidence interval.

Table 2-11. ANOVA contrasts for ln(total basal area) (Table 2-9: Model 2.3.1). All statistical inferences occurred using ln(total basal area) and Tukey's Honestly Significant Difference Test. Values within brackets represent total basal area in $m^2$/hectare. Gray cells indicate p-values ≤ 0.05.

| Contrast | Estimate | SE | $d_f$ | t-ratio | p-value |
|---|---|---|---|---|---|
| BM-U vs. DT-T | 0.49 (1.63) | 0.18 | 11 | 2.75 | 0.08 |
| BM-U vs. DT-U | -0.04 (0.96) | 0.18 | 11 | -0.25 | 0.99 |
| BM-U vs. VP-U | 0.04 (1.04) | 0.18 | 11 | 0.20 | 1.00 |
| DT-T vs. DT-U | -0.53 (0.59) | 0.16 | 11 | -3.24 | 0.03 |
| DT-T vs. VP-U | -0.45 (0.64) | 0.16 | 11 | -2.75 | 0.08 |
| DT-U vs. VP-U | 0.08 (1.08) | 0.16 | 11 | 0.49 | 0.96 |

**Note:** SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

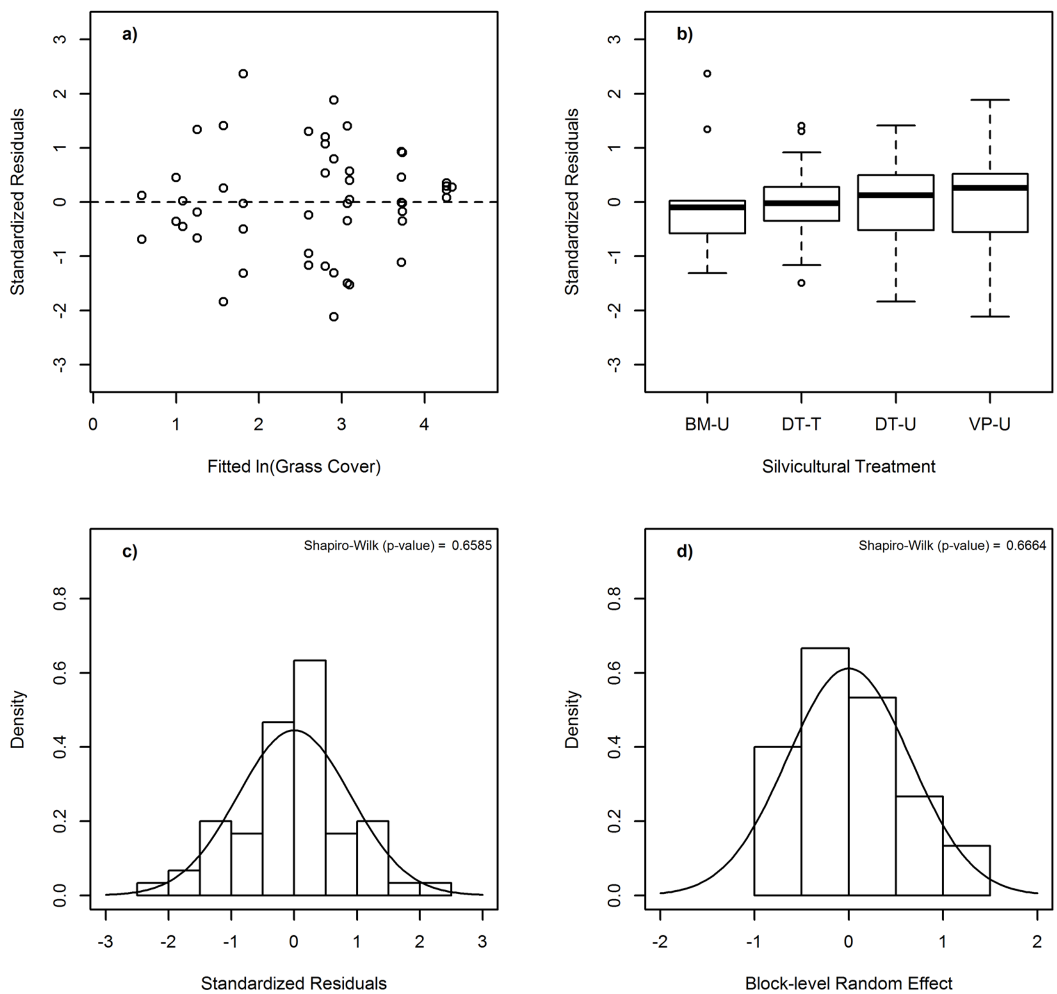


Figure 2-9. ANOVA residuals and random-effects for ln(grass cover) (Table 2-9: Model 2.3.10): a) standardized residuals versus fitted ln(grass cover), b) standardized residuals by silvicultural treatment, c) standardized residual distribution; d) stand-level random effect distribution; and e) plot-level random effect distribution. BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

Table 2-12. ANOVA 'least squares means' for ln(grass cover) (Table 2-9: Model 2.3.10). All statistical inferences occurred using ln(grass cover). Values within brackets represent grass cover (%).

| Treatment | LSMEAN | SE | $d_f$ | Lower 95% CI | Upper 95% CI |
|---|---|---|---|---|---|
| BM-U | 1.38 ( 2.98) | 0.54 | 14 | 0.23 ( 0.26) | 2.53 (11.59) |
| DT-T | 3.43 (29.88) | 0.47 | 11 | 2.41 (10.10) | 4.45 (84.95) |
| DT-U | 1.49 ( 3.43) | 0.47 | 11 | 0.46 ( 0.59) | 2.51 (11.32) |
| VP-U | 3.49 (31.90) | 0.47 | 11 | 2.47 (10.82) | 4.52 (90.57) |

**Note:** LSMEAN = least squares mean; SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; CI = confidence interval.

Table 2-13. ANOVA contrasts for ln(grass cover) (Table 2-9: Model 2.3.10). All statistical inferences occurred using ln(grass cover) and Tukey's Honestly Significant Difference Test. Values within brackets represent grass cover (%). Gray cells indicate p-values ≤ 0.05.

| Contrast | Estimate | SE | $d_f$ | t-ratio | p-value |
|---|---|---|---|---|---|
| BM-U vs. DT-T | -2.05 (0.13) | 0.71 | 11 | -2.88 | 0.06 |
| BM-U vs. DT-U | -0.11 (0.90) | 0.71 | 11 | -0.15 | 1.00 |
| BM-U vs. VP-U | -2.11 (0.12) | 0.71 | 11 | -2.97 | 0.05 |
| DT-T vs. DT-U | 1.94 (6.98) | 0.66 | 11 | 2.95 | 0.05 |
| DT-T vs. VP-U | -0.06 (0.94) | 0.66 | 11 | -0.10 | 1.00 |
| DT-U vs. VP-U | -2.01 (0.13) | 0.66 | 11 | -3.05 | 0.05 |

**Note:** SE = standard error; $d_f$ = degrees of freedom; BM-U = Bracke mounding/untended; DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended.

## 2.4 Discussion

*Silvicultural Trends*

Across the TSP dataset, silvicultural treatments did not influence juvenile white spruce height. However, silviculture had a significant effect on juvenile white spruce DBH. In particular, v-plow scarification appeared to increase white spruce DBH relative to Bracke mounding. These results correspond with literature; often, silvicultural effects are insignificant unless contrasting mild and aggressive treatments (Sutton et al. 2001; Boateng et al. 2006; Hawkins et al. 2006; Boateng et al. 2009). Although grass competition differed between v-plow and Bracke treatments, white spruce diameter effects could not be linked with significant differences in overstory vegetation (e.g. deciduous basal area). This result was not expected since overstory vegetation has a strong influence on white spruce DBH (e.g. Fu et al. 2007; Sharma and Parton 2007). Spatial differences in competition (i.e. linear vs. diffuse) may also have contributed to the observed diameter effect between v-plow and Bracke treatments (e.g. Figures 3-16 and 3-17); however, without spatially explicit data, this hypothesis could not be explored. Finally, for most ANOVA and ANCOVA models, *nlme* assumptions were partially or incompletely satisfied, casting doubt on some 'significant trends'.

*Limitations to Silvicultural Inference*

In this study, stand establishment occurred over a 5 year period, and each white spruce plantation occupied a different site with varying ecosites, soil moisture regimes, soil nutrient regimes, etc. (Table 2-2). Cumulatively, these factors complicated and/or confounded the interpretation of silvicultural responses. When evaluating silvicultural effects on white spruce growth, ANCOVA analysis was used to compensate for these site differences (e.g. soil moisture regime, soil nutrient regime, or planting year covariates). However, to prevent over-parameterization and complex interactions, only one 'site covariate' (e.g. soil moisture regime, soil nutrient regime, etc.) was incorporated into each ANCOVA model (Tables 2-5 and 2-6). In reality, site productivity can depend on many interacting factors like climate, soil moisture, soil nutrients, site preparation, thinning regime, and local environmental conditions (Beckingham et al. 1996; Wang 1995; Wang and Klinka 1996; Skovsgaard and Vanclay 2008). Moreover, "*the influence of site as an exogenous factor can blot out or bias the effects of the treatment being tested in some circumstances*" (Pretzsch 2009, pg 131).

White spruce growth was also compared between silvicultural treatments without a 'raw planted' control. In designed silvicultural experiments, control treatments can serve as a site-specific baseline to evaluate silvicultural efficacy, explore long-term silvicultural outcomes (e.g. Hawkins et al. 2006; Boateng et al. 2009; Cortini et al. 2010), and apply meta-analysis (Youngblood et al. 2011). Furthermore, subtle silvicultural effects are often insignificant unless contrasting against a 'raw planted' control (e.g. Sutton et al. 2001; Boateng et al. 2006; Hawkins et al. 2006; Boateng et al. 2009). Since a 'raw planted' control could not be located in the PAFMA, silvicultural efficacy and subtle silvicultural effects could not be explored.

The small TSP sample and clustered TSP plantations also limited silvicultural inference. In particular, all Bracke plantations were located within a small sample area (Figure 2-1). From an operational perspective, clustered silvicultural treatments may be reasonable since adjacent stands may share similar soil textures, soil moisture regimes, soil nutrient regimes, and competition intensities. Similarly, logistics may also contribute to clustered silvicultural treatments, given seasonal access issues and the high cost of transporting heavy equipment.

*Silviculture for White Spruce Plantations*

Historically, white spruce plantations have required site preparation to assure adequate survival and growth (Lieffers and Beck 1994). Poor outplanting performance was especially common in 'raw planted' bareroot stock of the 1980s (Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006). Today, modern nursery practices and resilient containerized stock make 'raw planting' possible (Boateng et al. 2009; Boateng et al. 2012). However, on sites with excess soil moisture and thick organic layers, mechanical site preparation can improve microsite favourability and enhance seedling performance (Orlander et al. 1990; Sutton 1993; Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006; Boateng et al. 2009).

In long-term silvicultural studies, top-performing treatments often provide extended competition control (Boateng et al. 2009). These treatments can include windrow burning, plow inverting, fine mixing, 'mineral-on-mineral' mounds, herbicide application(s), and multiple motor-manual cuttings (Hawkins et al. 2006; Boateng et al. 2006; Boateng et al. 2009). Alone, mechanical site preparation often provides poor vegetation control, unless mechanical treatments are extremely aggressive (Lof et al. 2012). If vegetation control is a primary objective, chemical site preparation and chemical release can restrict competition, alter stand structure, and produce strong crop tree growth (Fu et al. 2007; Boateng et al. 2009; Youngblood et al. 2011; Comeau 2014). Similarly, repeated motor-manual cuttings (i.e. brush saw cleaning) can also improve seedling performance

(Boateng et al. 2009; Pitt et al. 2010). However, single motor-manual treatments rarely have a lasting impact on white spruce, given vigorous aspen regeneration (Pitt and Bell 2005; Kabzems et al. 2011; Milakovsky et al. 2011). On poorly or imperfectly drained sites, large inverted mounds or large 'mineral-on-mineral' mounds can also increase spruce performance (Sutton et al. 2001; Hawkins et al. 2006). Functionally, mounding can displace surface organic layers, elevate microsites, aerate soils, and increase soil temperatures (Sutton 1993). In addition, mounding's patch arrangement can minimize the soil erosion and nutrient leaching common in large, continuous treatments (Ryans and Sutherland 2001; Munson et al. 1993). Finally, mounding can create diffuse stand structures that appear more 'natural' than linear treatments (Figure 3-16 and 3-17).

Bracke mounding, disc trenching, and blade scarification (e.g. v-plow scarification) rarely appear to produce outstanding spruce performance. For example, Bracke mounding produced similar height, DBH, and volume growth as the 'raw planted' control in Boateng et al. (2009). Alternately, Bracke mounding improved height and root collar growth in Sutton et al. (2001) and Boateng et al. (2006); however, silvicultural gains were intermediate relative to top performing treatments (e.g. large mounds). Disc trenching produced similar height, DBH, and volume growth as the 'raw planted' control in Boateng et al. (2009). In addition, disc trenching did not improve height growth in Sutton et al. (2001). Finally, blade scarification produced similar height and root collar growth as the 'raw planted' control in Sutton et al. (2001) and Boateng et al. (2006). However, in some cases, blade scarification may improve white spruce growth on well-drained sites (Youngblood et al. 2011), provided scarification does not "*exacerbate drainage problems*" (Sutton et al. 2001).

*Theoretical Performance vs. Operational Performance*

Ideally, site preparation should create optimal conditions for seedling establishment, growth, and survival (Long et al. 2004; Orlander et al. 1990). Site preparation should also suppress competition, release soil nutrients, optimize soil temperatures, and moderate soil moisture extremes (Orlander et al. 1990; Long et al. 2004; Sutton 1993). However, site preparation often interacts with site factors, obscuring the 'true' causal relationship(s) that drive seedling growth (Lof et al. 2012). For example, blade scarification (e.g. v-plow scarification) exposes large areas of mineral soil, increases soil temperatures, eliminates standing vegetation, and removes competing seeds or rhizomes (McMinn and Hedin 1990; Spittlehouse and Stathers 1990; Archibold et al. 2000). As a result, blade scarification *should* enhance seedling growth. However, in practice, blade scarification can create compacted depressions that restrict infiltration, collect water, and inadvertently desiccate the soil (Archibold et al. 2000). Blade scarification can also remove nutrient-rich horizons, reduce nutrient availability, (Brand 1991; Munson et al. 1993), and provide an ideal seedbed for competing vegetation (Archibold et al. 2000; Youngblood et al. 2011). Finally, blade scarification can encourage frost heaving on fine-textured soils (Sutton et al. 2001). Given these adverse effects, blade scarification often produces unimpressive white spruce growth (Sutton et al. 2001; Boateng et al. 2006), except on well-drained and nutrient rich sites (Sutton and Weldon 2003; Youngblood et al. 2011).

Similarly, disc trenching exposes mineral soil, increases soil temperatures, and provides elevated microsites (Orlander et al. 1990). However, this treatment often stimulates competition (Figure 3-17; Archibold et al. 2000; Orlander et al. 1990) and provides ineffective vegetation control (Boateng et al. 2009). As a result, disc trenching may not improve white spruce growth (Sutton et al. 2001; Boateng et al. 2009)

*Silvicultural Experiment Design and Measurement*

Successful silvicultural experiments are usually established as long-term permanent trials with a local (e.g. Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006; Boateng et al. 2009) or regional scope (e.g. Bokalo et al. 2007; Fu et al. 2007). To address systematic error (Pretzsch 2009, pg 148), silvicultural experiments often use Randomized Block, Randomized Complete Block, or Split-Plot designs; furthermore, these studies also include on-site replication and control treatments (Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006; Bokalo et al. 2007; Fu et al. 2007; Boateng et al. 2009). Treated buffers are essential to minimize edge effects and prevent interference from adjacent plots (Pretzsch 2009, pg 122). For example, Bokalo et al. (2007) used a 5m treated buffer to separate density-manipulation plots in juvenile spruce-aspen stands. Similarly, Pretzsch (2009) recommends treated buffers ≥7.5m to assure 1 'buffer tree' at maturity. In a growth and yield context, individual plots should contain 40 to 80 individuals (Pretzsch 2009, pg 127). Furthermore, these plots must be large enough to include an adequate number of trees at the end of the trial (Pretzsch 2009, pg 126). For example, to enclose 50 mature Norway spruce (*Picea abies* (L.) Karst.), sample plots must exceed 1000m$^2$ (Pretzsch 2009, pg 127). Blocked site preparation trials in western Canada often include 80 seedlings within 1200m$^2$ plots (Sutton et al. 2001; Hawkins et al. 2006; Boateng et al. 2006; Boateng et al. 2009).

Silvicultural experiments chronicle dynamic forest processes. As a result, experimental measurements should enumerate all trees (Pretzsch 2009, pg 113) and track growth over time (e.g. Sutton et al. 2001; Boateng et al. 2006; Boateng et al. 2009). Crop tree height and root collar diameter should be measured to compute volume and height-diameter ratios, and DBH should be sampled when trees exceed breast height (e.g. Boateng et al. 2009). In addition, height and DBH measurements on competing trees can aid silvicultural interpretation (e.g. Fu et al. 2007; Boateng et al. 2009). 'Overtopping' and visual cover can also indicate competition load (e.g. Boateng et al. 2009; Youngblood et al. 2011). Stem mapping may be desirable to identify trees (Pretzsch 2009, pg 115) and deploy spatial growth models like GYPSY (Huang et al. 2009). Finally, on-site weather, soil moisture, and soil temperature observations may be useful to explain treatment responses (Brand 1991; Cortini et al. 2011b).

### *Silvicultural Experiment Pitfalls*

When designing silvicultural experiments, research questions must be clearly formulated and identify the target treatment(s), study accuracy, spatio-temporal resolution, and project purpose (Pretzsch 2009, pgs 123-125). Furthermore, confounding factors must be controlled to establish cause and effect relationships (Pretzsch 2009, pg 148). Failure to restrict research objectives and limit confounding effects can complicate analysis. For example, Youngblood et al. (2011) assessed spruce growth with 30 treatments across 5 sites in Alaska. Each site occupied a different vegetation community, soil type (i.e. mollisols, inceptisols, and spodosols), and climate regime (i.e. continental and continental-maritime). In addition, site preparation treatments were applied operationally, using different equipment, operators, and methodologies at each site. As a result, treatment efficacy varied by site, and Youngblood et al. (2011) required meta-analytical techniques to offset site-level interactions. Finally, silvicultural experiments must avoid designs with pseudoreplication (e.g. Archibold et al. 2000).

**2.5 Conclusion**

Across the TSP dataset, silvicultural treatments did not influence juvenile white spruce height but did influence juvenile white spruce DBH. Paired comparisons indicated that v-plow scarification increased white spruce DBH relative to Bracke mounding. This DBH effect was linked with a significant difference in grass competition but could not be linked to a significant difference in overstory vegetation.

ANCOVA analysis partially addressed TSP site differences by adjusting for soil moisture regime. However, silvicultural effects were difficult to isolate from interacting site factors, including stand age, soil moisture regime, soil nutrient regime, and local environmental conditions. In addition, silvicultural efficacy was not explored, since a ‘raw planted’ control could not be located. A relatively small sample size, marginal ANCOVA fits, and clustered treatments may have limited silvicultural inferences.

In the past, white spruce plantations were difficult to establish without aggressive site preparation and/or tending. Today, modern stock types make ‘raw planting’ possible. However, on sites with excess soil moisture and thick organic layers, large inverted mounds or 'mineral-on-mineral' mounds can aid plantation establishment. If desirable, chemical site preparation, chemical release, and multiple cuttings can also reduce competition and increase white spruce growth.

Effective silvicultural treatments encourage seedling establishment and provide lasting competition control. Bracke mounding, disc trenching, and blade scarification often support seedling establishment; however, these treatments usually fail to control competing vegetation. In some cases, disc trenching and blade scarification may stimulate herbs, shrubs, and competing trees. Furthermore, blade scarification can compromise soil drainage, displace soil nutrients, and encourage nutrient leaching, possibly nullifying silvicultural gains.

Successful silvicultural experiments are developed with explicit research questions that define a study's accuracy, spatio-temporal resolution, and purpose. "*This rather trivial principle is often violated, in which case a more resource-intensive approach may not provide results that are more meaningful*" (Pretzsch 2009, pg 123) à la Youngblood et al. (2011). Successful silvicultural experiments also incorporate designs that address systematic error, support treatment replication, and include an untreated control. Finally, silvicultural experiments must prioritize treatment uniformity; operational treatments are often variable and produce confounding silvicultural effects.

## Chapter 3. Estimating tree height with generalized mixed-effects models.

### 3.1 Introduction

Tree height is a fundamental stand attribute, a key variable in volume calculation (Curtis 1967; Avery and Burkhart 2002), and a crucial input for forest growth models (e.g. Bokalo et al. 2010; Dixon 2002; Hann 2011). Unfortunately, measuring tree height is time consuming and expensive, especially in stands with tall trees, high densities (Arabatzis and Burkhart 1992; Trincado et al. 2007), or visually obscured treetops (Sharma and Parton 2007). To reduce costs, height subsamples are often measured, and height-diameter relationships are used to estimate unobserved height values (Huang et al. 2000; Robinson and Wykoff 2004; Sharma and Parton 2007; Temesgen et al. 2007).

Height-diameter relationships estimate tree height as a function of tree diameter (Curtis 1967; Huang et al. 1992; Fang and Bailey 1998). However, height-diameter relationships vary relative to competition (Sharma and Zhang 2004; Saunders and Wagner 2008), social position (Temesgen and Gadow 2004; Temesgen et al. 2007), site productivity (Rijal et al. 2012), ecoregion (Huang et al. 2000; Calama and Montero 2004), and stand age (Curtis 1967; Assmann 1970, pg 146). To address this variation, many contemporary height-diameter relationships include covariates to explain tree-level, plot-level, or regional differences (Sharma and Zhang 2004; Temesgen and Gadow 2004; Calama and Montero 2004; Temesgen et al. 2007) in tree slenderness. Height-diameter relationships with covariates are often termed 'generalized height-diameter models' (Temesgen and Gadow 2004; Castedo-Dorado et al. 2006; Temesgen et al. 2007; Rijal et al. 2012) and frequently outperform height-diameter models only informed by diameter (Sharma and Zhang 2004; Temesgen and Gadow 2004; Temesgen et al. 2007; Temesgen et al. 2008; Rijal et al. 2012). Fixed-effects modeling has been widely used to develop height-diameter relationships across North America (Huang et al. 1992; Zhang 1997; Huang et al. 2000; Peng et al. 2001) and abroad (Fang and Bailey 1998). However, recent studies have pursued a mixed-effects modeling approach (e.g. Calama and Montero 2004; Robinson and Wykoff 2004;

Castedo-Dorado et al. 2006; Sharma and Parton 2007; Trincado et al. 2007; Saunders and Wagner 2008; Temesgen et al. 2008; Crecente-Campo et al. 2010; Paulo et al. 2011; Rijal et al. 2012; Crecente-Campo et al. 2014).

Mixed-effects modeling provides a variety of benefits over traditional fixed-effects techniques:

1. Mixed-effects models can incorporate both ‘fixed’ population-level effects (i.e. intra-plot variation) and ‘random’ plot-level effects (i.e. inter-plot variation) (Pinheiro and Bates 2000, pgs 3, 306, 359), allowing the development of population-specific or plot-specific models (Pinheiro and Bates 2000, pgs 94, 149, 361; Trincado et al. 2007).
2. Mixed-effects models acknowledge plot-level correlation through the development of random-effects covariance structures (Pinheiro and Bates 2000, pgs 3, 58, 306; Calama and Monetero 2004).
3. Mixed-effects models can provide more representative standard error estimates by incorporating both population-level and plot-level variation (Pinheiro and Bates 2000, pgs 154, 359).
4. Mixed-effects models implicitly predict plot-level variation that is usually associated with additional fixed-effects (Robinson and Wykoff 2004).
5. Mixed-effects models can complement subsampled data by allowing individual subsamples to calibrate relationships at the plot-level (Calama and Montero 2004; Trincado et al. 2007; Temesgen et al. 2008).
6. Mixed-effects models can yield more parsimonious solutions (i.e. fewer model parameters) than individual fixed-effects models fit at the plot-level (Robinson and Wykoff 2004; Pinheiro and Bates 2000, pg 357).
7. Mixed-effects models can moderate plot-level outliers by ‘pooling subjects’ and shrinking plot-level estimates toward population-level predictions (Pinheiro and Bates 2000, pgs 152-153). ‘Shrinkage estimation’ also allows mixed-effects models to robustly model plots with small sample sizes (Robinson and Wykoff 2004).

For these reasons, mixed-effects height-diameter models often achieve better fit statistics than alternative fixed-effects models (e.g. Castedo-Dorado et al. 2006; Sharma and Parton 2007; Saunders and Wagner 2008; Paulo et al. 2011; Rijal et al. 2012).

*Objectives*

This chapter has 3 objectives: 1) Develop height-estimation models for the Managed Stand Permanent Sample Plots (MS-PSP's) of north-central Saskatchewan using a generalized mixed-effects modeling approach; 2) Evaluate generalized mixed-model construction and the common covariates that influence height-estimation relationships; and 3) Explore mixed-model calibration methods and sampling methodologies that support mixed-model deployment.

## 3.2 Methods

*Plot Establishment, Treatment(s), and Measurements*

In the early 1990's, Weyerhaeuser Canada established 18 Managed Stand Permanent Sample Plots (MS-PSP's) to assess growth in juvenile white spruce stands across the PAFMA (Figure 3-1; Table 3-1). Each 20×20m MS-PSP was placed within a randomly selected white spruce plantation treated with Bracke Mounding, Disc Trenching, or V-Plow Scarification (McMinn and Hedin 1990; Figure 3-1; Figure 3-2; Table 3-1). Target white spruce plantations were planted between 1982 and 1991 using 3-0 bareroot stock (Table 3-1). Among the 18 MS-PSP's sampled, 6 MS-PSP's were measured from each mechanical site preparation treatment (Figure 3-1; Table 3-1). In addition, 12 MS-PSP's were operationally thinned between 1989 and 1995 (Table 3-1). Thinning treatments were applied at the stand-level and removed deciduous competition within a 1 to 2m radius of planted white spruce. Stand-level thinning prescriptions were not archived and post-thinning stand densities were not recorded. A 'raw planted' control (i.e. treatment without site preparation or thinning) was not established within the MS-PSP network.

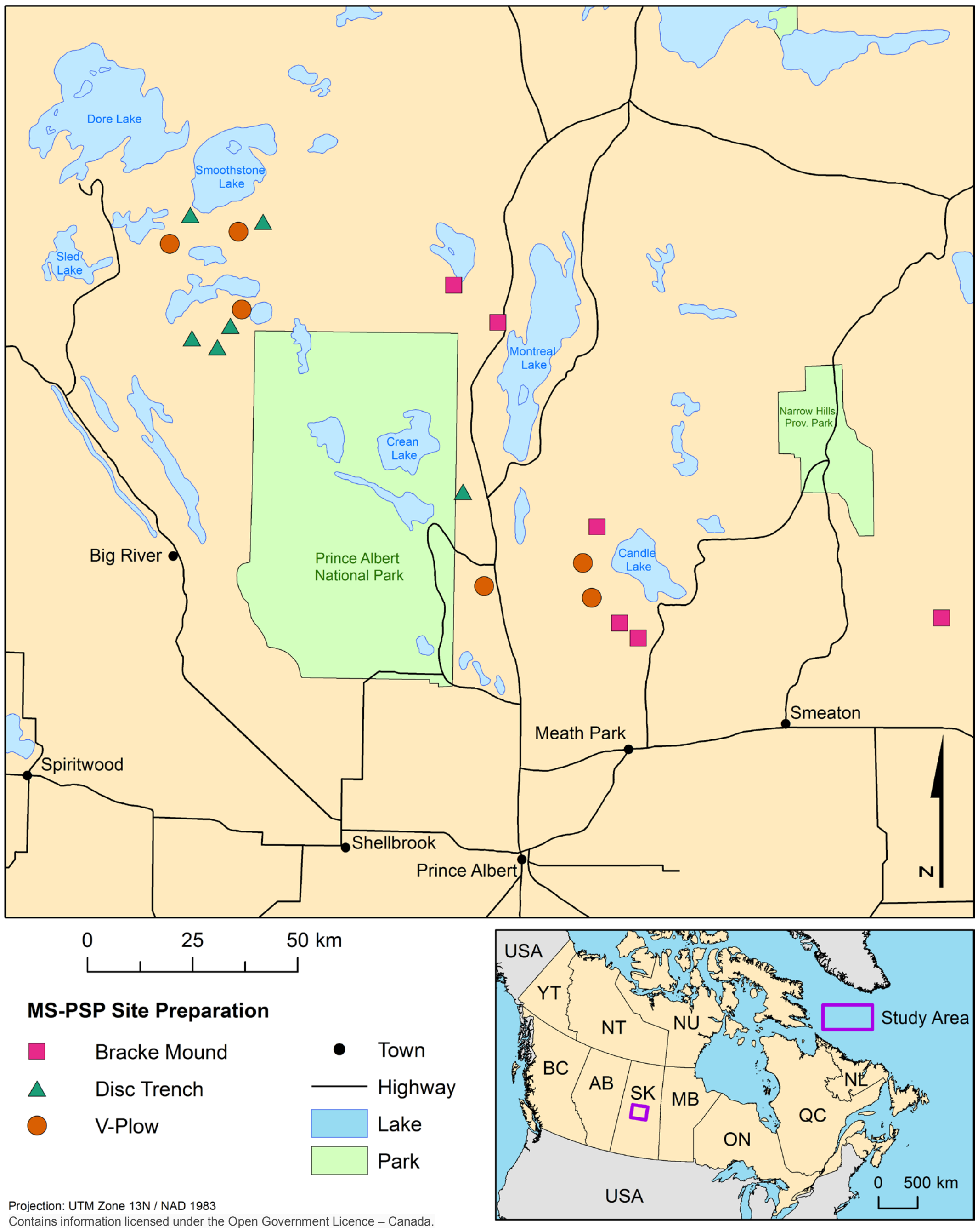


Figure 3-1. MS-PSP locations and mechanical site preparation treatments.

Most MS-PSP’s were established between 1992 and 1994, and 1 MS-PSP (i.e. 92204) was established in 1996 (Table 3-1). However, comprehensive MS-PSP measurements were performed in 1996 and 2011-2012 (Table 3-1). All 1996 measurements were collected between April and July (Table 3-1), and all 2011-2012 measurements were collected between October 2011 and May 2012 (Table 3-1). Given comprehensive samples and limited sampling periods (≤ 8 months), MS-PSP analysis focused on the 1996 and 2011-2012 measurements.

*MS-PSP Site Characteristics*

The MS-PSP’s occupy Luvisolic or Brunisolic soils with submesic to subhygric soil moisture regimes, poor to rich soil nutrients, and well-drained to imperfectly drained soil profiles (Table 3-2). Most MS-PSP’s occur on low relief sites (0 to 8%) across upper slope, mid-slope, lower-slope, toe slope, and level topographic positions (Table 3-2). MS-PSP elevations ranged from 430 to 630m above sea level (Table 3-2). Given these site characteristics, the MS-PSP’s are classified under ecosites ‘b’ (submesic/medium), ‘d’ (mesic/medium), ‘e’ (subhygric/rich), and ‘h’ (hygric/rich) (Beckingham et al. 1996; Table 3-2). EnviResource Consulting performed all MS-PSP soil and ecosite classifications in 1996.

*Basic MS-PSP Design*

Each MS-PSP is comprised of a 20×20m (400$m^2$) ‘primary plot’ and a nested 10×10m (100$m^2$) ‘natural origin subplot’ (Figure 3-2). All planted white spruce (30 to 150 trees/plot) were assessed within the primary plot, and naturally regenerated trees were evaluated within the natural origin subplot (Figure 3-2). Sampling protocols for the primary plot and natural origin subplot varied substantially between each measurement event (Table 3-1). Protocol details for the 1996 and 2011-2012 measurements are defined below:

Table 3-1. MS-PSP treatment regime and measurement events.

| **MS-PSP** | **Name** | **MSP** | **Plant Yr** | **Spp** | **Stock** | **Tend Date** (dd/mm/yyyy) | **Measurement Events** (dd/mm/yyyy) 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|---|---|
| 92101 | Revo Road | DT | 1988 | WS | 3+0 BR | . | 13/05/1992 | 03/05/1996 | 23/05/2012 |
| 92102 | Listen Lake Road #1 | DT | 1988 | WS | 3+0 BR | 02/09/1993 | 09/06/1992 | 04/05/1996 | 25/05/2012 |
| 92104 | Bittern Creek | DT | 1989 | WS | 3+0 BR | 21/11/1993 | 26/05/1992 | 01/05/1996 | 07/10/2011 |
| 92111 | Charbonneau Junction | DT | 1987 | WS | - | . | 06/10/1992 | 05/05/1996 | 18/10/2011 |
| 92113 | Elaine Lake Road | DT | 1989 | WS | 3+0 BR | 02/10/1995 | 24/06/1992 | 05/05/1996 | 21/10/2011 |
| 92204 | Montreal Lake | BM | 1987 | WS | 3+0 BR | 05/11/1992 | . | 01/07/1996 | 08/10/2011 |
| 93117 | Listen Lake Road #2 | DT | 1988 | WS | 3+0 BR | . | 06/05/1993 | 04/05/1996 | 25/10/2011 |
| 93201 | Snowfield Road #2 | BM | 1988 | WS | 3+0 BR | 29/09/1993 | 27/04/1993 | 29/04/1996 | 30/05/2012 |
| 93203 | Roundhill Tower | BR | 1986 | WS | 3+0 BR | . | 28/04/1993 | 25/04/1996 | 12/10/2011 |
| 93207 | Rock Lake Road | BM | 1988 | WS | 3+0 BR | 15/10/1992 | 10/05/1993 | 08/05/1996 | 10/10/2011 |
| 94209 | Snowfield Road #1 | BM | 1988 | WS | 3+0 BR | 18/10/1991 | 11/05/1994 | 28/04/1996 | 17/11/2011 |
| 94210 | Harding Lake Road | BM | 1986 | WS | 3+0 BR | 01/10/1993 | 13/06/1994 | 23/04/1996 | 23/05/2012 |
| 94302 | Lakeland Landfill | VP | 1982 | WS | - | 24/08/1990 | 09/05/1994 | 01/05/1996 | 05/10/2011 |
| 94303 | McConechy Lake Road | VP | 1983 | WS | - | . | 12/05/1994 | 28/04/1996 | 16/05/2012 |
| 94304 | Clearsand Lake | VP | 1983 | WS | 3+0 BR | 03/11/1989 | 11/05/1994 | 22/04/1996 | 04/10/2011 |
| 94308 | Listen Lake Road #3 | VP | 1991 | WS | 3+0 BR | . | 18/05/1994 | 04/05/1996 | 23/10/2011 |
| 94310 | Mirasty Lake | VP | 1991 | WS | 3+0 BR | 08/08/1993 | 18/05/1994 | 06/05/1996 | 29/05/2012 |
| 94312 | Smoothstone River | VP | 1985 | WS | - | 09/11/1990 | 18/05/1994 | 06/05/1996 | 20/10/2011 |

**Note:** MSP = mechanical site preparation; DT = disc trenching; BM = Bracke mounding; VP = v-plow scarification; Plant Yr = Planting Year (yyyy); Spp = planted tree species; WS = white spruce; BR = bareroot; dd/mm/yyyy = day/month/year; Tend Date = Tending Date; “-” = data unavailable; “.” = not applicable

Table 3-2. MS-PSP site information. Ecosite classes (b-h), topographic positions, moisture regimes, nutrient regimes, drainage classes, and effective soil textures are defined in Beckingham et al. (1996). Aspect, slope, soil, ecosite, and topographic position information were collected in 1996 by EnviResource Consulting Ltd. All elevation values are from Google Earth (Google Inc. 2013).

| **MS-PSP** | **Name** | **Elev.** (m) | **Aspect** (°) | **Slope** (%) | **Soil Order** | **Ecosite** | **Topo. Position** | **Moisture Regime** | **Nutrient Regime** | **Drainage Class** |
|---|---|---|---|---|---|---|---|---|---|---|
| 92101 | Revo Road | 527 | 0 | 0 | Luvisol | d | Level | Mesic | Rich | Well |
| 92102 | Listen Lake Road #1 | 549 | 0 | 0 | Luvisol | e | Level | Subhygric | Medium | Imperfect |
| 92104 | Bittern Creek | 536 | 0 | 0 | Luvisol | b | Level | Mesic | Medium | M. Well |
| 92111 | Charbonneau Junction | 490 | 0 | 0 | Brunisol | b | Level | Submesic | Medium | M. Well |
| 92113 | Elaine Lake Road | 552 | 358 | 8 | Luvisol | b | Upper Slope | Mesic | Medium | M. Well |
| 92204 | Montreal Lake | 596 | 90 | 0 | Brunisol | d | Toe | Mesic | Medium | Well |
| 93117 | Listen Lake Road #2 | 527 | 0 | 0 | Luvisol | b | Level | Mesic | Medium | Well |
| 93201 | Snowfield Road #2 | 559 | 65 | 8.5 | Luvisol | d | Mid-Slope | Mesic | Rich | Well |
| 93203 | Roundhill Tower | 525 | 0 | 0 | Luvisol | d | Level | Mesic | Medium | M. Well |
| 93207 | Rock Lake Road | 628 | 160 | 3 | Luvisol | d | Upper Slope | Mesic | Poor | M. Well |
| 94209 | Snowfield Road #1 | 552 | 0 | 0 | Luvisol | d | Level | Subhygric | Rich | M. Well |
| 94210 | Harding Lake Road | 434 | 0 | 0 | Brunisol | h | Level | Subhygric | Medium | Imperfect |
| 94302 | Lakeland Landfill | 564 | 143 | 8 | Luvisol | e | Mid-Slope | Mesic | Medium | Well |
| 94303 | McConechy Lake Road | 540 | 50 | 1.5 | Luvisol | d | Lower Slope | Mesic | Medium | Well |
| 94304 | Clearsand Lake | 518 | 176 | 1.5 | Luvisol | d | Lower Slope | Mesic | Rich | M. Well |
| 94308 | Listen Lake Road #3 | 527 | 0 | 0 | Luvisol | b | Level | Submesic | Medium | Well |
| 94310 | Mirasty Lake | 516 | 180 | 7 | Luvisol | b | Mid-Slope | Mesic | Medium | M. Well |
| 94312 | Smoothstone River | 516 | 130 | 5 | Brunisol | b | Lower Slope | Submesic | Medium | M. Well |

**Note:** Elev. = elevation; Topo. = topographic; M.Well = moderately well.

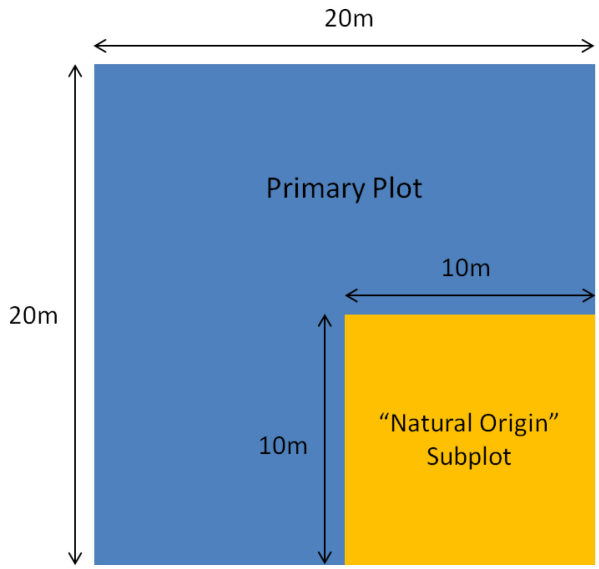

Figure 3-2. The 1996 MS-PSP plot design.

*1996 MS-PSP Measurement Protocol*

Within each MS-PSP, planted white spruce and naturally regenerated trees occupied the entire 20×20m primary plot (Table 3-1). During the 1996 MS-PSP measurement (Table 3-1), height was randomly sampled on (only) 15 planted white spruce within the 20×20m primary plot (Figure 3-2). For each naturally regenerated tree species, height was tallied into discrete classes within the 10×10m natural origin subplot (Figure 3-1; Table 3-3). Height class midpoints were used to define height for all tallied trees (Table 3-3).

Table 3-3. Natural origin height classes used during the 1996 MS-PSP measurement.

| **Height Class** | **Height Class Min** (m) | **Height Class Max** (m) | **Height Class Range** (m) | **Height Class Midpoint** (m) |
|---|---|---|---|---|
| 1 | 0.00 | 0.38 | 0.38 | 0.19 |
| 2 | 0.38 | 0.63 | 0.25 | 0.51 |
| 3 | 0.63 | 0.88 | 0.25 | 0.76 |
| 4 | 0.88 | 1.13 | 0.25 | 1.01 |
| 5 | 1.13 | 1.38 | 0.25 | 1.26 |
| … | … | … | … | … |
| 20 | 4.88 | 5.13 | 0.25 | 5.01 |

**Note:** "..." = continued progression

DBH was measured on all planted white spruce (>1.3m height) within the 20×20m primary plot (Figure 3-2). For each naturally regenerated tree species, DBH was tallied into discrete classes within the 10×10m natural origin subplot (Figure 3-1; Table 3-4). DBH class midpoints were used to define diameter for all tallied trees (Table 3-4).

Table 3-4. Natural origin DBH classes used during the 1996 MS-PSP measurement.

| **DBH Class** | **DBH Class Min** (cm) | **DBH Class Max** (cm) | **DBH Class Range** (cm) | **DBH Class Midpoint** (cm) |
|---|---|---|---|---|
| 1 | 0.00 | 1.50 | 1.50 | 0.75 |
| 2 | 1.60 | 2.50 | 1.00 | 2.00 |
| 3 | 2.60 | 3.50 | 1.00 | 3.00 |
| 4 | 3.60 | 4.50 | 1.00 | 4.00 |
| 5 | 4.60 | 5.50 | 1.00 | 5.00 |
| ... | ... | ... | ... | ... |
| 9 | 8.60 | 9.50 | 1.00 | 9.00 |

**Note:** DBH = diameter at breast height (1.3m); "..." = continued progression

Root collar diameter (RCD) and defect (e.g. forking, browsing) were recorded on all planted white spruce within the 20×20m primary plot (Figure 3-2). In addition, all planted white spruce were also marked with aluminum tags for long-term identification. Naturally regenerated trees were not tagged. Finally, visual estimates of grass, herb, and shrub cover were averaged across four 4×4m quadrats randomly located within each primary plot.

*1996 Height Estimation*

Since tree height was subsampled in the 1996 MS-PSP measurement, height estimates were required for planted white spruce. Unlike many height-diameter studies (e.g. Huang et al. 1992; Huang et al. 2000; Calama and Montero 2004; Trincado et al. 2007), the 1996 MS-PSP measurement exclusively sampled young stands (5 to 14 years) (Table 3-5). As a result, 75% of all planted white spruce were below breast height, and 8 MS-PSP's had ≥95% of planted white spruce below breast height (Table 3-5). This caused most 1996 DBH measurements to occur on older plots and/or disproportionately favour large trees (Table 3-5). Due to inconsistent and biased DBH observations, a height-diameter relationship was not developed for planted white spruce in the 1996 MS-PSP measurement. Alternately, root collar measurements were collected on all planted white spruce in 1996, regardless of tree size or age. Given this uniform and unbiased sample, a height-root collar relationship was developed for planted white spruce in the 1996 MS-PSP measurement.

Table 3-5. Planted white spruce size (<1.3m) for the 1996 MS-PSP measurement. All planted white spruce above breast height were measured at DBH. N = number of observations.

| **MS-PSP** | **Age** | **Planted WS** (N) | **Planted WS<1.3m** (N) | **Planted WS<1.3m** (%) |
|---|---|---|---|---|
| 92101 | 8 | 98 | 98 | 100 |
| 92102 | 8 | 45 | 45 | 100 |
| 92104 | 7 | 82 | 81 | 99 |
| 92111 | 9 | 145 | 143 | 99 |
| 92113 | 7 | 119 | 114 | 96 |
| 92204 | 9 | 61 | 47 | 77 |
| 93117 | 8 | 54 | 54 | 100 |
| 93201 | 8 | 110 | 91 | 83 |
| 93203 | 10 | 36 | 35 | 97 |
| 93207 | 8 | 94 | 74 | 79 |
| 94209 | 8 | 69 | 34 | 49 |
| 94210 | 10 | 62 | 52 | 84 |
| 94302 | 14 | 72 | 16 | 22 |
| 94303 | 13 | 46 | 4 | 9 |
| 94304 | 13 | 70 | 3 | 4 |
| 94308 | 5 | 86 | 83 | 97 |
| 94310 | 5 | 107 | 64 | 60 |
| 94312 | 11 | 33 | 0 | 0 |
| | ***Total:*** | *1389* | *1038* | *75* |

*1996 Data Management*

To assure equal representation, height-root collar trees were randomly removed from any MS-PSP with more than 15 height-root collar trees per plot. Height-root collar trees with extensive lean or extreme leader damage were excluded from analysis. However, height-root collar trees with forking, sweep, or moderate leader damage (e.g. abrasion, browse, pine weevil, frost kill, multiple leaders) were retained; these trees were considered representative of juvenile spruce growth. After initial filtering, 263 planted white spruce were used to develop the 1996 height-root collar relationship (Table 3-6; Figure 3-3).

Basal area larger (BAL) was also computed for each MS-PSP in a 3 step process (Table 3-6). First, tree lists for the primary plot and natural origin subplot were combined (Figure 3-2). Second, 'basal area per hectare' was calculated for each tree within the ‘combined tree list’. Finally, BAL was calculated by progressively summing ‘basal area per hectare’ relative to descending DBH. Conifer basal area larger (CBAL) and deciduous basal area larger (DBAL) were computed similarly to BAL; however, CBAL and DBAL only summed ‘basal area per hectare’ for conifer and deciduous trees, respectively (Table 3-6). Tree-level and plot-level variables for the 1996 height-root collar relationship are listed in Tables 3-6 and 3-7.

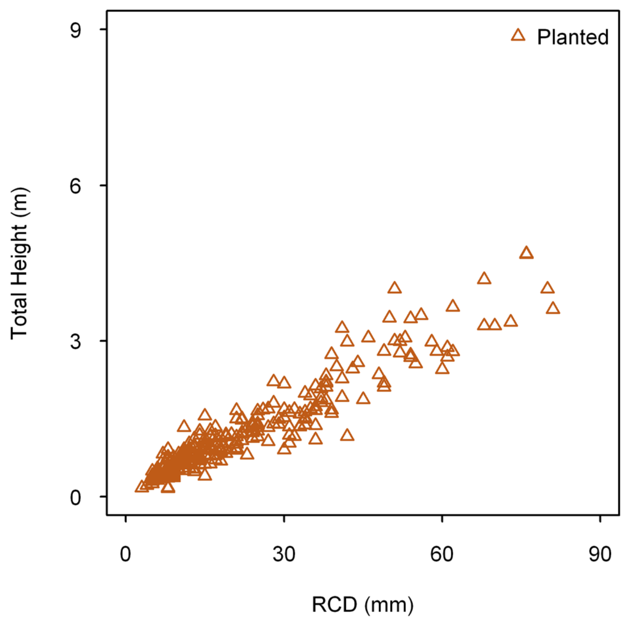


Figure 3-3. Source and distribution of white spruce height-root collar trees for the 1996 MS-PSP measurement.

Table 3-6. Tree-level variables for the 1996 height-root collar relationship.

| **Species** | **N** | **Variable** | **Mean** | **Min** | **Max** | **SD** |
|---|---|---|---|---|---|---|
| WS | 263 | WS Total Height (m) | 1.3 | 0.2 | 4.7 | 0.9 |
| | | WS RCD (mm) | 23.0 | 3.0 | 81.0 | 17.0 |
| | | Basal Area Larger ($m^2$/ha) | 2.6 | 0.0 | 8.1 | 2.0 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 0.9 | 0.0 | 5.9 | 1.5 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 1.7 | 0.0 | 7.5 | 1.8 |

**Note:** WS = white spruce; N = number of observations; SD = standard deviation.

Table 3-7. Plot-level variables for the 1996 height-root collar relationship.

| Species | Plots | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| WS | 18 | WS Top Height DBH (cm) | 1.6 | 0.0 | 5.0 | 1.7 |
| | | WS Top Height RCD (cm) | 3.8 | 1.3 | 8.0 | 2.1 |
| ALL | 18 | Total Density (Trees/ha) | 14,657 | 1,650 | 28,150 | 8,368 |
| | | Conifer Density (Trees/ha) | 6,807 | 1,525 | 25,750 | 7,281 |
| | | Deciduous Density (Trees/ha) | 7,850 | 100 | 25,100 | 6,826 |
| | | Total Basal Area ($m^2$/ha) | 2.8 | 0.0 | 8.1 | 2.3 |
| | | Conifer Basal Area ($m^2$/ha) | 0.9 | 0.0 | 5.9 | 1.6 |
| | | Deciduous Basal Area ($m^2$/ha) | 1.9 | 0.0 | 7.5 | 2.1 |
| | | Planting Year | 1987 | 1982 | 1991 | 2.5 |
| | | Grass Cover (%) | 16.9 | 0.0 | 77.5 | 20.6 |
| | | Herb Cover (%) | 30.8 | 1.3 | 74.3 | 18.8 |
| | | Shrub Cover (%) | 19.2 | 5.3 | 44.3 | 12.6 |
| | | Total Cover (%) | 66.8 | 7.9 | 151.0 | 32.6 |

**Note:** WS = white spruce; Plots = number of plots; SD = standard deviation; ALL = all species.

*2011-2012 MS-PSP Measurement Protocol*

During the 2011-2012 MS-PSP measurement (Table 3-1), height was randomly sampled on 6 planted white spruce within the 20×20m primary plot (Figure 3-4). For each naturally regenerated tree species, height was randomly sampled on 5 trees (>1.3m height) within the 10×10m natural origin subplot (Figure 3-4). DBH was measured on all planted white spruce (>1.3m height) within the 20×20m primary plot and all naturally regenerated trees (>1.3m height) within the 10×10m natural origin subplot (Figure 3-4). Defect (e.g. forking, browsing) and social class (i.e. suppressed, intermediate, codominant, dominant) were also evaluated on planted white spruce (Smith et al. 1997, pg 29; Figure 3-4). Within the natural origin subplot, naturally regenerated trees (<1.3m height) were tallied by species, and naturally regenerated trees (>1.3m height) were marked with aluminum tags for long-term identification (Figure 3-3). Pre-existing tags on planted white spruce were replaced or re-established as needed.

Height, DBH, social class, and increment cores were also sampled from top height trees across 4 circular 100$m^2$ top height plots (Figure 3-4). Under the top height selection protocol, 1 top height tree was sampled for every species within a top height plot. Top height sampling progressed sequentially across top height plots '1' through '4' until 2 top height trees were sampled for each species (Figure 3-4). Top height trees with substantial defects were not measured.

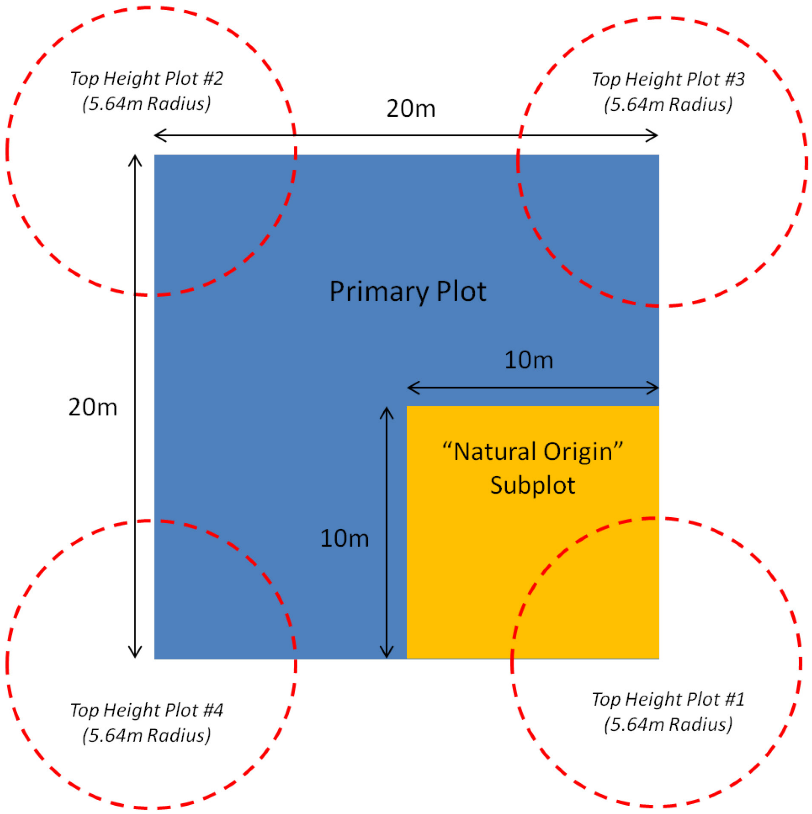


Figure 3-4. Basic MS-PSP plot design. A 5.64m radius yields a $100m^2$ plot.

On each top height tree, increment cores were collected on the 'lower-bole' and at 1.3m. The height of 'lower-bole' increment cores varied between 0.10 to 0.20m, depending on local micro-topography. Breast height increment cores that 'missed the pith' were resampled at 1.25m. To minimize stem damage within the MS-PSP, top height trees inside the primary plot were replaced with 'proxy' top height trees outside the primary plot (Figure 3-4). Proxy top height trees had similar height, diameter, and social class attributes as top height trees inside the primary plot. After increment core collection, all samples were air-dried and mounted on grooved wooden boards. Next, each increment core was sanded with multiple sandpaper grades (120 to 600 grit) to discern latewood and earlywood boundaries (Speer 2010). Processed increment cores were then aged under a 6.3x-30x power stereomicroscope.

*2011-2012 Height Estimation*

Since tree height was subsampled in the 2011-2012 MS-PSP measurement, height estimates were required for balsam poplar, black spruce, jack pine, trembling aspen, white birch, and white spruce. Unlike the 1996 MS-PSP measurement, 93% of planted white spruce and 94% of naturally regenerated trees were above breast height in 2011-2012. Furthermore, the 2011-2012 MS-PSP measurement protocol sampled DBH on all planted white spruce (>1.3m height) within the primary plot and all naturally regenerated trees (>1.3m height) within the natural origin subplot (Figure 3-4), yielding comprehensive DBH observations.

*2011-2012 Data Management*

To assure equal representation, height-diameter trees were randomly removed from any MS-PSP exceeding the subsample quota: 1) 6 planted white spruce per plot; or 2) 5 trees from each competing species per plot. Planted white spruce with extensive lean or extreme breakage were also excluded from analysis. However, planted white spruce with forking, sweep, or moderate leader damage (e.g. abrasion) were retained; these trees were considered representative of mid-successional growth. Since defect was only assessed on planted white spruce, naturally regenerated trees were not screened for deformities. After initial filtering, height-diameter trees from the primary plot and natural origin subplot were merged and sorted by species (Table 3-8; Figure 3-5). Then, top height trees were appended to each height-diameter relationship, increasing the overall sample size and adding ‘upper end’ observations (Table 3-8; Figure 3-5). For all height-diameter relationships, 1.3m was subtracted from total tree height, yielding ‘Height >1.3m’. This conversion forced tree height to approach zero as DBH approached zero.

Table 3-8. Source and quantity of height-diameter trees for the 2011-2012 MS-PSP measurement.

| Species | Source | N |
|---|---|---|
| BP | Natural Origin Subplot | 22 |
| | Top Height | 7 |
| | *Total:* | *29* |
| BS | Primary Plot (Planted) | 4 |
| | Natural Origin Subplot | 16 |
| | Top Height | 5 |
| | *Total:* | *25* |
| JP | Natural Origin Subplot | 37 |
| | Top Height | 9 |
| | *Total:* | *46* |
| TA | Natural Origin Subplot | 67 |
| | Top Height | 22 |
| | *Total:* | *89* |
| WB | Natural Origin Subplot | 48 |
| | Top Height | 13 |
| | *Total:* | *61* |
| WS | Primary Plot (Planted) | 101 |
| | Natural Origin Subplot | 44 |
| | Top Height | 30 |
| | *Total:* | *175* |

**Note:** N = number of observations; BP = balsam poplar; BS = black spruce; JP = jack pine; TA = trembling aspen; WB = white birch; WS = white spruce.

BAL was computed for each MS-PSP in a 4 step process. First, tree lists for the primary plot and natural origin subplot were combined. Second, 'basal area per hectare' was calculated for each tree within the 'combined tree list'. Third, BAL was calculated by progressively summing 'basal area per hectare' relative to descending DBH. Finally, each top height tree was designated a 'proxy BAL' from the 'combined tree list' (i.e. Step 3). Proxy BAL was assigned by matching top height DBH with similarly sized trees (i.e. DBH) within the 'combined tree list'. CBAL and DBAL were computed similarly to BAL; however, CBAL and DBAL only summed 'basal area per hectare' for conifer and deciduous trees, respectively.

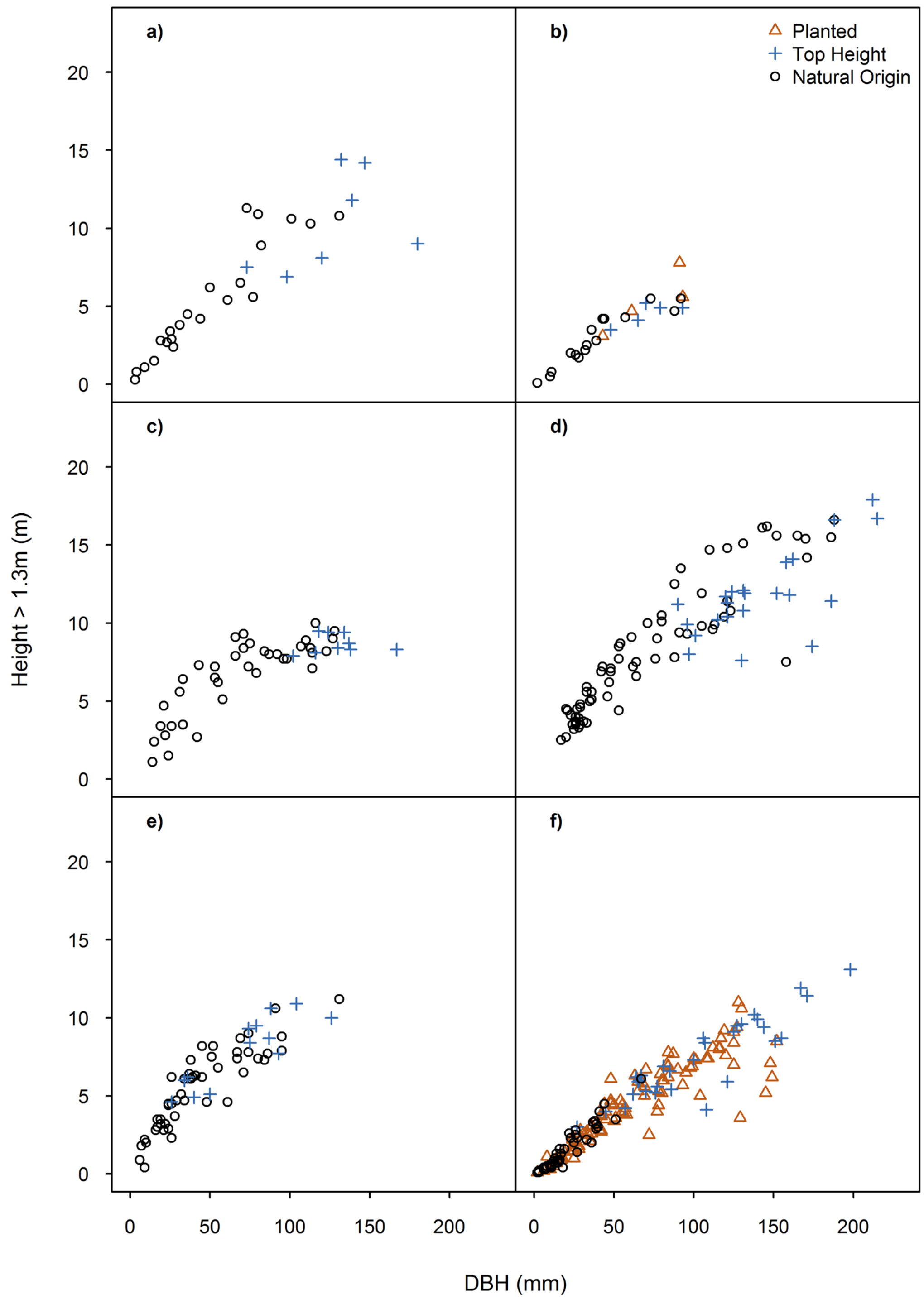


Figure 3-5. Source and distribution of height-diameter trees for the 2011-2012 MS-PSP measurement: a) balsam poplar, b) black spruce, c) jack pine, d) trembling aspen, e) white birch, and f) white spruce.

Table 3-9. Tree-level variables for the 2011-2012 height-diameter relationships. All variables are sorted by species.

| Species | N | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| BP | 29 | BP DBH (mm) | 69.0 | 3.0 | 180.0 | 49.0 |
| | | BP Height >1.3m (m) | 6.5 | 0.3 | 14.4 | 4.1 |
| | | Basal Area Larger ($m^2$/ha) | 17.0 | 0.0 | 31.8 | 8.7 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 6.2 | 0.0 | 14.9 | 4.2 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 10.9 | 0.0 | 24.7 | 7.8 |
| BS | 25 | BS DBH (mm) | 51.0 | 2.0 | 93.0 | 28.0 |
| | | BS Height >1.3m (m) | 3.6 | 0.0 | 7.8 | 1.9 |
| | | Basal Area Larger ($m^2$/ha) | 20.5 | 8.4 | 31.8 | 8.3 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 11.7 | 0.8 | 31.4 | 11.2 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 8.7 | 0.0 | 22.6 | 7.3 |
| JP | 46 | JP DBH (mm) | 81.0 | 14.0 | 167.0 | 41.0 |
| | | JP Height >1.3m (m) | 7.0 | 1.1 | 10.0 | 2.4 |
| | | Basal Area Larger ($m^2$/ha) | 17.0 | 0.0 | 37.0 | 11.9 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 11.7 | 0.0 | 29.7 | 9.7 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 5.3 | 0.0 | 31.9 | 9.5 |
| TA | 89 | TA DBH (mm) | 90.0 | 17.0 | 215.0 | 54.0 |
| | | TA Height >1.3m (m) | 9.1 | 2.5 | 17.9 | 4.1 |
| | | Basal Area Larger ($m^2$/ha) | 15.2 | 0.0 | 32.4 | 11.2 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 9.0 | 0.0 | 31.5 | 10.6 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 6.2 | 0.0 | 24.3 | 6.5 |
| WB | 61 | WB DBH (mm) | 50.0 | 6.0 | 131.0 | 31.0 |
| | | WB Height >1.3m (m) | 6.0 | 0.4 | 11.2 | 2.6 |
| | | Basal Area Larger ($m^2$/ha) | 22.9 | 0.0 | 37.8 | 8.4 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 11.8 | 0.0 | 28.5 | 8.4 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 11.1 | 0.0 | 31.9 | 9.0 |
| WS | 176 | WS DBH (mm) | 60.0 | 2.0 | 198.0 | 45.0 |
| | | WS Height >1.3m (m) | 4.3 | 0.0 | 13.1 | 3.0 |
| | | Basal Area Larger ($m^2$/ha) | 21.1 | 0.0 | 37.8 | 9.8 |
| | | Conifer Basal Area Larger ($m^2$/ha) | 11.6 | 0.0 | 31.5 | 9.9 |
| | | Deciduous Basal Area Larger ($m^2$/ha) | 9.5 | 0.0 | 31.9 | 8.9 |

**Note:** N = number of observations; SD = standard deviation; BP = balsam poplar; BS = black spruce; JP = jack pine; TA = trembling aspen; WB = white birch; WS = white spruce.

Site index (m@50yrs) was also estimated for MGM's component species (i.e. black spruce, jack pine, trembling aspen, and white spruce) (Bokalo et al. 2013) using the Alberta Central Mixedwood (Huang 1997c; Huang et al. 1997) and Saskatchewan Provincial (Cieszewski et al. 1993) site index equations. To estimate site index, top height and breast height age were entered into each height-age-site index equation. Then, tree-level site index estimates were averaged at the plot-level. White spruce site index estimates were calculated for all MS-PSP's. However, poor form and null top height samples prevented comprehensive site index estimates for black spruce, jack pine, and trembling aspen. For example, top height trees with severe forks or crooks (e.g. trembling aspen) were not measured. In addition, some species (e.g. black spruce) were sporadically distributed and not sampled by the MS-PSP top height plots. Tree-level and plot-level variables for the 2011-2012 height-diameter relationships are listed in Tables 3-9 and 3-10.

Table 3-10. Plot-level variables for the 2011-2012 height-diameter relationships. All variables are sorted by species.

| **Species** | **Plots** | **Variable** | **Mean** | **Min** | **Max** | **SD** |
|---|---|---|---|---|---|---|
| BP | 5 | BP Top Height (m) | 10.4 | 4.7 | 15.6 | 4.2 |
| | | BP Top Height DBH (cm) | 10.8 | 2.5 | 15.0 | 5.3 |
| BS | 6 | BS Top Height (m) | 6.1 | 4.8 | 9.1 | 1.6 |
| | | BS Top Height DBH (cm) | 6.6 | 3.6 | 9.1 | 2.1 |
| JP | 9 | JP Top Height (m) | 10.1 | 9.4 | 10.8 | 0.6 |
| | | JP Top Height DBH (cm) | 13.0 | 11.6 | 16.7 | 1.5 |
| TA | 15 | TA Top Height (m) | 13.4 | 9.3 | 18.6 | 2.8 |
| | | TA Top Height DBH (cm) | 13.9 | 9.6 | 21.4 | 3.3 |
| WB | 13 | TA Top Height (m) | 8.9 | 5.9 | 11.9 | 1.9 |
| | | TA Top Height DBH (cm) | 6.4 | 2.6 | 9.6 | 2.5 |
| WS | 18 | WS Top Height (m) | 8.5 | 4.3 | 13.8 | 2.5 |
| | | WS Top Height DBH (cm) | 10.1 | 2.7 | 18.3 | 4.2 |
| | | WS Site Index [SK] (m@50yrs) | 19.8 | 9.3 | 25.8 | 4.2 |
| | | WS Site Index [AB] (m@50yrs) | 21.6 | 11.1 | 27.0 | 4.0 |
| ALL | 18 | Total Density (Trees/ha) | 8,278 | 3,050 | 19,275 | 4,453 |
| | | Conifer Density (Trees/ha) | 4,794 | 1,525 | 13,950 | 4,064 |
| | | Deciduous Density (Trees/ha) | 3,483 | 1,200 | 10,400 | 2,383 |
| | | Total Basal Area ($m^2$/ha) | 27.4 | 10.6 | 37.8 | 6.9 |
| | | Conifer Basal Area ($m^2$/ha) | 14.5 | 1.9 | 31.5 | 9.8 |
| | | Deciduous Basal Area ($m^2$/ha) | 12.9 | 1.0 | 31.9 | 9.5 |
| | | Planting Year | 1987 | 1982 | 1991 | 2.5 |

**Note:** BP = balsam poplar; BS = black spruce; JP = jack pine; TA = trembling aspen; WB = white birch; WS = white spruce; SK = Saskatchewan Provincial Site Index Curves (Cieszewski et al. 1993; AB = Alberta Central Mixedwood Site Index Curves (Huang 1997c; Huang et al. 1997) ALL = all species.

*Height-Root Collar Function*

Although many linear and nonlinear equations have been advanced for height-diameter relationships (Curtis 1967; Fang and Bailey 1998; Huang et al. 2000), few functions have been proposed for height-root collar relationships. Pitt and Bell (2004) found a linear/heteroscedastic height-root collar relationship when developing a biomass equation for young white spruce. In this study, the 1996 height-root collar relationship appears linear when plotted (Figure 3-3). Given an apparent linear relationship between height and root collar, a linear function (Equation 3-1) was selected to model the 1996 height-root collar relationship.

$$Ht_{ij} = \beta_0 + \beta_1 RCD_{ij} + \varepsilon_{ij} \qquad \text{(Equation 3-1)}$$

where *Ht* is total height (m) for tree *j* in plot *i*, $\beta_0$ is the intercept parameter, $\beta_1$ is the slope parameter, $RCD_{ij}$ is root collar diameter (mm) for tree *j* in plot *i*, and $\varepsilon_{ij}$ is the residual error.

*Height-Diameter Function*

Height-diameter relationships usually assume a concave or sigmoid form (Yuancai and Parresol 2001; Avery and Burkhart 2002, pgs 185-186; Figure 3-5) with a "*monotonic increment, an asymptotic value, and an inflection point*" (Yuancai and Parresol 2001). In North America, common height-diameter equations include the power (Arabatzis and Burkhart 1992; Trincado et al. 2007), exponential (Meyer 1940; Buford 1986), Gompertz (Windsor 1932; Huang et al. 1992), Weibull (Yang et al. 1978; Temesgen and Gadow 2004), Chapman-Richards (Richards 1959; Temesgen et al. 2007), Logistic (Huang et al. 1992; Huang et al. 2000), Schnute (Schnute 1981; Peng et al. 2001), or Korf functions (Stage 1963; Peng et al. 2001). Specifically, the Chapman-Richards equation (Equation 3-2) has been recognized for its relative accuracy, reasonable fits, and flexibility (Huang et al. 1992; Peng et al. 2001; Yuancai and Parresol 2001). Yuancai and Parresol (2001) also praised the Chapman-Richards equation for its tendency to "*produce satisfactory curves under wide ranging biological-ecological modeling circumstances*"(Yuancai and Parresol 2001).

$$Hta_{ij} = \beta_0\left(1 - e^{-\beta_1(DBH_{ij})}\right)^{\beta_2} + \varepsilon_{ij} \qquad \text{(Equation 3-2)}$$

where $Hta_{ij}$ is height above breast height (m) for tree *j* in plot *i*, $\beta_0$ is the asymptote parameter, $\beta_1$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm) for tree *j* in plot *i*, $\beta_2$ is the shape parameter, and $\varepsilon_{ij}$ is the residual error.

In practice, the Chapman-Richards equation has been applied to height-diameter relationships across North America, ranging from boreal (Huang et al. 1992; Peng et al. 2001), Acadian (Saunders and Wagner 2008; Rijal et al. 2012), and Pacific Northwest forests (Zhang 1997; Temesgen et al. 2007). Furthermore, the Chapman-Richards equation has been used to model height-diameter relationships for balsam poplar, black spruce, jack pine, trembling aspen, white birch, and white spruce (Huang et al. 1992; Peng et al. 2001; Sharma and Parton 2007). Given its wide use and relative accuracy, the Chapman-Richards equation (Equation 3-2) was selected to model the 2011-2012 height-diameter relationships.

*Analytical Software*

All analyses were performed using the *nlme* package in *R* (Pinheiro et al. 2015; Pinheiro and Bates 2000). Model assumptions were tested using residual variance plots, residual histograms, and random-effect histograms. For each analytical graph, residuals were expressed as 'standardized residuals' (i.e. raw residuals / estimated standard deviation) (Pinheiro and Bates 2000, pg 149). Shapiro-Wilk normality tests were performed on each model's standardized residuals and estimated random-effects.

All *nlme* models were fit using maximum likelihood (ML) estimation; this allowed direct comparisons of the Bayesian Information Criterion (BIC) (Pinheiro and Bates 2000, pg 10) between models with different fixed effects (Pinheiro and Bates 2000, pgs 19, 76; Yang and Huang 2011). Unstructured positive-definite random-effects variance-covariance matrices (Unstructured *D* Matrices) were also used on all preliminary models with more than 2 random-effects. For models that failed to converge, the default number of iterations was increased to 500, and alternate starting values were tested.

Nonlinear mixed-effects models were computed using the 'LME Approximation' defined by Pinheiro and Bates (2000). This procedure uses a first-order Taylor Series expansion to linearize a target nonlinear function. Then, fixed and random-effects are iteratively computed with an algorithm that alternates between 'penalized nonlinear least squares' and 'linear mixed-effects' steps. Iterations continue until convergence criteria are met (Pinheiro and Bates 2000, pgs 313-315). All random-effects were estimated by expanding the first-order Taylor Series around Empirical Best Linear Unbiased Predictors (EBLUP's) (Pinheiro and Bates 2000, pgs 312-313; Littell et al. 2006; Fang and Bailey 2001; Temesgen et al. 2008).

*Mixed-Effects Model Specification*

Mixed-effects model specification followed the approach outlined by Fang and Bailey (2001): First, parameter variability was explored at the plot-level, and each parameter was defined as either a fixed-effect or a mixed-effect. Second, a suitable variance structure was applied to assure homoscedasticity. Finally, covariates were selected to explain inter-plot variability (i.e. random variation).

*Defining Mixed-Effects*

Three methods for assigning mixed-effects parameters were explored. In the 'parameter variation approach', fixed-effects models are fit at the plot-level, and parameter estimates are compared between plots. Then, parameters exhibiting high variation and distinct confidence intervals are selected as mixed-effect(s) (Pinheiro and Bates 1998, pg 3; Pinheiro and Bates 2000, pgs 350, 353, 360; Saunders and Wagner 2008; Paulo et al. 2011). In the 'backward-selection approach', random-effects are assigned to all model parameters, yielding a 'full' mixed-effects model (Equations 3-3 and 3-4).

The ‘full’ mixed-effects model for the 1996 height-root collar relationship:

$$Ht_{ij} = \beta_0 + b_{0i} + (\beta_1 + b_{1i})RCD_{ij} + \varepsilon_{ij} \qquad \text{(Equation 3-3)}$$

where $Ht_{ij}$ is total height (m) for tree $j$ in plot $i$, $\beta_0$ is the intercept parameter, $\beta_1$ is the slope parameter, $RCD_{ij}$ is root collar diameter (mm), $b_{0i}$ and $b_{1i}$ are the random-effects, and $\varepsilon_{ij}$ is the residual error.

The ‘full’ mixed-effects model for the 2011-2012 height-diameter relationship(s):

$$Hta_{ij} = (\beta_0 + b_{0i})\left(1 - e^{(-\beta_1 + b_{1i})(DBH_{ij})}\right)^{(\beta_2 + b_{2i})} + \varepsilon_{ij} \qquad \text{(Equation 3-4)}$$

where $Hta_{ij}$ is height above breast height (m) for tree $j$ in plot $i$, $\beta_0$ is the asymptote parameter, $\beta_1$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_2$ is the shape parameter, $b_{0i}$, $b_{1i}$, and $b_{2i}$ are random-effects, and $\varepsilon_{ij}$ is the residual error.

Then, the ‘full’ mixed-effects model is contrasted with simpler models (i.e. fewer random-effects) using likelihood-ratio tests, BIC, and RMSE. Thereafter, the backward-selection model achieving maximum explanatory power with the fewest random-effects is preferred (Pinheiro and Bates 1998, pg 3; Pinheiro and Bates 2000, pgs 364-365; Fang and Bailey 2001; Sharma and Parton 2007). Finally, in the ‘forward-selection approach’, random-effects are added incrementally to all model parameters. Then, competing models are evaluated using likelihood-ratio tests, BIC, and RMSE. Ultimately, the forward-selection model achieving maximum explanatory power with the fewest random-effects is preferred (Pinheiro and Bates 1998, pg 3; Pinheiro and Bates 2000, pg 37).

*Applying Variance Structures*

Heteroscedastic residuals were weighted using the *varPower* function in *nlme* (Pinheiro and Bates 2000, pgs 210-211; Saunders and Wagner 2008; Rijal et al. 2012). Under the *varPower* function, residual variance is weighted as an optimized power of a 'variance-covariate' (e.g. DBH or RCD) (Equation 3-5).

$$Variance(\varepsilon_{ij}) = \sigma^2 |v_{ij}|^{2\delta} \qquad \text{(Equation 3-5)}$$

where $\varepsilon_{ij}$ is the residual error for tree $j$ in plot $i$, $\sigma$ is the model variance, $v$ is the covariate defining the variance relationship, and $\delta$ is an optimized variance parameter yielding the best model fit.

Computationally, *varPower* weighting occurs within a reformulated version of *nlme*'s Maximum Likelihood algorithm (Pinheiro and Bates 2000; pgs 202-203, 328-332). Under this reformulation, the model function (e.g. Equations 3-1 and 3-2), parameter estimates, and raw residuals retain their original form and/or scale. However, model optimization uses internally transformed residuals (Equation 3-5), and *nlme*'s default estimate of 'residual standard error' is rescaled relative to Equation 3-5. As a result, Root Mean Square Error (RMSE) was used to assess bias between weighted and unweighted models (Equation 3-6).

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n} {\varepsilon_j}^2}{n-p}} \qquad \text{(Equation 3-6)}$$

where $n$ is the sample size, $p$ is the number of model parameters, and $\varepsilon_j$ is the raw residual error for tree $j$ (e.g. Robinson and Wykoff 2004; Castedo-Dorado et al. 2006). Raw residual error was defined at the plot-level for all mixed-effects models and at the population-level for all fixed-effects models.

*Tested Covariates*

In other height-estimation studies, common plot-level covariates include density, basal area, dominant height, (Calama and Montero 2004; Sharma and Parton 2007), dominant diameter (Crecente-Campo et al. 2010; Crecente-Campo et al. 2014), log-transformed density (Calama and Montero 2004; Saunders and

Wagner 2008), stand age (Curtis 1967; Castedo-Dorado et al. 2006), silvicultural treatment (Saunders and Wagner 2008; Boateng et al. 2009), and site index (Castedo-Dorado et al. 2006; Rijal et al. 2012). Common tree-level covariates include BAL, Crown Competition Factor (CCF), and Crown Competition Factor Larger (CCFL) than subject tree (Temesgen et al. 2007; Temesgen et al. 2008; Rijal et al. 2012).

For all MS-PSP height-estimation models, 9 plot-level covariates were considered: density, basal area, top height, top height DBH, log-transformed density, planting year, thinning treatment, site preparation treatment, and ecosite. Plot-level averages of grass, herb, shrub, and 'total' cover were also applied to the 1996 white spruce height-root collar relationship (Table 3-7; Cortini and Comeau 2008). Site index estimates from Cieszewski et al. (1993), Huang (1997c), and Huang et al. (1997) were applied to the 2011-2012 white spruce height-diameter relationship (Table 3-10). Among tree-level covariates, BAL was considered for all height-estimation models. CCF and CCFL were not pursued, given the additional requirement to model crown area (Krajicek et al. 1961). Finally, the covariates for density, basal area, log-transformed density, and BAL were subdivided into conifer and deciduous classes to represent the multi-strata nature of juvenile mixedwood stands (Chen and Popadiouk 2001).

*Covariate Selection Method*

After defining a 'preferred' mixed-effects modeling structure, each mixed-effect was supplemented with fixed-effect covariates to explore random variation. All covariates were assumed to have a linear relationship with their respective mixed-effect. Given the large number of covariates (18 to 22), covariate modeling followed a forward-stepwise approach (e.g. Pinheiro and Bates 2000, pgs 367-368) with 2 rounds of covariate inclusion. All tree-level (e.g. BAL) covariates and categorical plot-level covariates (e.g. site preparation treatment) were evaluated during each round (Appendix 3: Tables A-3-1 to A-3-13). Continuous plot-level covariates (e.g. density) were pre-screened against the estimated random-effects of each 'preferred' mixed-effects model (Appendix 2:

Tables A-2-1, A-2-2, A-2-3, and A-2-4) using Pearson correlation coefficients. Continuous plot-level covariates that produced the largest *r*-values ($r \geq 0.55$) were formally evaluated (Tables A-3-1 to A-3-13). Competing covariate models were assessed after each round of covariate inclusion using BIC. Model(s) achieving the lowest BIC were advanced to the next stage of model development.

*Final Model Selection*

Covariate mixed-model(s) achieving the lowest BIC were evaluated under a 7 step final selection process. This procedure sought to generate biologically relevant models with robust fits, minimal complexity, and meaningful covariates:

1. Contrast preliminary models with 'Unstructured *D* Matrices' against simpler models with diagonal random-effects variance-covariance matrices (Diagonal *D* Matrices) using likelihood-ratio tests (Pinheiro and Bates 2000, pg 364; Paulo et al. 2011). Favour models with 'Diagonal *D* Matrices', provided both random-effects structures are statistically equivalent.
2. Assess covariate explanatory power using sequential F-Tests (Pinheiro and Bates 2000, pg 90), and disqualify models with insignificant covariates.
3. Contrast mixed-effects models against nested fixed-effects models using likelihood-ratio tests (Pinheiro and Bates 2000, pg 377). Favour fixed-effects models, provided mixed-effects and fixed-effects models are statistically equivalent.
4. Examine model homoscedasticity, and apply weighted variance structures to heteroscedastic models.
5. Explore covariate interactions, and disqualify models with significant covariate interactions.
6. Assess the biological implications of covariate models, and reject biologically inconsistent covariates.
7. Select 'Final Models' by lowest BIC.

## 3.3 Results

*Defining Mixed-Effects*

Mixed-effects specification depended on data and computational limitations. The ‘parameter variation approach’ could not be applied to the MS-PSP dataset. Often, MS-PSP’s contained insufficient observations to fit plot-level fixed-effects models. Furthermore, if plot-level fixed-effects models could be developed, large parameter confidence intervals obscured inter-plot trends (Pinheiro and Bates 1998, pgs 3-4; Fang and Bailey 2001). The ‘backward-selection approach’ was applied to the 1996 height-root collar relationship (Table A-2-1). However, non-convergence restricted the ‘backward-selection approach’ on the 2011-2012 height-diameter relationships (Tables A-2-2 to A-2-4). As noted in Pinheiro and Bates (1998), backward-selection may be difficult to implement when ‘full’ mixed-effects models are over-parameterized and fail to converge (Pinheiro and Bates 1998, pg 3). Finally, the ‘forward-selection approach’ was deployed on the 2011-2012 height-diameter relationships (Tables A-2-2 to A-2-4). Pinheiro and Bates (1998) describe forward-selection as an alternative when backward-selection cannot be applied. Unfortunately, the ‘forward-selection approach’ requires all mixed-effect parameter combinations to be modeled (Pinheiro and Bates 1998, pg 3; Tables A-2-2 to A-2-4).

After backward or forward-selection, ‘preferred’ mixed-effects structures were determined using likelihood-ratio tests, BIC, and RMSE. For the linear white spruce height-root collar relationship, the ‘preferred’ mixed-effects structure included random-effects on parameters $\beta_0$ and $\beta_1$ (Equation 3-3; Table A-2-1: Model 3.1.A). Among height-diameter relationships, mixed-effects structures varied by species. The ‘preferred’ balsam poplar mixed-effects structure included random-effects on Chapman-Richards parameters $\beta_0$ and $\beta_2$ (Equation 3-7; Table A-2-2: Model 3.2.C).

$$Hta_{ij} = (\beta_0 + b_{0i})\left(1 - e^{(-\beta_1)(DBH_{ij})}\right)^{(\beta_2 + b_{2i})} + \varepsilon_{ij} \qquad \text{(Equation 3-7)}$$

where $Hta_{ij}$ is height above breast height (m) for tree $j$ in plot $i$, $\beta_0$ is the asymptote parameter, $\beta_1$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_2$ is the shape parameter, $b_{0i}$, and $b_{2i}$ are random-effects, and $\varepsilon_{ij}$ is the residual error.

The 'preferred' black spruce, trembling aspen, white birch, and white spruce mixed-effects structure included 1 random-effect on Chapman-Richards parameter $\beta_0$ (Equation 3-8; Table A-2-2: Model 3.3.E; Table A-2-3: Model 3.5.E; Table A-2-4: Models 3.6.E and 3.7.E).

$$Hta_{ij} = (\beta_0 + b_{0i})\left(1 - e^{(-\beta_1)(DBH_{ij})}\right)^{(\beta_2)} + \varepsilon_{ij} \qquad \text{(Equation 3-8)}$$

where $Hta_{ij}$ is height above breast height (m) for tree $j$ in plot $i$, $\beta_0$ is the asymptote parameter, $\beta_1$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_2$ is the shape parameter, $b_{0i}$, is the random-effect, and $\varepsilon_{ij}$ is the residual error.

Finally, the 'preferred' jack pine mixed-effects structure included 1 random-effect on Chapman-Richards parameter $\beta_1$ (Equation 3-9; Table A-2-3: Model 3.4.F).

$$Hta_{ij} = (\beta_0)\left(1 - e^{(-\beta_1 + b_{1i})(DBH_{ij})}\right)^{(\beta_2)} + \varepsilon_{ij} \qquad \text{(Equation 3-9)}$$

where $Hta_{ij}$ is height above breast height (m) for tree $j$ in plot $i$, $\beta_0$ is the asymptote parameter, $\beta_1$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_2$ is the shape parameter, $b_{2i}$ is the random-effect, and $\varepsilon_{ij}$ is the residual error.

Among preliminary fits, mixed-effects models always yielded lower RMSE values than equivalent fixed-effect models (Tables A-2-1 to A-2-4). Mixed-effects models also produced the lowest BIC values for balsam poplar, jack pine, trembling aspen, white birch, and white spruce height-estimation relationships (Tables A-2-1 to A-2-4). Only the black spruce fixed-effects height-diameter model achieved a lower BIC value than equivalent mixed-effects models (Table A-2-2: Model 3.3.H). However, this low BIC is caused by the small black spruce sample size (Table 3-8), reflects internally weighted residuals (Equation 3-5), and fails to correspond with a large reduction in RMSE (Table A-2-2: Model 3.3.H).

*Applying Variance Structures*

Variance assumptions were evaluated during preliminary model development (Tables A-2-1 to A-2-4) and final model selection (Tables 3-11, 3-13, 3-15, 3-17, 3-19, 3-21, and 3-23). Heteroscedastic height-root collar models were weighted using predicted height (Tables A-2-1, 3-11, and 3-12; Equation 3-5), and heteroscedastic height-diameter models were weighted using DBH (Tables A-2-2 to A-2-4). Variance weighting was required on all height-root collar models (Tables A-2-1, 3-11, and 3-12) and the preliminary fixed-effects height-diameter models for balsam poplar, black spruce, trembling aspen, and white spruce (Tables A-2-2 to A-2-4). Interestingly, mixed-effects models moderated heteroscedastic trends for most height-diameter models (Tables A-2-2 to A-2-4).

*Final White Spruce Height-Root Collar Model*

The 'preferred' white spruce height-root collar model (Equation 3-3) was supplemented with covariates under 1 round of covariate inclusion (Table A-3-1). Covariates failed to produce lower BIC values than the 'preferred' white spruce height-root collar model (Equation 3-9; Tables A-3-6 and A-3-7). Therefore, a second round of covariate inclusion was not performed, and the 'preferred' white spruce height-root collar model was evaluated under the final selection protocol (Equation 3-3; Table 3-11: Model 3.1.1). Model 3.1.1's 'Unstructured *D* Matrix' produced correlated random-effects and did not significantly improve model fit (Table 3-11: Models 3.1.1). A simpler model with a 'Diagonal *D* Matrix' eliminated random-effect correlation (Table 3-13: Model 3.1.9). This 'Diagonal

*D* Matrix' model included influential random-effects and required variance weighting to yield homoscedastic residuals. As a result, the final white spruce height-root collar model conformed to Equation 3-3, included a 'Diagonal *D* Matrix', and required variance weighting (Table 3-13: Model 3.1.12). Model summary statistics and graphical fits are displayed in Table 3-12, Figure 3-8, and Figure 3-9.

Table 3-11. Final model building procedure for the 1996 white spruce height-root collar relationship. Model numbers reference Appendix 3: Table A-3-1.

| Model | $b_0$ SD | $b_1$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|---|
| **3.1.1. LME – (Unstructured D Matrix)** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\varepsilon_{ij}$ | 0.1219 | 0.0092 | 0.21 | 13.6 | Random effects ($b_0$ and $b_1$) are moderately correlated (r = -0.67). A likelihood-ratio test against Model 3.1.9 indicated that an unstructured *D* matrix is not necessary. Heteroscedastic residuals. |
| **3.1.9. LME – (Diagonal D Matrix)** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\varepsilon_{ij}$ | 0.0580 | 0.0074 | 0.21 | 10.6 | A likelihood-ratio test against Model 3.1.10 indicated that random effects ($b_0$ and $b_1$) were necessary. Heteroscedastic residuals. |
| **3.1.10. LFE** $Ht_{ij}=\beta_0+\beta_1RCD_{ij}+\varepsilon_{ij}$ | . | . | 0.30 | 124.6 | Heteroscedastic residuals. |
| **3.1.11. LFE – (varPower)** $Ht_{ij}=\beta_0+\beta_1RCD_{ij}+\varepsilon_{ij}$ | . | . | 0.30 | 21.2 | Homoscedastic residuals. Variance weighted as an optimized power of the predicted height (δ = 0.76). |
| **3.1.12. LME – (Diagonal *D* Matrix)+(varPower)** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\varepsilon_{ij}$ | 0.0535 | 0.0072 | 0.21 | -53.8 | Homoscedastic residuals. Variance weighted as an optimized power of the predicted height (δ = 0.64). |

**Note:** $b_0$/$b_2$ = mixed-effects parameters; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; LME = linear mixed-effects model; D Matrix = radom-effects variance-covariance matrix; Ht = total height; i = plot; j = tree; $\beta_0$/$\beta_1$ = linear parameters; RCD = root collar diameter; ε = residual; LFE = linear fixed-effects model; varPower = variance weighting function (Eq. 3-5); δ = optimized variance parameter (Eq. 3-5).

Table 3-12. Summary statistics for the final white spruce height-root collar model (Equation 3-3). All values were developed using a diagonal random-effects variance-covariance matrix. Variance was weighted as an optimized power of the predicted height (Equation 3-5).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 0.1577 | 0.0298 | 0.0992 | 0.2162 | <0.0001 |
| | $\beta_1$ | 0.0481 | 0.0024 | 0.0435 | 0.0528 | <0.0001 |
| **Random-Effect** | $b_0$ SD | 0.0535 | | 0.0173 | 0.1650 | |
| **Variation** | $b_1$ SD | 0.0072 | | 0.0046 | 0.0114 | |
| **varPower** | $\delta$ | 0.6444 | | | | |
| **RMSE** | | 0.2135 | | | | |
| **BIC** | | -53.7878 | | | | |

**Note:** SE = standard error; CI = confidence interval; SD = standard deviation; varPower = variance weighing function (Eq. 3-5); RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

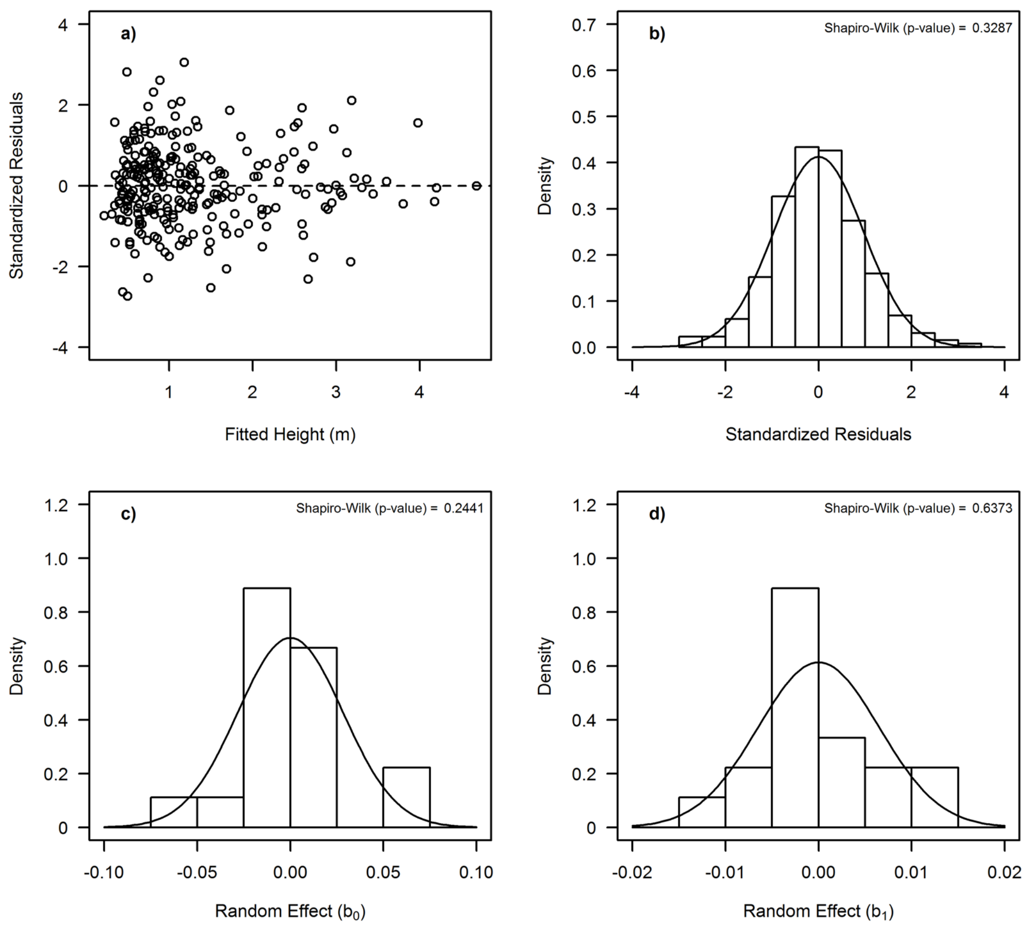


Figure 3-6. Distribution of residuals and random-effects for the final white spruce height-root collar model (Equation 3-3; Table 3-12): a) standardized residuals against fitted height, b) standardized residual distribution, c) random-effect ($b_0$) distribution, and d) random-effect ($b_1$) distribution.

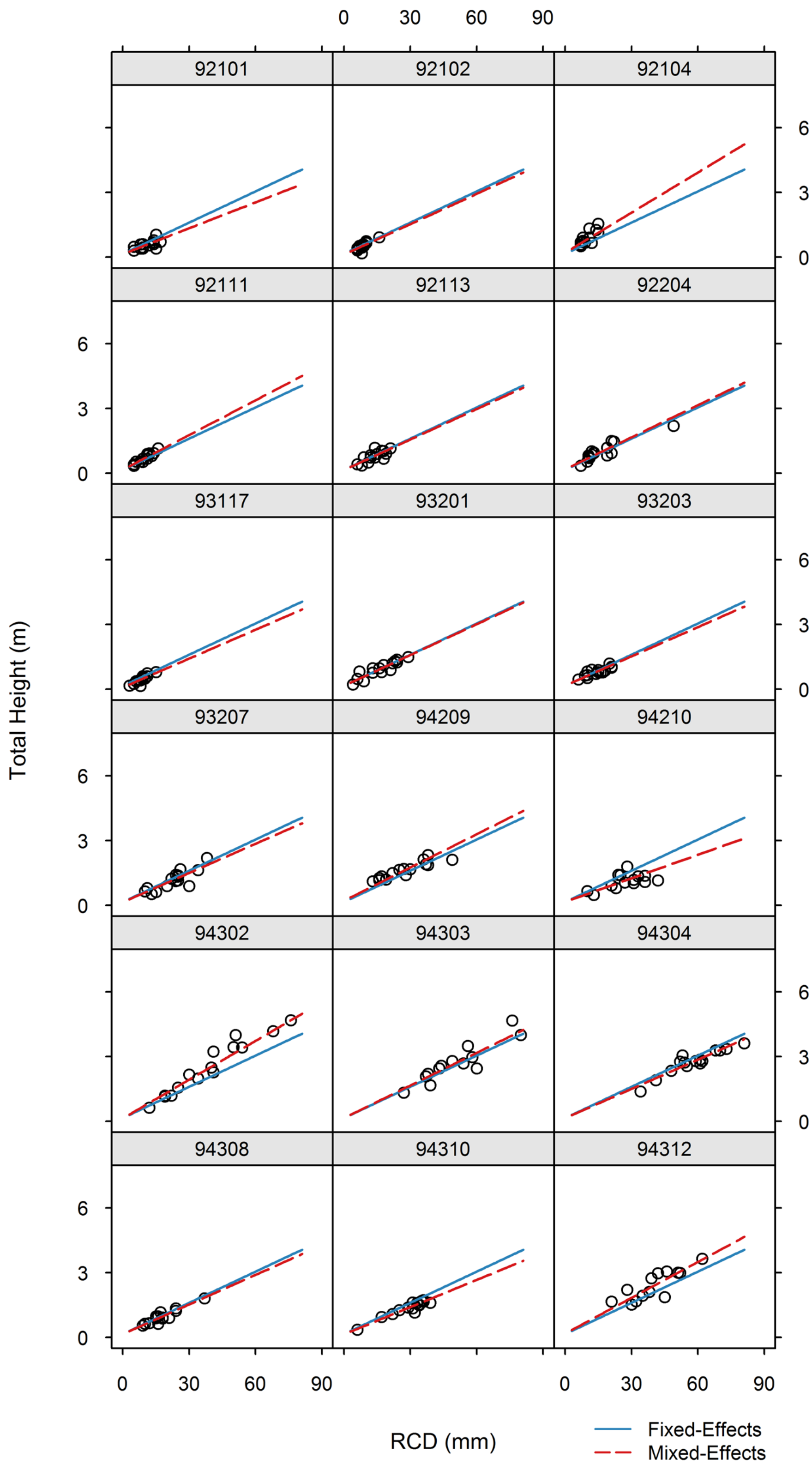


Figure 3-7. Population-level (fixed-effects) and plot-level (mixed-effects) fits for the final white spruce height-root collar model (Equation 3-3; Table 3-12). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-root collar values are identified by the "○" symbol.

*Final Balsam Poplar Height-Diameter Model*

The 'preferred' balsam poplar height-diameter model (Equation 3-7) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-2 and A-3-3). A covariate model incorporating deciduous basal area on mixed-effects $\beta_0$ and $\beta_2$ yielded the lowest BIC and largest reductions in random variation (Equation 3-7; Tables A-3-4 and A-3-5). Model 3.2.14's 'Unstructured *D* Matrix' produced correlated random-effects and did not significantly improve model fit (Table 3-13: Models 3.2.14). A simpler model with a 'Diagonal *D* Matrix' eliminated random-effect correlation (Table 3-13: Model 3.2.15). This 'Diagonal *D* Matrix' model included significant covariates, extraneous random-effects, and homoscedastic residuals under the final selection protocol.

Table 3-13. Final model building procedure for the 2011-2012 balsam poplar height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-2 and A-3-3. Parameter formulas modify Equation 3-2.

| Model | $b_0$ SD | $b_2$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|---|
| **3.2.14. NLME – DBA – (Unstructured D Matrix)** $\beta_0=\beta_{00}+\beta_{01}DBA_i+b_{0i}$ $\beta_2=\beta_{20}+\beta_{21}DBA_i+b_{2i}$ | 0.85 | 0.24 | 0.65 | 87.6 | Random effects ($b_0$ and $b_2$) are correlated (r = 1). A likelihood-ratio test against Model 3.2.15 indicated that the unstructured *D* matrix is not necessary. A Wald F-test indicated that the terms for DBA ($\beta_{01}$) and DBA ($\beta_{21}$) were significant. Homoscedastic residuals given limited sample size. |
| **3.2.15. NLME – DBA – (Diagonal *D* Matrix)** $\beta_0=\beta_{00}+\beta_{01}DBA_i+b_{0i}$ $\beta_2=\beta_{20}+\beta_{21}DBA_i+b_{2i}$ | 2.40E-5 | 3.34E-6 | 0.81 | 87.8 | A Wald F-test indicated that the terms for DBA ($\beta_{01}$) and DBA ($\beta_{21}$) were significant; the term for ($\beta_{10}$) is not significant (p-value = 0.21). A likelihood-ratio test against Model 3.2.16 indicated that random effects ($b_0$ and $b_2$) were not necessary. Homoscedastic residuals given limited sample size. |
| **3.2.16. NLFE – DBA** $\beta_0=\beta_{00}+\beta_{01}DBA_i$ $\beta_2=\beta_{20}+\beta_{21}DBA_i$ | . | . | 0.78 | 81.0 | A Wald F-test indicated that the terms for DBA ($\beta_{01}$) and DBA ($\beta_{21}$) were significant; the term for ($\beta_1$) is not significant (p-value = 0.21). Homoscedastic residuals given limited sample size. |

**Note:** $b_0/b_2$ = mixed-effects parameters; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; D Matrix = radom-effects variance-covariance matrix; $\beta_0/\beta_2$ = Chapman-Richards parameters; DBA = deciduous basal area; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

As a result, the final balsam poplar height-diameter model included deciduous basal area on both mixed-effects, yielding Equation 3-10 (Table 3-13: Model 3.2.16). Model summary statistics and graphical fits are displayed in Table 3-14, Figure 3-8, and Figure 3-9.

$$Hta_{ij} = (\beta_{00} + \beta_{01}DBA_i)\left(1 - e^{(-\beta_{10}DBH_{ij})}\right)^{(\beta_{20}+\beta_{21}DBA_i)} + \varepsilon_{ij} \quad \text{(Equation 3-10)}$$

where $Hta_{ij}$ is height above breast height (m) for balsam poplar $j$ in plot $i$, $\beta_{00}$ is the asymptote 'intercept' parameter, $\beta_{01}$ is the asymptote 'slope' parameter, $DBA_i$ is deciduous basal area ($m^2$/ha), $\beta_{10}$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_{20}$ is the shape 'intercept' parameter, $\beta_{21}$ is the shape 'slope' parameter, and $\varepsilon_{ij}$ is the residual error.

Table 3-14. Summary statistics for the final balsam poplar height-diameter model (Equation 3-10).

| | | **Estimate** | **SE** | **Lower 95% CI** | **Upper 95% CI** | **p-value** |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 7.0005 | 0.7127 | 5.5295 | 8.4715 | <0.0001 |
| | $\beta_{01}$ | 0.3605 | 0.0478 | 0.2618 | 0.4593 | <0.0001 |
| | $\beta_{10}$ | 0.0199 | 0.0047 | 0.0102 | 0.0296 | 0.0003 |
| | $\beta_{20}$ | 0.9983 | 0.2213 | 0.5414 | 1.4552 | 0.0001 |
| | $\beta_{21}$ | 0.0387 | 0.0181 | 0.0013 | 0.0761 | 0.0429 |
| **RMSE** | | 0.7757 | | | | |
| **BIC** | | 81.0486 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

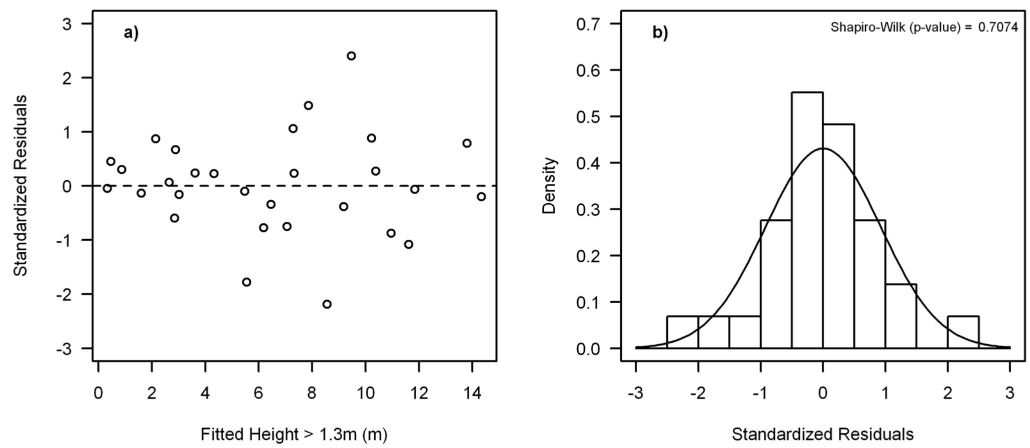


Figure 3-8. Distribution of residuals and random-effects for the final balsam poplar height-diameter model (Equation 3-10; Table 3-14): a) standardized residuals against fitted height and b) standardized residual distribution.

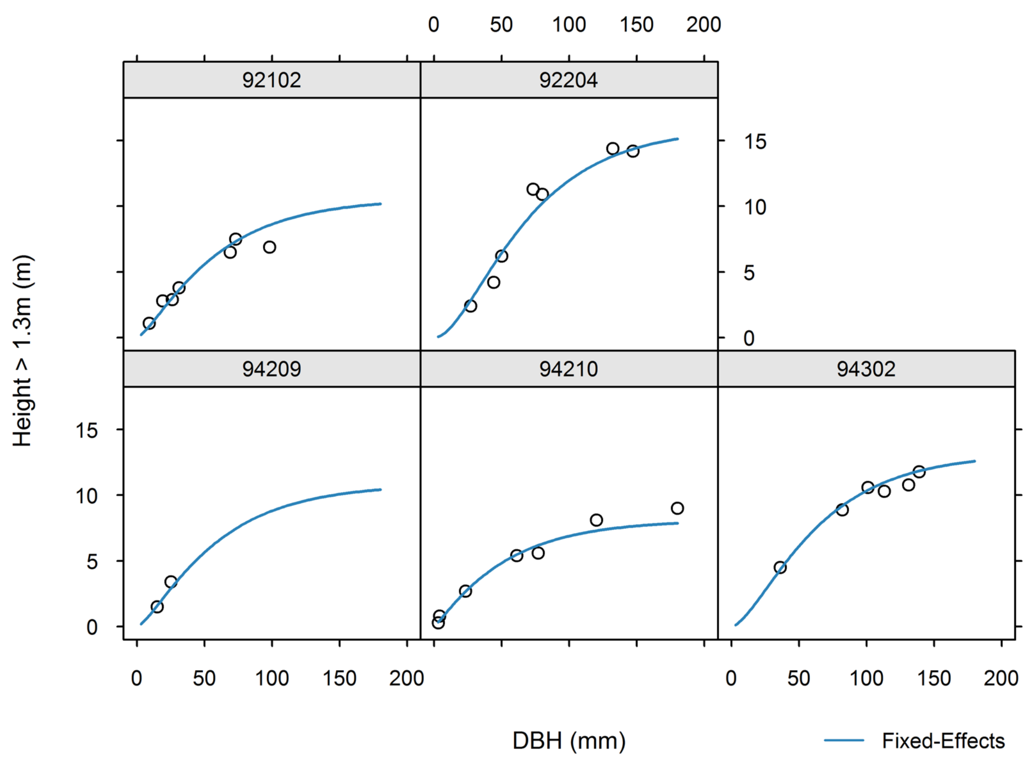


Figure 3-9. Population-level (fixed-effects) fit for the final balsam poplar height-diameter model (Equation 3-10; Table 3-14). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

*Final Black Spruce Height-Diameter Model*

The 'preferred' black spruce height-diameter model (Equation 3-8) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-4 and A-3-5). A covariate model incorporating black spruce top height and BAL on mixed-effect $\beta_0$ yielded the lowest BIC and largest reductions in random variation (Equation 3-8; Tables A-3-4 and A-3-5). This model included significant covariates, extraneous random-effects, and homoscedastic residuals under the final selection protocol (Table 3-15: Models 3.3.9 and 3.3.16). Interactions between black spruce top height and BAL were not significant (Table 3-15: Model 3.3.17). As a result, the final black spruce height-diameter model included black spruce top height and BAL, yielding Equation 3-11 (Table 3-15: Model 3.3.16). Model summary statistics and graphical fits are displayed in Table 3-16, Figure 3-10, and Figure 3-11.

Table 3-15. Final model building procedure for the 2011-2012 black spruce height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-4 and A-3-5. Parameter formulas modify Equation 3-2.

| Model | $b_0$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|
| **3.3.9. NLME – THT + BAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}BAL_{ij}+b_{0i}$ | 7.40E-6 | 0.45 | 45.9 | Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.14). A Wald F-test indicated that the terms for THT ($\beta_{01}$) and BAL ($\beta_{02}$) were significant; the term for ($\beta_{10}$) is not significant (p-value = 0.24). A likelihood-ratio test against Model 3.3.16 indicated that random effect ($b_0$) was not necessary. Homoscedastic residuals given limited sample size. |
| **3.3.16. NLFE – THT + BAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}BAL_{ij}$ | . | 0.44 | 42.6 | Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.22). A Wald F-test indicated that the terms for THT ($\beta_{01}$) and BAL ($\beta_{02}$) were significant; the term for ($\beta_{10}$) is not significant (p-value = 0.23). Homoscedastic residuals given limited sample size. |
| **3.3.17. NLFE – THT + BAL +THT × BAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}BAL_{ij}+\beta_{03}THT_i\times BAL_{ij}$ | . | 0.45 | 45.1 | Covariate interaction coefficient ($\beta_{03}$) is not significantly different from zero (p-value = 0.47). |

**Note:** $b_0$ = mixed-effects parameter; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; THT = black spruce top height; BAL = basal area larger; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

$$Hta_{ij} = (\beta_{00} + \beta_{01}THT_i + \beta_{02}BAL_{ij})\left(1 - e^{(-\beta_{10}DBH_{ij})}\right)^{(\beta_{20})} + \varepsilon_{ij}$$

(Equation 3-11)

where $Hta_{ij}$ is height above breast height (m) for black spruce $j$ in plot $i$, $\beta_{00}$ is the asymptote 'intercept' parameter, $\beta_{01}$ and $\beta_{02}$ are the asymptote 'slope' parameters, $THT_i$ is black spruce top height (m), $BAL_{ij}$ is basal area larger ($m^2$/ha), $\beta_{10}$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_{20}$ is the shape parameter, and $\varepsilon_{ij}$ is the residual error.

Table 3-16. Summary statistics for the final black spruce height-diameter model (Equation 3-11).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 1.8042 | 1.1884 | -0.6747 | 4.2831 | 0.1446 |
| | $\beta_{01}$ | 0.5816 | 0.1523 | 0.2639 | 0.8993 | 0.0011 |
| | $\beta_{02}$ | 0.0676 | 0.0284 | 0.0084 | 0.1267 | 0.0272 |
| | $\beta_{10}$ | 0.0291 | 0.0109 | 0.0063 | 0.0519 | 0.0148 |
| | $\beta_{20}$ | 1.9141 | 0.6072 | 0.6476 | 3.1806 | 0.0050 |
| **RMSE** | | 0.4426 | | | | |
| **BIC** | | 42.6396 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

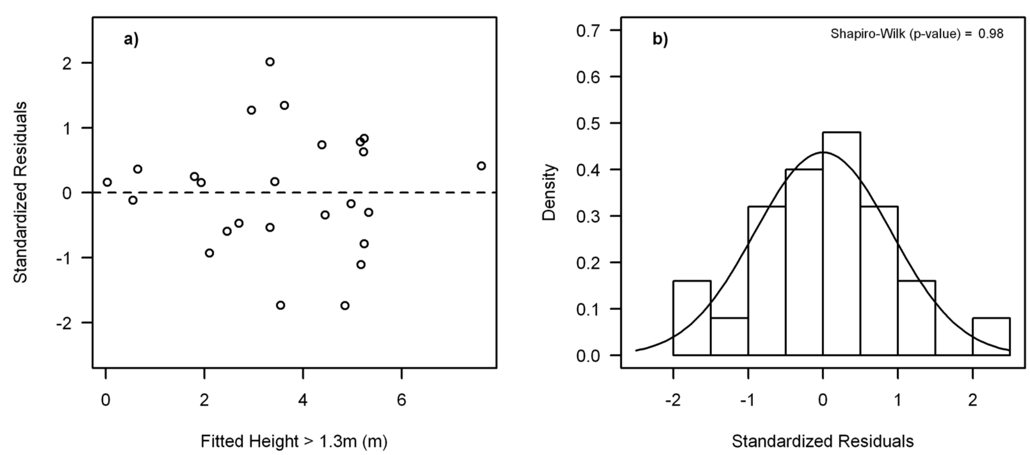


Figure 3-10. Distribution of residuals and random-effects for the final black spruce height-diameter model (Equation 3-11; Table 3-16): a) standardized residuals against fitted height and b) standardized residual distribution.

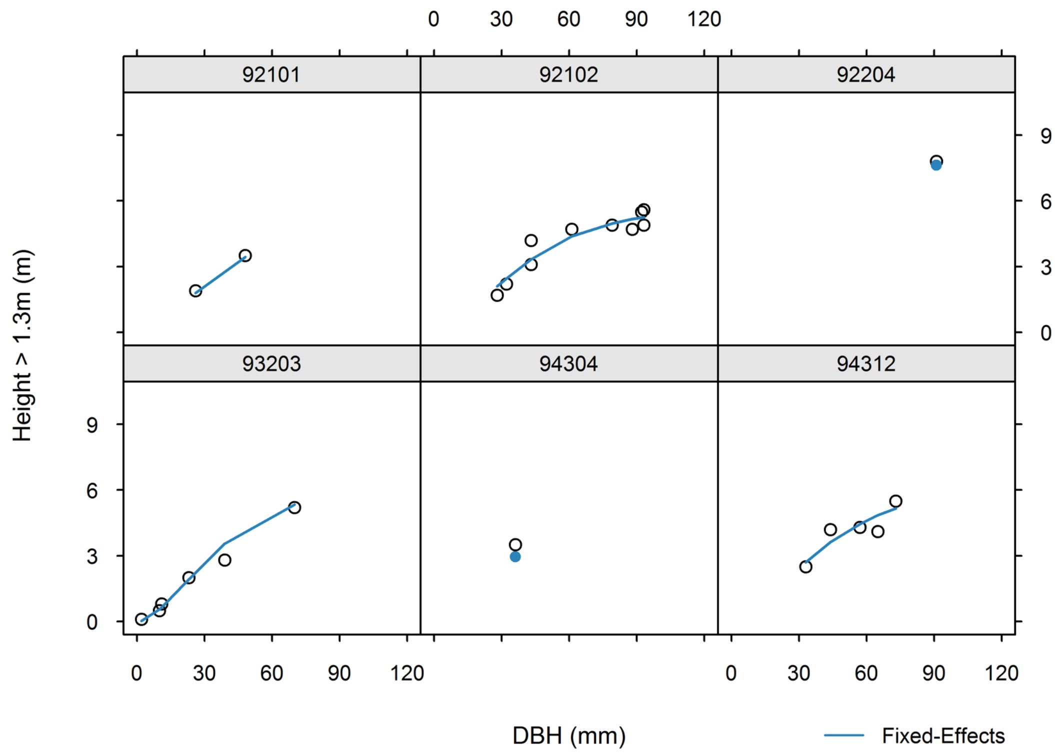


Figure 3-11. Population-level (fixed-effects) fit for the final black spruce height-diameter model (Equation 3-11; Table 3-16). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

*Final Jack Pine Height-Diameter Model*

The 'preferred' jack pine height-diameter model (Equation 3-9) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-6 and A-3-7). Covariate models with 1) conifer BAL and ecosite; 2) conifer BAL and jack pine top height diameter; 3) conifer BAL; and 4) conifer basal area on mixed-effect $\beta_1$ yielded low BIC values and substantial reductions in random variation (Equation 3-9; Tables A-3-6 and A-3-7). These models were disqualified under the final selection protocol, given insignificant covariates (Table 3-17: Models 3.4.12, 3.4.13, 3.4.3, 3.4.8). None of the remaining covariate models produced a lower BIC than the 'preferred' jack pine mixed-model (Equation 3-9; Tables A-3-6 and A-3-7). Therefore, the 'preferred' jack pine height-diameter model was evaluated under the final selection protocol (Table 3-17: Model 3.4.1). This model included influential random-effects and homoscedastic residuals. As a result, the final jack pine height-diameter model conformed to Equation 3-9 (Table 3-17: Model 3.4.1). Model summary statistics and graphical fits are displayed in Table 3-18, Figure 3-12, and Figure 3-13.

Table 3-17. Final model building procedure for the 2011-2012 jack pine height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-6 and A-3-7. Parameter formulas modify Equation 3-2.

| Model | $b_1$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|
| **3.4.12. NLME – CBAL + Ecosite** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}D_i+b_{1i}$ | 1.42E-3 | 0.58 | 107.1 | Model disqualified. A Wald F-test indicated that the terms for CBAL ($\beta_{11}$) and Ecosite ($\beta_{12}$) are not significant (p-value = 0.28 and 0.71). B and D are indicator variables. B is the control variable (0). |
| **3.4.13. NLME – CBAL + THTD** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}THTD_i+b_{1i}$ | 8.43E-6 | 0.67 | 112.5 | Model disqualified. A Wald F-test indicated that the term for THTD ($\beta_{12}$) is not significant (p-value = 0.92). THTD had the strongest correlation with the random effect ($b_0$) in Model 3.4.3 (r = -0.75). |
| **3.4.3. NLME – CBAL** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+b_{1i}$ | 1.76E-7 | 0.78 | 124.0 | Model disqualified. A Wald F-test indicated that the term for CBAL ($\beta_{11}$) is not significant (p-value = 0.06). |
| **3.4.8. NLME – CBA** $\beta_1=\beta_{10}+\beta_{11}CBA_{ij}+b_{1i}$ | 7.01E-3 | 0.63 | 124.5 | Model disqualified. A Wald F-test indicated that the term for CBA ($\beta_{11}$) is not significant (p-value = 0.65). |
| **3.4.1. NLME** $\beta_1 = \beta_{10}+b_{1i}$ | 8.90E-3 | 0.62 | 125.4 | A likelihood-ratio test against Model 3.4.13 indicated that random effect ($b_1$) was necessary. Homoscedastic residuals given limited sample size. |
| **3.4.14. NLFE** $\beta_1=\beta_{10}$ | . | 1.06 | 147.4 | Homoscedastic residuals given limited sample size. |

**Note:** $b_1$ = mixed-effects parameter; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; $\beta_1$ = Chapman-Richards parameter; CBAL = conifer basal area larger; B/D = Beckingham et al. (1996) ecosites; THTD = jack pine top height diameter; CBA = conifer basal area; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

Table 3-18. Summary statistics for the final jack pine height-diameter model (Equation 3-9).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 9.0601 | 0.2471 | 8.5751 | 9.5451 | <0.0001 |
| | $\beta_1$ | 0.0331 | 0.0063 | 0.0207 | 0.0455 | <0.0001 |
| | $\beta_2$ | 1.5751 | 0.3030 | 0.9803 | 2.1699 | <0.0001 |
| **Random-Effect Variation** | $b_1$ SD | 0.0089 | | 0.0044 | 0.0180 | |
| **RMSE** | | 0.6245 | | | | |
| **BIC** | | 125.4379 | | | | |

**Note:** SE = standard error; CI = confidence interval; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

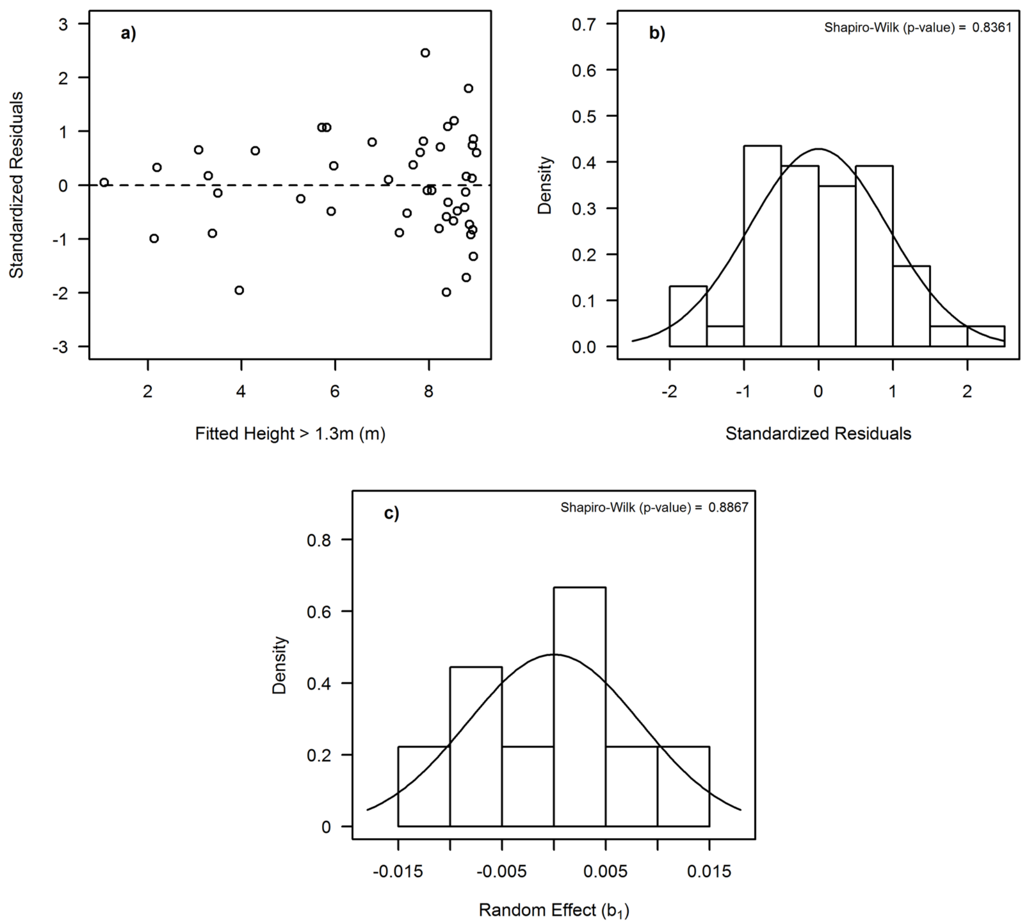


Figure 3-12. Distribution of residuals and random-effects for the final jack pine height-diameter model (Equation 3-9; Table 3-18): a) standardized residuals against fitted height, b) standardized residual distribution, and c) random-effect ($b_1$) distribution.

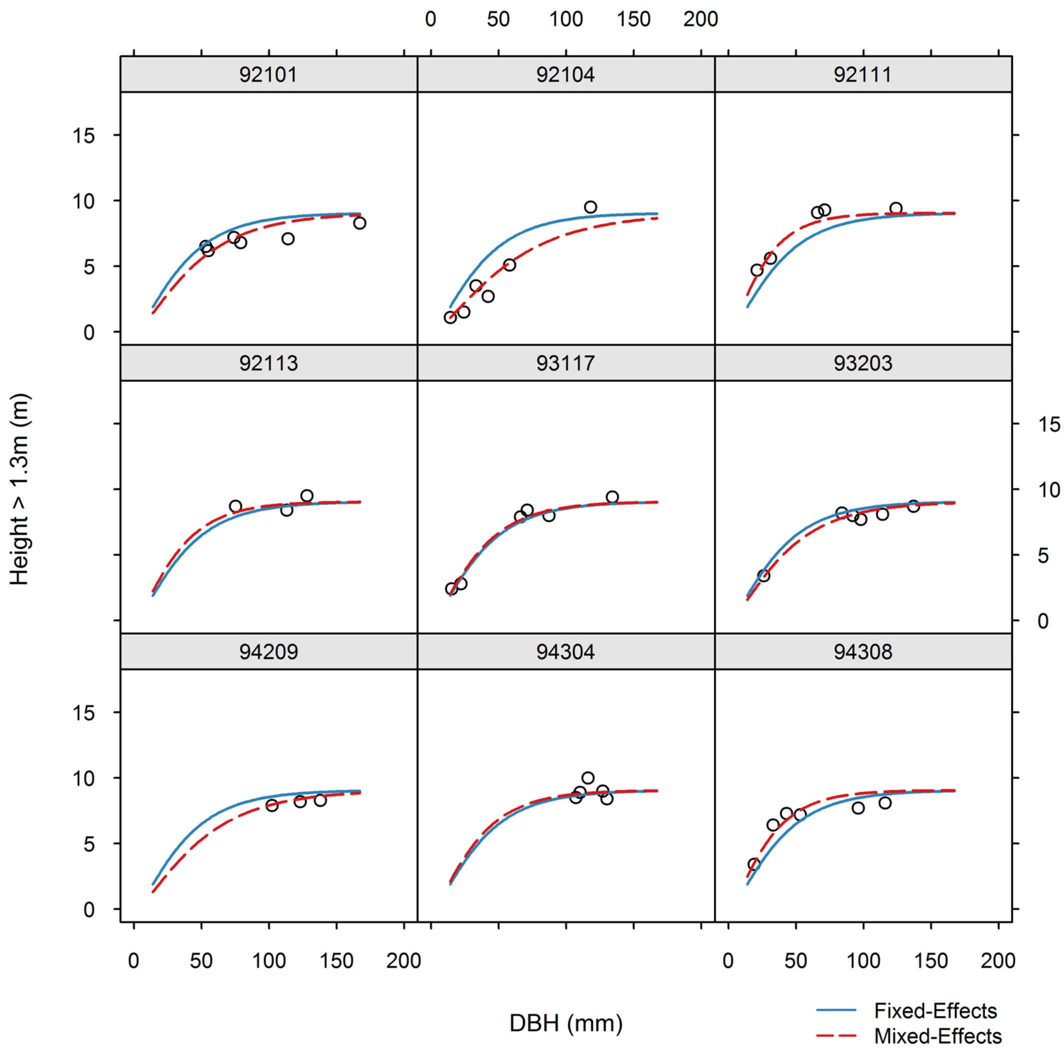


Figure 3-13. Population-level (fixed-effects) and plot-level (mixed-effects) fits for the final jack pine height-diameter model (Equation 3-9; Table 3-18). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

*Final Trembling Aspen Height-Diameter Model*

The 'preferred' trembling aspen height-diameter model (Equation 3-8) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-8 and A-3-9). A covariate model incorporating aspen top height and total basal area on mixed-effect $\beta_0$ yielded the lowest BIC and largest reductions in random variation (Equation 3-8; Tables A-3-8 and A-3-9). This model included significant covariates, extraneous random-effects, and homoscedastic residuals under the final selection protocol (Table 3-19: Models 3.5.15 and 3.5.16). Furthermore, interactions between aspen top height and total basal area were not significant. As a result, the final trembling aspen height-diameter model included aspen top height and total basal area, yielding Equation 3-12 (Table 3-19: Model 3.5.17). Model summary statistics and graphical fits are displayed in Table 3-20, Figure 3-14, and Figure 3-15.

Table 3-19. Final model building procedure for the 2011-2012 trembling aspen height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-8 and A-3-9. Parameter formulas modify Equation 3-2.

| Model | $b_0$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|
| **3.5.15. NLME – THT + TBA** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TBA_i+b_{0i}$ | 1.14E-4 | 0.85 | 247.9 | Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.12). A Wald F-test indicated that the terms for ($\beta_{01}$) THT and ($\beta_{02}$) TBA were significant (p-values = <0.0001). A likelihood-ratio test against Model 3.5.16 indicated that random effect ($b_0$) was not necessary. Homoscedastic residuals. |
| **3.5.16. NLFE – THT + TBA** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TBA_i$ | . | 0.85 | 243.4 | Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.12). A Wald F-test indicated that the terms for ($\beta_{01}$) THT and ($\beta_{02}$) TBA were significant (p-values = <0.0001). Homoscedastic residuals. |
| **3.5.17. NLFE – THT + TBA +THT × TBA** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TBA_i+\beta_{03}THT_i\times TBA_i$ | . | 0.84 | 246.4 | Covariate interaction coefficient ($\beta_{03}$) is not significantly different from zero (p-value = 0.24). |

**Note:** $b_0$ = mixed-effects parameter; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; THT = trembling aspen top height; TBA = total basal area; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

$$Hta_{ij} = (\beta_{00} + \beta_{01}THT_i + \beta_{02}TBA_i)\left(1 - e^{(-\beta_{10}DBH_{ij})}\right)^{(\beta_{20})} + \varepsilon_{ij}$$

(Equation 3-12)

where $Hta_{ij}$ is height above breast height (m) for trembling aspen $j$ in plot $i$, $\beta_{00}$ is the asymptote ‘intercept’ parameter, $\beta_{01}$ and $\beta_{02}$ are the asymptote ‘slope’ parameters, $THT_i$ is trembling aspen top height (m), $TBA_i$ is total basal area ($m^2$/ha), $\beta_{10}$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_{20}$ is the shape parameter, and $\varepsilon_{ij}$ is the residual error.

Table 3-20. Summary statistics for the final trembling aspen height-diameter model (Equation 3-12).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 1.2194 | 0.7752 | -0.3221 | 2.7610 | 0.1195 |
| | $\beta_{01}$ | 0.7016 | 0.0503 | 0.6015 | 0.8017 | <0.0001 |
| | $\beta_{02}$ | 0.1052 | 0.0214 | 0.0626 | 0.1478 | <0.0001 |
| | $\beta_{10}$ | 0.0167 | 0.0025 | 0.0117 | 0.0217 | <0.0001 |
| | $\beta_{20}$ | 1.1179 | 0.1233 | 0.8727 | 1.3631 | <0.0001 |
| **RMSE** | | 0.8457 | | | | |
| **BIC** | | 243.4605 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

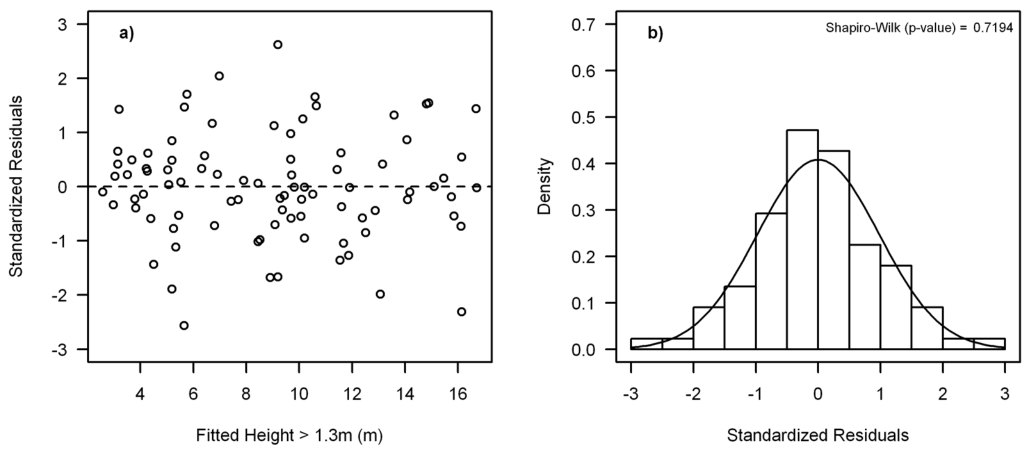


Figure 3-14. Distribution of residuals and random-effects for the final trembling aspen height-diameter model (Equation 3-12; Table 3-20): a) standardized residuals against fitted height and b) standardized residual distribution.

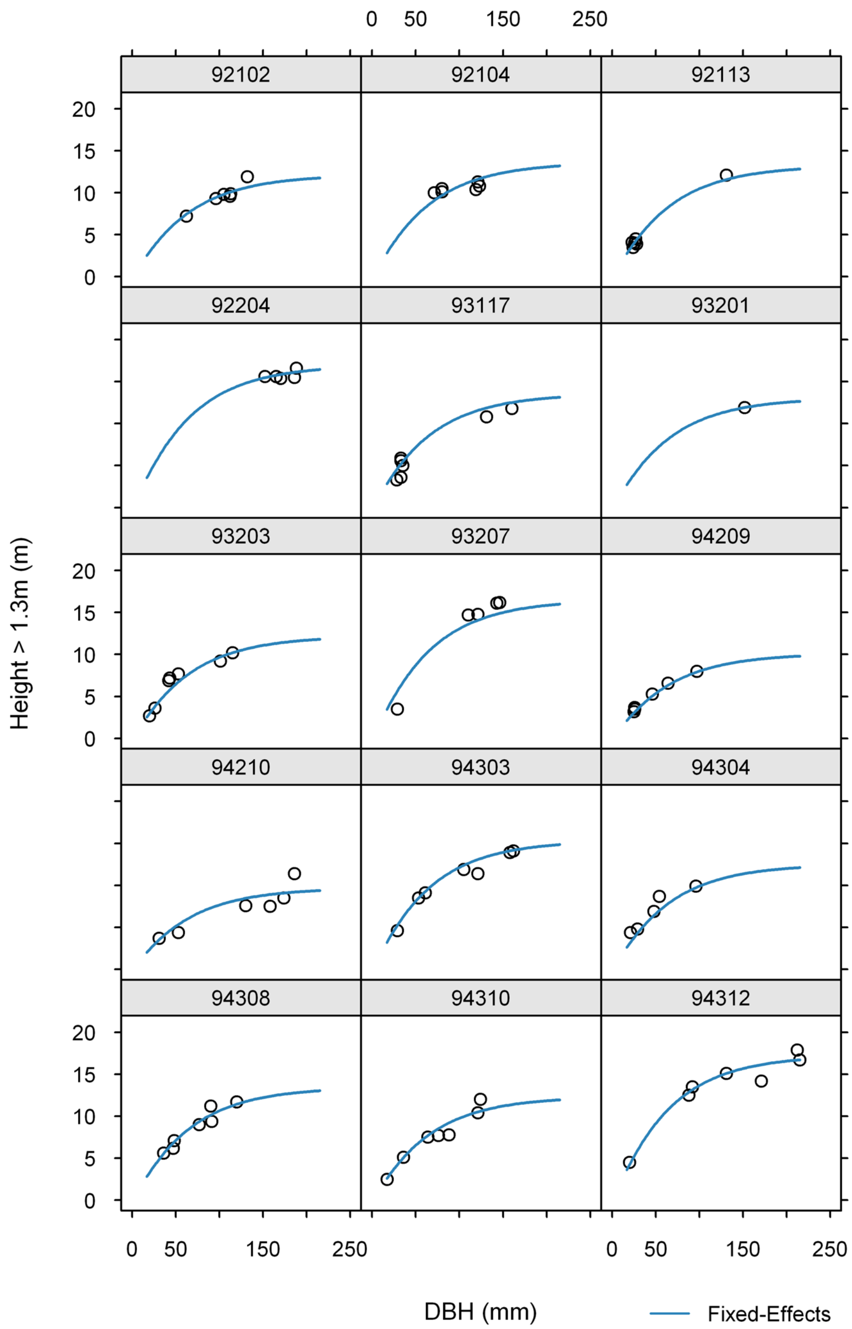


Figure 3-15. Population-level (fixed-effects) fit for the final trembling aspen height-diameter model (Equation 3-12; Table 3-20). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

*Final White Birch Height-Diameter Model*

The 'preferred' white birch height-diameter model (Equation 3-8) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-10 and A-3-11). A covariate model incorporating log-transformed deciduous density and mechanical site preparation on mixed-effect $\beta_0$ yielded the lowest BIC and largest reductions in random variation (Equation 3-8; Tables A-3-10 and A-3-11). This model was deemed biologically inconsistent under the final selection protocol, given stand density can be influenced by site preparation (Table 3-21: Model 3.6.15). Prevost (1997) found that mechanical site preparation strongly influenced white birch density by altering seedbed availability, seedbed characteristics, and subsequent recruitment. Furthermore, white birch recruitment appeared to be influenced by site preparation within the MS-PSP network. Bracke mounded sites often contained diffuse white birch regeneration while disc trenched sites contained linear white birch regeneration (Figures 3-16 and 3-17). In addition, mechanical site preparation effects may have been confounded by inconsistent and irregularly timed cleaning treatments (Table 3-1). Among the remaining covariate models, a model incorporating log-transformed deciduous density on mixed-effect $\beta_0$ yielded the second lowest BIC (Equation 3-8; Tables A-3-10 and A-3-11). This model included significant covariates, influential random-effects, and homoscedastic residuals under the final selection protocol (Table 3-21: Models 3.6.8 and 3.6.17). As a result, the final white birch height-diameter model included log-transformed deciduous density and random-effects, yielding Equation 3-13 (Table 3-21: Models 3.6.8). Model summary statistics and graphical fits are displayed in Table 3-22, Figure 3-18, and Figure 3-19.

Table 3-21. Final model building procedure for the 2011-2012 white birch height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-10 and A-3-11. Parameter formulas modify Equation 3-2.

| Model | $b_0$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|
| **3.6.12. NLME – ln(DTPH) + MSP**<br>$\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i$<br>$+\beta_{02}DT_i+\beta_{03}VP_i+b_{0i}$ | 0.41 | 0.76 | 173.7 | A Wald F-test indicated that the terms for ln(DTPH) ($\beta_{01}$) and MSP are significant (p-value = <0.0001 and 0.05). A likelihood-ratio test against Model 3.6.15 indicated that random effect ($b_0$) was not necessary. Homoscedastic residuals. BM, DT, and VP are indicator variables. BM is the control variable (0). Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.12). |
| **3.6.15. NLFE – ln(DTPH) + MSP**<br>$\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i$<br>$+\beta_{02}DT_i+\beta_{03}VP_i$ | . | 0.82 | 170.9 | A Wald F-test indicated that the terms for ln(DTPH) and MSP ($\beta_{01}$) are significant (p-value = <0.0001). Homoscedastic residuals. BM, DT, and VP are indicator variables. BM is the control variable (0). Model biologically inconsistent. |
| **3.6.16. NLFE – ln(DTPH) + MSP +ln(DTPH) × MSP**<br>$\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i$<br>$+\beta_{02}DT_i+\beta_{03}VP_i$<br>$+\beta_{04}ln(DTPH)_i\times DT_i$<br>$+\beta_{05}ln(DTPH)_i+VP_i$ | . | 0.81 | 175.1 | Covariate interaction coefficients ($\beta_{04}$ and $\beta_{05}$) are not significantly different from zero (p-value = 0.08 and 0.19). BM, DT, and VP are indicator variables. BM is the control variable (0). |
| **3.6.8. NLME – ln(DTPH)**<br>$\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i$<br>$+b_{0i}$ | 0.72 | 0.74 | 174.4 | A Wald F-test indicated that the term for ln(DTPH) ($\beta_{01}$) is significant (p-value = <0.0001). A likelihood-ratio test against Model 3.6.17 indicated that random effect ($b_0$) was necessary. Homoscedastic residuals. Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.46). |
| **3.6.17. NLFE – ln(DTPH)**<br>$\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i$ | . | 0.91 | 177.2 | ln(DTPH) had the strongest correlation with the random effect ($b_0$) in Model 3.6.1 (r = 0.46). Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.16). |

**Note:** $b_0$ = mixed-effects parameter; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; ln(DTPH) = natural logarithm of deciduous density; MSP = mechanical site preparation; BM = Bracke mounding; DT = disc trenching; VP = v-plow scarification; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

Figure 3-16. Diffuse stand structure on Bracke mounded MS-PSP 94209. In this figure, white spruce, trembling aspen, and white birch are scattered throughout the plot.

Figure 3-17. Linear stand structure on disc trenched MS-PSP 92111. In this figure, white spruce, white birch, and jack pine are clustered near a disc-trenched row, and untreated areas do not contain trees.

$$Hta_{ij} = (\beta_{00} + \beta_{01}\ln(DTPH)_i + b_{0i})\left(1 - e^{(-\beta_{10}DBH_{ij})}\right)^{(\beta_{20})} + \varepsilon_{ij}$$

(Equation 3-13)

where $Hta_{ij}$ is height above breast height (m) for white birch *j* in plot *i*, $\beta_{00}$ is the asymptote 'intercept' parameter, $\beta_{01}$ is the asymptote 'slope' parameter, $ln(DTPH)_i$ is the natural logarithm of deciduous density (trees/ha), $b_{0i}$ is the random-effect, $\beta_{10}$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_{20}$ is the shape parameter, and $\varepsilon_{ij}$ is the residual error.

Table 3-22. Summary statistics for the final 2011-2012 white birch height-diameter model (Equation 3-13).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | -3.2495 | 4.3337 | -11.6869 | 5.1879 | 0.4573 |
| | $\beta_{01}$ | 1.6522 | 0.5317 | 0.6170 | 2.6873 | 0.0033 |
| | $\beta_{10}$ | 0.0221 | 0.0065 | 0.0095 | 0.0347 | 0.0014 |
| | $\beta_{20}$ | 1.0386 | 0.1865 | 0.6754 | 1.4017 | <0.0001 |
| **Random-Effect Variation** | $b_0$ SD | 0.7230 | | 0.3666 | 1.4261 | |
| **RMSE** | | 0.7374 | | | | |
| **BIC** | | 174.3647 | | | | |

**Note:** SE = standard error; CI = confidence interval; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

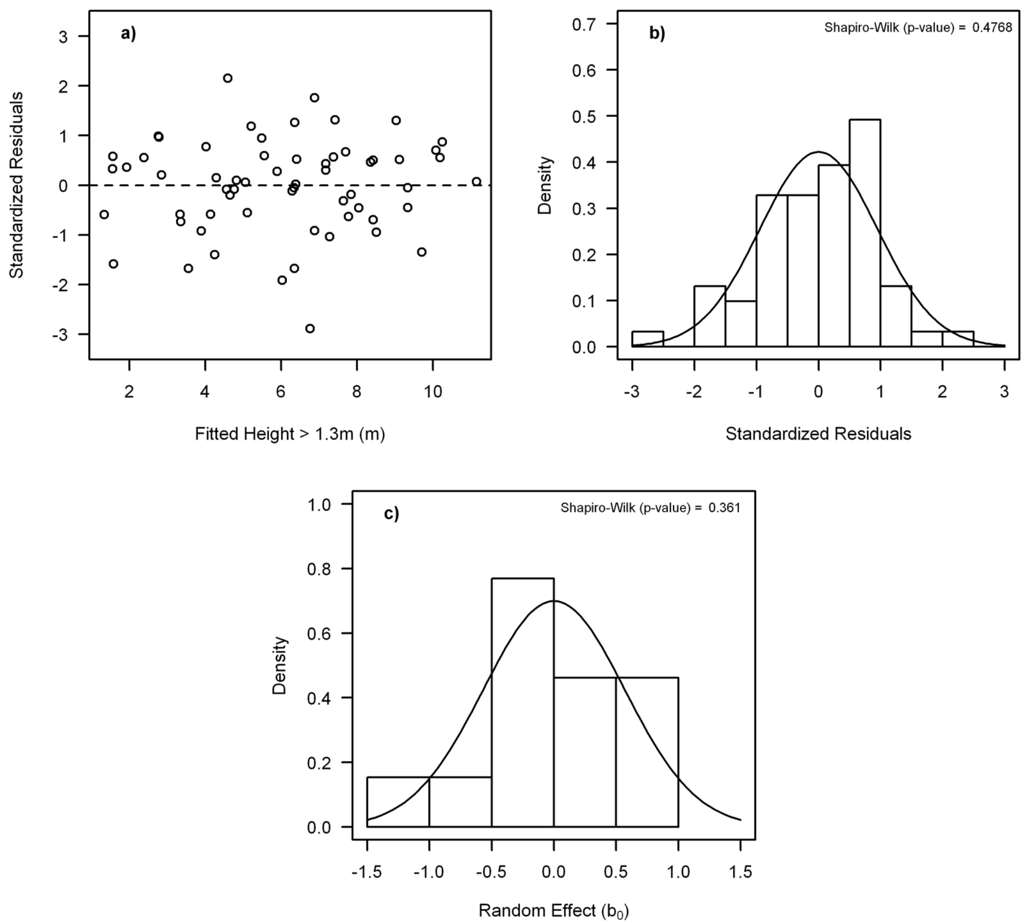


Figure 3-18. Distribution of residuals and random-effects for the final white birch height-diameter model (Equation 3-13; Table 3-22): a) standardized residuals against fitted height, b) standardized residual distribution, and c) random-effect ($b_0$) distribution.

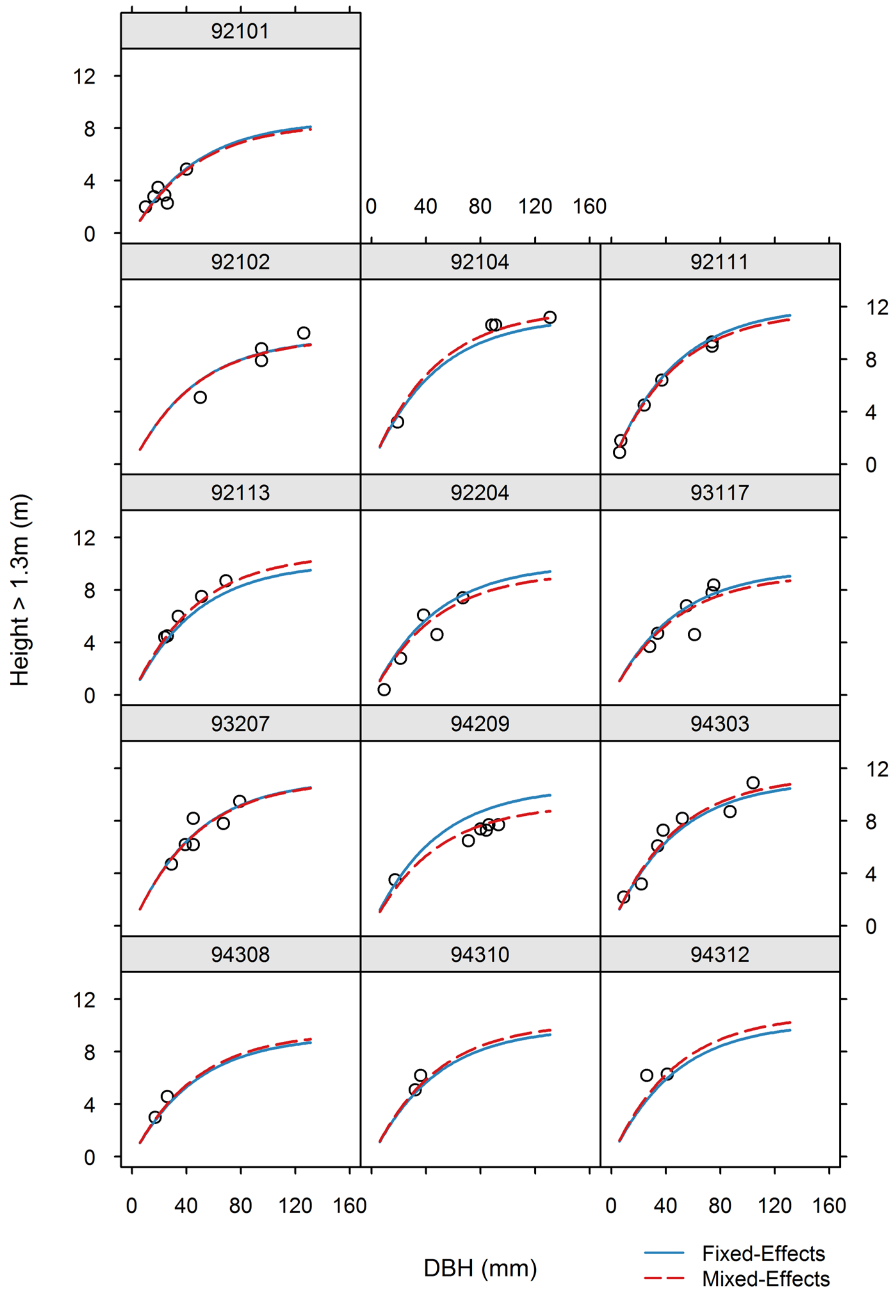


Figure 3-19. Population-level (fixed-effects) and plot-level (mixed-effects) fits for the final white birch height-diameter model (Equation 3-13; Table 3-22). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

*Final White Spruce Height-Diameter Model*

The 'preferred' white spruce height-diameter model (Equation 3-8) was supplemented with covariates under 2 rounds of covariate inclusion (Tables A-3-12 and A-3-13). A covariate model incorporating total basal area on mixed-effect $\beta_0$ yielded the lowest BIC and substantial reductions in random variation (Equation 3-8; Tables A-3-12 and A-3-13). This model included significant covariates, influential random-effects, and homoscedastic residuals under the final selection protocol (Table 3-23: Models 3.7.8 and 3.7.15). As a result, the final white spruce height-diameter model included total basal area and random-effects, yielding Equation 3-14 (Table 3-23: Model 3.7.8). Model summary statistics and graphical fits are displayed in Table 3-24, Figure 3-20, and Figure 3-21.

Table 3-23. Final model building procedure for the 2011-2012 white spruce height-diameter relationship. Model numbers reference Appendix 3: Tables A-3-12 and A-3-13. Parameter formulas modify Equation 3-2.

| Model | $b_0$ SD | RMSE | BIC | Comment |
|---|---|---|---|---|
| **3.7.8. NLME – TBA** $\beta_0=\beta_{00}+\beta_{01}TBA_i+b_{0i}$ | 1.01 | 0.56 | 359.9 | A Wald F-test indicated that the term for TBA ($\beta_{01}$) is significant (p-value = <0.0001). A likelihood-ratio test against Model 3.7.15 indicated that random effect ($b_0$) was necessary. Homoscedastic residuals. |
| **3.7.15. NLFE – TBA** $\beta_0=\beta_{00}+\beta_{01}TBA_i$ | . | 0.70 | 392.7 | A Wald F-test indicated that the term for TBA ($\beta_{01}$) is significant (p-value = <0.0001). Homoscedastic residuals. |

**Note:** $b_0$ = mixed-effects parameter; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; TBA = total basal area; i = plot; j = tree; NLFE = nonlinear fixed-effects model.

$$Hta_{ij} = (\beta_{00} + \beta_{01}TBA_i + b_{0i})\left(1 - e^{(-\beta_{10}DBH_{ij})}\right)^{(\beta_{20})} + \varepsilon_{ij} \qquad \text{(Equation 3-14)}$$

where $Hta_{ij}$ is height above breast height (m) for white spruce $j$ in plot $i$, $\beta_{00}$ is the asymptote 'intercept' parameter, $\beta_{01}$ is the asymptote 'slope' parameter, $TBA_i$ is total basal area ($m^2$/ha), $b_{0i}$ is the random-effect, $\beta_{10}$ is the rate parameter, $DBH_{ij}$ is diameter at breast height (mm), $\beta_{20}$ is the shape parameter, and $\varepsilon_{ij}$ is the residual error.

Table 3-24. Summary statistics for the final white spruce height-diameter model (Equation 3-14).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 7.3542 | 1.3251 | 4.7666 | 9.9417 | <0.0001 |
| | $\beta_{01}$ | 0.2238 | 0.0464 | 0.1332 | 0.3143 | <0.0001 |
| | $\beta_{10}$ | 0.0100 | 0.0016 | 0.0069 | 0.0130 | <0.0001 |
| | $\beta_{20}$ | 1.3010 | 0.0873 | 1.1304 | 1.4715 | <0.0001 |
| **Random-Effect Variation** | $b_0$ SD | 1.0056 | | 0.6204 | 1.6301 | |
| **RMSE** | | 0.5593 | | | | |
| **BIC** | | 359.8530 | | | | |

**Note:** SE = standard error; CI = confidence interval; SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

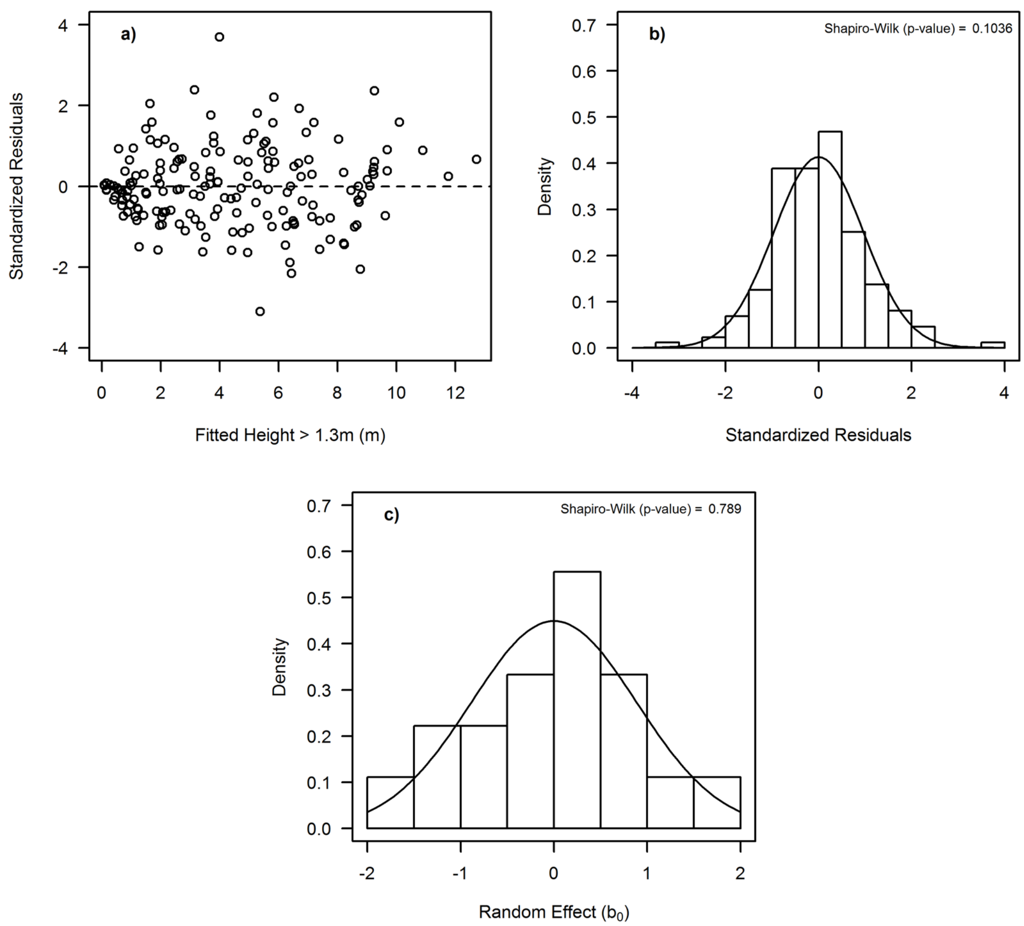


Figure 3-20. Distribution of residuals and random-effects for the final white spruce height-diameter model (Equation 3-14; Table 3-24): a) standardized residuals against fitted height, b) standardized residual distribution, and c) random-effect ($b_0$) distribution.

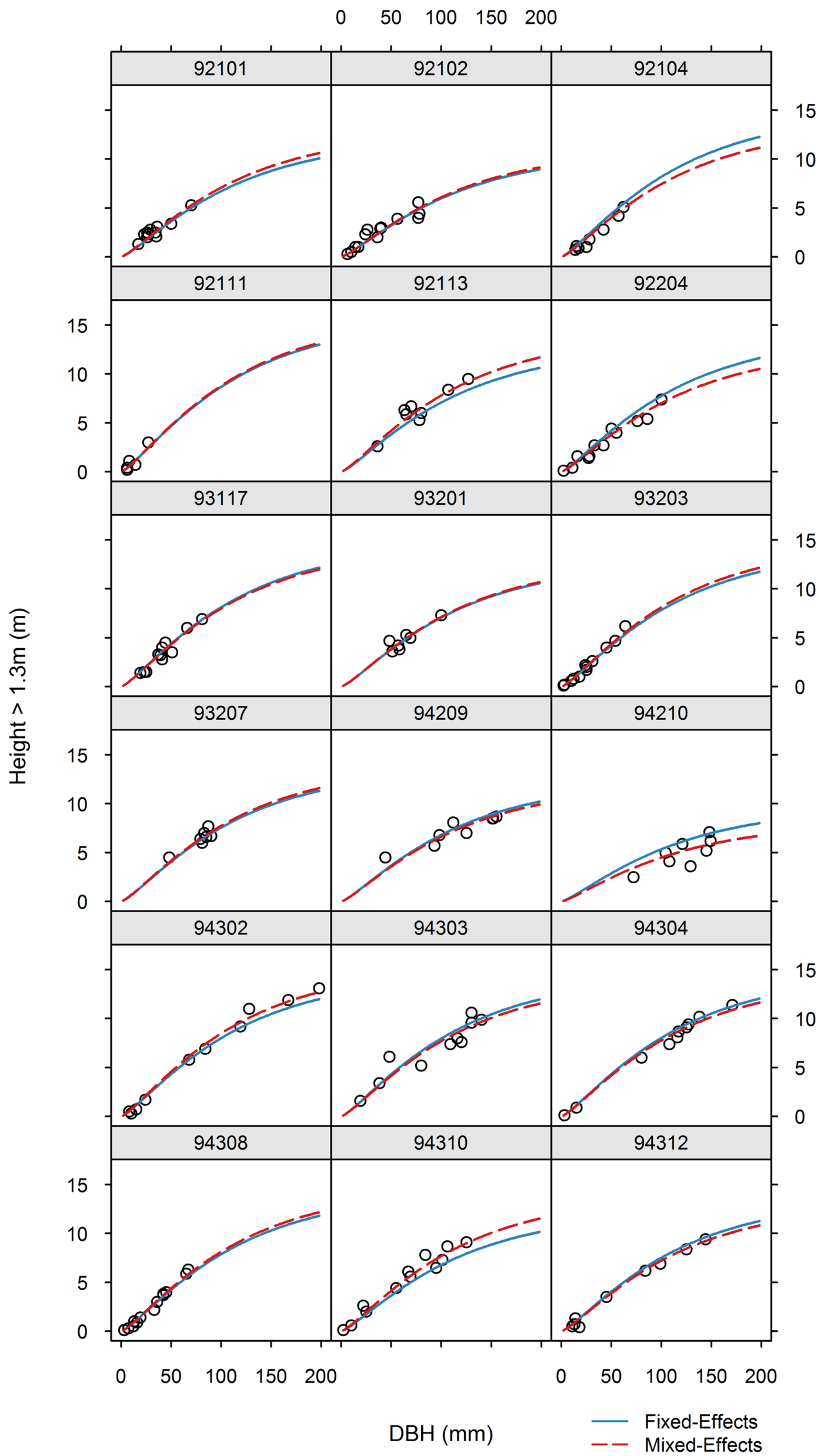


Figure 3-21. Population-level (fixed-effects) and plot-level (mixed-effects) fits for the final white spruce height-diameter model (Equation 3-14; Table 3-24). MS-PSP plot numbers (Table 3-1) are listed at the top of each graph. Observed height-diameter values are identified by the "○" symbol.

### 3.4 Discussion

*Model Development Issues*

Generalized model specification was complicated by the evaluation of tree-level, categorical plot-level, and continuous plot-level covariates. In height-diameter literature, generalized model specification appears to be influenced by covariate type (i.e. tree-level, categorical, or continuous). For example, studies that incorporated tree-level covariates (e.g. Temesgen and Gadow 2004; Temesgen et al. 2007; Rijal et al. 2012) often fitted many model formulations to produce an optimal covariate combination. Alternately, studies that incorporated categorical plot-level covariates (e.g. Fang and Bailey 2001) and continuous plot-level covariates (e.g. Calama and Montero 2004; Castedo-Dorado et al. 2006) often developed plot-level mixed-effects models and correlated covariates with estimated random-effects. Then, covariate/random-effect relationships were assessed graphically or via regression (Fang and Bailey 2001; Calama and Montero 2004; Castedo-Dorado et al. 2006). For the MS-PSP height-estimation models, tree-level and categorical plot-level covariates were incorporated individually, and continuous plot-level covariates were evaluated with 'covariate/random-effect relationships' (Tables A-3-1 and A-3-13). Small sample sizes restricted covariate/random-effect regression analysis (Tables 3-6, 3-8, and 3-10). Given the complexity and workload associated with generalized model development, height-diameter studies often adopt generalized equations from literature (e.g. Sharma and Parton 2007; Temesgen et al. 2008; Crecente-Campo et al. 2010; Castano-Santamaria et al. 2013; Crecente-Campo et al. 2014). This reduces the number of equations and/or covariate formulations to evaluate, allowing more time for mixed-effects specification, model calibration, and regional validation (e.g. Sharma and Parton 2007; Temesgen et al. 2008).

*Mixed-Effects Trends*

Among preliminary fits (Equations 3-3, 3-7, 3-8, and 3-9; Tables A-2-1 to A-2-4), mixed-effects models generally outperformed equivalent fixed-effects models, coinciding with height-diameter literature (Saunders and Wagner 2008;

Temesgen et al. 2008; Rijal et al. 2011). However, among generalized fits (Equations 3-10, 3-11, 3-12, 3-13, and 3-14), random-effects were only significant in the white birch and white spruce height-diameter models (Tables 3-21 and 3-23). Random-effects were not significant in the generalized balsam poplar, black spruce, and trembling aspen height-diameter models (Tables 3-13, 3-15, and 3-19).

*Covariate Trends*

Covariates explained a significant amount of random variation in the balsam poplar, black spruce, trembling aspen, white birch, and white spruce height-diameter models (Tables 3-13, 3-15, 3-19, 3-21, and 3-23). Among models with significant covariates, no single covariate (e.g. total basal area) explained random variation across all species. However, top height, basal area, and/or density consistently advanced through final model selection (Tables 3-13, 3-15, 3-19, 3-21, and 3-23), matching covariates in Calama and Montero (2004), Sharma and Parton (2007), and Paulo et al. (2011). Together, top height and density (i.e. trees/ha or basal area) describe the local competitive environment. Top height also serves as an imperfect indicator of site productivity (Skovsgaard and Vanclay 2008) and an indirect temporal variable (Calama and Montero 2004). Meanwhile, density (i.e. trees/ha or basal area) specifies the local competition load which can influence height-diameter ratios (Calama and Montero 2004; Saunders and Wagner 2008; Vanclay 2009). Increasing top height and competition are usually associated with increasing height-diameter ratios (Calama and Montero 2004; Saunders and Wagner 2008; Paulo et al. 2011). For the MS-PSP dataset, top height and competition covariates positively influenced Chapman-Richards parameters (i.e. $\beta_0/\beta_2$) (Equation 3-2; Tables 3-14, 3-16, 3-20, 3-22, and 3-24) and modified height-diameter ratios (Figures 3-9; 3-11, 3-15, 3-19, and 3-21).

Alternately, covariates were not significant for the white spruce height-root collar relationship or the jack pine height-diameter relationship (Tables 3-11 and 3-17). Unlike the 2011-2012 height-diameter models (Tables 3-14, 3-16, 3-

18, 3-20, 3-22, and 3-24), the 1996 white spruce height-root collar relationship used RCD as a predictor variable (Equation 3-3) and represented an earlier stage of stand development (5-14 years). Covariates such as thinning, site preparation, visual cover, and basal area are often associated with juvenile white spruce growth (Boateng et al. 2009; Cortini and Comeau 2008; Cortini et al. 2012); however, these covariates failed to reduce height-root collar BIC (Table A-3-1). Visual cover may have been poorly characterized under the 1996 MS-PSP measurement protocol, given extremely small sample sizes. [i.e. Visual cover was only assessed across four 4×4m quadrats, representing only 16% of each 20×20m primary plot (Figure 3-4)]. The jack pine height-diameter relationship also included sparse data that may have influenced covariate performance. Specifically, the jack pine height-diameter relationship was uniformly asymptotic and lacked intermediate diameter trees (Figure 3-13). This encouraged a random-effect on Chapman-Richards parameter $\beta_1$ (Equation 3-9; Table A-2-3). As a result, all generalized jack pine height-diameter models included covariates on Chapman-Richards parameter $\beta_1$ (Equation 3-9; Tables A-3-6 and A-3-7); this was contrary to other height-diameter studies that included covariates and random-effects on Chapman-Richards parameters $\beta_0$ and $\beta_2$ (Saunders and Wagner 2008; Temesgen et al. 2007; Temesgen et al. 2008; Rijal et al. 2012).

Thinning and mechanical site preparation often yielded insignificant parameter statistics during covariate inclusion (Tables A-3-1 and A-3-13) and did not advance through final model selection for any height-diameter relationships (Equations 3-3, 3-9, 3-10, 3-11, 3-12, 3-13, and 3-14). Incidentally, mechanical site preparation was found to influence the white birch height-diameter relationship (Table 3-21); however, this effect was confounded by treatment-dependent regeneration patterns (Figures 3-16 and 3-17; Prevost 1997) and irregular thinning regimes (Table 3-1). Although thinning and site preparation are known to influence height-diameter ratios (Boateng et al. 2009), differences between individual treatments can be small or inconsistent, unless treatment effects are contrasted against an untreated control (e.g. Boateng et al. 2009). No untreated control exists within the MS-PSP network. In any case, potential interactions between thinning and mechanical site preparation confound definitive silvicultural conclusions.

BAL (i.e. BAL, CBAL, and DBAL) also failed to yield significant parameter statistics during covariate inclusion (Tables A-3-1 and A-3-13) and only advanced through final model selection for the black spruce height-diameter relationship (Table 3-15). BAL's poor performance is particularly surprising since similar one-sided competition metrics (e.g. sum of DBH larger than subject, density above subject) are featured in the Mixedwood Growth Model (Bokalo et al. 2010). Furthermore, BAL has strongly influenced height-diameter relationships across different forest regions (Temesgen et al. 2007; Temesgen et al. 2008; Rijal et al. 2012). Several factors may have restricted BAL's performance. First, BAL is a one-sided competition metric (Rijal et al. 2012) that disregards the competitive effect of smaller trees. Second, natural origin subsamples may not have adequately characterized primary plot competition (Figures 3-2 and 3-4) and skewed BAL estimates. Third, 'proxy BAL' values were assigned to all top height trees in the 2011-2012 measurement, potentially introducing bias.

Height-diameter relationships are also known to change over time (Curtis 1967; Assmann 1970); however, in this study, stand age did not achieve prominence during covariate inclusion (Tables A-3-1 to A-3-13) or final model selection (Tables 3-11, 3-13, 3-15, 3-17, 3-19, 3-21, and 3-23). Similarly, stand age failed to influence the generalized height-diameter models in Calama and Montero (2004) and Castedo-Dorado et al. (2006). These authors hypothesized that the covariate 'dominant height' indirectly explained temporal effects (Calama and Montero 2004; Castedo-Dorado et al. 2006). For the MS-PSP's, radial thinning treatments, irregular establishment times (e.g. jack pine/white birch), and a limited range of stand ages (Table 3-1) may have obscured age-effects. Moreover, stand age may be a poor predictor of growth, particularly for suppressed white spruce (Bokalo et al. 2010).

*MS-PSP Model Limitations*

Given the small sample size (Tables 3-6 and 3-8), limited range (e.g. stand age, tree size) (Tables 3-1, 3-6, and 3-9), and sub-regional nature (Figure 3-1) of the MS-PSP dataset, the MS-PSP height-estimation models have a limited end-use. Most height-diameter studies use large datasets that incorporate a range of tree diameters and heights (Huang et al. 1992; Huang et al. 2000; Calama and Montero 2004; Castedo-Dorado et al. 2006; Trincado et al. 2007). In addition, many height-diameter studies include a variety of ecosites, ecoregions, stand densities, and stand ages: factors that are known to influence height-diameter relationships (Huang et al. 1992; Huang et al. 2000; Calama and Montero 2004; Castedo-Dorado et al. 2006; Trincado et al. 2007).

Small samples sizes also hindered model validation for the MS-PSP height-estimation models. In this study, BIC and residual error were used to assess model fit; however, model fit statistics do not necessarily indicate predictive performance (Robinson and Wykoff 2004). As a result, many authors have employed data-splitting (Huang et al. 1992; Huang et al. 2000; Calama and Montero 2004; Castedo-Dorado et al. 2006) or cross-validation (Robinson and Wykoff 2004; Temesgen et al. 2008) to validate model predictions. Since a formal validation could not be performed, the predictive capability of the MS-PSP height-estimation models cannot be fully evaluated.

*Predicting Height with Mixed-Models*

If a subsample of height and DBH information is available, calibrated mixed-effects models frequently outperform equivalent population-level fixed-effects models (Sharma and Parton 2007; Temesgen et al. 2008). Noticeable gains in mixed-model performance (i.e. RMSE) are often achieved by calibrating with at least 1 subsample tree (Sharma and Parton 2007; Calama and Montero 2004; Temesgen et al. 2008). Increasing the number of calibration trees tends to decrease prediction error (Calama and Montero 2004; Castedo-Dorado et al. 2006; Temesgen et al. 2008; Meng et al. 2009); however, relative gains in accuracy often decrease as the number of calibration trees increases (Calama and Montero

2004; Temesgen et al. 2008). For example, Calama and Montero (2004) recommended sampling 4 calibration trees per plot but conceded that 'optimal' subsample sizes should be determined with a cost-benefit analyses. Interestingly, the fixed-effects component in mixed-effects models often yields poor predictions (Robinson and Wykoff 2004; Castedo-Dorado et al. 2006) and may produce worse predictions than population-level fixed-effects models (Temesgen et al. 2008; Meng et al. 2009). In addition, the fixed-effects component in nonlinear mixed-effects models may not faithfully represent a population-level response (Meng et al. 2009). Therefore, if subsamples are not available and mixed-model calibration is not possible, some authors recommend estimating tree height with population-level fixed-effects models (Temesgen et al. 2008; Meng et al. 2009). As a result, alternative population-level fixed-effects models for the MS-PSP dataset are listed in Appendix 4 (Tables A-4-1 to A-4-4; Figures A-4-1 to A-4-4).

The predictive performance of calibrated mixed-effect models may also depend on the model form and calibration-tree sampling protocol. For example, studies that included the covariate 'dominant height' often maximized predictive performance when calibrating with small (Castedo-Dorado et al. 2006) or randomly selected trees (Calama and Montero 2004). Similarly, studies that included the covariate 'dominant height' yielded relatively poor predictions when calibrating with dominant trees; nevertheless, these calibrated predictions were generally better than population-level estimates (Calama and Montero 2004; Castedo-Dorado et al. 2006). Overall, these findings indicate that generalized models should be integrated with field sampling protocols to maximize mixed-model calibration and deployment.

*Calibrating Mixed-Effects Models*

Mixed-effects model calibration generally follows a 4 step process: First, a mixed-effects model is fit to a robust dataset (Trincado et al. 2007; Temesgen et al. 2008; Meng and Huang 2009). Second, the random-effects variance-covariance matrix $\widehat{D}$, within-plot variance-covariance matrix $\hat{R}$, and fixed-effects parameters $\hat{\beta}$ are extracted from the fitted mixed-effects model. Third, the extracted mixed-model components are combined with observations from an independent dataset to estimate new subject-specific (e.g. plot-level) random-effects. Finally, these new random effects are applied to each subject, yielding calibrated predictions (e.g. height) (Trincado et al. 2007; Temesgen et al. 2008; Meng and Huang 2009).

Mixed-effects model calibration should occur using the same computational methodology as the original mixed-model fit. Substantial calibration errors can occur when using an incorrect random-effects estimation technique or subject-specific prediction method (Meng and Huang 2009; Yang and Huang 2013). In some cases, 'mixing and matching' calibration techniques can also yield biologically inconsistent trends (Yang and Huang 2013). For linear mixed-effects models, random-effects estimation should follow Equation 15:

$$\hat{b}_i = \hat{D}Z_i^T\left(Z_i\hat{D}Z_i^T + \hat{R}_i\right)^{-1}\left(y_i - f\left(x_i, \hat{\beta}\right)\right) \quad \text{(Equation 3-15)}$$

where $\hat{b}_i$ is a new random effect for plot *i*, $\hat{D}$ is the estimated random-effects variance-covariance matrix, $Z_i$ is a design matrix (without random effects), $Z_i^T$ is the transpose of design matrix $Z_i$, $\hat{R}_i$ is the estimated within-plot variance-covariance matrix, $y_i$ is the response variable, $f(.)$ is a linear function, $x_i$ is the predictor variable, and $\hat{\beta}$ are the estimated fixed-effects (Trincado et al. 2007; Meng and Huang 2009).

For nonlinear mixed-effects models linearized with a first-order Taylor Series expanded around EBLUP's, random-effect estimation should follow Equation 16:

$$\hat{b}_i = \hat{D}Z_i^T\left(Z_i\hat{D}Z_i^T + \hat{R}_i\right)^{-1}\left(y_i - f\left(x_i, \hat{\beta}, \hat{b}_i\right) + Z_i\hat{b}_i\right) \quad \text{(Equation 3-16)}$$

where $\hat{b}_i$ is a new random effect for plot *i*, $\hat{D}$ is the estimated random-effects variance-covariance matrix, $Z_i$ is a design matrix (with random effects), $Z_i^T$ is the transpose of design matrix $Z_i$, $\hat{R}_i$ is the estimated within-plot variance-covariance matrix, $y_i$ is the response variable, $f(.)$ is a nonlinear function, $x_i$ is the predictor variable, and $\hat{\beta}$ are the estimated fixed-effects (Temesgen et al. 2008; Meng and Huang 2009). Since random-effects occur on both sides of Equation 16, $\hat{b}_i$ must be iteratively solved (Temesgen et al. 2008; Meng and Huang 2009).

For Equations 15 and 16, subject-specific predictions are then estimated with equation:

$$\hat{y}_i = f\left(x_i, \hat{\beta}, \hat{b}_i\right) \quad \text{(Equation 3-17)}$$

where $\hat{y}_i$ is the estimated response variable for plot $i$, $f(.)$ is a linear or nonlinear function, $\hat{\beta}$ are the estimated fixed-effects, and $\hat{b}_i$ are the estimated random effects (Trincado et al. 2007; Meng and Huang 2009; Yang and Huang 2013).

**3.5 Conclusion**

Height-estimation models were developed for the MS-PSP dataset using a generalized mixed-effects approach. Generalized mixed-effects models attempt to explain random variation with covariates and random-effects. As a result, generalized mixed-effects models often produce better height estimates than 'pure' fixed-effects models informed solely by height and stem diameter. Generalized mixed-effects models that included density (i.e. basal area and density) or top height often explained the most random variation, suggesting competition, site productivity, and stand age influence height-diameter relationships. In some cases, covariates can eliminate the need for random-effects.

To assess 'true' model performance, generalized mixed-effects models must be developed with regional data, integrated sampling, careful calibration, and model validation. The MS-PSP height-estimation models were developed using a small dataset that limited model validation. As a result, the MS-PSP height-estimation models are not transferrable and should only be used on the fitted dataset.

## Chapter 4. Modeling juvenile forest growth in the mixedwoods of Saskatchewan.

### 4.1 Introduction

In the absence of long-term post-harvest data (Bokalo et al. 2013), forest growth models allow social, environmental, and economic objectives to be evaluated during forest management planning (Crookston and Dixon 2005; Havis and Crookston 2008). Across western Canada, forest growth models have been used to assess silvicultural treatments (Pitt et al. 2004; Hawkins et al. 2006; Cortini et al. 2010), evaluate economic outcomes (Hawkins et al. 2006; Comeau 2014), game alternative management scenarios (Welham et al. 2002; Comeau et al. 2005), and explore novel management strategies (Comeau 2014; Grover et al. 2014). Furthermore, forest growth models support sustainable management and regulatory decision-making across provincial jurisdictions (BCMFNRO 2014; AESRD 2014; SME 2007b; Bokalo et al. 2013).

In Saskatchewan, forest management planning must consider the "*predicted future structure, composition, and condition of the forest*" (SFRMR 1999). Harvest volume schedules must also acknowledge silvicultural effects, incorporate expected volume losses, and weigh the short and long-term implications of alternative harvest rates (SFRMR 1999). Forest growth models can support these criteria, provided the target model(s) reflect local conditions, address variable stocking, consider site productivity, endure statistical evaluation, and undergo peer-review (SME 2007b). Finally, forest growth models must yield biologically reasonable estimates with independent data (SME 2007b).

*Forest Growth Models in Western Canada*

Across western Canada, various forest growth models have been deployed in boreal forests, including British Columbia's Tree and Stand Simulator (TASS) (BCMFLNO 2014; Hawkins et al. 2006), Alberta's Growth and Yield Projection System (GYPSY) (Huang et al. 2009), the University of Alberta's Mixedwood Growth Model (MGM) (Bokalo et al. 2013; Bokalo et al. 2010), the University of

British Columbia's FORECAST (Kimmins et al. 1999; Welham et al. 2002), and the open-source SORTIE-ND (Coates et al. 2003; Astrup et al. 2008). Of these models, only MGM is peer-reviewed, statistically validated, and operationally supported in Saskatchewan (Bokalo et al. 2013).

*Objectives*

To support regulatory decision-making and forest growth modeling in Saskatchewan, this chapter has 5 objectives: 1) Validate MGM's juvenile white spruce functions using independent data; 2) Examine MGM's growth and succession forecasts across a range of stand densities, species compositions, and site productivities; 3) Discuss protocols to optimize MGM projections; 4) Explore alternative data sources for modeling juvenile stands; and 5) Highlight sampling protocols that support MGM simulations.

## 4.2 Methods

*The Mixedwood Growth Model*

The Mixedwood Growth Model (MGM) is a "*deterministic, distance-independent, individual tree-based stand growth model developed for the western Canadian boreal forest*" (Bokalo et al. 2013). In MGM, height-age-site index models predict the 'maximum potential' height increment of all trees. Then, individual trees interact within a local competitive environment (e.g. plot or stand) to yield competition-adjusted height increment, diameter increment, and survival probability. Tree-level estimates are updated annually and summarized at user-defined intervals. MGM (i.e. *MGM 2010A1 Rev 3099*) currently models pure or mixed stands of white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*), trembling aspen (*Populus tremuloides*), and black spruce (*Picea mariana*). Other boreal species are modeled using species surrogates. For example, jack pine (*Pinus banksiana*) is modeled as lodgepole pine. Balsam fir (*Abies balsamea*) and tamarack (*Larix laricina*) are modeled as black spruce, and balsam poplar (*Populus balsamifera*) and white birch (*Betula papyrifera*) are modeled as trembling aspen. MGM projections require plot-level treelists with comprehensive height and diameter at breast height (DBH @ 1.3m) information (Trees >1.3m), or representative stand-level summaries with density, height (i.e. mean, max, and standard deviation), and DBH (i.e. mean) data. All MGM projections must specify stand age, site index, and a representative suite of height-age-site index models.

For each ‘component species’, MGM’s height increment, diameter increment, and survival probability functions are subdivided into 3 stand development phases (Bokalo et al. 2013). Juvenile functions apply to trees < 4cm DBH. Mid-rotation functions apply to trees > 4cm DBH and < 80% the regional maximum height, and old-growth functions apply to trees > 80% the regional maximum height. Currently, all MGM height increment, diameter increment, and survival probability functions are calibrated with Alberta data. Complete MGM equations and coefficients are described on the MGM website: http://www.rr.ualberta.ca/Research/MixedwoodGrowthModel.aspx.

*Evaluation Datasets*

In this study, MGM projections were evaluated using 3 datasets: Managed Stand Permanent Sample Plots (MS-PSP’s), Temporary Sample Plots (TSP’s), and establishment surveys. Sample design and sample frequency dictated each dataset’s application(s). The MS-PSP measurement protocol is listed in Chapter 3. The TSP measurement protocol is listed in Chapter 2, and the establishment surveys are described in Chapter 4.

*MS-PSP Measurements*

All 18 MS-PSP’s were measured in 1996 and 2011-2012 (Table 3-1). The 1996 MS-PSP measurements were collected between April and July (Table 3-1), and the 2011-2012 MS-PSP measurements were collected between October 2011 and May 2012 (Table 3-1). Given comprehensive samples and limited sampling periods (≤ 8 months), MGM growth modeling focused on the 1996 and 2011-2012 MS-PSP measurements.

*1996 MS-PSP Data Management*

For the 1996 MS-PSP measurement, white spruce height was imputed with a linear mixed-effects height-root collar model. The methodology, equation, parameters, and summary statistics for the linear mixed-effects height-root collar model are described in Chapter 3. Although most white spruce heights were successfully estimated, height-root collar predictions near 1.3m often produced 2 errors: 1) On trees less than 1.3m, DBH measurements were not observed, and imputed heights exceeded 1.3m. 2) On trees greater than 1.3m, DBH measurements were observed, and imputed heights fell below 1.3m. Since these errors adversely affect MGM, 48 'Case 1' white spruce were assigned a 'default height' of 1.31m, and 32 'Case 2' white spruce were assigned a 'default height' of 1.29m. Table 4-1 contains summary statistics for the 1996 MS-PSP measurement with height-root collar estimates and 'default heights'.

Table 4-1. Summary statistics for 18 MS-PSP's measured in 1996. White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 14622 | 1625 | 28100 | 8369 |
| | Basal Area ($m^2$/ha) | 2.8 | 0.0 | 8.1 | 2.3 |
| | Volume ($m^3$/ha) | 5.1 | 0.0 | 16.9 | 4.7 |
| | Top Height (m) | 4.0 | 1.4 | 5.0 | 1.2 |
| | Height (m) | 1.5 | 0.9 | 3.0 | 0.6 |
| | DBH (cm) | 0.8 | 0.1 | 2.4 | 0.6 |
| BS | Density (Trees/ha) | 11 | 0 | 100 | 32 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.0 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.0 | 0.0 |
| | Top Height (m) | 0.0 | 0.0 | 0.0 | 0.0 |
| | Height (m) | 0.1 | 0.0 | 0.8 | 0.2 |
| | DBH (cm) | 0.0 | 0.0 | 0.0 | 0.0 |
| JP | Density (Trees/ha) | 4194 | 0 | 22500 | 6890 |
| | Basal Area ($m^2$/ha) | 0.7 | 0.0 | 4.6 | 1.5 |
| | Volume ($m^3$/ha) | 1.3 | 0.0 | 9.7 | 2.7 |
| | Top Height (m) | 1.4 | 0.0 | 4.8 | 1.6 |
| | Height (m) | 0.8 | 0.0 | 3.1 | 1.0 |
| | DBH (cm) | 0.5 | 0.0 | 3.5 | 0.9 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table 4-1 (continued). Summary statistics for 18 MS-PSP's measured in 1996. White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| TA | Density (Trees/ha) | 7850 | 100 | 25100 | 6826 |
| | Basal Area ($m^2$/ha) | 1.9 | 0.0 | 7.5 | 2.1 |
| | Volume ($m^3$/ha) | 3.5 | 0.0 | 16.0 | 4.4 |
| | Top Height (m) | 3.7 | 0.0 | 5.0 | 1.5 |
| | Height (m) | 2.0 | 0.8 | 3.4 | 0.7 |
| | DBH (cm) | 1.0 | 0.0 | 2.6 | 0.7 |
| WS | Density (Trees/ha) | 2567 | 1525 | 4300 | 809 |
| | Basal Area ($m^2$/ha) | 0.2 | 0.0 | 1.3 | 0.4 |
| | Volume ($m^3$/ha) | 0.3 | 0.0 | 1.8 | 0.5 |
| | Top Height (m) | 2.0 | 0.0 | 4.6 | 1.1 |
| | Height (m) | 1.2 | 0.5 | 2.4 | 0.6 |
| | DBH (cm) | 0.5 | 0.0 | 2.5 | 0.8 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

*2011-2012 MS-PSP Data Management*

For the 2011-2012 MS-PSP measurement, balsam poplar, black spruce, and trembling aspen heights were imputed with generalized nonlinear fixed-effects height-diameter models. Unmeasured jack pine heights were predicted with a nonlinear mixed-effects height-diameter model, and unmeasured white birch and white spruce heights were estimated with generalized nonlinear mixed-effects height-diameter models. The methodology, equations, parameters, and summary statistics for each height-diameter model are listed in Chapter 3. In addition, tallied trees less than 1.3m were assigned a 'default height' of 0.65m. Table 4-2 contains summary statistics for the 2011-2012 MS-PSP measurement with height-diameter estimates and 'default heights'.

Site index (m@50yrs) was also estimated for MGM's component species using the Alberta Central Mixedwood site index equations (Huang 1997c; Huang et al. 1997). To estimate site index, top height and breast height age were entered into each height-age-site index equation. Then, tree-level site index estimates were averaged at the plot-level. Poor form and null top height samples prevented complete site index estimates for black spruce, jack pine, and trembling aspen. White spruce site index estimates were calculated for all MS-PSP's (Table 4-3).

Table 4-2. Summary statistics for 18 MS-PSP's measured in 2011-2012. White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 8275 | 3050 | 19275 | 4453 |
| | Basal Area ($m^2$/ha) | 27.4 | 10.6 | 37.8 | 6.9 |
| | Volume ($m^3$/ha) | 126.0 | 27.9 | 188.9 | 43.6 |
| | Top Height (m) | 12.4 | 8.8 | 18.0 | 2.8 |
| | Height (m) | 6.6 | 4.2 | 8.9 | 1.5 |
| | DBH (cm) | 5.9 | 2.9 | 9.1 | 1.8 |
| BS | Density (Trees/ha) | 318 | 0 | 2000 | 588 |
| | Basal Area ($m^2$/ha) | 0.4 | 0.0 | 3.8 | 1.0 |
| | Volume ($m^3$/ha) | 1.1 | 0.0 | 10.8 | 2.8 |
| | Top Height (m) | 2.1 | 0.0 | 9.1 | 3.1 |
| | Height (m) | 1.6 | 0.0 | 9.1 | 2.6 |
| | DBH (cm) | 1.4 | 0.0 | 9.1 | 2.6 |
| JP | Density (Trees/ha) | 2117 | 0 | 9900 | 3394 |
| | Basal Area ($m^2$/ha) | 8.0 | 0.0 | 27.8 | 11.3 |
| | Volume ($m^3$/ha) | 35.3 | 0.0 | 121.0 | 50.0 |
| | Top Height (m) | 4.9 | 0.0 | 10.8 | 5.1 |
| | Height (m) | 4.1 | 0.0 | 10.2 | 4.4 |
| | DBH (cm) | 3.8 | 0.0 | 12.3 | 4.5 |
| TA | Density (Trees/ha) | 3483 | 1200 | 10400 | 2383 |
| | Basal Area ($m^2$/ha) | 12.9 | 1.0 | 31.9 | 9.5 |
| | Volume ($m^3$/ha) | 67.2 | 3.1 | 171.7 | 58.6 |
| | Top Height (m) | 12.3 | 8.4 | 18.0 | 3.1 |
| | Height (m) | 8.0 | 3.9 | 11.4 | 2.2 |
| | DBH (cm) | 5.6 | 2.6 | 9.5 | 2.0 |
| WS | Density (Trees/ha) | 2357 | 1400 | 4000 | 813 |
| | Basal Area ($m^2$/ha) | 6.2 | 0.3 | 15.1 | 4.9 |
| | Volume ($m^3$/ha) | 22.5 | 0.4 | 75.2 | 22.3 |
| | Top Height (m) | 8.3 | 4.1 | 13.6 | 2.5 |
| | Height (m) | 5.1 | 1.5 | 8.5 | 2.1 |
| | DBH (cm) | 5.3 | 0.6 | 9.4 | 2.8 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

Table 4-3. Top height summary statistics for 18 MS-PSP's measured in 2011-2012. All observations originate from MS-PSP top height plots. Site index estimates reflect the height-age-site index equations from Huang (1997c) and Huang et al. (1997).

| **Species** | **N** | **Variable** | **Mean** | **Min** | **Max** | **SD** |
|---|---|---|---|---|---|---|
| BS | 4 | Top Height (m) | 5.7 | 4.8 | 6.5 | 0.8 |
| | | Top Height DBH (cm) | 6.7 | 4.8 | 8.6 | 1.6 |
| | | Breast Height Age (yrs) | 14.3 | 11.0 | 16.0 | 2.4 |
| | | Site Index (m@50yrs) | 15.3 | 13.3 | 16.6 | 1.4 |
| JP | 8 | Top Height (m) | 10.0 | 9.4 | 10.8 | 0.6 |
| | | Top Height DBH (cm) | 13.1 | 11.6 | 16.7 | 1.6 |
| | | Breast Height Age (yrs) | 18.7 | 16.5 | 21.0 | 1.6 |
| | | Site Index (m@50yrs) | 19.9 | 18.3 | 21.6 | 1.3 |
| TA | 17 | Top Height (m) | 12.6 | 6.2 | 18.4 | 2.9 |
| | | Top Height DBH (cm) | 12.7 | 4.0 | 19.6 | 4.0 |
| | | Breast Height Age (yrs) | 22.7 | 17.0 | 31.5 | 3.9 |
| | | Site Index (m@50yrs) | 21.9 | 14.8 | 29.3 | 3.3 |
| WS | 18 | Top Height (m) | 8.3 | 2.9 | 13.8 | 2.7 |
| | | Top Height DBH (cm) | 9.8 | 2.3 | 18.3 | 4.2 |
| | | Breast Height Age (yrs) | 17.9 | 13.0 | 24.0 | 3.4 |
| | | Site Index (m@50yrs) | 21.6 | 11.1 | 27.0 | 4.0 |

**Note:** SD = standard deviation; N = number of MS-PSP's

*TSP Data Management*

64 TSP's were measured across 16 white spruce plantations in 2011-2012 (Table 2-1). For spruce between 0.3m and 1.3m, height was tallied into 2 discrete classes (Class 1: 0.3m-0.8m; Class 2: 0.81m-1.3m) within the 100m$^2$ primary plot. Spruce in TSP Height Class 1 were assigned a 'default height' of 0.55m, and spruce in TSP Height Class 2 were assigned a 'default height' of 1.05m. For competing trees between 0.3m and 1.3m, height was tallied into 2 discrete classes (Class 1: 0.3m-0.8m; Class 2: 0.81m-1.3m) within 1 to 4 circular 10m$^2$ subplots. Competing trees in TSP Height Class 1 were assigned a 'default height' of 0.55m, and competing trees in TSP Height Class 2 were assigned a 'default height' of 1.05m. Table 4-4 provides summary statistics for the 2011-2012 TSP measurement.

Table 4-4. Summary statistics for 16 TSP stands measured in 2011-2012. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 15851 | 6050 | 27000 | 6725 |
| | Basal Area ($m^2$/ha) | 16.1 | 5.5 | 23.6 | 5.7 |
| | Volume ($m^3$/ha) | 54.9 | 12.6 | 104.7 | 27.0 |
| | Top Height (m) | 8.5 | 4.4 | 11.7 | 1.9 |
| | Height (m) | 3.8 | 1.2 | 5.6 | 1.2 |
| | DBH (cm) | 2.6 | 0.5 | 4.4 | 1.0 |
| BS | Density (Trees/ha) | 1807 | 0 | 11975 | 3618 |
| | Basal Area ($m^2$/ha) | 0.4 | 0.0 | 3.7 | 0.9 |
| | Volume ($m^3$/ha) | 0.7 | 0.0 | 7.7 | 1.9 |
| | Top Height (m) | 1.2 | 0.0 | 3.7 | 1.4 |
| | Height (m) | 0.6 | 0.0 | 2.3 | 0.7 |
| | DBH (cm) | 0.4 | 0.0 | 1.9 | 0.5 |
| JP | Density (Trees/ha) | 945 | 0 | 6875 | 1828 |
| | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 7.8 | 2.3 |
| | Volume ($m^3$/ha) | 3.2 | 0.0 | 21.5 | 6.1 |
| | Top Height (m) | 1.3 | 0.0 | 4.8 | 1.7 |
| | Height (m) | 1.1 | 0.0 | 3.8 | 1.4 |
| | DBH (cm) | 1.0 | 0.0 | 4.5 | 1.4 |
| TA | Density (Trees/ha) | 11228 | 4150 | 20667 | 5261 |
| | Basal Area ($m^2$/ha) | 13.9 | 1.3 | 22.7 | 6.8 |
| | Volume ($m^3$/ha) | 49.7 | 2.8 | 104.1 | 30.1 |
| | Top Height (m) | 8.3 | 2.3 | 11.7 | 2.4 |
| | Height (m) | 5.0 | 1.5 | 8.7 | 1.6 |
| | DBH (cm) | 3.4 | 0.8 | 6.9 | 1.4 |
| WS | Density (Trees/ha) | 1870 | 675 | 7100 | 1497 |
| | Basal Area ($m^2$/ha) | 0.7 | 0.0 | 1.4 | 0.5 |
| | Volume ($m^3$/ha) | 1.2 | 0.0 | 3.1 | 0.9 |
| | Top Height (m) | 3.5 | 0.5 | 5.0 | 1.0 |
| | Height (m) | 2.1 | 0.6 | 3.3 | 0.7 |
| | DBH (cm) | 1.6 | 0.1 | 3.3 | 0.9 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

*Establishment Surveys*

Hard copy establishment surveys were obtained for 8 TSP plantations: U07_23, U07_41, U07_77.2, U07_103, U14_273.1, U14_337.1, U23_93, and U23_158 (Tables 2-1 and 2-2). All establishment surveys occurred in 1997 and 2000 when TSP plantations were 3 to 4 years old. Measurements took place on a systematic grid with $5m^2$ circular plots. Stocking was categorically assessed on every plot, and height, density, and vegetation cover were measured on every fourth plot. Sample intensity ranged from 1.97 to 3.27 plots/hectare for stocking and 0.49 to 0.82 plots/hectare for height, density, and vegetation cover.

*Selecting a Height-Age-Site Index Model*

In MGM, height-age-site index models drive tree-level growth and influence long-term succession. As a result, height-age-site index models must accurately depict regional growth to ensure reasonable MGM performance. Currently, the Saskatchewan height-age-site index models from Cieszewski et al. (1993) are under review with revised stem-analysis data (Lane Gelhorn, Saskatchewan Environment, personal communication, 20/08/2014). Preliminary analysis indicates that the 'Alberta Central Mixedwood' height-age-site index models fit the revised stem-analysis data better than Cieszewski et al. (1993) (Lane Gelhorn, Saskatchewan Environment, personal communication, 20/08/2014). Therefore, all MGM simulations used the 'Alberta Central Mixedwood' height-age-site index models (Huang 1997c; Huang et al. 1997).

*Planted White Spruce Validation*

Validation is widely applied in forest biometrics to assess model predictions and determine model credibility (Yang et al. 2004; Robinson and Froese 2004; Robinson et al. 2005). Validation also facilitates model improvement and user decision-making (Yang et al. 2004; Robinson et al. 2005). Nevertheless, validation is often contentious, subjective, and dependent on the intended application (Kozak and Kozak 2003; Robinson and Froese 2004; Yang et al. 2004). In practice, validation should incorporate independent data and evaluate model performance using graphical and statistical techniques (Robinson and Froese 2004; Yang et al. 2004). Graphical techniques frequently involve scatter plots, and statistical techniques often include simple statistics and/or hypothesis tests (Yang et al. 2004; Robinson and Froese 2004; Robinson et al. 2005; Bokalo et al. 2013). Although many validation tools are available, no single validation technique is universally applied (Yang et al. 2004; Robinson and Froese 2004). As a result, models are often validated with various statistical tests that describe different aspects of model behaviour (Bokalo et al. 2013).

Conceptually, MGM validation followed a 3 step process. First, MGM was initialized using plot-level treelists from the 1996 MS-PSP measurement. Then, each MS-PSP was simulated from 1996 to 2011, and MGM predictions for 2011 were contrasted with observations from the 2011-2012 MS-PSP measurement[2]. Comparisons occurred at the plot-level and tree-level. Since the 1996 MS-PSP measurement did not enumerate naturally regenerated trees, validation was restricted to planted white spruce.

At the plot-level, juvenile white spruce validation used graphical analysis, simple statistics, and equivalence tests. Plot-level predictions were graphed against plot-level observations, and model performance was assessed relative to a 1:1 relationship through the origin. Three simple statistics were used to describe plot-level bias: efficiency, average model bias, and relative model bias. Efficiency (EF) describes the relative variation and precision of model predictions (Equation 4-1; Bokalo et al. 2013). EF values range from 1 (i.e. perfect fit), 0 (i.e. predictions =mean observation), and <0 (i.e. extremely poor fit). Average model bias (AMB) indicates the average residual error in predicted units (Equation 4-2). Finally, relative model bias (RMB) expresses average residual error as a percentage of the observed mean, signifying the magnitude of average error (Equation 4-3). Both AMB and RMB express overestimates as negative values and underestimates as positive values.

$$EF_{pl} = 1 - \frac{\sum_{i=1}^{m}(O_i - P_i)^2}{\sum_{i=1}^{m}(O_i - \bar{O}_m)^2} \qquad \text{(Equation 4-1)}$$

[2] The 2011-2012 MS-PSP measurement occurred between October 2011 and June 2012 (Chapter 3: Table 3-1). Therefore, the 2011-2012 MS-PSP measurement approximates year-end growth for 2011. Hereafter, all 2011-2012 MS-PSP observations will be labeled '2011 MS-PSP observations'.

where $EF_{pl}$ is efficiency calculated from plot-level values, $m$ is the number of plots, $O_i$ represents an observation for plot $i$, $P_i$ represents a MGM prediction for plot $i$, and $\bar{O}_m$ represents the mean observation among plots.

$$AMB_{pl} = \frac{1}{m}\sum_{i=1}^{m}(O_i - P_i) \quad \text{(Equation 4-2)}$$

where $AMB_{pl}$ is average mean bias calculated from plot-level values, $m$ is the number of plots, $O_i$ represents an observation for plot $i$, and $P_i$ represents a MGM prediction for plot $i$.

$$RMB_{pl} = \left(\frac{1}{m}\sum_{i=1}^{m}\frac{(O_i - P_i)}{\bar{O}_m}\right) \times 100 \quad \text{(Equation 4-3)}$$

where $RMB_{pl}$ is relative mean bias calculated from plot-level values, $m$ is the number of plots, $O_i$ represents an observation for plot $i$, and $P_i$ represents a MGM prediction for plot $i$, and $\bar{O}_m$ represents the mean observation among plots.

Regression-based equivalence tests were also used to evaluate the slope $\beta_1$ and intercept $\beta_0$ of plot-level observations against plot-level predictions (Robinson et al. 2005). Under this procedure, two one-sided confidence intervals were generated around each slope and intercept. Then, if the confidence intervals fell within a user-defined equivalence region, the predictions and observations were considered equivalent. To perform this test, the mean plot-level prediction was subtracted from all plot-level predictions; this transformation allowed the intercept to represent mean performance and the slope to represent "*point-to-point agreement*" (Robinson et al. 2005). Next, equivalence regions were defined around the slope and intercept using 'strict' (±10%) and 'liberal' (±25%) criteria (Robinson and Froese 2004; Robinson et al. 2005). Given nonparametric data, two one-sided confidence intervals were bootstrapped for the slope and intercept using the *R* package *Equivalence* (Robinson et al. 2005; Robinson 2014). Experimental α was set at 0.05. However, α was controlled to reflect separate equivalence tests on the slope and intercept (Robinson et al. 2005): $\alpha = 1 - (1 - 0.05)^{0.5} = 0.02532$.

At the tree-level, juvenile white spruce validation used graphical analysis, simple statistics, and linear mixed-effects model(s). Tree-level predictions were graphed against tree-level observations, and MGM performance was assessed relative to a 1:1 relationship through the origin. To address plot-level correlation, efficiency, average model bias, and relative mean bias were calculated for each plot using tree-level observations. Then, efficiency, average model bias, and relative mean bias were summarized across the MS-PSP dataset (Equations 4-4, 4-5, and 4-6).

$$EF_{tl} = 1 - \frac{\sum_{j=1}^{n_i}(O_{ij} - P_{ij})^2}{\sum_{j=1}^{n_i}(O_{ij} - \bar{O}_i)^2} \qquad \text{(Equation 4-4)}$$

where $EF_{tl}$ is efficiency calculated from tree-level values, $n_i$ is the number of trees in plot $i$, $O_{ij}$ represents an observation for tree $j$ in plot $i$, $P_{ij}$ represents a MGM prediction for tree $j$ in plot $i$, and $\bar{O}_i$ represents the mean observation in plot $i$.

$$AMB_{tl} = \frac{1}{n_i}\sum_{j=1}^{n_i}(O_{ij} - P_{ij}) \qquad \text{(Equation 4-5)}$$

where $AMB_{tl}$ is average mean bias calculated from tree-level values, $n_i$ is the number of trees in plot $i$, $O_{ij}$ represents an observation for tree $j$ in plot $i$, and $P_{ij}$ represents a MGM prediction for tree $j$ in plot $i$.

$$RMB_{tl} = \left(\frac{1}{n_i}\sum_{j=1}^{n_i}\frac{(O_{ij} - P_{ij})}{\bar{O}_i}\right) \times 100 \qquad \text{(Equation 4-6)}$$

where $RMB_{tl}$ is relative mean bias calculated from tree-level values, $n_i$ is the number of trees in plot $i$, $O_{ij}$ represents an observation for tree $j$ in plot $i$, and $P_{ij}$ represents a MGM prediction for tree $j$ in plot $i$, and $\bar{O}_i$ represents the mean observation in plot $i$.

Linear mixed-effects models were also used to evaluate tree-level MGM performance relative to the hierarchical structure of the MS-PSP dataset. Ideally, tree-level predictions and tree-level observations should follow a 1:1 relationship through the origin (Yang et al. 2004). As a result, strong tree-level predictions should produce a linear mixed-effects model with a slope of 1 and an intercept of 0 (Yang et al. 2004). Two-sided t-tests and 95% confidence intervals were used to assess each mixed-model's slope and intercept. Experimental α was set at 0.05. However, α was controlled to reflect separate t-tests on the slope and intercept (e.g. Robinson et al. 2005): $\alpha = 1 - (1 - 0.05)^{0.5} = 0.02532$.

All linear mixed-effects models were fit with the *R* package *nlme* using Restricted Maximum Likelihood (REML) and diagonal random-effects variance-covariance matrices (Pinheiro et al. 2015; Pinheiro and Bates 2000). During mixed-model development, random-effects were assigned to the slope and intercept parameters (Equation 4-7).

$$O_{ij} = \beta_0 + b_{0i} + (\beta_1 + b_{1i})P_{ij} + \varepsilon_{ij} \qquad \text{(Equation 4-7)}$$

where $O_{ij}$ is observed height, DBH, or volume for tree *j* in plot *i*, $\beta_0$ is the intercept parameter, $\beta_1$ is the slope parameter, $P_{ij}$ is predicted height, DBH, or volume, $u_{0i}$ and $u_{1i}$ are the random-effects, and $\varepsilon_{ij}$ is the residual error.

Then, the random-effects were evaluated using likelihood-ratio tests and the Bayesian Information Criterion (BIC). Models achieving maximum explanatory power with the fewest random-effects were given precedence. Heteroscedastic residuals were weighted as an optimized power of the fitted values (Equation 4-8).

$$Variance(\varepsilon_{ij}) = \sigma^2 |v_{ij}|^{2\delta} \qquad \text{(Equation 4-8)}$$

where $\varepsilon_{ij}$ is the residual error for tree *j* in plot *i*, $\sigma$ is the model variance, $v_{ij}$ is the covariate defining the variance relationship for tree *j* in plot *i*, and $\delta$ is an optimized variance parameter yielding the best model fit.

Since variance weighting optimizes each mixed-model with transformed residuals (Equation 4-8), *nlme*'s default estimate of 'residual standard error' reflects Equation 4-8. Therefore, Root Mean Square Error (RMSE) was used to describe population-level (i.e. fixed-effects) bias (Equation 4-9).

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n} \varepsilon_j{}^2}{n-p}} \qquad \text{(Equation 4-9)}$$

where $n$ is the number of trees, $p$ is the number of model parameters, and $\varepsilon_j$ is the raw population-level residual error for tree $j$.

*MGM Validation Settings*

For planted white spruce validation, each MS-PSP was modeled from 1996 to 2011 using 5 site index treatments: 1) Submesic site indices (Table 4-5); 2) Mesic site indices; 3) Subhygric site indices (Table 4-5); 4) Site indices that represent 'plot-level ecosite' classifications (Tables 2-2 and 4-5); and 5) Retrospective 'height-age' site indices from the 2011-2012 MS-PSP measurement (Table 4-3; Huang 1997c; Huang et al. 1997). Gap area was set at 20%, and stand density was restricted with maximum size-density relationships. 'Years to breast height' was assigned using MGM defaults: 20 years for black spruce, 10 years for jack pine, 2 years for trembling aspen, and 15 years for white spruce. Plot-level treelists were not replicated, and natural regeneration, annual volume loss, and 'late-succession breakup' were not modeled (i.e. MAFlag = False). Finally, to track non-merchantable trees, volume was calculated without a minimum DBH, minimum top diameter, or default stump height.

*Long-term Succession*

Long-term succession was modeled in MGM and tracked using line graphs of relative conifer basal area and relative white spruce basal area. To aid interpretation, each line graph was subdivided by initial cover group: 'hardwood-leading', 'hardwood-leading softwood', 'softwood-leading hardwood', and ‘softwood-leading’ (Table 4-6). Succession matrices were also used to evaluate the influence of juvenile competition on long-term succession. Each succession matrix plotted predicted relative basal area against observed conifer and deciduous basal area at initialization. Succession matrices were developed for stand ages 60, 90, and 120 years.

Table 4-5. Ecosite-based site index estimates from Beckingham et al. (1996).

| **Ecosite Name** | **Ecosite** | **Species** | **Site Index** (m @50yrs) | **SE** (m) | **N** |
|---|---|---|---|---|---|
| Submesic / Medium | B | BS | 15.8 | - | 1 |
| | | JP | 18.2 | 0.4 | 18 |
| | | TA | 18.3 | 0.4 | 35 |
| | | WS | 16.1 | 1.0 | 10 |
| Mesic / Medium | D | BS | 14.9 | 0.6 | 5 |
| | | JP | 18.6 | 0.9 | 7 |
| | | TA | 20.0 | 0.2 | 98 |
| | | WS | 19.7 | 0.4 | 79 |
| Subhygric / Rich | E | BS | 13.6 | 1.1 | 2 |
| | | JP | - /● | - | - |
| | | TA | 21.3 | 0.5 | 16 |
| | | WS | 18.5 | 0.5 | 19 |
| Hygric / Rich* | H | BS | 14.3 | 0.9 | 4 |
| | | JP | - /● | - | - |
| | | TA | 19.9 | 1.4 | 4 |
| | | WS | 18.1 | 1.0 | 14 |

**Note:** BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce; SE = standard error; N = number of sample sites; ‘-’ = data unavailable; ‘●’ = Mesic jack pine site index (18.6m@50yrs) was used as a proxy; ‘*’ = All TSP’s with ‘G’ (hygric/poor) ecosites were modeled as ‘H’ (hygric / rich) ecosites. Typical ‘G’ (hygric/poor) ecosites do not support deciduous trees (Beckingham et al. 1996); however, all TSP’s with ‘G’ (hygric/poor) ecosites supported deciduous trees.

Table 4-6. Cover group classes.

| **Cover Group** | **Relative Conifer Basal Area** (%) |
|---|---|
| Softwood-leading | ≥75 |
| Softwood-leading Hardwood | >50 to <75 |
| Hardwood-leading Softwood | >25 to ≤50 |
| Hardwood-leading | ≤25 |

*Long-term MGM Settings*

For long-term MGM projections, each MS-PSP and TSP was modeled from 2011 to 120 years using 4 site index treatments: 1) Submesic site indices (Table 4-5); 2) Mesic site indices; 3) Subhygric site indices (Table 4-5); and 4) Site indices that represent 'plot-level ecosite' classifications (Tables 2-2 and 4-5). Gap area was set at 20%, and stand density was restricted with maximum size-density relationships. 'Late-succession breakup' (i.e. MAFlag = True) was assumed to restrict MGM predictions (e.g. basal area, volume) within a biologically reasonable range. 'Years to breast height' was assigned using MGM defaults: 20 years for black spruce, 10 years for jack pine, 2 years for trembling aspen, and 15 years for white spruce. Plot-level treelists were not replicated, and natural regeneration and annual volume loss were not modeled. To track non-merchantable trees, volume was calculated without a minimum DBH, minimum top diameter, or default stump height. Finally, MS-PSP predictions were expressed at the plot-level, and TSP predictions were averaged at the stand-level for all long-term analysis.

Height-age site index estimates were not used for long-term MGM projections. For many boreal species, height-age site index estimates are unstable during early stand development (Figure 4-6; Huang 1994; Nigh and Sit 1996; Huang 1997a; Huang 1997b; Chen et al. 1998; Monserud and Huang 2002) and may not represent long-term productivity. Juvenile site index instability varies, depending on the species, region, site index model, and stand origin (Huang 1997a; Chen et al. 1998; Huang 1997b; Huang et al. 2004). Spruce site index stabilizes between 20 and 35 years breast height age (Figure 4-1; Huang 1994; Huang 1997b; Nigh and Sit 1996), and pine site index stabilizes between 10 and 20 years breast height age (Huang 1997a; Huang et al. 2004; Monserud and Huang 2002).

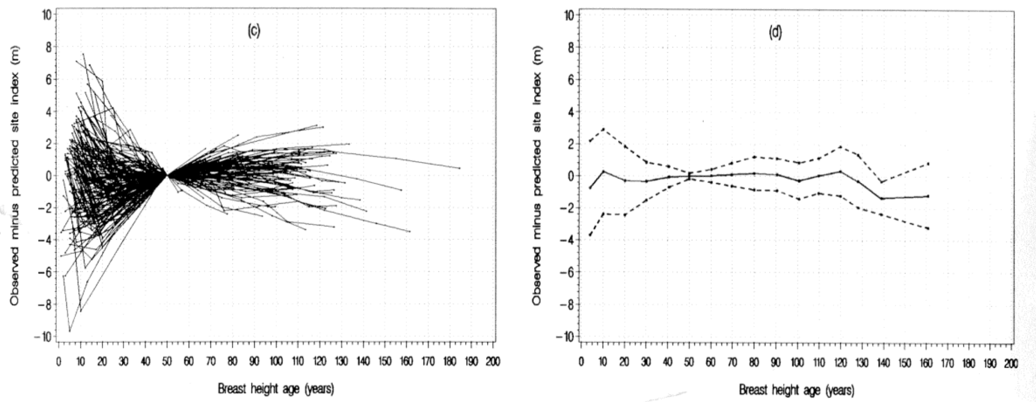


Figure 4-1. Site index prediction bias for black spruce across the Parkland and Boreal Forest Natural Regions of Alberta (Huang 1997b). Graph (c) displays site index prediction bias against breast height age for individual sectioned trees. Graph (d) displays mean site index prediction bias against breast height age; solid lines represent mean bias, and dashed lines represent 1 standard deviation. Since the height-age-site index model is forced through the point (Site Index, Age 50), site index prediction bias decreases until breast height age 50 and increases after breast height age 50. Mean site index prediction bias exceeds 1m under breast height age 25.

Relative to spruce and pine (Huang 1997a; Huang 1997b), trembling aspen site index exhibits less variation and stabilizes between 10 and 20 years breast height age (Chen et al. 1998). Nevertheless, Chen et al. (1998) observed low-precision site index estimates when aspen were under 30 years breast height age. Dominant trees within the MS-PSP and TSP datasets failed to exceed these stabilization thresholds. For top height trees across MS-PSP dataset, average breast height age was under 24 years for trembling aspen and under 20 years for spruce and pine (Table 4-3). Finally, since all TSP plantations were clearcut after 1991 (Table 2-1), trees across the TSP dataset could not exceed 20 years breast height age.

Growth-intercept models were also excluded as a long-term site index source. To my knowledge, no growth intercept models have been developed for Saskatchewan (SME 2007a), and growth intercept models from British Columbia (e.g. Nigh and Klinka 2001; Nigh 2004), Alberta (e.g. Huang 1996), or Ontario (e.g. Carmean et al. 2006; Guo and Wang 2006; Kwiaton et al. 2011) have not been adapted for Saskatchewan.

## 4.3 Results

*Plot-level White Spruce Validation*

Site index strongly influenced MGM predictions of juvenile white spruce growth. Height-age site index estimates from Huang (1997c) and Huang et al. (1997) lead to the best top height predictions (Tables 4-3 and 4-7; Figure 4-2). As a result, height-age site index estimates maximized efficiency for basal area, volume, mean height, and mean DBH (Table 4-7; Figure 4-2). Height-age site index estimates also minimized AMB and RMB for basal area and volume. Surprisingly, height-age site index estimates produced large AMB and RMB for mean height and mean DBH (Table 4-7). In both cases, mean height and mean DBH tracked a 1:1 relationship, but low-end overestimates generated large AMB and RMB values (Figure 4-2).

Among ecosite-based site index estimates, mesic site indices produced strong top height, basal area, volume, and mean height predictions (Table 4-7; Appendix 5: Figure A-5-2). Subhygric and 'plot-level ecosite' site indices yielded intermediate top height, basal area, volume, and mean height predictions (Table 4-7; Figures A-5-3 and A-5-4), and submesic site indices generated poor top height, basal area, volume, and mean height predictions (Table 4-7; Figure A-5-1). Cumulatively, ecosite-based site indices produced less accurate top height, basal area, and volume predictions than height-age site index estimates (Table 4-7; Figure 4-2; Figures A-5-1, A-5-2, A-5-3, and A-5-4).

All site indices yielded strong efficiencies for density (EF = 0.88); however, AMB and RMB indicate that MGM is overestimating juvenile white spruce survival, regardless of site index assumptions (Table 4-7). Site indices with strong top height predictions (i.e. mesic and height-age site indices) produced large overestimates of survival (Table 4-7). In addition, all site indices yielded bifurcated mean DBH distributions with pronounced low-end overestimates (Figure 4-2; Figures A-5-1, A-5-2, A-5-3, and A-5-4). When summarized across the MS-PSP dataset, these bifurcated distributions indicate that MGM is overestimating mean DBH (Table 4-7).

Table 4-7. Summary of validation statistics for plot-level white spruce MGM predictions across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and 5 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996); and 5) Height-age site indices from Huang (1997c) and Huang et al. (1997).

| **Variable** | **Site Index Treatment** | **EF** | **AMB** | **RMB** |
|---|---|---|---|---|
| Top Height (m) | Submesic | -0.30 | 2.46 | 29.74 |
| | Mesic | 0.38 | 1.34 | 16.16 |
| | Subhygric | 0.13 | 1.84 | 22.23 |
| | Plot-level Ecosite | 0.11 | 1.85 | 22.34 |
| | Height-Age Estimation | 0.79 | 0.67 | 8.13 |
| Density (Trees/ha) | Submesic | 0.88 | -116.20 | -7.05 |
| | Mesic | 0.88 | -129.22 | -7.84 |
| | Subhygric | 0.88 | -125.64 | -7.62 |
| | Plot-level Ecosite | 0.88 | -123.92 | -7.52 |
| | Height-Age Estimation | 0.88 | -140.51 | -8.52 |
| Basal Area ($m^2$/ha) | Submesic | 0.31 | 1.13 | 18.98 |
| | Mesic | 0.42 | 0.33 | 5.55 |
| | Subhygric | 0.39 | 0.68 | 11.48 |
| | Plot-level Ecosite | 0.39 | 0.69 | 11.57 |
| | Height-Age Estimation | 0.67 | -0.30 | -5.02 |
| Volume ($m^3$/ha) | Submesic | 0.05 | 11.37 | 51.73 |
| | Mesic | 0.31 | 7.02 | 31.92 |
| | Subhygric | 0.22 | 9.03 | 41.09 |
| | Plot-level Ecosite | 0.21 | 8.95 | 40.72 |
| | Height-Age Estimation | 0.75 | 2.53 | 11.49 |
| Mean Height (m) | Submesic | 0.40 | 0.89 | 16.36 |
| | Mesic | 0.57 | -0.09 | -1.57 |
| | Subhygric | 0.54 | 0.37 | 6.74 |
| | Plot-level Ecosite | 0.55 | 0.37 | 6.75 |
| | Height-Age Estimation | 0.76 | -0.61 | -11.28 |
| Mean DBH (cm) | Submesic | 0.44 | -0.19 | -3.28 |
| | Mesic | 0.43 | -0.63 | -11.07 |
| | Subhygric | 0.45 | -0.43 | -7.60 |
| | Plot-level Ecosite | 0.46 | -0.43 | -7.60 |
| | Height-Age Estimation | 0.53 | -0.88 | -15.46 |

**Note:** EF = efficiency; AMB = average model bias; RMB = relative model bias.

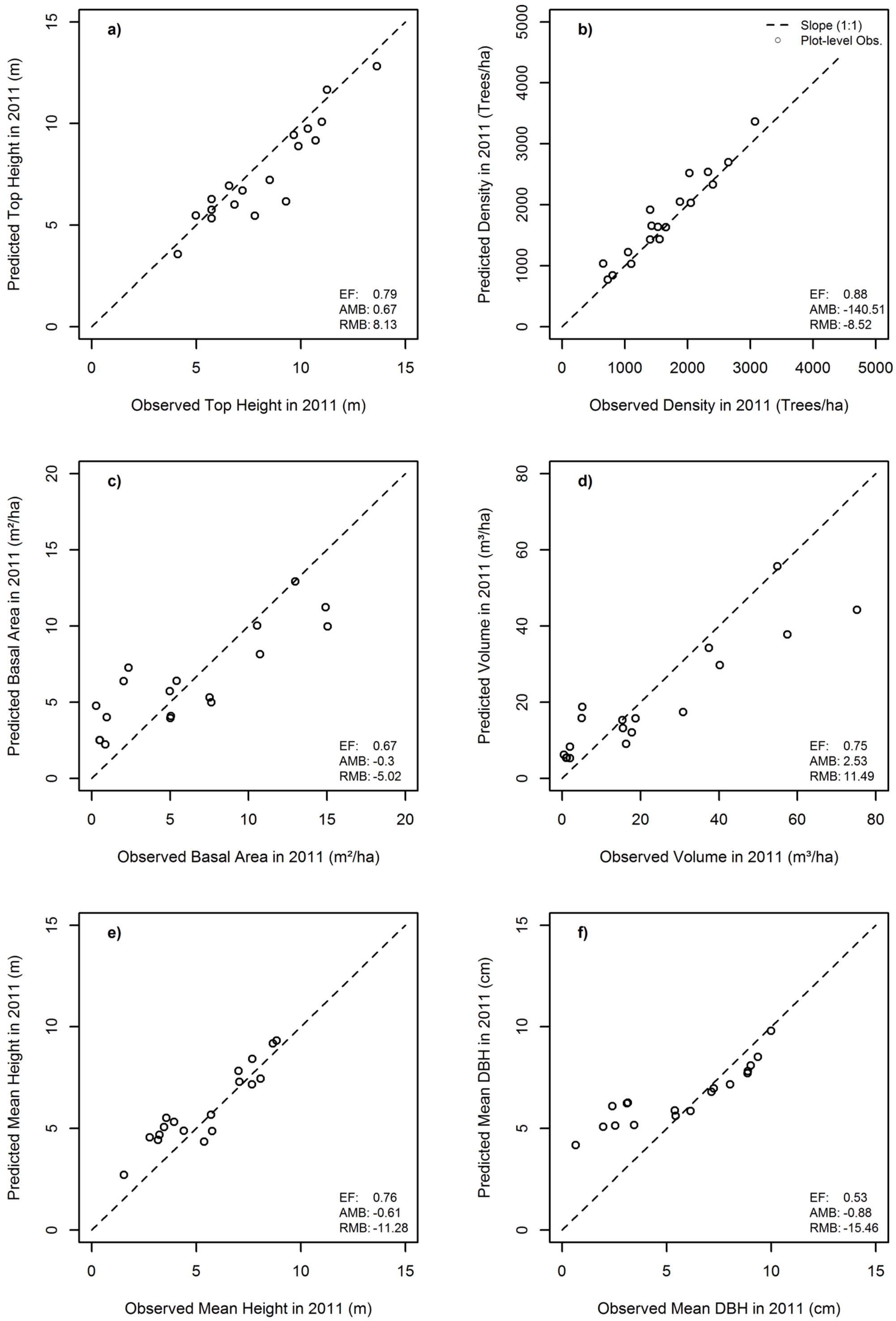


Figure 4-2. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Individual scatter plots represent white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997). Model efficiency (EF), average model bias (AMB), and relative model bias (RMB) are listed in each figure.

MGM performance was also validated using regression-based equivalence tests. Under a ‘strict’ 10% equivalence region, all MGM predictions failed to achieve equivalence with observations (Table 4-8), and under a ‘liberal’ 25% equivalence region, a few MGM predictions achieved equivalence with observations. Height-age site indices produced average (i.e. intercept) and point-to-point (i.e. slope) agreement for top height and density (Table 4-9). Height-age site indices also yielded average agreement for basal area, mean height, and mean DBH. Ecosite-based site indices produced average and point-to-point agreement for density and average agreement for mean DBH. Finally, mesic, subhygric, and ‘plot-level ecosite’ site indices generated average agreement for mean height (Table 4-9).

Table 4-8. Equivalence tests for plot-level white spruce MGM predictions across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and 5 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996); and 5) Height-age site indices from Huang (1997c) and Huang et al. (1997). All equivalence tests used the regression-based strategy outlined in Robinson et al. (2005) and reflect 'strict' (±10%) equivalence regions (Robinson and Froese 2004). Two one-sided confidence intervals were bootstrapped to address nonparametric responses (Robinson 2014). In all cases, the null hypothesis was rejected if the two one-sided confidence interval was encapsulated within a respective equivalence region.

| | | $\beta_0$ | | | $\beta_1$ | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Site Index** | **ER** | **TOST CI** | **$H_0$** | **ER** | **TOST CI** | **$H_0$** |
| Top Height | Submesic | 5.23-6.39 | 7.70-8.93 | NR | 0.90-1.10 | 1.30-1.96 | NR |
| | Mesic | 6.24-7.63 | 7.70-8.96 | NR | 0.90-1.10 | 1.23-1.92 | NR |
| | Subhygric | 5.79-7.08 | 7.69-8.93 | NR | 0.90-1.10 | 1.21-1.90 | NR |
| | Plot-level Ecosite | 5.78-7.07 | 7.62-8.99 | NR | 0.90-1.10 | 0.91-1.63 | NR |
| | Height-Age Estimation | 6.84-8.36 | 7.83-8.76 | NR | 0.90-1.10 | 0.80-1.13 | NR |
| Density (Trees/ha) | Submesic | 1588.33-1941.29 | 1555.30-1734.30 | NR | 0.90-1.10 | 0.80-1.06 | NR |
| | Mesic | 1600.05-1955.61 | 1559.97-1733.93 | NR | 0.90-1.10 | 0.80-1.04 | NR |
| | Subhygric | 1596.82-1951.67 | 1557.44-1734.35 | NR | 0.90-1.10 | 0.80-1.07 | NR |
| | Plot-level Ecosite | 1595.28-1949.78 | 1558.35-1736.06 | NR | 0.90-1.10 | 0.81-1.06 | NR |
| | Height-Age Estimation | 1610.21-1968.03 | 1570.47-1730.39 | NR | 0.90-1.10 | 0.81-1.04 | NR |
| Basal Area (m²/ha) | Submesic | 4.34-5.31 | 4.21-7.53 | NR | 0.90-1.10 | 0.92-2.50 | NR |
| | Mesic | 5.06-6.18 | 4.10-7.55 | NR | 0.90-1.10 | 0.89-2.18 | NR |
| | Subhygric | 4.74-5.80 | 4.11-7.55 | NR | 0.90-1.10 | 0.90-2.31 | NR |
| | Plot-level Ecosite | 4.74-5.79 | 4.28-7.60 | NR | 0.90-1.10 | 1.06-2.45 | NR |
| | Height-Age Estimation | 5.63-6.88 | 4.69-7.14 | NR | 0.90-1.10 | 1.05-1.75 | NR |

**Note:** $\beta_0$ = predicted vs. observed intercept; $\beta_1$ = predicted vs. observed slope; ER = equivalence region (±10%); TOST CI = two one-sided confidence interval bootstrapped using 1000 replicates ($\alpha$=0.05); $H_{0:}$ = predictions ≠ observations; R = rejected; NR = not rejected.

Table 4-8 (continued). Equivalence tests for plot-level white spruce MGM predictions across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and 5 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996); and 5) Height-age site indices from Huang (1997c) and Huang et al. (1997). All equivalence tests used the regression-based strategy outlined in Robinson et al. (2005) and reflect 'strict' (±10%) equivalence regions (Robinson and Froese 2004). Two one-sided confidence intervals were bootstrapped to address nonparametric responses (Robinson 2014). In all cases, the null hypothesis was rejected if the two one-sided confidence interval was encapsulated within a respective equivalence region.

| | | $\beta_0$ | | | $\beta_1$ | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Site Index** | **ER** | **TOST CI** | $H_0$ | **ER** | **TOST CI** | $H_0$ |
| Volume (m³/ha) | Submesic | 9.55-11.67 | 16.26-28.60 | NR | 0.90-1.10 | 2.47-5.47 | NR |
| | Mesic | 13.47-16.47 | 15.70-28.05 | NR | 0.90-1.10 | 1.75-3.97 | NR |
| | Subhygric | 11.66-14.25 | 16.05-28.93 | NR | 0.90-1.10 | 1.97-4.56 | NR |
| | Plot-level Ecosite | 11.73-14.34 | 16.12-29.66 | NR | 0.90-1.10 | 1.68-4.54 | NR |
| | Height-Age Estimation | 17.52-21.41 | 17.59-26.37 | NR | 0.90-1.10 | 1.05-1.85 | NR |
| Mean Height (m) | Submesic | 4.09-5.00 | 4.89-6.06 | NR | 0.90-1.10 | 1.55-2.39 | NR |
| | Mesic | 4.97-6.07 | 4.94-6.00 | NR | 0.90-1.10 | 1.51-2.39 | NR |
| | Subhygric | 4.56-5.57 | 4.90-6.01 | NR | 0.90-1.10 | 1.47-2.33 | NR |
| | Plot-level Ecosite | 4.56-5.57 | 4.86-6.11 | NR | 0.90-1.10 | 1.08-1.93 | NR |
| | Height-Age Estimation | 5.44-6.65 | 5.03-5.88 | NR | 0.90-1.10 | 0.93-1.33 | NR |
| Mean DBH (cm) | Submesic | 5.30-6.48 | 5.02-6.39 | NR | 0.90-1.10 | 2.21-3.58 | NR |
| | Mesic | 5.70-6.97 | 5.01-6.39 | NR | 0.90-1.10 | 1.98-3.28 | NR |
| | Subhygric | 5.52-6.75 | 5.01-6.44 | NR | 0.90-1.10 | 1.99-3.23 | NR |
| | Plot-level Ecosite | 5.52-6.75 | 4.99-6.48 | NR | 0.90-1.10 | 1.81-3.14 | NR |
| | Height-Age Estimation | 5.92-7.24 | 5.13-6.30 | NR | 0.90-1.10 | 1.52-2.36 | NR |

**Note:** $\beta_0$ = predicted vs. observed intercept; $\beta_1$ = predicted vs. observed slope; ER = equivalence region (±10%); TOST CI = two one-sided confidence interval bootstrapped using 1000 replicates ($\alpha$=0.05); $H_{0:}$ = predictions ≠ observations; R = rejected; NR = not rejected.

Table 4-9. Equivalence tests for plot-level white spruce MGM predictions across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and 5 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996); and 5) Height-age site indices from Huang (1997c) and Huang et al. (1997). All equivalence tests used the regression-based strategy outlined in Robinson et al. (2005) and reflect 'liberal' (±25%) equivalence regions (Robinson and Froese 2004). Two one-sided confidence intervals were bootstrapped to address nonparametric responses (Robinson 2014). In all cases, the null hypothesis was rejected if the two one-sided confidence interval was encapsulated within a respective equivalence region.

| | | $\beta_0$ | | | $\beta_1$ | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Site Index** | **ER** | **TOST CI** | **$H_0$** | **ER** | **TOST CI** | **$H_0$** |
| Top Height | Submesic | 4.36-7.26 | 7.71-8.93 | NR | 0.75-1.25 | 1.28-2.02 | NR |
| | Mesic | 5.20-8.67 | 7.70-8.93 | NR | 0.75-1.25 | 1.24-1.95 | NR |
| | Subhygric | 4.82-8.04 | 7.70-8.96 | NR | 0.75-1.25 | 1.27-1.93 | NR |
| | Plot-level Ecosite | 4.82-8.03 | 7.63-9.01 | NR | 0.75-1.25 | 0.92-1.64 | NR |
| | Height-Age Estimation | 5.70-9.50 | 7.88-8.71 | R | 0.75-1.25 | 0.81-1.13 | R |
| Density (Trees/ha) | Submesic | 1323.61-2206.01 | 1559.50-1734.54 | R | 0.75-1.25 | 0.80-1.04 | R |
| | Mesic | 1333.37-2222.29 | 1563.67-1734.91 | R | 0.75-1.25 | 0.80-1.05 | R |
| | Subhygric | 1330.69-2217.81 | 1563.60-1732.07 | R | 0.75-1.25 | 0.81-1.05 | R |
| | Plot-level Ecosite | 1329.40-2215.66 | 1558.39-1727.74 | R | 0.75-1.25 | 0.82-1.05 | R |
| | Height-Age Estimation | 1341.84-2236.40 | 1557.08-1728.80 | R | 0.75-1.25 | 0.80-1.05 | R |
| Basal Area ($m^2$/ha) | Submesic | 3.62-6.03 | 4.08-7.70 | NR | 0.75-1.25 | 0.91-2.49 | NR |
| | Mesic | 4.22-7.03 | 4.20-7.58 | NR | 0.75-1.25 | 0.90-2.18 | NR |
| | Subhygric | 3.95-6.59 | 4.23-7.73 | NR | 0.75-1.25 | 0.96-2.32 | NR |
| | Plot-level Ecosite | 3.95-6.58 | 4.15-7.53 | NR | 0.75-1.25 | 1.02-2.40 | NR |
| | Height-Age Estimation | 4.69-7.81 | 4.69-7.18 | R | 0.75-1.25 | 1.07-1.76 | NR |

**Note:** $\beta_0$ = predicted vs. observed intercept; $\beta_1$ = predicted vs. observed slope; ER = equivalence region (±25%); TOST CI = two one-sided confidence interval bootstrapped using 1000 replicates ($\alpha$=0.05); $H_{0:}$ = predictions ≠ observations; R = rejected; NR = not rejected.

Table 4-9 (continued). Equivalence tests for plot-level white spruce MGM predictions across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and 5 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996); and 5) Height-age site indices from Huang (1997c) and Huang et al. (1997). All equivalence tests used the regression-based strategy outlined in Robinson et al. (2005) and reflect 'liberal' (±25%) equivalence regions (Robinson and Froese 2004). Two one-sided confidence intervals were bootstrapped to address nonparametric responses (Robinson 2014). In all cases, null hypothesis was rejected if the two one-sided confidence interval was encapsulated within a respective equivalence region.

| | | $\beta_0$ | | | $\beta_1$ | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Site Index** | **ER** | **TOST CI** | $H_0$ | **ER** | **TOST CI** | $H_0$ |
| Volume (m³/ha) | Submesic | 7.96-13.27 | 15.75-28.33 | NR | 0.75-1.25 | 2.45-5.58 | NR |
| | Mesic | 11.23-18.71 | 15.85-28.37 | NR | 0.75-1.25 | 1.70-3.96 | NR |
| | Subhygric | 9.72-16.19 | 15.30-28.37 | NR | 0.75-1.25 | 1.91-4.46 | NR |
| | Plot-level Ecosite | 9.78-16.29 | 15.62-30.04 | NR | 0.75-1.25 | 1.69-4.38 | NR |
| | Height-Age Estimation | 14.60-24.33 | 17.95-26.23 | NR | 0.75-1.25 | 1.05-1.85 | NR |
| Mean Height (m) | Submesic | 3.41-5.68 | 4.94-6.00 | NR | 0.75-1.25 | 1.56-2.40 | NR |
| | Mesic | 4.14-6.90 | 4.92-6.07 | R | 0.75-1.25 | 1.49-2.35 | NR |
| | Subhygric | 3.80-6.33 | 4.92-6.04 | R | 0.75-1.25 | 1.47-2.36 | NR |
| | Plot-level Ecosite | 3.80-6.33 | 4.88-6.14 | R | 0.75-1.25 | 1.05-1.92 | NR |
| | Height-Age Estimation | 4.54-7.56 | 5.03-5.89 | R | 0.75-1.25 | 0.92-1.32 | NR |
| Mean DBH (cm) | Submesic | 4.42-7.36 | 5.02-6.36 | R | 0.75-1.25 | 2.25-3.64 | NR |
| | Mesic | 4.75-7.92 | 4.95-6.45 | R | 0.75-1.25 | 1.99-3.27 | NR |
| | Subhygric | 4.60-7.67 | 4.96-6.43 | R | 0.75-1.25 | 1.99-3.32 | NR |
| | Plot-level Ecosite | 4.60-7.67 | 5.00-6.52 | R | 0.75-1.25 | 1.81-3.13 | NR |
| | Height-Age Estimation | 4.94-8.23 | 5.14-6.27 | R | 0.75-1.25 | 1.55-2.37 | NR |

**Note:** $\beta_0$ = predicted vs. observed intercept; $\beta_1$ = predicted vs. observed slope; ER = equivalence region (±25%); TOST CI = two one-sided confidence interval bootstrapped using 1000 replicates ($\alpha$=0.05); $H_{0:}$ = predictions ≠ observations; R = rejected; NR = not rejected.

*Tree-level White Spruce Validation*

MGM performance was also validated for tree-level height, DBH, and volume. To aid interpretation, tree-level analysis focused on the ‘best performing’ site index treatment (Tables 4-7 and 4-9): height-age site indices from Huang (1997c) and Huang et al. (1997). Tree-level performance varied across the MS-PSP dataset (Table 4-10). Individual MS-PSP’s exhibited poor (EF < 0) or intermediate (EF = 0.62 to 0.64) efficiencies for height, DBH, and volume (Table 4-10). In absolute terms, AMB ranged from -1.98m to 0.88m for height, -3.65cm to 1.10cm for DBH, and -5.95m$^3$/ha to 18.96m$^3$/ha for volume. However, minimum and maximum RMB indicated large overpredictions (RMB = -80.85% to -1345.76%) and intermediate underpredictions (RMB = 12.45% to 45.09%) of height, DBH, and volume. Since very poor predictions skewed mean efficiency (e.g. EF = -35.74), mean AMB (e.g. AMB = 18.96 m$^3$/ha), and mean RMB (e.g. RMB = -1346%), medians were used to express cumulative tree-level performance (Table 4-10). Median efficiency was relatively poor (EF < 0.25) for all tested variables, and median AMB and RMB indicated slight underpredictions of volume and slight overpredictions of height and DBH (Table 4-10).

Table 4-10. Summary of validation statistics for tree-level white spruce MGM predictions. All summary statistics were computed at the plot-level and summarized across the MS-PSP dataset. MGM predictions reflect a 15-year projection (i.e. 1996-2011) and site height-age site indices from Huang (1997c) and Huang et al. (1997).

| Variable | Site Index Treatment | Metric | Median | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|---|
| Height (m) | Height-Age Estimation | EF | 0.12 | -0.15 | -1.65 | 0.64 | 0.71 |
| | | AMB | -0.72 | -0.64 | -1.98 | 0.88 | 0.91 |
| | | RMB | -10.35 | -20.64 | -80.85 | 15.86 | 28.91 |
| DBH (cm) | Height-Age Estimation | EF | 0.24 | -1.85 | -18.47 | 0.62 | 4.58 |
| | | AMB | -0.20 | -0.91 | -3.65 | 1.10 | 1.83 |
| | | RMB | -3.72 | -65.59 | -566.05 | 12.45 | 138.71 |
| Volume (dm$^3$/ha) | Height-Age Estimation | EF | 0.21 | -3.14 | -35.74 | 0.64 | 8.58 |
| | | AMB | 1.34 | 2.26 | -5.95 | 18.96 | 6.64 |
| | | RMB | 9.84 | -142.51 | -1345.76 | 45.09 | 335.67 |

**Note:** EF = efficiency; AMB = average model bias; RMB = relative model bias.

Linear mixed-effects models were used to explore tree-level performance for height, DBH, and volume (Tables 4-11, 4-12, and 4-13). Without exception, likelihood-ratio tests and BIC indicated that slope and intercept random-effects improved model fit. Therefore, the linear mixed-effects models for height, DBH, and volume conformed to Equation 4-7. All linear mixed-effects models included variance weighting to satisfy homoscedasticity assumptions (Tables 4-11, 4-12, and 4-13).

Table 4-11. Summary statistics for the linear mixed-effects height validation model for white spruce (Equation 4-7; Figure 4-3). All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997).

| | | **Estimate** | **SE** | **$d_f$** | **$H_0$** | **t-value** | **p-value** | **95% CI** |
|---|---|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 4.29 | 0.22 | 1163 | $\beta_0 = 0$ | 19.85 | <0.0001 | 3.86-4.71 |
| | $\beta_1$ | 0.31 | 0.02 | 1163 | $\beta_1 = 1$ | -32.56 | <0.0001 | 0.27-0.35 |
| **varPower** | $\delta$ | 1.06 | | | | | | |
| **RMSE** | | 1.37 | | | | | | |

**Note:** SE = standard error; $d_f$ = degrees of freedom, $H_0$ = t-test null hypothesis; CI = confidence interval; varPower = variance weighing function (Eq. 4-8); RMSE = root mean square error for the fixed-effects (Eq. 4-9).

Table 4-12. Summary statistics for the linear mixed-effects DBH validation model for white spruce (Equation 4-7; Figure 4-3). All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997).

| | | **Estimate** | **SE** | **$d_f$** | **$H_0$** | **t-value** | **p-value** | **95% CI** |
|---|---|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 4.92 | 0.13 | 1163 | $\beta_0 = 0$ | 38.54 | <0.0001 | 4.67-5.17 |
| | $\beta_1$ | 0.30 | 0.03 | 1163 | $\beta_1 = 1$ | -27.84 | <0.0001 | 0.25-0.35 |
| **varPower** | $\delta$ | 1.10 | | | | | | |
| **RMSE** | | 1.00 | | | | | | |

**Note:** SE = standard error; $d_f$ = degrees of freedom, $H_0$ = t-test null hypothesis; CI = confidence interval; varPower = variance weighing function (Eq. 4-8); RMSE = root mean square error for the fixed-effects (Eq. 4-9).

Table 4-13. Summary statistics for the linear mixed-effects volume validation model for white spruce (Equation 4-7; Figure 4-3). All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997).

| | | **Estimate** | **SE** | **$d_f$** | **$H_0$** | **t-value** | **p-value** | **95% CI** |
|---|---|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 6.47 | 0.71 | 1163 | $\beta_0 = 0$ | 9.07 | <0.0001 | 5.07-7.87 |
| | $\beta_1$ | 0.55 | 0.11 | 1163 | $\beta_1 = 1$ | -3.97 | 0.0001 | 0.33-0.77 |
| **varPower** | $\delta$ | 1.03 | | | | | | |
| **RMSE** | | 7.40 | | | | | | |

**Note:** SE = standard error; $d_f$ = degrees of freedom, $H_0$ = t-test null hypothesis; CI = confidence interval; varPower = variance weighing function (Eq. 4-8); RMSE = root mean square error for the fixed-effects (Eq. 4-9).

Graphically, tree-level height, DBH, and volume diverged from a 1:1 relationship through the origin (Figure 4-3). Height, DBH, and volume were consistently overestimated for small trees. For large trees, DBH and volume were underestimated; however, trees with large heights tracked a 1:1 relationship. Linear mixed-effects models confirmed these results. Population-level slopes and intercepts were skewed by small-tree overestimates (Figure 4-3). Two-sided t-tests and 95% confidence intervals indicated significant departures from a 1:1 relationship through the origin (Tables 4-11, 4-12, and 4-13).

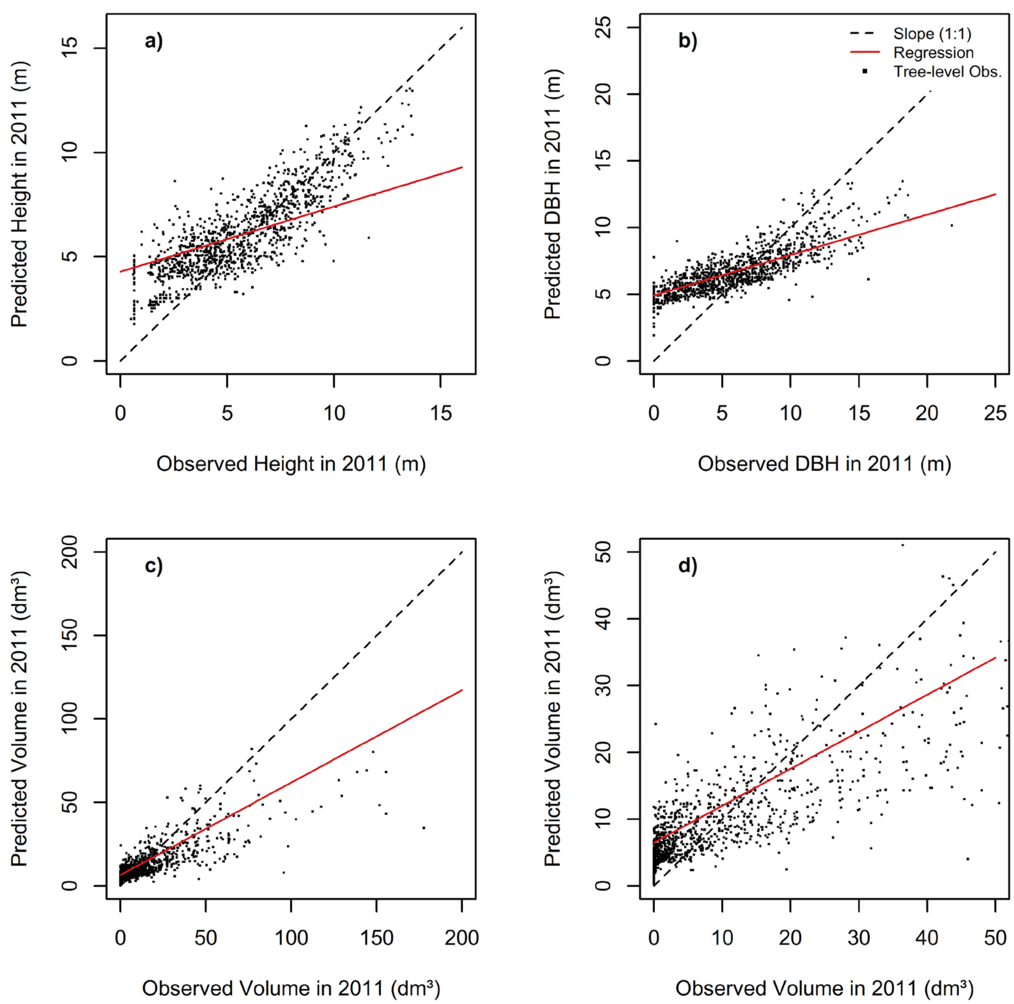


Figure 4-3. Tree-level MGM predictions versus tree-level observations across the MS-PSP dataset. Individual scatter plots represent a) height, b) DBH, c) volume, and d) small-tree volume (Subset < $50dm^3$) for white spruce. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997). A linear mixed-model was fit to each tree-level relationship (Tables 4-11, 4-12, and 4-13), identifying the population-level response (i.e. red line).

*Juvenile MS-PSP Growth Estimates*

Since naturally regenerated trees were not enumerated during the 1996 MS-PSP measurement, validation was restricted to planted white spruce. Juvenile MS-PSP projections are summarized for all 'component species' in Table 4-14.

Table 4-14. MGM summary statistics for 18 MS-PSP's modeled under a 15-year projection (i.e. 1996-2011). All MGM predictions reflect height-age site index estimates from Huang (1997c) and Huang et al. (1997). White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 6612 | 1469 | 10966 | 2514 |
| | Basal Area ($m^2$/ha) | 26.8 | 5.4 | 38.2 | 9.1 |
| | Volume ($m^3$/ha) | 110.8 | 12.5 | 171.4 | 44.0 |
| | Top Height (m) | 11.8 | 6.0 | 16.7 | 2.4 |
| | Height (m) | 7.1 | 4.9 | 9.7 | 1.1 |
| | DBH (cm) | 6.1 | 4.3 | 7.2 | 0.8 |
| BS | Density (Trees/ha) | 10 | 0 | 93 | 30 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Top Height (m) | 0.3 | 0.0 | 3.5 | 1.0 |
| | Height (m) | 0.3 | 0.0 | 3.5 | 1.0 |
| | DBH (cm) | 0.2 | 0.0 | 2.7 | 0.7 |
| JP | Density (Trees/ha) | 1406 | 0 | 6040 | 1980 |
| | Basal Area ($m^2$/ha) | 7.7 | 0.0 | 26.8 | 10.4 |
| | Volume ($m^3$/ha) | 31.6 | 0.0 | 115.8 | 43.9 |
| | Top Height (m) | 4.8 | 0.0 | 11.9 | 5.1 |
| | Height (m) | 3.8 | 0.0 | 9.2 | 4.0 |
| | DBH (cm) | 3.7 | 0.0 | 10.1 | 4.0 |
| TA | Density (Trees/ha) | 2774 | 34 | 8145 | 2278 |
| | Basal Area ($m^2$/ha) | 11.4 | 0.1 | 25.3 | 8.7 |
| | Volume ($m^3$/ha) | 56.4 | 0.3 | 156.4 | 49.4 |
| | Top Height (m) | 11.5 | 6.9 | 16.7 | 2.6 |
| | Height (m) | 8.4 | 6.2 | 12.4 | 1.6 |
| | DBH (cm) | 5.5 | 3.2 | 7.6 | 1.2 |
| WS | Density (Trees/ha) | 2422 | 1408 | 4035 | 764 |
| | Basal Area ($m^2$/ha) | 7.7 | 4.0 | 14.6 | 2.8 |
| | Volume ($m^3$/ha) | 22.8 | 6.3 | 60.1 | 14.0 |
| | Top Height (m) | 7.8 | 3.6 | 12.8 | 2.4 |
| | Height (m) | 5.9 | 2.7 | 9.2 | 1.7 |
| | DBH (cm) | 6.4 | 4.2 | 9.3 | 1.3 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

MGM predictions reflect height-age site indices from Huang (1997c) and Huang et al. (1997). Juvenile MS-PSP projections are available for submesic, mesic, subhygric, and 'plot-level ecosite' site indices in Appendix 5 (Tables A-5-1, A-5-2, A-5-3, and A-5-4).

*MGM Succession*

MGM was used to project each MS-PSP and TSP from 2011 to 120 years. During the 2011 initialization, most MS-PSP's and TSP's contained understory spruce and overstory intolerants (Tables 4-2 and 4-4). As a result, MGM's height, diameter, and survival functions modeled 'convergent' mixedwood succession (Chen and Popadiouk 2002), characterized by the conversion of trembling aspen (e.g. Figure 4-4) and jack pine (e.g. Figure 4-5) mixedwoods to spruce-dominated stands. Often, white spruce dominated plot-level basal area by age 120 (e.g. Figures 4-4 and 4-5), and trembling aspen and jack pine persisted as large, low-density remnants (e.g. Figures 4-4 and 4-5).

*Cumulative MS-PSP Succession*

Under 'plot-level ecosite' assumptions, 'hardwood-leading' and 'hardwood-leading softwood' MS-PSP's transitioned to 'softwood-leading' or 'softwood-leading hardwood' plots (Figure 4-6). Furthermore, 'softwood-leading' and 'softwood-leading hardwood' MS-PSP's maintained or intensified softwood dominance (Figure 4-6). At age 60, 89% of MS-PSP's were 'softwood-leading' or 'softwood-leading hardwood', and at age 90, 94% of MS-PSP's were 'softwood-leading' or 'softwood-leading hardwood'. Finally, at age 120, 100% of MS-PSP's were 'softwood-leading' or 'softwood-leading hardwood' (Figure 4-6). White spruce basal area also increased across all MS-PSP's (Figure 4-7). At age 60, 83% of MS-PSP's were 'white spruce dominant' (i.e. >50% white spruce basal area), and at age 90, 94% of MS-PSP's were 'white spruce dominant'. Finally, at age 120, 100% of MS-PSP's were 'white spruce dominant' (Figure 4-7).

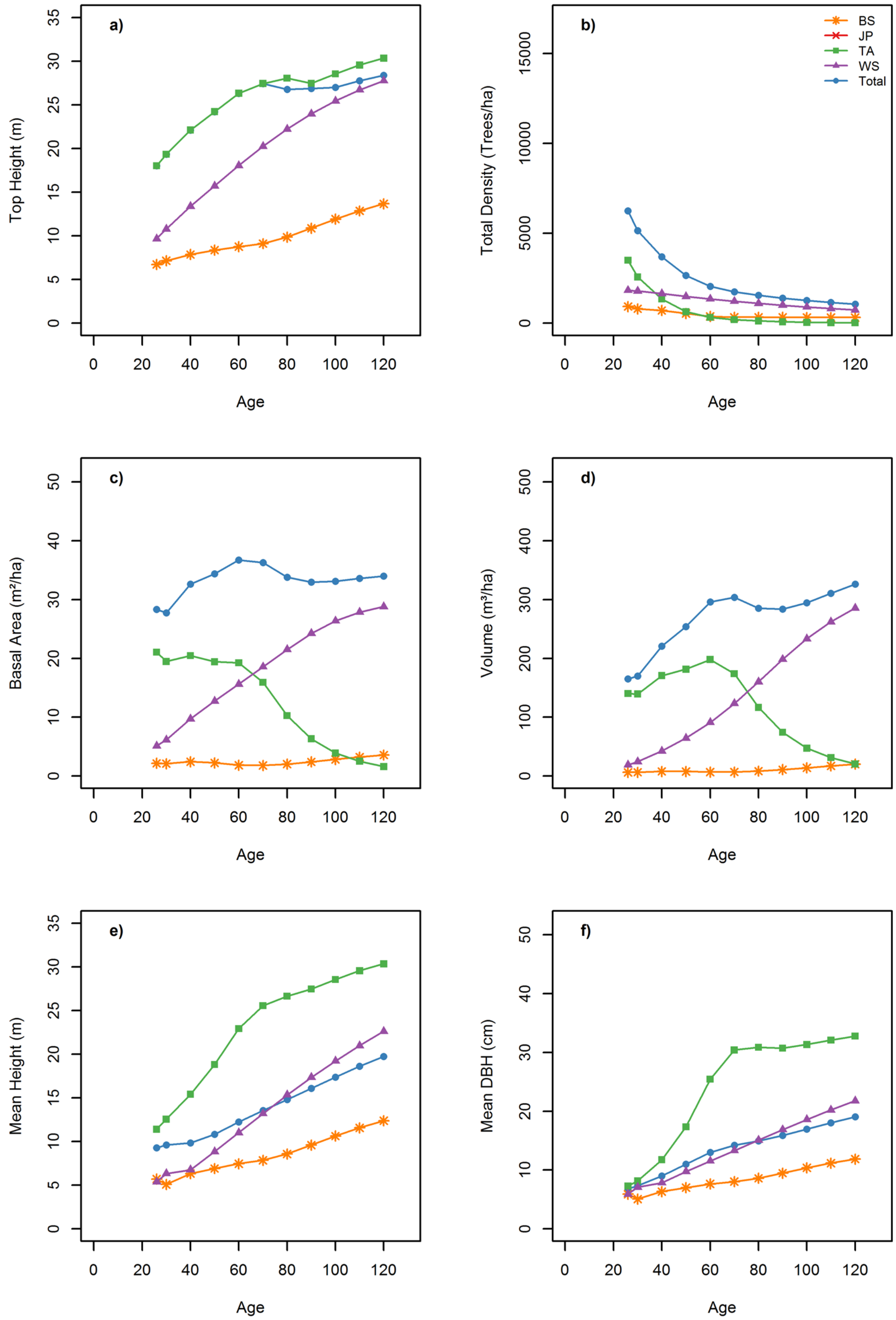


Figure 4-4. Long-term MGM projection for the 'hardwood-leading softwood' (HS Cover Group) MS-PSP 94312. Individual figures represent plot-level a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH from the 2011 measurement to stand age 120. Site index estimates reflect the plot's submesic ecosite classification under Beckingham et al. (1996). BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce; Total = plot-level sum or mean.

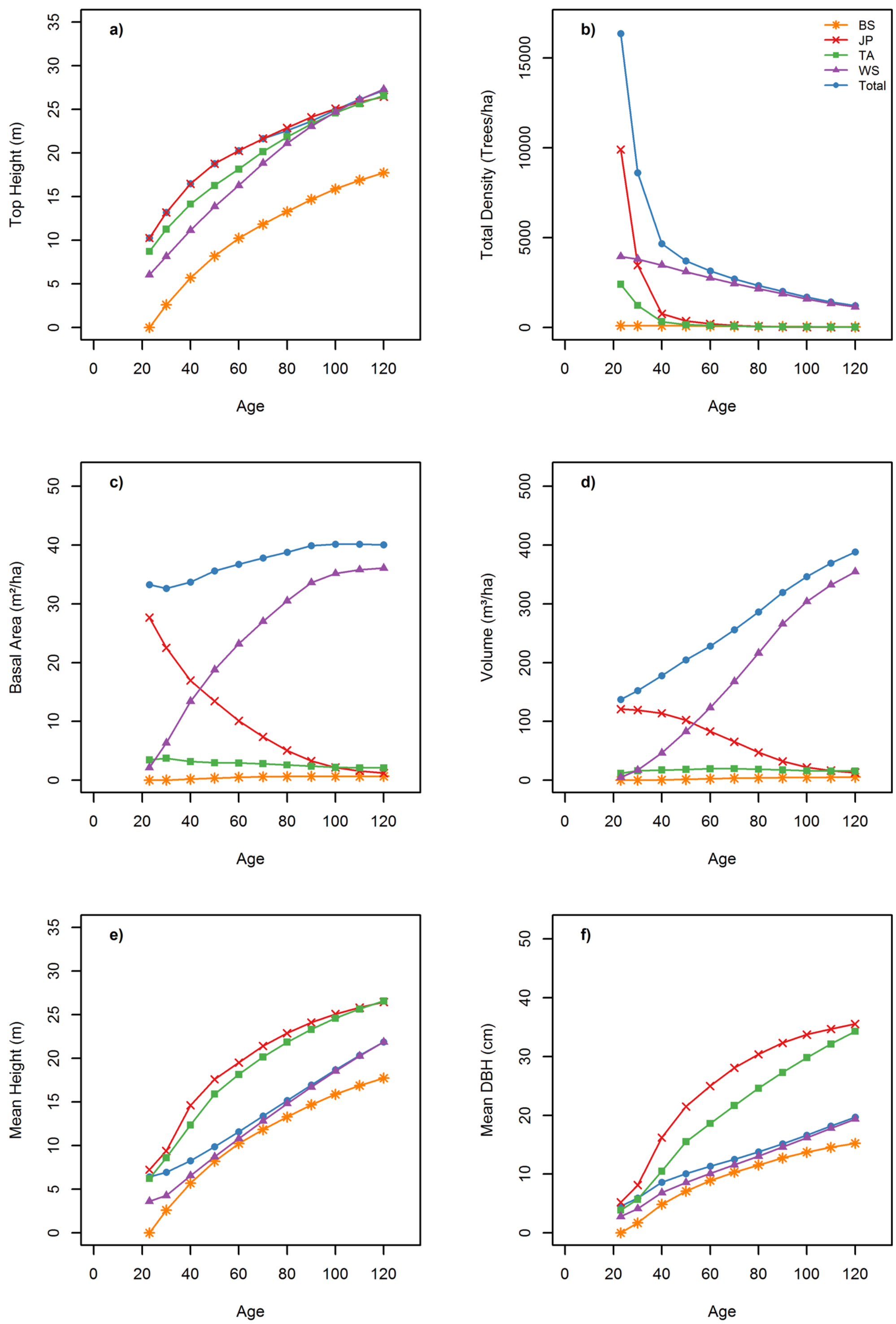


Figure 4-5. Long-term MGM projection for the 'softwood-leading' (S Cover Group) MS-PSP 93117. Individual figures represent plot-level a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH from the 2011 measurement to stand age 120. Site index estimates reflect the plot's submesic ecosite classification under Beckingham et al. (1996). BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce; Total = plot-level sum or mean.

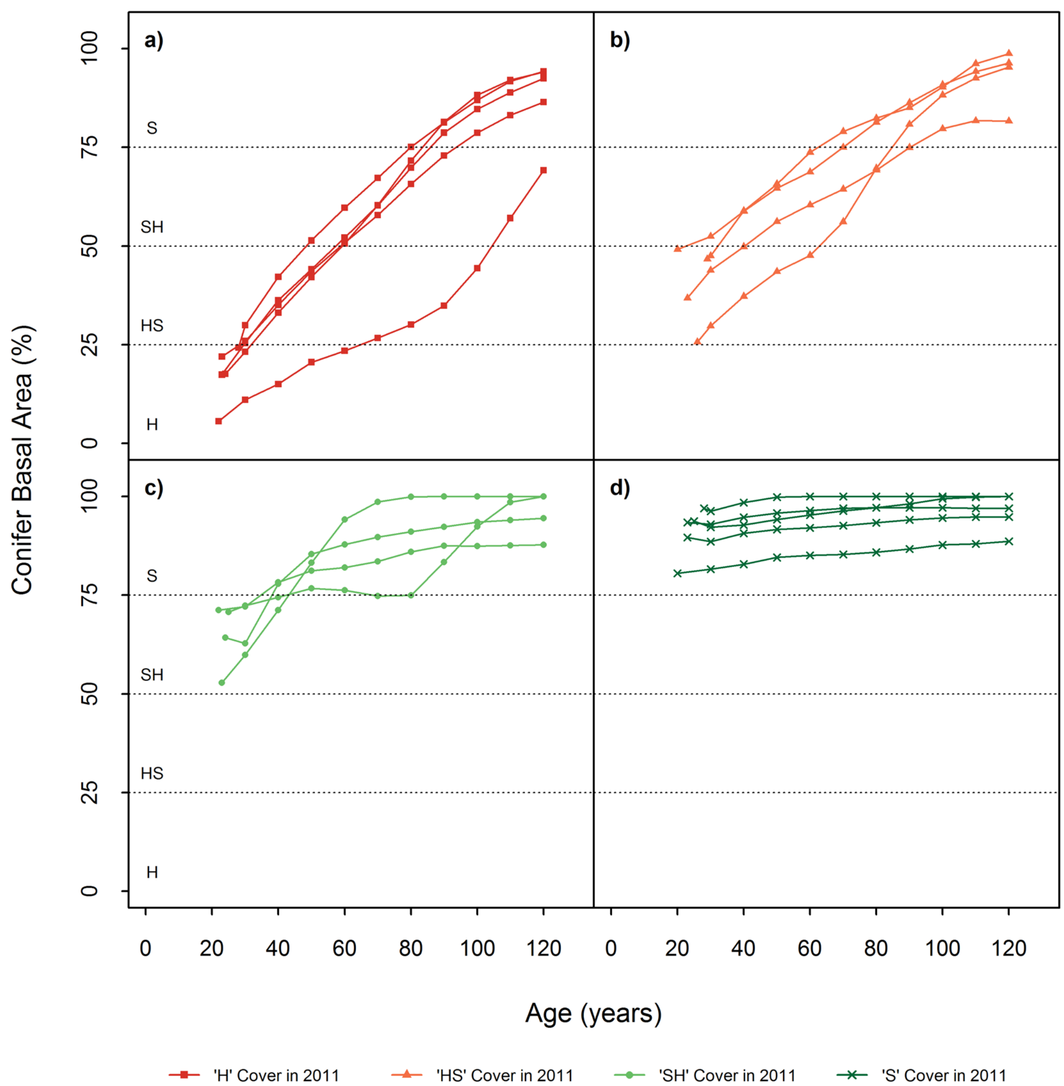


Figure 4-6. MGM conifer succession across 18 MS-PSP's. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

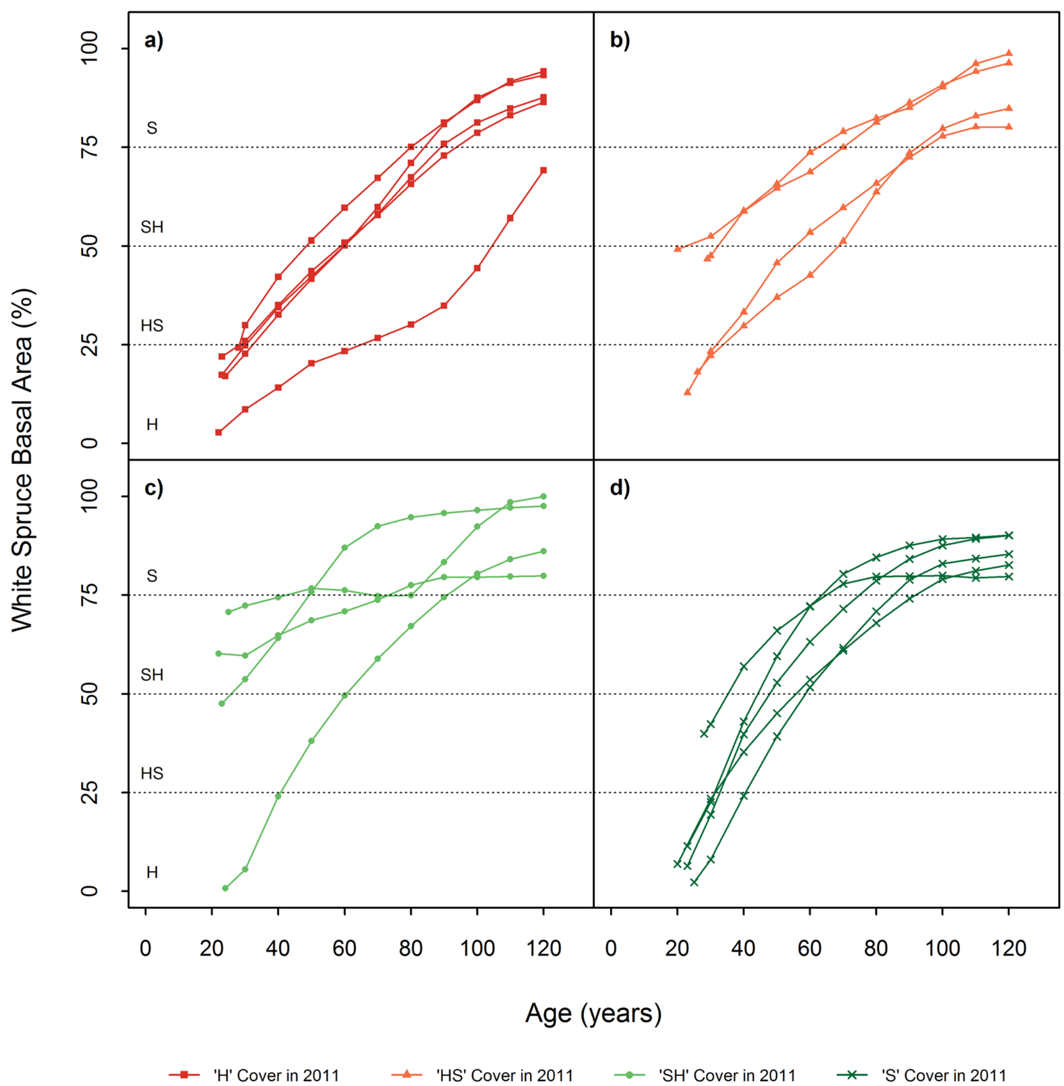


Figure 4-7. MGM white spruce succession across 18 MS-PSP's. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Increasing deciduous competition (~32m$^2$/hectare) slowed MS-PSP succession (Tables 4-15, 4-16, and 4-17); however, intense deciduous competition did not prevent most 'hardwood-leading' and 'hardwood-leading softwood' MS-PSP's from transitioning to 'softwood-leading' strata by age 120 (Table 4-17).

Table 4-15. MGM conifer succession across 18 MS-PSP's: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 23 |
| 5.0 | | | | | | | | | | | | | | | 52 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 51 | |
| 5.4 | | | | | | | | | | | | | 51 | | | | | |
| 5.8 | | | | | | | | 60 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 48 | | | | |
| 7.5 | | | | 76 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 60 | | |
| 10.9 | | | | | | | | | | 69 | | | | | | | | |
| 11.9 | | | | | | | | | 94 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 74 | | | | | | |
| 17.6 | | | | | | | 82 | | | | | | | | | | | |
| 20.4 | | 96 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 88 | | | | | | | |
| 25.1 | | | | | | 85 | | | | | | | | | | | | |
| 29.0 | | | 95 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 92 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table 4-16. MGM conifer succession across 18 MS-PSP's: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 35 |
| 5.0 | | | | | | | | | | | | | | | 79 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 81 | |
| 5.4 | | | | | | | | | | | | | 73 | | | | | |
| 5.8 | | | | | | | | 75 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 81 | | | | |
| 7.5 | | | | 83 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 81 | | |
| 10.9 | | | | | | | | | | 86 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 85 | | | | | | |
| 17.6 | | | | | | | 87 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 92 | | | | | | | |
| 25.1 | | | | | | 87 | | | | | | | | | | | | |
| 29.0 | | | 98 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 94 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table 4-17. MGM conifer succession across 18 MS-PSP's: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 69 |
| 5.0 | | | | | | | | | | | | | | | 92 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 94 | |
| 5.4 | | | | | | | | | | | | | 86 | | | | | |
| 5.8 | | | | | | | | 82 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 95 | | | | |
| 7.5 | | | | 100 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 94 | | |
| 10.9 | | | | | | | | | | 96 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 99 | | | | | | |
| 17.6 | | | | | | | 88 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 94 | | | | | | | |
| 25.1 | | | | | | 89 | | | | | | | | | | | | |
| 29.0 | | | 100 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 95 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Site index assumptions also influenced MS-PSP succession. At age 60, mesic and 'plot-level ecosite' site indices produced aggressive succession (Table 4-18). Subhygric site indices yielded intermediate succession, and submesic site indices generated conservative succession. However, in all cases, 100% of MS-PSP's achieved 'softwood dominant' (>50% conifer basal area) and 'white spruce dominant' (>50% white spruce basal area) status by age 120 (Table 4-18).

Table 4-18. The percentage of MS-PSP's achieving 'softwood dominant' (>50% conifer basal area) and 'white spruce dominant' (>50% white spruce basal area) status at ages 60, 90, and 120. MGM predictions reflect 4 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); and 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996).

| | | **Site Index Treatment** | | | |
|---|---|---|---|---|---|
| | **Age** | **Submesic** | **Mesic** | **Subhygric** | **Plot-level Ecosite** |
| Softwood Dominant (%) | 60 | 72 | 94 | 78 | 89 |
| | 90 | 94 | 100 | 94 | 94 |
| | 120 | 100 | 100 | 100 | 100 |
| White Spruce Dominant (%) | 60 | 56 | 94 | 67 | 83 |
| | 90 | 94 | 100 | 94 | 94 |
| | 120 | 100 | 100 | 100 | 100 |

Supporting MS-PSP figures and succession matrices are available for submesic, mesic, and subhygric site indices in Appendix 6 (Figures A-6-1 to A-6-6; Tables A-6-1 to A-6-3, A-6-5 to A-6-7, and A-6-9 to A-4-11).

*Long-Term MS-PSP Growth Estimates*

Long-term MS-PSP projections are summarized in Table 4-19. All MGM predictions reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). Long-term summaries are available for submesic, mesic, and subhygric site indices in Appendix 6 (Tables A-6-4, A-6-8, and A-6-12).

Table 4-19. MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 2121 | 1412 | 3150 | 516 |
| | | Basal Area ($m^2$/ha) | 36.9 | 30.1 | 41.4 | 2.7 |
| | | Volume ($m^3$/ha) | 274.0 | 195.5 | 334.1 | 35.5 |
| | | Top Height (m) | 22.1 | 18.0 | 27.2 | 2.7 |
| | | Height (m) | 14.2 | 11.4 | 16.1 | 1.5 |
| | | DBH (cm) | 13.9 | 11.3 | 16.4 | 1.4 |
| | 90 | Density (Trees/ha) | 1297 | 764 | 2012 | 327 |
| | | Basal Area ($m^2$/ha) | 39.4 | 33.0 | 42.5 | 2.3 |
| | | Volume ($m^3$/ha) | 363.4 | 283.6 | 418.3 | 34.5 |
| | | Top Height (m) | 26.4 | 23.6 | 29.3 | 1.7 |
| | | Height (m) | 19.8 | 16.1 | 23.8 | 2.0 |
| | | DBH (cm) | 18.9 | 15.1 | 23.6 | 2.4 |
| | 120 | Density (Trees/ha) | 839 | 511 | 1217 | 204 |
| | | Basal Area ($m^2$/ha) | 37.1 | 29.1 | 41.4 | 3.6 |
| | | Volume ($m^3$/ha) | 396.3 | 290.7 | 444.9 | 42.6 |
| | | Top Height (m) | 29.2 | 26.7 | 31.3 | 1.3 |
| | | Height (m) | 24.4 | 19.7 | 28.2 | 2.1 |
| | | DBH (cm) | 23.2 | 19.0 | 27.8 | 2.5 |

**Note:** SD = standard deviation; ALL = all species.

Table 4-19 (continued). MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| BS | 60 | Density (Trees/ha) | 93 | 0 | 468 | 150 |
| | | Basal Area ($m^2$/ha) | 0.6 | 0.0 | 3.4 | 1.0 |
| | | Volume ($m^3$/ha) | 2.7 | 0.0 | 17.2 | 4.9 |
| | | Top Height (m) | 4.5 | 0.0 | 12.4 | 5.4 |
| | | Height (m) | 4.3 | 0.0 | 11.5 | 5.1 |
| | | DBH (cm) | 4.0 | 0.0 | 12.9 | 4.9 |
| | 90 | Density (Trees/ha) | 57 | 0 | 327 | 106 |
| | | Basal Area ($m^2$/ha) | 0.5 | 0.0 | 2.4 | 0.8 |
| | | Volume ($m^3$/ha) | 2.8 | 0.0 | 16.4 | 4.6 |
| | | Top Height (m) | 5.9 | 0.0 | 16.3 | 7.1 |
| | | Height (m) | 5.8 | 0.0 | 16.2 | 7.0 |
| | | DBH (cm) | 5.3 | 0.0 | 16.4 | 6.4 |
| | 120 | Density (Trees/ha) | 52 | 0 | 326 | 103 |
| | | Basal Area ($m^2$/ha) | 0.6 | 0.0 | 3.6 | 1.0 |
| | | Volume ($m^3$/ha) | 4.0 | 0.0 | 20.6 | 6.6 |
| | | Top Height (m) | 7.1 | 0.0 | 18.9 | 8.4 |
| | | Height (m) | 6.9 | 0.0 | 18.9 | 8.2 |
| | | DBH (cm) | 6.3 | 0.0 | 18.5 | 7.5 |
| JP | 60 | Density (Trees/ha) | 90 | 0 | 325 | 116 |
| | | Basal Area ($m^2$/ha) | 4.2 | 0.0 | 14.2 | 5.5 |
| | | Volume ($m^3$/ha) | 33.9 | 0.0 | 115.8 | 44.5 |
| | | Top Height (m) | 9.2 | 0.0 | 21.8 | 9.9 |
| | | Height (m) | 9.0 | 0.0 | 20.9 | 9.6 |
| | | DBH (cm) | 10.9 | 0.0 | 26.4 | 12.0 |
| | 90 | Density (Trees/ha) | 29 | 0 | 100 | 36 |
| | | Basal Area ($m^2$/ha) | 2.1 | 0.0 | 7.7 | 2.7 |
| | | Volume ($m^3$/ha) | 19.6 | 0.0 | 70.0 | 25.8 |
| | | Top Height (m) | 10.4 | 0.0 | 25.1 | 11.9 |
| | | Height (m) | 10.4 | 0.0 | 25.1 | 11.9 |
| | | DBH (cm) | 13.1 | 0.0 | 33.3 | 15.4 |
| | 120 | Density (Trees/ha) | 16 | 0 | 69 | 22 |
| | | Basal Area ($m^2$/ha) | 1.3 | 0.0 | 6.9 | 1.9 |
| | | Volume ($m^3$/ha) | 13.3 | 0.0 | 68.1 | 19.2 |
| | | Top Height (m) | 11.2 | 0.0 | 26.7 | 12.9 |
| | | Height (m) | 11.2 | 0.0 | 26.7 | 12.9 |
| | | DBH (cm) | 14.0 | 0.0 | 35.7 | 16.5 |

**Note:** SD = standard deviation; BS = black spruce; JP = jack pine.

Table 4-19 (continued). MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 279 | 2 | 926 | 223 |
| | | Basal Area ($m^2$/ha) | 10.3 | 0.0 | 28.0 | 8.0 |
| | | Volume ($m^3$/ha) | 93.5 | 0.0 | 232.8 | 78.6 |
| | | Top Height (m) | 20.8 | 11.6 | 27.2 | 4.5 |
| | | Height (m) | 19.1 | 9.8 | 26.3 | 4.7 |
| | | DBH (cm) | 20.4 | 6.2 | 33.0 | 7.5 |
| | 90 | Density (Trees/ha) | 75 | 0 | 358 | 83 |
| | | Basal Area ($m^2$/ha) | 6.2 | 0.0 | 25.6 | 5.9 |
| | | Volume ($m^3$/ha) | 64.7 | 0.0 | 247.2 | 59.8 |
| | | Top Height (m) | 23.1 | 0.0 | 31.5 | 9.1 |
| | | Height (m) | 22.8 | 0.0 | 31.5 | 9.0 |
| | | DBH (cm) | 29.2 | 0.0 | 47.8 | 13.0 |
| | 120 | Density (Trees/ha) | 21 | 0 | 102 | 24 |
| | | Basal Area ($m^2$/ha) | 2.6 | 0.0 | 9.0 | 2.6 |
| | | Volume ($m^3$/ha) | 29.9 | 0.0 | 99.4 | 30.9 |
| | | Top Height (m) | 23.3 | 0.0 | 34.6 | 12.0 |
| | | Height (m) | 23.3 | 0.0 | 34.6 | 12.0 |
| | | DBH (cm) | 31.9 | 0.0 | 52.5 | 18.2 |
| WS | 60 | Density (Trees/ha) | 1659 | 977 | 2797 | 549 |
| | | Basal Area ($m^2$/ha) | 21.9 | 8.5 | 29.8 | 5.4 |
| | | Volume ($m^3$/ha) | 143.9 | 42.4 | 224.4 | 50.1 |
| | | Top Height (m) | 18.6 | 13.9 | 22.2 | 2.4 |
| | | Height (m) | 13.4 | 9.8 | 17.4 | 2.0 |
| | | DBH (cm) | 12.7 | 9.8 | 17.6 | 2.1 |
| | 90 | Density (Trees/ha) | 1137 | 710 | 1881 | 333 |
| | | Basal Area ($m^2$/ha) | 30.7 | 13.7 | 35.4 | 5.0 |
| | | Volume ($m^3$/ha) | 276.3 | 101.4 | 355.2 | 60.1 |
| | | Top Height (m) | 25.1 | 20.0 | 28.0 | 2.1 |
| | | Height (m) | 19.8 | 16.1 | 23.9 | 2.2 |
| | | DBH (cm) | 18.2 | 14.5 | 24.0 | 2.6 |
| | 120 | Density (Trees/ha) | 749 | 483 | 1146 | 185 |
| | | Basal Area ($m^2$/ha) | 32.6 | 20.1 | 36.1 | 3.5 |
| | | Volume ($m^3$/ha) | 349.1 | 191.3 | 395.4 | 47.0 |
| | | Top Height (m) | 29.0 | 25.1 | 31.3 | 1.7 |
| | | Height (m) | 24.9 | 21.4 | 28.5 | 2.0 |
| | | DBH (cm) | 23.3 | 19.4 | 28.3 | 2.5 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

*Cumulative TSP Succession*

Under ‘plot-level ecosite’ assumptions, most TSP blocks with ‘hardwood-leading’ or ‘hardwood-leading softwood’ compositions transitioned to ‘softwood-leading’ or ‘softwood-leading hardwood’ stands (Figure 4-8). Furthermore, TSP blocks with ‘softwood-leading’ or ‘softwood-leading hardwood’ compositions maintained or intensified softwood dominance (Figure 4-8). At age 60, 31% of TSP stands were ‘softwood-leading’ or ‘softwood-leading hardwood’, and at age 90, 63% of TSP stands were ‘softwood-leading’ or ‘softwood-leading hardwood’. Finally, at age 120, 94% of TSP stands were ‘softwood-leading’ or ‘softwood-leading hardwood’ (Figure 4-8). White spruce basal area also increased across all TSP stands (Figure 4-9). At age 60, 25% of TSP stands were ‘white spruce dominant’ (i.e. >50% white spruce basal area), and at age 90, 56% of TSP stands were ‘white spruce dominant’. Finally, at age 120, 88% of TSP stands were ‘white spruce dominant’ (Figure 4-9).

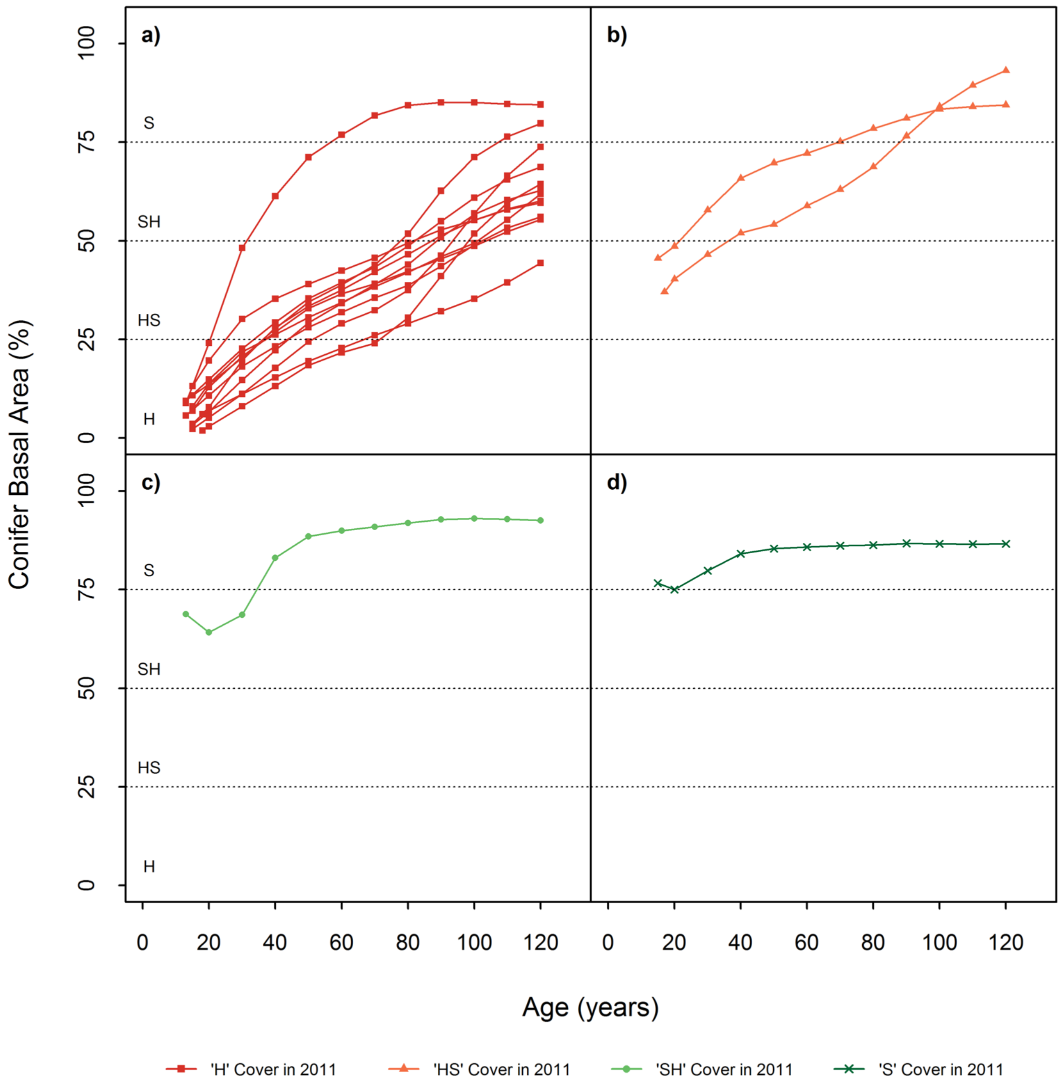


Figure 4-8. MGM conifer succession across 16 TSP stands. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

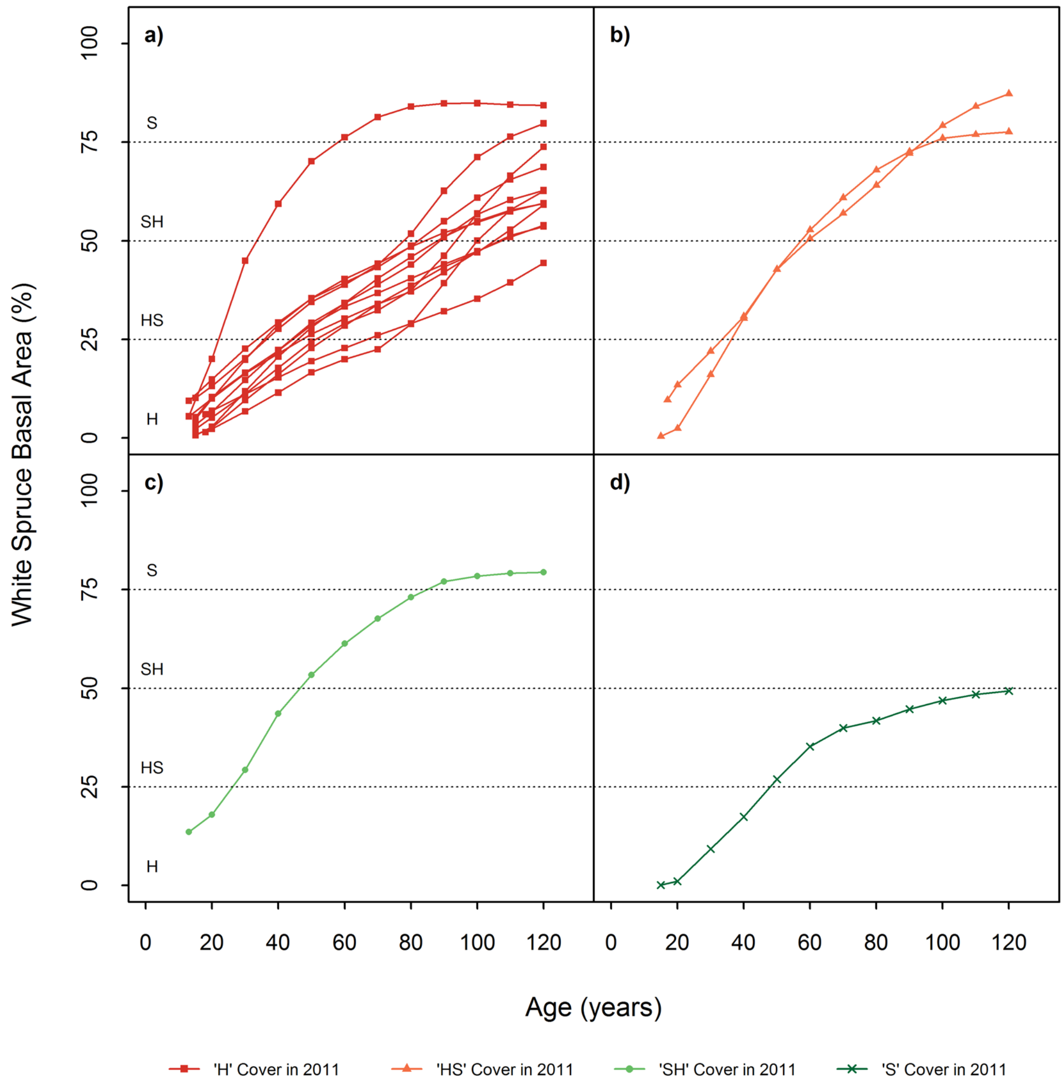


Figure 4-9. MGM white spruce succession across 16 TSP stands. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Increasing deciduous competition slowed TSP succession; however, deciduous competition did not prevent most ‘hardwood-leading’ and ‘hardwood-leading softwood’ TSP stands from transitioning to ‘softwood-leading’ or ‘softwood-leading hardwood’ strata by age 120 (Table 4-22).

Table 4-20. MGM conifer succession across 16 TSP stands: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 22 | | | |
| 0.5 | | | | | | | | | | | | 29 | | | | |
| 0.6 | | | 37 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 32 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 34 | | |
| 0.8 | | | | | | | | | | | | | | | | 38 |
| 1.1 | | | | | | 39 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 23 | | | | | | |
| 1.5 | | | | | | | | 39 | | | | | | | | |
| 1.8 | | | | | | | | | | | 77 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 34 | |
| 2.0 | | | | | | | | | 42 | | | | | | | |
| 4.2 | 86 | | | | | | | | | | | | | | | |
| 4.9 | | | | 59 | | | | | | | | | | | | |
| 5.9 | | 90 | | | | | | | | | | | | | | |
| 8.1 | | | | | 72 | | | | | | | | | | | |

Table 4-21. MGM conifer succession across 16 TSP stands: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 41 | | | |
| 0.5 | | | | | | | | | | | | 46 | | | | |
| 0.6 | | | 45 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 44 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 51 | | |
| 0.8 | | | | | | | | | | | | | | | | 51 |
| 1.1 | | | | | | 55 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 32 | | | | | | |
| 1.5 | | | | | | | | 63 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 46 | |
| 2.0 | | | | | | | | | 53 | | | | | | | |
| 4.2 | 87 | | | | | | | | | | | | | | | |
| 4.9 | | | | 77 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 81 | | | | | | | | | | | |

Table 4-22. MGM conifer succession across 16 TSP stands: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 64 | | | |
| 0.5 | | | | | | | | | | | | 74 | | | | |
| 0.6 | | | 55 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 56 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 63 | | |
| 0.8 | | | | | | | | | | | | | | | | 60 |
| 1.1 | | | | | | 69 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 44 | | | | | | |
| 1.5 | | | | | | | | 80 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 62 | |
| 2.0 | | | | | | | | | 60 | | | | | | | |
| 4.2 | 87 | | | | | | | | | | | | | | | |
| 4.9 | | | | 93 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 84 | | | | | | | | | | | |

Site index assumptions also influenced TSP succession, particularly 'white spruce dominance'. At age 60, mesic and 'plot-level ecosite' site indices produced aggressive succession (Table 4-23). Subhygric site indices yielded intermediate succession, and submesic site indices generated conservative succession. However, in all cases, more than 88% of TSP stands were 'softwood dominant', and more than 69% of TSP stands were 'white spruce dominant' status by age 120 (Table 4-23).

Table 4-23. The percentage of TSP stands achieving 'softwood dominant' (>50% conifer basal area) and 'white spruce dominant' (>50% white spruce basal area) status at ages 60, 90, and 120. MGM predictions reflect 4 site index treatments: 1) Submesic site indices under Beckingham et al. (1996); 2) Mesic site indices under Beckingham et al. (1996); 3) Subhygric site indices under Beckingham et al. (1996); and 4) Site indices that represent plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996).

| | | **Site Index Treatment** | | | |
|---|---|---|---|---|---|
| | **Age** | **Submesic** | **Mesic** | **Subhygric** | **Plot-level Ecosite** |
| Softwood Dominant (%) | 60 | 31 | 31 | 31 | 31 |
| | 90 | 31 | 63 | 63 | 63 |
| | 120 | 88 | 94 | 94 | 94 |
| White Spruce Dominant (%) | 60 | 13 | 25 | 19 | 25 |
| | 90 | 25 | 56 | 56 | 56 |
| | 120 | 69 | 94 | 88 | 88 |

Supporting TSP figures and succession matrices are available for submesic, mesic, and subhygric site indices in Appendix 7 (Figures A-7-1 to A-7-6; Tables A-7-1 to A-7-3, A-7-5 to A-7-7, and A-7-9 to A-4-11).

*Long-Term TSP Growth Estimates*

Long-term TSP projections are summarized in Table 4-24. All MGM predictions reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). Long-term TSP summaries are available for submesic, mesic, and subhygric site indices in Appendix 7 (Tables A-7-4, A-7-8, and A-7-12).

Table 4-24. MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 1973 | 1194 | 3972 | 651 |
| | | Basal Area ($m^2$/ha) | 39.1 | 35.4 | 42.2 | 2.1 |
| | | Volume ($m^3$/ha) | 299.0 | 240.1 | 340.4 | 26.4 |
| | | Top Height (m) | 22.4 | 18.6 | 24.5 | 1.6 |
| | | Height (m) | 15.1 | 12.7 | 17.1 | 1.3 |
| | | DBH (cm) | 15.3 | 10.8 | 17.5 | 1.7 |
| | 90 | Density (Trees/ha) | 1098 | 714 | 1832 | 266 |
| | | Basal Area ($m^2$/ha) | 40.8 | 31.9 | 44.6 | 3.2 |
| | | Volume ($m^3$/ha) | 385.9 | 289.7 | 435.2 | 36.4 |
| | | Top Height (m) | 27.0 | 23.0 | 29.2 | 1.6 |
| | | Height (m) | 20.6 | 17.4 | 22.7 | 1.3 |
| | | DBH (cm) | 21.0 | 15.7 | 23.5 | 1.9 |
| | 120 | Density (Trees/ha) | 691 | 469 | 1018 | 155 |
| | | Basal Area ($m^2$/ha) | 38.4 | 29.0 | 44.3 | 4.5 |
| | | Volume ($m^3$/ha) | 413.8 | 313.7 | 491.7 | 46.3 |
| | | Top Height (m) | 29.3 | 25.9 | 30.4 | 1.2 |
| | | Height (m) | 24.9 | 20.4 | 27.1 | 1.7 |
| | | DBH (cm) | 26.0 | 21.4 | 28.5 | 2.1 |

**Note:** SD = standard deviation; ALL = all species.

Table 4-24 (continued). MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| BS | 60 | Density (Trees/ha) | 229 | 0 | 1297 | 351 |
| | | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 9.4 | 2.3 |
| | | Volume ($m^3$/ha) | 5.3 | 0.0 | 44.4 | 11.1 |
| | | Top Height (m) | 3.0 | 0.0 | 11.4 | 3.4 |
| | | Height (m) | 2.8 | 0.0 | 10.0 | 3.1 |
| | | DBH (cm) | 2.7 | 0.0 | 9.5 | 2.9 |
| | 90 | Density (Trees/ha) | 105 | 0 | 628 | 171 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 8.3 | 2.0 |
| | | Volume ($m^3$/ha) | 4.8 | 0.0 | 50.4 | 12.4 |
| | | Top Height (m) | 3.7 | 0.0 | 15.1 | 4.4 |
| | | Height (m) | 3.6 | 0.0 | 14.2 | 4.3 |
| | | DBH (cm) | 3.4 | 0.0 | 14.1 | 4.0 |
| | 120 | Density (Trees/ha) | 84 | 0 | 454 | 133 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 7.8 | 1.9 |
| | | Volume ($m^3$/ha) | 5.3 | 0.0 | 53.9 | 13.4 |
| | | Top Height (m) | 4.1 | 0.0 | 16.7 | 5.0 |
| | | Height (m) | 4.1 | 0.0 | 16.2 | 4.9 |
| | | DBH (cm) | 3.8 | 0.0 | 15.8 | 4.5 |
| JP | 60 | Density (Trees/ha) | 41 | 0 | 178 | 70 |
| | | Basal Area ($m^2$/ha) | 1.9 | 0.0 | 11.6 | 3.9 |
| | | Volume ($m^3$/ha) | 15.3 | 0.0 | 100.3 | 32.5 |
| | | Top Height (m) | 3.9 | 0.0 | 15.9 | 5.7 |
| | | Height (m) | 3.8 | 0.0 | 15.7 | 5.6 |
| | | DBH (cm) | 4.5 | 0.0 | 21.7 | 7.6 |
| | 90 | Density (Trees/ha) | 14 | 0 | 101 | 31 |
| | | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 8.8 | 2.7 |
| | | Volume ($m^3$/ha) | 11.5 | 0.0 | 82.4 | 26.5 |
| | | Top Height (m) | 4.0 | 0.0 | 19.0 | 6.9 |
| | | Height (m) | 4.0 | 0.0 | 19.0 | 6.9 |
| | | DBH (cm) | 4.9 | 0.0 | 26.5 | 9.5 |
| | 120 | Density (Trees/ha) | 9 | 0 | 76 | 22 |
| | | Basal Area ($m^2$/ha) | 1.0 | 0.0 | 7.4 | 2.3 |
| | | Volume ($m^3$/ha) | 10.1 | 0.0 | 74.1 | 23.4 |
| | | Top Height (m) | 3.3 | 0.0 | 20.6 | 7.2 |
| | | Height (m) | 3.3 | 0.0 | 20.6 | 7.2 |
| | | DBH (cm) | 4.6 | 0.0 | 28.6 | 10.0 |

**Note:** SD = standard deviation; BS = black spruce; JP = jack pine.

Table 4-24 (continued). MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect plot-level ecosite classifications (i.e. mesic-hygric) under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| **Species** | **Age** | **Variable** | **Mean** | **Min** | **Max** | **SD** |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 477 | 102 | 965 | 221 |
| | | Basal Area ($m^2$/ha) | 20.5 | 4.1 | 29.3 | 8.4 |
| | | Volume ($m^3$/ha) | 181.4 | 33.8 | 258.0 | 78.9 |
| | | Top Height (m) | 21.8 | 15.1 | 24.5 | 2.7 |
| | | Height (m) | 20.1 | 15.2 | 23.8 | 2.4 |
| | | DBH (cm) | 22.9 | 15.0 | 29.0 | 3.9 |
| | 90 | Density (Trees/ha) | 174 | 32 | 373 | 91 |
| | | Basal Area ($m^2$/ha) | 16.4 | 3.1 | 26.1 | 7.5 |
| | | Volume ($m^3$/ha) | 170.7 | 31.3 | 265.1 | 82.9 |
| | | Top Height (m) | 25.5 | 12.5 | 29.2 | 4.7 |
| | | Height (m) | 24.5 | 12.5 | 28.8 | 4.4 |
| | | DBH (cm) | 33.4 | 17.7 | 41.5 | 6.9 |
| | 120 | Density (Trees/ha) | 76 | 20 | 158 | 38 |
| | | Basal Area ($m^2$/ha) | 11.2 | 2.5 | 18.2 | 5.5 |
| | | Volume ($m^3$/ha) | 124.3 | 29.9 | 215.5 | 65.4 |
| | | Top Height (m) | 27.3 | 13.9 | 31.8 | 4.8 |
| | | Height (m) | 27.1 | 13.9 | 31.8 | 4.7 |
| | | DBH (cm) | 40.0 | 21.9 | 51.1 | 8.4 |
| WS | 60 | Density (Trees/ha) | 1226 | 503 | 3784 | 769 |
| | | Basal Area ($m^2$/ha) | 15.5 | 7.1 | 32.2 | 6.4 |
| | | Volume ($m^3$/ha) | 97.0 | 41.9 | 193.7 | 40.4 |
| | | Top Height (m) | 16.4 | 11.8 | 18.9 | 1.7 |
| | | Height (m) | 13.6 | 10.5 | 15.1 | 1.1 |
| | | DBH (cm) | 12.7 | 10.1 | 14.1 | 1.0 |
| | 90 | Density (Trees/ha) | 805 | 404 | 1777 | 340 |
| | | Basal Area ($m^2$/ha) | 22.3 | 12.3 | 34.6 | 6.8 |
| | | Volume ($m^3$/ha) | 198.9 | 105.5 | 310.0 | 62.9 |
| | | Top Height (m) | 23.2 | 17.3 | 25.7 | 2.0 |
| | | Height (m) | 20.1 | 16.0 | 21.4 | 1.3 |
| | | DBH (cm) | 18.6 | 15.1 | 20.1 | 1.3 |
| | 120 | Density (Trees/ha) | 522 | 311 | 980 | 177 |
| | | Basal Area ($m^2$/ha) | 25.4 | 14.5 | 34.8 | 6.1 |
| | | Volume ($m^3$/ha) | 274.1 | 152.1 | 372.6 | 67.4 |
| | | Top Height (m) | 27.9 | 21.0 | 29.6 | 2.0 |
| | | Height (m) | 25.5 | 20.0 | 26.8 | 1.6 |
| | | DBH (cm) | 24.8 | 20.5 | 26.9 | 1.7 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

## 4.4 Discussion

*Exploring Juvenile MGM Performance*

To explore MGM performance, biased predictions must be assessed in the context of MGM's computational structure. Foremost, MGM assumes a 'height-driven architecture'. Under this platform, height increment is predicted first; then, height increment estimates are used to inform diameter increment and survival probability. Therefore, biased height increment estimates propagate error throughout MGM and distort all derivative predictions (e.g. volume). Biased height increment estimates are especially problematic during juvenile growth. In particular, excessive height increment estimates cause juvenile spruce to surpass breast height early. Then, juvenile spruce prematurely accrue diameter increment, skewing basal area and volume predictions.

MGM's juvenile white spruce height increment function links annual growth to deciduous competition, initial tree size, and a height-age-site index model (Bokalo et al. 2010). However, many factors that influence juvenile white spruce growth are not explicitly modeled by MGM, including conifer competition (Bokalo et al. 2010), understory vegetation (Cortini and Comeau 2008), site effects (Filipescu and Comeau 2007; Cortini et al. 2012), climate variables (Cortini et al. 2011b; Cortini et al. 2012), frost damage (Voicu and Comeau 2006; Filipescu and Comeau 2011), leader whip (Osika et al. 2013), and herbivory (Taylor et al. 1996; Comeau et al. 2005; Cortini et al. 2010). Across the MS-PSP dataset, juvenile white spruce were damaged by varying agents, and 30% of juvenile white spruce exhibited stem deformities during the 2011-2012 measurement. Unfortunately, MGM did not model any of these growth losses. Finally, MGM's juvenile white spruce height increment function was developed using a small Alberta dataset. As a result, MGM may be poorly calibrated for Saskatchewan.

MGM's height-age-site index model(s) were also developed using data from unmanaged stands (Huang 1997c; Huang 1997a; Huang et al. 1997) and may inadequately predict managed stand growth. Silvicultural treatments can alter 1) plant competition, 2) moisture, nutrient, and light availability, 3) soil density and drainage, and 4) microclimatic conditions (Long et al. 2004). Therefore, managed stands may produce different growth trajectories than unmanaged stands (Boateng et al. 2009; Cortini et al. 2010; Osika et al. 2013; Huang et al. 2004). In this study, 39% of white spruce height-age site indices (Table 4-3) exceeded the site index range of the Huang (1997c) stem analysis dataset (i.e. Site Index Estimates > 23.18m), suggesting poor juvenile site index estimates (e.g. Huang 1994) or altered trajectories of managed stand growth (e.g. Cortini et al. 2010). Cumulatively, external limiting factors, inadequate calibration, silvicultural treatments, and poor juvenile site index estimates may explain poor MGM performance.

Much of MGM's prediction error can be attributed to 'cumulative external factors' and MGM's height-driven architecture. Under height-age site indices, plot-level top height tracked a 1:1 relationship through the origin, suggesting reasonable estimates of dominant growth (Figure 4-10). Alternately, mean height was overestimated on MS-PSP's with strong jack pine competition (i.e. Jack Pine Basal Area > 50%), considerable spruce ingress (i.e. 3500 Spruce/ha), or high aspen retention (i.e. Aspen Basal Area @ Age 22 = 32$m^2$/ha). In each case, MGM appeared to underestimate competition and overestimate white spruce growth. Overall, these mean height overestimates seemed rational since MGM's juvenile white spruce height increment function does not incorporate conifer competition. Ingress was not assumed on any MS-PSP simulation, and poor predictions under high aspen competition may implicate MGM's Alberta calibration. Ultimately, these mean height overestimates propagated through MGM and skewed low-end DBH, basal area, and volume estimates (Figure 4-10).

For 'mixedwood' MS-PSP's without jack pine competition, top height, mean height, and mean DBH generally tracked a 1:1 relationship through the origin (Figure 4-10).

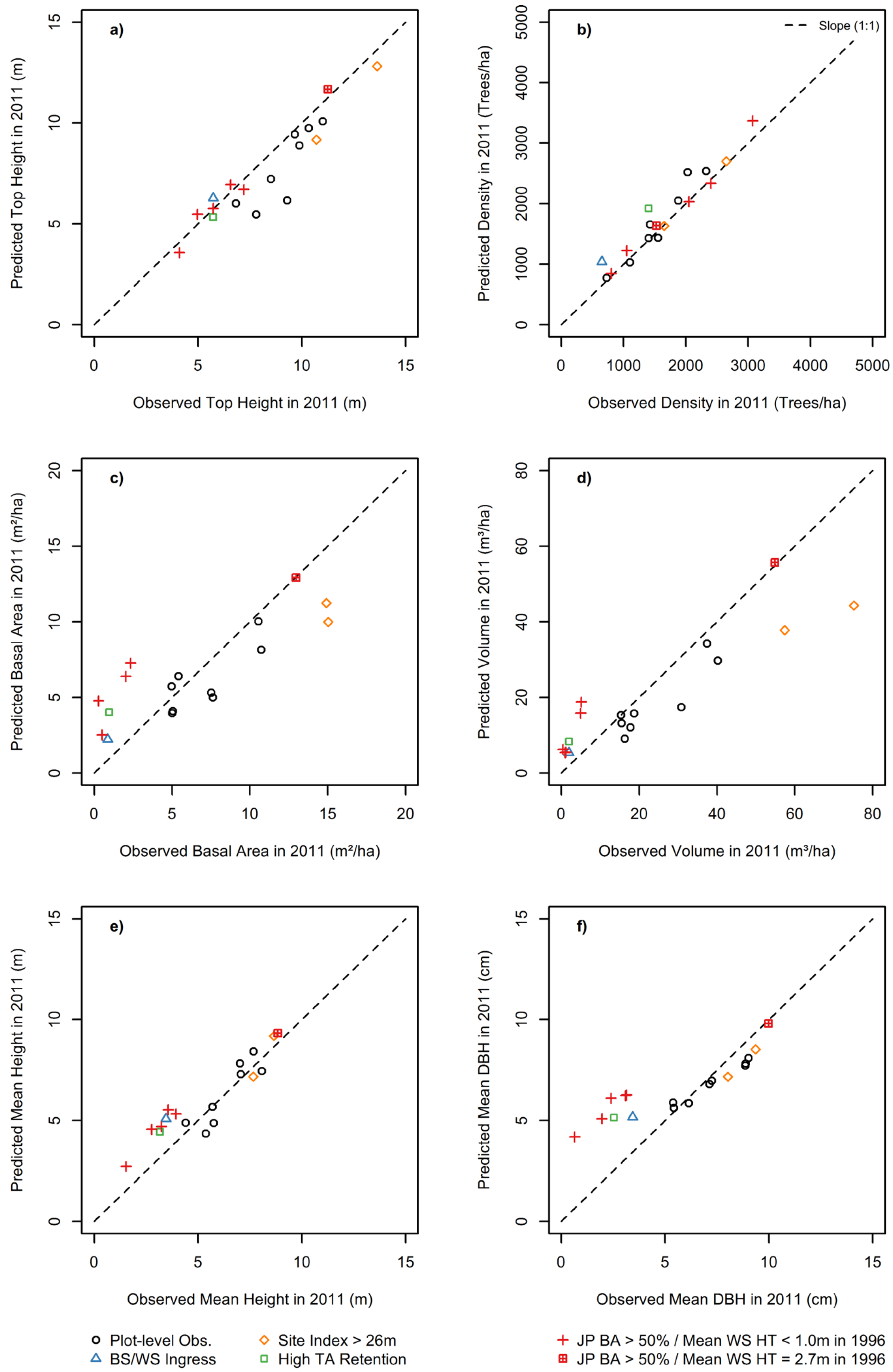


Figure 4-10. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Each scatter plot represents white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH in 2011. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997). Plots with considerable spruce ingress (i.e. 3500 Spruce/ha), large white spruce site index values (Site Index > 26m @ 50yrs), high aspen retention (i.e. Aspen Basal Area @ Age 22 = 32m$^2$/ha), or substantial jack pine components (i.e. Jack Pine Basal Area > 50%) are identified in each figure. Jack pine dominant plots are also subdivided by mean white spruce height at initialization.

Density was overestimated, and basal area and volume were often underestimated. In addition, large basal area and volume underestimates occurred on MS-PSP's with excessive site index predictions (i.e. Site Index > 26m) (Figure 4-10). MGM's Alberta calibration may drive these basal area, volume, and density biases.

MGM performance also appears to be influenced by initial white spruce size and the duration white spruce were modeled under MGM's juvenile functions. For MS-PSP's with strong jack pine competition, considerable spruce ingress, or high aspen retention, bias increased when white spruce were under 1m at initialization (Figure 4-10).

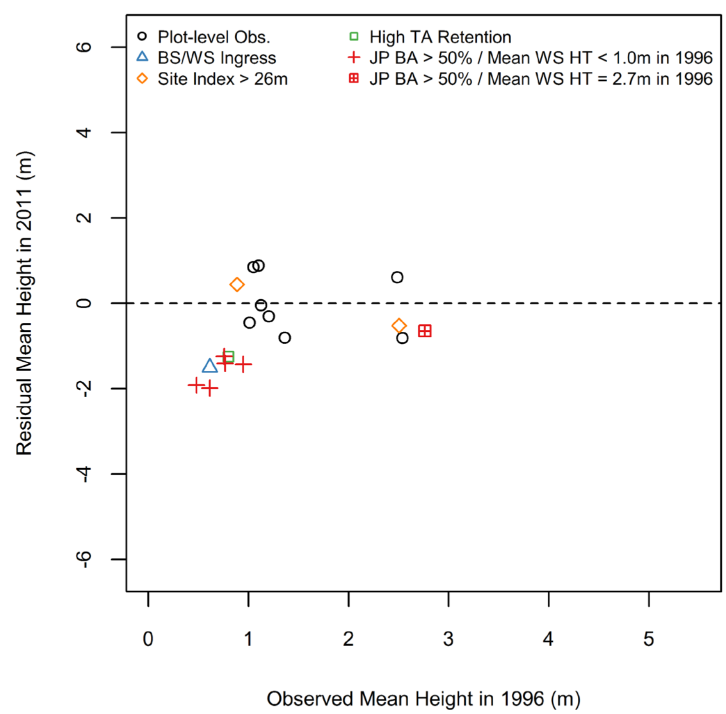


Figure 4-11. Plot-level residual mean height for white spruce in 2011 (i.e. 2011 plot-level height observations for white spruce – 2011 plot-level MGM height predictions for white spruce) versus plot-level observed mean height for white spruce in 1996. Points represent individual MS-PSP's. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997). MS-PSP's with considerable spruce ingress (i.e. 3500 Spruce/ha), large white spruce site index values (Site Index > 26m @ 50yrs), high aspen retention, or substantial jack pine components (i.e. Jack Pine Basal Area > 50%) are identified in the figure. MS-PSP's with a substantial jack pine component are also subdivided by mean white spruce height at initialization.

In contrast, the jack pine dominant MS-PSP 94304 produced relatively low bias (Figure 4-11; Symbol = ⊞); this MS-PSP was initialized with white spruce averaging 2.7m tall and 2.9cm DBH. As a result, juvenile white spruce on MS-PSP 94304 spent less time under MGM's juvenile functions (DBH ≤ 4cm) and more time under MGM's mid-rotation functions (DBH > 4cm). Since MGM's mid-rotation functions (DBH > 4cm) incorporate both deciduous and conifer competition (Bokalo et al. 2010), strong performance on MS-PSP 94304 may be explained by better competition estimates (Figure 4-10; Symbol = ⊞). Across the MS-PSP dataset, plot-level and tree-level bias declined when 1) larger trees were initialized and 2) trees were modeled for less time under MGM's juvenile white spruce functions (DBH ≤ 4cm) (Figures 4-11 and 4-12). At the tree-level, juvenile white spruce initialized under 1.3m were often overestimated, and juvenile white spruce modeled entirely with MGM's mid-rotation functions (DBH > 4cm) produced very low bias (Figure 4-12).

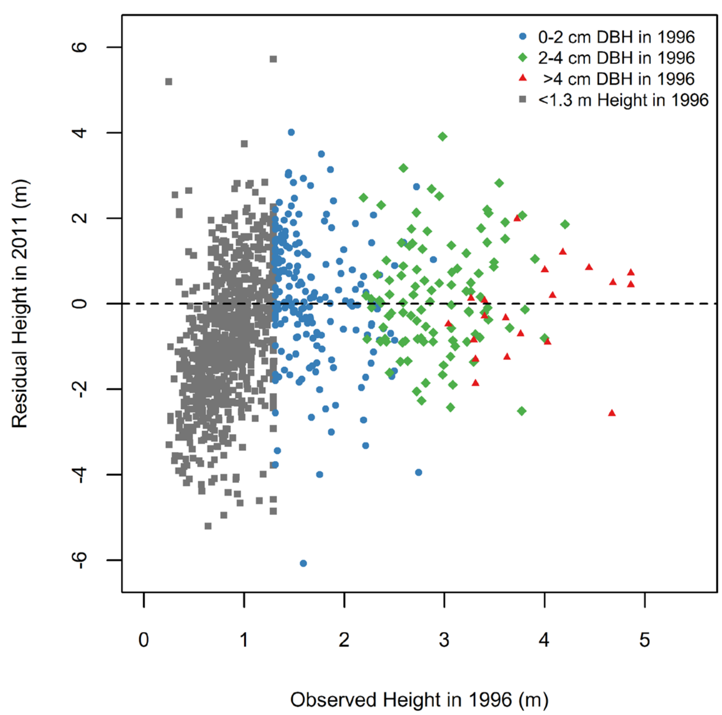


Figure 4-12. Tree-level residual height in 2011 (i.e. 2011 tree-level height observations – 2011 tree-level MGM height predictions) versus tree-level observed height in 1996 across the MS-PSP dataset. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and height-age site index estimates from Huang (1997c) and Huang et al. (1997).

*Issues with Juvenile MGM Projections*

Given MGM's biased small-tree estimates (Figures 4-11 and 4-12) and the many factors influencing juvenile growth, MGM projections should be initialized with well-established white spruce that exceed breast height (1.3m) and/or the Saskatchewan 'Free-to-Grow' assessment period (i.e. 14 years). In addition, juvenile white spruce stands with strong conifer competition should be initialized with spruce that exceed 4cm DBH. This diameter limit places white spruce on MGM's mid-rotation functions and allows MGM to model white spruce under conifer competition (e.g. Figure 4-12; Symbol = ▲).

However, many factors hinder juvenile MGM projections, including complex stand dynamics (e.g. browsing, frost, woody/herbaceous competition), juvenile site index instability (e.g. Huang 1994; Huang 1997b; Nigh and Sit 1996), and accuracy issues with ecosite-based site indices (e.g. Table 4-7; Kayahara et al. 1998). In addition, conifer competition also appears to bias MGM's juvenile white spruce predictions (Figures 4-10 and 4-11). Cumulatively, these factors also restrict MGM's ability to model white spruce silvicultural effects in juvenile stands, unless white spruce site indices stabilize (i.e. 20-35 years breast height age) and white spruce exceed 4cm DBH.

*Exploring Long-Term MGM Performance*

In long-term projections, MGM consistently modeled 'convergent' mixedwood succession, transitioning most MS-PSP's and TSP's to white spruce dominance (Chen and Popadiouk 2002; Figures 4-6, 4-7, 4-8, and 4-14). Mixedwoods initialized with a strong white spruce component (~2000 Trees/ha) generally exceeded 50% white spruce basal area by age 60 and 75% white spruce basal area by age 120 (Figure 4-13). Alternately, mixedwoods initialized with fewer white spruce (675-2000 Trees/ha) often exceeded 25% white spruce basal area by age 60 and 50% white spruce basal area by age 120 (Figure 4-13).

High levels of deciduous competition slowed but did not stop mixedwood succession (Tables 4-17 and 4-22; Figure 4-13). Long-term deciduous competitive effects were apparent under the MS-PSP dataset (Tables 4-15, 4-16, and 4-17). However, deciduous competitive effects were less clear under the TSP dataset, since many TSP stands were initialized with less conifer basal area, lower white spruce densities, and less extreme deciduous competition (Tables 4-17 and 4-22; Figure 4-13). In addition, succession rates were dramatically influenced by site index assumptions (Tables 4-18 and 4-23), indicating that reliable site index estimates are essential for accurate MGM performance.

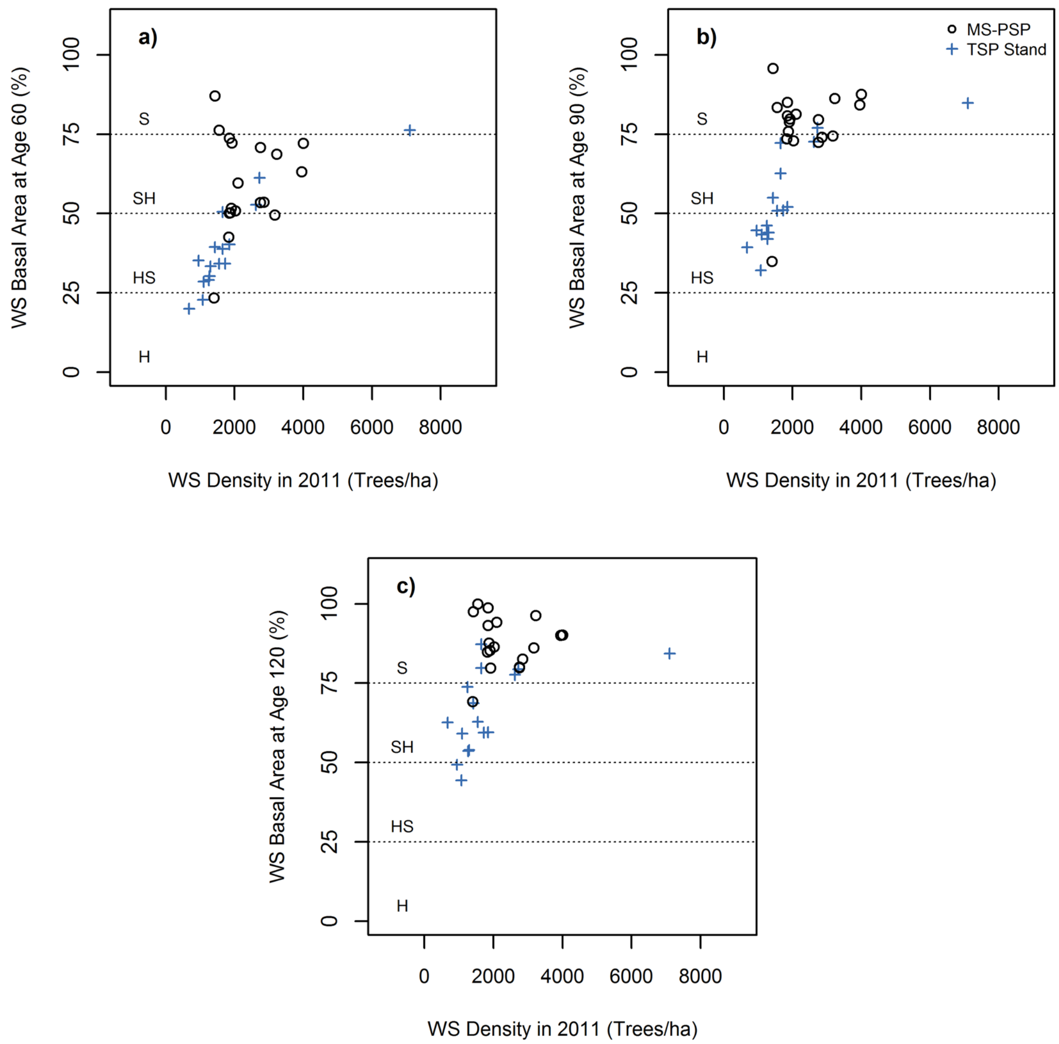


Figure 4-13. MGM white spruce succession across 18 MS-PSP's and 16 TSP stands. Relative white spruce basal area at age a) 60, b) 90, and c) 120 versus observed white spruce density in 2011. Site index estimates reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

*Issues with Long-Term MGM Projections*

To constrain long-term MGM predictions (e.g. volume) within a biologically reasonable range, 'late-succession breakup' (i.e. MAFlag = True) was assumed for trembling aspen, jack pine, and white spruce. MGM models 'late-succession breakup' by increasing mortality after trees reach empirical size (e.g. Quadratic Mean Diameter > 26cm) and basal area (e.g. Plot Basal Area > 55 $m^2$/ha) thresholds (Bokalo et al. 2010). However, the timing of 'late-succession breakup' varies (Epp et al. 2009, pg 309), depending on stand composition, structure, and density (Epp et al. 2009, pgs 299-302). 'Late-succession breakup' is also influenced by windthrow, stem decay (e.g. *Fomes igniarius*), insect outbreaks (e.g. *Malacosoma disstria*) (Chen and Popadiouk 2002; Epp et al. 2009, pg 302), and "*variations in the physical environment*" (Epp et al. 2009, pg 309). In particular, trembling aspen decline is driven by complex interactions between climate, drought, insects, pathogens, and site quality (Hogg et al. 2002; Hogg et al. 2008). As a result, MGM's 'late-succession breakup' may oversimplify mixedwood succession and grant undue authority to size or basal area thresholds. 'Late-succession breakup' may also have limited relevance after 120 years, particularly if 'breakup assumptions' encourage total stand collapse (LeBlanc 2014). In some regions, old mixedwoods (i.e. >120 years) may persist (Kabzems and Garcia 2004), enter gap dynamics, and/or transition to multi-cohort stands (Chen and Popadiouk 2002; LeBlanc 2014). Currently, MGM does not model late-succession gap dynamics; therefore, long-term MGM projections should be limited to 120 years.

*Alternative Data Sources for Forest Growth Modeling*

Sampling protocols are often developed to meet specific management objectives. In this study, historic establishment surveys were designed to assess site occupancy and competing vegetation, using a relatively small systematic sample and binary observations. To a lesser degree, these historic establishment surveys also quantified tree height and density. However, height and density observations were only measured on every fourth plot, and DBH observations were not sampled. For MGM simulations, mensuration data must 1) completely enumerate plot-level height and DBH (Trees >1.3m), 2) summarize stand-level height, DBH, and density, or 3) collect enough information to reliably impute plot-level or stand-level attributes. Of these data sources, plot-level observations are preferred. Representative plot-level samples characterize ‘natural distributions’ (e.g. multimodal) of height and DBH, allowing MGM to model growth under realistic competitive environments. Alternately, stand-level observations simplify mensuration data and yield simplistic height, DBH, and density distributions. As a result, stand-level observations may poorly characterize competition and skew MGM predictions.

Forest growth models require representative and error-free data (Weiskittel et al. 2011, pg 312). If data do not meet these minimum requirements, sample error can *“have a larger influence on prediction variability than [..] the underlying growth model equations”* (Weiskittel et al. 2011, pg 312). In particular, extremely small plots may poorly represent competition and produce unrealistic growth model predictions (Weiskittel et al. 2011, pg 312). Therefore, larger plots should be preferred (Weiskittel et al. 2011, pg 314). Plot-level samples should also contain 1 or more trees at maturity. In the context of long-term experiments, Pretzsch (2009) recommends that *“plot size must be sufficiently large [...] to still maintain a sufficient number of trees at the end of an observation period to produce the desired accuracy”* (Pretzsch 2009, pg 126). For example, Cortini et al. (2011b) observed mature trembling aspen crown areas up to $112m^2$ and mature white spruce crown areas up to $84m^2$ in Alberta. Similarly, Beaudet et al. (2011) observed mature trembling aspen crown areas up to $75m^2$ (i.e. crown radius = 4.9m) and mature white spruce crown areas up to $36m^2$ (i.e. crown radius = 3.4m) in northwestern Quebec. As a result, the $5m^2$ historic establishment survey plots are likely inadequate as a basis for long-term plot-level MGM simulations.

Similarly, stand-level MGM simulations should use representative samples that meet robust provincial sampling protocols. The historic establishment surveys quantified tree height and density with $5m^2$ plots at 0.49 to

0.82 plots/hectare. In contrast, the 2008 Saskatchewan establishment survey protocol quantifies tree height, root collar diameter, and density with $10m^2$ plots at ≥2.77 plots/hectare (SME 2008). Given extremely low sample intensities, historic establishment surveys also appear insufficient to run stand-level MGM simulations.

*Preferred Sampling Methods for MGM*

To support MGM simulations and model validation, large plots (≥$100m^2$) should be used to accommodate multiple trees at maturity. During early stand development, subplots may be useful to characterize extensive coniferous (e.g. jack pine) or deciduous competition (e.g. trembling aspen); however, after initial stem exclusion, subplots should be expanded to incorporate dominant trees or other rare strata. Complete enumeration of height and DBH are essential to track long-term growth and facilitate model validation. In this study, the 1996 MS-PSP measurement did not enumerate any naturally regenerated trees, restricting MGM validation to planted white spruce. Height and DBH may be imputed using height-RCD, height-DBH (Calama and Montero 2004), or DBH-height (Cortini et al. 2011a) relationships. Unfortunately, imputation can complicate data processing, impart additional bias, and mask natural variation of the predicted variable. In this study, white spruce height-RCD models for the 1996 MS-PSP measurement produced logical errors when trees approached 1.3m. [For example, target spruce were less than 1.3m, and DBH observations could not be measured; however, imputed heights were greater than 1.3m. Alternately, target spruce were greater than 1.3m, and DBH observations were measured; however, imputed heights were less than 1.3m.] Furthermore, white spruce height-DBH models could not be developed for the 1996 MS-PSP measurement since most white spruce were under breast height. (See Chapter 3.) As a result, many juvenile white spruce in the 1996 MS-PSP measurement were assigned 'default heights' (i.e. 1.29m or 1.31m) when height-RCD imputation errors occurred. To address these issues, height measurements should occur on all trees below breast height, and height imputation should be limited to trees above breast height.

*Site Classification and Site Productivity*

When height-age site indices cannot be readily determined, ecosite, habitat type, and biogeoclimatic classification systems are often linked to tree productivity (Wang 1995; Beckingham et al. 1996; Cooper et al. 1991; Pojar et al. 1987). This linkage is particularly strong in mountainous regions where elevation, slope, and aspect correlate with climate, precipitation, drainage, soil type, and plant community (e.g. Pojar et al. 1987; Cooper et al. 1991). However, in the boreal forest, relief is generally low (Rowe 1972), and white spruce site index changes incrementally between ecosites, except at soil moisture and soil nutrient extremes (Beckingham et al. 1996; Wang and Klinka 1996). In some cases, site classification may poorly predict spruce site index (Kayahara et al. 1998). Given these issues, it is probably best to determine white spruce site index before harvesting to indicate historic site potential.

Furthermore, ecosite classification can be extremely challenging in managed stands. Harvesting and site preparation can disrupt, damage, or destroy key diagnostic indicators like overstory vegetation, understory vegetation, soil organic layers, and upper soil horizons. In addition, planting and tending can alter the 'natural plant communities' that characterize ecosites. As a result, ecosite classification should occur prior to harvesting, particularly when ecosites will inform site productivity.

## 4.5 Conclusion

When modeling juvenile white spruce growth, MGM's performance is largely determined by accurate site index estimates. In this study, height-age site indices maximized MGM performance. Unfortunately, height-age site index estimates are unstable until trees dominate their local environment and/or approach reference age. As a result, height-age site indices for the MS-PSP dataset are not reliable indicators of long-term productivity. Ecosite classifications provided an alternative site index source, but this approach may lack the accuracy of height-age site estimates.

For juvenile white spruce validation, plot-level MGM predictions did not match observations under a 10% equivalence region. However, plot-level MGM predictions were marginally equivalent, provided a 25% equivalence region and height-age site index indices. At the tree-level, height, DBH, and volume deviated from an 'ideal' 1:1 relationship through the origin and produced low median efficiencies (EF < 0.25). Tree-level AMB and RMB varied greatly between individual MS-PSP's and indicated large overestimates of small-tree growth.

MGM's juvenile white spruce functions do not explicitly model many factors that influence juvenile spruce, including conifer competition, understory vegetation, climate variables, or damaging agents (e.g. herbivory). Furthermore, MGM's juvenile white spruce functions were calibrated using Alberta data. As a result, MGM's performance suffers when modeling plots with small white spruce, strong conifer competition, or low aspen mortality. Recalibrating MGM's juvenile white spruce functions may ameliorate some of these issues. However, a Saskatchewan recalibration would require substantial datasets, reliable estimates of juvenile productivity (e.g. site index), and dependable height-age-site index models.

Given stochastic juvenile growth and competition-related biases under *MGM 2010A1 Rev 3099*, MGM projections should be initialized with well-established white spruce that exceed breast height and/or the Saskatchewan 'Free-to-Grow' assessment period (i.e. 14 years). In addition, stands with strong conifer competition should be initialized with white spruce that exceed 4cm DBH. This diameter limit places white spruce on MGM's mid-rotation functions and allows MGM to model conifer competition. Finally, modeling white spruce silvicultural effects may be problematic until juvenile site indices stabilize and white spruce exceed 4cm DBH.

In this study, long-term MGM projections transitioned most hardwood leading and pine leading mixedwoods to white spruce dominance (>50% basal area) by age 120. Mixedwood stands initialized with a well-established white spruce component (~2000 trees/ha) generally exceeded 50% white spruce basal area by age 60 and 75% white spruce basal area by age 120. Mixedwood stands initialized with <2000 trees/ha took longer to achieve white spruce dominance. Deciduous competition slowed but did not stop mixedwood development. Again, site index assumptions strongly influenced long-term MGM succession, indicating that accurate site indices are essential to model long-term mixedwood growth.

'Late-succession breakup' assumptions (i.e. MAFlag = True) were used to constrain MGM's long-term volume estimates within a biologically reasonable range. These 'breakup assumptions' increase stand mortality after trees reach empirical size-basal area thresholds. However, many stochastic factors influence 'late-succession breakup', and these 'breakup assumptions' become less valid as mixedwood stands transition to gap dynamics (>120 years). Since MGM does not model late-succession gap dynamics, long-term MGM projections may be unreliable after 120 years.

To model long-term growth in MGM, sampling protocols must adequately characterize subject stands. In addition, sample plots must incorporate 1 or more trees at maturity, accurately depict local competition, and fully enumerate height and DBH. Tree height should be measured on all trees below 1.3m to avoid imputation problems. Finally, model validation requires large, completely enumerated plots that are tracked over time; tallied or temporary observations limit growth and mortality inferences, particularly after silvicultural treatments (e.g. cleaning).

In the absence of height-age site indices, site classification systems can inform site index assumptions. However, site classification systems do not always provide accurate site index estimates. Site classification systems may also be difficult to implement in managed stands, given overstory removal, soil disturbance, and silvicultural treatments. As a result, site index assessment and site classification should occur prior to harvesting, indicating historic and ecological site potential.

## Chapter 5. Conclusions

In Saskatchewan, Provincial Forests are managed to assure long-term productivity while balancing economic, social, and cultural needs. To realize these goals, sustainable forest management requires quantified silvicultural outcomes and reliable estimates of managed-stand growth. This knowledge can aid forest management planning, inform sustainable harvest levels, and promote the development of a diverse forest landscape. In the PAFMA, the long-term impact of modern silviculture is somewhat unclear, since intensive forest management only dates from the late 1960's (e.g. Kabzems 1971). Furthermore, most silvicultural trials in western Canada are relatively young and have not reached rotation age. As a result, operational white spruce silviculture was explored across the PAFMA, and MGM was used to model short and long-term growth in managed stands.

Across the TSP dataset, juvenile white spruce height was not significantly different between Bracke mounded, v-plow scarified, disc trenched, and disc trenched/tended treatments. However, v-plow scarification appeared to increase juvenile white spruce DBH relative to Bracke mounding. This DBH effect was linked with a significant difference in grass competition but could not be linked to a significant difference in overstory vegetation. Although site differences were considered with ANCOVA analysis, silvicultural effects could not be completely isolated from complex interacting factors such as stand age, soil moisture regime, and soil nutrient regime. Small sample sizes, marginal model fits, and locally clustered treatments may have also limited silvicultural inferences. Finally, the silvicultural effectiveness could not be explored, given the absence of a 'raw planted' control.

In the literature, successful silvicultural experiments are often established as long-term trials and incorporate blocked or split-plot designs to address systematic error. Furthermore, these studies include on-site replication, uniform treatments, and an untreated control. Successful silvicultural experiments also contain treated buffers, large plots, and completely enumerated trees. Stem mapping and climatic information may also support silvicultural analysis.

To initialize MGM simulations, generalized mixed-effects height-estimation models were developed for the MS-PSP dataset. These models explained height-diameter variation with covariates and random-effects. Among candidate covariates, top height and density often explained the most random variation, indicating that competition, site productivity, and stand age influence tree slenderness. Small sample sizes prevented validation of the MS-PSP height-estimation models, limiting their application outside the MS-PSP dataset. To deploy generalized height-estimation models, model development must include regional data, calibration, and validation.

When modeling short- and long-term growth, MGM performance is highly dependent on accurate site index estimates. Height-age site indices produced strong MGM performance for juvenile white spruce under short-term validation. However, in juvenile stands, white spruce site index does not stabilize until trees are well-established and/or approach reference age. As a result, juvenile height-age site indices do not indicate long-term white spruce productivity. Ecosite guides can serve as an alternative site index source, but this approach may lack accuracy.

For the juvenile white spruce validation, plot-level MGM predictions failed 'strict' equivalence tests (±10% equivalence region) and marginally satisfied 'liberal' equivalence tests (±25% equivalence region). Tree-level validation indicated that height, DBH, and volume deviated from an 'ideal' 1:1 relationship through the origin. Tree-level AMB and RMB indicated large overestimates of small trees, and median tree-level efficiencies were low ($EF < 0.25$). Poor validation performance can be related to MGM's juvenile white spruce functions. These functions do not explicitly model many factors that influence juvenile white spruce: conifer competition, understory vegetation, climate, herbivory, etc. As a result, MGM's performance declined when modeling plots with small white spruce and high conifer competition. To address these issues, juvenile MGM projections should be initialized with white spruce that exceed breast height and/or 'Free-to-Grow' status (i.e. 14 years). Furthermore, juvenile stands with abundant conifer competition should be initialized with white spruce ≥4cm DBH; this allows MGM to model white spruce under 'mid-rotation' functions that incorporate conifer competition. Finally, modeling silvicultural effects for juvenile white spruce may be problematic until height-age site indices stabilize and white spruce exceed 4cm DBH.

Under long-term MGM projections hardwood leading and pine leading mixedwoods transitioned to white spruce dominance (>50% basal area) by age 120. Mixedwood stands initialized with a strong white spruce component (~2000 trees/hectare) generally became white spruce-leading mixedwoods by age 60 and white spruce dominated (>75% basal area) by age 120. Mixedwoods initialized with <2000 white spruce/hectare took more time to achieve spruce dominance. Deciduous competition slowed but did not stop succession. In long-term MGM projections, 'late succession breakup' (i.e. MAFlag = True) may be required to restrict volume estimates within a reasonable range. However, these 'breakup assumptions' may not apply to old mixedwood stands (>120 years) that have transitioned to gap-dynamics. Since MGM does not model gap dynamics, long-term MGM projections should be limited to 120 years, unless reinitiating modeled stands. To model long-term MGM growth, sample plots should be large enough to contain several trees at maturity. In addition, these plots should accurately characterize local competition and fully enumerate height and DBH for all trees. Finally, MGM validation requires large enumerated plots without tallied or temporary observations.

Forests are complex systems, driven by past, present, and future factors. Subtle site differences, stochastic events (e.g. drought, insect outbreaks), and silvicultural intervention add to this complexity. As a result, modeling managed stands is difficult, and predicting managed-stand growth may not always achieve success. Nevertheless, sustainable forest management requires quantified silvicultural outcomes and forest growth models to manage public resources. In this study, 1) operational, 2) retrospective, and 3) repurposed, forest measurements complicated analysis and sometimes failed to support key project goals. For example, establishment surveys in Chapter 4 were designed to assure uniform stocking in young plantations; however, establishment survey plot size and sample intensity were not large enough to reliably initialize MGM. Therefore, university, government, and industrial partners must commit to long-term silvicultural experiments with explicit research questions, robust designs, and uniform treatments. Well-designed silvicultural experiments are essential to isolate silvicultural effects, calibrate forest growth models, and verify model projections.

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## Appendix 1. Preliminary ANOVA and ANCOVA Models for White Spruce

Table A-1-1. Preliminary ANOVA and ANCOVA summary statistics for white spruce height. All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | Parameters | | | | | | | | | | | | F-Test p-values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.1.1 | HT=ST | *2.44* | 0.33 | 0.10 | 0.39 | . | 0.79 | 1894.06 | ○ | ◒ | ○ | ● | ○ | 0.46 | . | . |
| 2.1.2 | HT=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.3 | HT=ST×DC | *3.14* | 2.02 | 1.34 | -0.26 | -0.16 | 0.79 | 1912.31 | ○ | ◒ | ○ | ● | ● | 0.35 | 0.52 | 0.28 |
| 2.1.4 | HT=ST×MR1 | *4.48* | 1.36 | 0.99 | -1.38 | -0.37 | 0.79 | 1909.88 | ○ | ◒ | ○ | ● | ● | 0.44 | 0.24 | 0.32 |
| 2.1.5 | HT=ST×MR2 | *3.78* | 2.20 | 2.79 | -0.84 | -0.25 | 0.80 | 1911.82 | ○ | ◒ | ○ | ● | ● | 0.31 | 0.48 | 0.23 |
| 2.1.6 | HT=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.7 | HT=ST×NR2 | 1.23 | 3.02 | *4.39* | 2.42 | 0.42 | 0.80 | 1912.07 | ○ | ◒ | ○ | ● | ○ | 0.22 | 0.43 | 0.19 |
| 2.1.8 | HT=ST+PY | 240.30 | 0.45 | 0.23 | 0.16 | -0.12 | 0.79 | 1899.04 | ○ | ◒ | ○ | ● | ○ | 0.47 | 0.22 | . |
| 2.1.9 | HT=ST+DC | *3.45* | 0.40 | 0.12 | 0.41 | *-0.23* | 0.79 | 1896.26 | ○ | ◒ | ○ | ● | ● | 0.34 | 0.04 | . |
| 2.1.10 | HT=ST+MR1 | *4.29* | 0.43 | 0.10 | 0.55 | *-0.34* | 0.80 | 1893.60 | ○ | ◒ | ○ | ● | ● | 0.14 | <0.01 | . |
| 2.1.11 | HT=ST+MR2 | *4.03* | 0.39 | 0.07 | 0.49 | *-0.30* | 0.80 | 1896.41 | ○ | ◒ | ○ | ● | ○ | 0.22 | 0.04 | . |
| 2.1.12 | HT=ST+NR1 | *2.01* | 0.32 | 0.11 | 0.35 | 0.14 | 0.79 | 1900.40 | ○ | ◒ | ○ | ● | ○ | 0.58 | 0.60 | . |
| 2.1.13 | HT=ST+NR2 | *3.60* | 0.35 | 0.20 | 0.60 | -0.40 | 0.80 | 1897.01 | ○ | ◒ | ○ | ● | ○ | 0.23 | 0.06 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; HT = height; "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

Table A-1-2. Preliminary ANOVA and ANCOVA summary statistics for ln(white spruce height). All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | **Parameters** | | | | | | | | | | | | **F-Test p-values** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.1.14 | ln(HT)=ST | *0.84* | 0.12 | 0.04 | 0.16 | . | 0.30 | 435.32 | ◒ | ◒ | ○ | ● | ● | 0.36 | . | . |
| 2.1.15 | ln(HT)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.16 | ln(HT)=ST×DC | *1.23* | 0.48 | 0.34 | -0.19 | -0.09 | 0.30 | 453.96 | ◒ | ◒ | ○ | ● | ● | 0.49 | 0.32 | 0.36 |
| 2.1.17 | ln(HT)=ST×MR1 | *1.84* | 0.08 | 0.07 | -0.71 | -0.18 | 0.30 | 451.08 | ◒ | ◒ | ○ | ● | ● | 0.54 | 0.10 | 0.37 |
| 2.1.18 | ln(HT)=ST×MR2 | *1.59* | 0.29 | 0.74 | -0.50 | -0.14 | 0.30 | 453.87 | ◒ | ◒ | ○ | ● | ● | 0.47 | 0.27 | 0.34 |
| 2.1.19 | ln(HT)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.20 | ln(HT)=ST×NR2 | 0.29 | 1.07 | *1.71* | 1.02 | 0.19 | 0.30 | 453.30 | ◒ | ◒ | ○ | ● | ● | 0.17 | 0.31 | 0.14 |
| 2.1.21 | ln(HT)=ST+PY | 68.13 | 0.15 | 0.08 | 0.09 | -0.03 | 0.30 | 440.83 | ◒ | ◒ | ○ | ● | ● | 0.48 | 0.31 | . |
| 2.1.22 | ln(HT)=ST+DC | *1.21* | 0.14 | 0.05 | 0.16 | *-0.09* | 0.30 | 437.23 | ◒ | ◒ | ○ | ● | ● | 0.25 | 0.03 | . |
| 2.1.23 | ln(HT)=ST+MR1 | *1.51* | 0.15 | 0.04 | *0.21* | *-0.12* | 0.30 | 434.45 | ◒ | ◒ | ○ | ● | ● | 0.09 | <0.01 | . |
| 2.1.24 | ln(HT)=ST+MR2 | *1.41* | 0.13 | 0.03 | 0.19 | *-0.11* | 0.30 | 437.47 | ◒ | ◒ | ○ | ● | ● | 0.15 | 0.03 | . |
| 2.1.25 | ln(HT)=ST+NR1 | *0.67* | 0.11 | 0.04 | 0.14 | 0.06 | 0.30 | 441.62 | ◒ | ◒ | ○ | ● | ○ | 0.50 | 0.56 | . |
| 2.1.26 | ln(HT)=ST+NR2 | *1.21* | 0.12 | 0.07 | *0.22* | -0.13 | 0.30 | 438.95 | ◒ | ◒ | ○ | ● | ○ | 0.18 | 0.09 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; ln(HT) = natural logarithm of height; "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

Table A-1-3. Preliminary ANOVA and ANCOVA summary statistics for sqrt(white spruce height). All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | **Parameters** | | | | | | | | | | | | **F-Test p-values** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.1.27 | sqrt(HT)=ST | *1.54* | 0.10 | 0.03 | 0.12 | . | 0.24 | 116.76 | ◒ | ◒ | ● | ● | ○ | 0.41 | . | . |
| 2.1.28 | sqrt(HT)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.29 | sqrt(HT)=ST×DC | *1.80* | 0.50 | 0.34 | -0.12 | -0.06 | 0.24 | 135.20 | ◒ | ◒ | ● | ● | ● | 0.42 | 0.41 | 0.32 |
| 2.1.30 | sqrt(HT)=ST×MR1 | 2.25 | 0.24 | 0.18 | -0.50 | -0.13 | 0.24 | 132.55 | ◒ | ◒ | ● | ● | ● | 0.49 | 0.16 | 0.35 |
| 2.1.31 | sqrt(HT)=ST×MR2 | 2.05 | 0.45 | 0.72 | -0.33 | -0.09 | 0.24 | 134.99 | ◒ | ◒ | ● | ● | ● | 0.40 | 0.36 | 0.29 |
| 2.1.32 | sqrt(HT)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.1.33 | sqrt(HT)=ST×NR2 | *1.14* | 0.88 | *1.35* | 0.77 | 0.14 | 0.24 | 134.74 | ◒ | ◒ | ● | ● | ● | 0.19 | 0.37 | 0.16 |
| 2.1.34 | sqrt(HT)=ST+PY | 64.41 | 0.13 | 0.07 | 0.06 | -0.03 | 0.24 | 122.01 | ◒ | ◒ | ● | ● | ○ | 0.48 | 0.26 | . |
| 2.1.35 | sqrt(HT)=ST+DC | *1.84* | 0.12 | 0.04 | 0.13 | *-0.07* | 0.24 | 118.80 | ◒ | ◒ | ● | ● | ● | 0.30 | 0.03 | . |
| 2.1.36 | sqrt(HT)=ST+MR1 | *2.09* | 0.12 | 0.03 | *0.17* | *-0.10* | 0.24 | 116.05 | ◒ | ◒ | ● | ● | ● | 0.11 | <0.01 | . |
| 2.1.37 | sqrt(HT)=ST+MR2 | *2.01* | 0.11 | 0.02 | 0.15 | *-0.09* | 0.24 | 119.00 | ◒ | ◒ | ● | ● | ● | 0.18 | 0.04 | . |
| 2.1.38 | sqrt(HT)=ST+NR1 | *1.41* | 0.09 | 0.03 | 0.11 | 0.04 | 0.24 | 123.07 | ◒ | ◒ | ● | ● | ○ | 0.54 | 0.58 | . |
| 2.1.39 | sqrt(HT)=ST+NR2 | *1.87* | 0.10 | 0.06 | 0.18 | -0.11 | 0.24 | 120.03 | ◒ | ◒ | ● | ● | ● | 0.21 | 0.07 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; sqrt(HT) = square root of height; "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

Table A-1-4. Preliminary ANOVA and ANCOVA summary statistics for white spruce DBH. All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | Parameters | | | | | | | | | | | | | F-Test p-values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.2.1 | DBH=ST | *1.67* | 0.84 | 0.41 | *1.10* | . | 1.22 | 2529.18 | ○ | ◒ | ○ | ● | ○ | 0.09 | . | . |
| 2.2.2 | DBH=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.3 | DBH=ST×DC | 2.50 | 3.41 | 2.86 | 0.76 | -0.19 | 1.22 | 2547.80 | ○ | ◒ | ○ | ● | ● | 0.43 | 0.63 | 0.37 |
| 2.2.4 | DBH=ST×MR1 | 4.32 | 1.72 | 3.02 | -1.26 | -0.48 | 1.22 | 2546.80 | ○ | ◒ | ○ | ● | ● | 0.50 | 0.33 | 0.34 |
| 2.2.5 | DBH=ST×MR2 | 2.95 | 2.60 | 6.39 | 0.12 | -0.24 | 1.22 | 2549.56 | ○ | ◒ | ○ | ● | ● | 0.43 | 0.68 | 0.33 |
| 2.2.6 | DBH=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.7 | DBH=ST×NR2 | -0.30 | 4.01 | *7.93* | 3.68 | 0.68 | 1.22 | 2546.98 | ○ | ◒ | ○ | ● | ● | 0.13 | 0.42 | 0.09 |
| 2.2.8 | DBH=ST+PY | 200.56 | *0.94* | 0.51 | 0.90 | -0.10 | 1.22 | 2535.28 | ○ | ◒ | ○ | ● | ○ | 0.14 | 0.49 | . |
| 2.2.9 | DBH=ST+DC | *3.34* | *0.95* | 0.43 | *1.11* | *-0.38* | 1.22 | 2531.02 | ○ | ◒ | ○ | ● | ● | 0.05 | 0.03 | . |
| 2.2.10 | DBH=ST+MR1 | *4.21* | *0.97* | 0.40 | *1.31* | *-0.46* | 1.22 | 2530.37 | ○ | ◒ | ○ | ● | ● | 0.02 | 0.02 | . |
| 2.2.11 | DBH=ST+MR2 | *3.61* | *0.91* | 0.37 | *1.22* | -0.36 | 1.22 | 2533.19 | ○ | ◒ | ○ | ● | ● | 0.05 | 0.11 | . |
| 2.2.12 | DBH=ST+NR1 | 0.10 | 0.81 | 0.41 | 0.94 | 0.52 | 1.22 | 2534.35 | ○ | ◒ | ○ | ● | ○ | 0.20 | 0.22 | . |
| 2.2.13 | DBH=ST+NR2 | *3.11* | 0.87 | 0.53 | *1.36* | -0.50 | 1.22 | 2533.52 | ○ | ◒ | ○ | ● | ○ | 0.05 | 0.13 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; DBH = diameter at breast height (1.3m); "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer sol nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

Table A-1-5. Preliminary ANOVA and ANCOVA summary statistics for ln(white spruce DBH+1). All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | **Parameters** | | | | | | | | | | | | **F-Test p-values** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.2.14 | ln(DBH)=ST | *0.89* | 0.26 | 0.14 | *0.36* | . | 0.37 | 774.64 | ◒ | ◒ | ○ | ● | ● | 0.06 | . | . |
| 2.2.15 | ln(DBH)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.16 | ln(DBH)=ST×DC | *1.35* | 0.59 | 0.65 | 0.07 | -0.10 | 0.37 | 793.86 | ◒ | ◒ | ○ | ● | ● | 0.64 | 0.37 | 0.50 |
| 2.2.17 | ln(DBH)=ST×MR1 | *2.17* | -0.18 | 0.38 | -0.74 | -0.23 | 0.37 | 792.06 | ◒ | ◒ | ○ | ● | ● | 0.62 | 0.11 | 0.36 |
| 2.2.18 | ln(DBH)=ST×MR2 | 1.69 | 0.13 | 1.43 | -0.25 | -0.15 | 0.37 | 795.37 | ◒ | ◒ | ○ | ● | ● | 0.57 | 0.38 | 0.42 |
| 2.2.19 | ln(DBH)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.20 | ln(DBH)=ST×NR2 | 0.14 | 1.20 | *2.38* | 1.35 | 0.26 | 0.37 | 793.25 | ◒ | ◒ | ○ | ● | ● | 0.13 | 0.29 | 0.10 |
| 2.2.21 | ln(DBH)=ST+PY | 41.48 | 0.28 | 0.16 | 0.32 | -0.02 | 0.37 | 781.01 | ◒ | ◒ | ○ | ● | ● | 0.12 | 0.64 | . |
| 2.2.22 | ln(DBH)=ST+DC | *1.39* | *0.29* | 0.14 | *0.37* | *-0.11* | 0.37 | 776.22 | ◒ | ◒ | ○ | ● | ● | 0.03 | 0.03 | . |
| 2.2.23 | ln(DBH)=ST+MR1 | *1.67* | *0.29* | 0.13 | *0.43* | *-0.14* | 0.37 | 775.26 | ◒ | ◒ | ○ | ● | ● | 0.02 | 0.01 | . |
| 2.2.24 | ln(DBH)=ST+MR2 | *1.50* | *0.28* | 0.12 | *0.40* | -0.11 | 0.37 | 778.33 | ◒ | ◒ | ○ | ● | ● | 0.03 | 0.09 | . |
| 2.2.25 | ln(DBH)=ST+NR1 | 0.50 | 0.25 | 0.14 | *0.32* | 0.13 | 0.37 | 780.14 | ◒ | ◒ | ○ | ● | ● | 0.14 | 0.29 | . |
| 2.2.26 | ln(DBH)=ST+NR2 | *1.26* | 0.26 | 0.17 | *0.43* | -0.12 | 0.37 | 779.61 | ◒ | ◒ | ○ | ● | ● | 0.04 | 0.20 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; ln(DBH+1) = natural logaritm of diameter at breast height (1.3m); "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

Table A-1-6. Preliminary ANOVA and ANCOVA summary statistics for sqrt(white spruce DBH+1). All models were fit using stand-level random-effects, plot-level random-effects, and ML estimation. Italic text indicates significant parameters (p-values ≤ 0.05). Gray cells indicate p-values ≤ 0.05.

| | | Parameters | | | | | | | | | | | | F-Test p-values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model** | **Variables** | **INT** | **DT-T** | **DT-U** | **VP-U** | **COV** | **ε SE** | **BIC** | **H** | **VE** | **N** | **NB1** | **NP1** | **ST** | **COV** | **ST×COV** |
| 2.2.27 | sqrt(DBH)=ST | *1.60* | 0.23 | 0.12 | *0.31* | . | 0.33 | 587.81 | ◒ | ◒ | ● | ● | ● | 0.07 | . | . |
| 2.2.28 | sqrt(DBH)=ST×PY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.29 | sqrt(DBH)=ST×DC | *1.91* | 0.73 | 0.68 | 0.14 | -0.07 | 0.33 | 606.72 | ◒ | ◒ | ● | ● | ● | 0.53 | 0.50 | 0.44 |
| 2.2.30 | sqrt(DBH)=ST×SMR1 | 2.51 | 0.17 | 0.59 | -0.48 | -0.17 | 0.33 | 605.37 | ◒ | ◒ | ● | ● | ● | 0.58 | 0.21 | 0.37 |
| 2.2.31 | sqrt(DBH)=ST×SMR2 | 2.12 | 0.42 | 1.51 | -0.08 | -0.10 | 0.33 | 608.40 | ◒ | ◒ | ● | ● | ● | 0.51 | 0.52 | 0.38 |
| 2.2.32 | sqrt(DBH)=ST×NR1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2.2.33 | sqrt(DBH)=ST×NR2 | 1.01 | 1.07 | *2.13* | 1.09 | 0.20 | 0.33 | 605.99 | ◒ | ◒ | ● | ● | ● | 0.13 | 0.36 | 0.10 |
| 2.2.34 | sqrt(DBH)=ST+PY | 46.05 | 0.25 | 0.14 | 0.26 | -0.02 | 0.33 | 594.07 | ◒ | ◒ | ● | ● | ● | 0.13 | 0.57 | . |
| 2.2.35 | sqrt(DBH)=ST+DC | *2.05* | *0.26* | 0.12 | *0.31* | *-0.10* | 0.33 | 589.47 | ◒ | ◒ | ● | ● | ● | 0.04 | 0.03 | . |
| 2.2.36 | sqrt(DBH)=ST+SMR1 | *2.29* | *0.26* | 0.11 | *0.37* | *-0.13* | 0.33 | 588.66 | ◒ | ◒ | ● | ● | ● | 0.02 | 0.02 | . |
| 2.2.37 | sqrt(DBH)=ST+SMR2 | *2.13* | *0.24* | 0.10 | *0.34* | -0.10 | 0.33 | 591.63 | ◒ | ◒ | ● | ● | ● | 0.04 | 0.10 | . |
| 2.2.38 | sqrt(DBH)=ST+NR1 | *1.21* | 0.22 | 0.12 | *0.27* | 0.13 | 0.33 | 593.14 | ◒ | ◒ | ● | ● | ● | 0.17 | 0.25 | . |
| 2.2.39 | sqrt(DBH)=ST+NR2 | *1.96* | 0.23 | 0.15 | *0.37* | -0.12 | 0.33 | 592.44 | ◒ | ◒ | ● | ● | ● | 0.05 | 0.16 | . |

**Note:** INT = model intercept (i.e. Bracke mounding/untended); DT-T = disc trenching/tended; DT-U = disc trenching/untended; VP-U = v-plow/untended; COV = Covariate; ε SE = residual standard error; BIC = Bayesian Information Criterion; H = homoscedastic residuals; VE = variance equality between treatments; N = normal residuals; NB1 = normal stand-level random-effects; NP1 = normal plot-level random-effects; ST = silvicultural treatment; ST×COV = silvicultural treatment / covariate interaction; sqrt(DBH+1) = square root of diameter at breast height (1.3m); "." = not applicable; "-" = model failed to converge; PY = planting year; DC = drainage class; MR1 = integer soil moisture regime; MR2 = rational soil moisture regime; NR1 = integer soil nutrient regime; NR2 = rational soil nutrient regime; "●" = yes; "○" = no; "◒" = partial.

## Appendix 2. Mixed-Effects Assignment for Height-Estimation Models

Table A-2-1. Summary statistics for the preliminary white spruce height-root collar models.

| Model | SPP | Mixed Effects | $\beta_0$ | $\beta_1$ | $b_0$ SD | $b_1$ SD | RMSE | BIC | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 3.1.A | WS | $\beta_0/\beta_1$ | 0.1596 | 0.0482 | 0.0886 | 0.0087 | 0.21 | -49.5 | Random effects $b_0$ and $b_1$ are moderately correlated (r = 0.54). Variance weighted as an optimized power of the predicted height (δ = 0.64). |
| 3.1.B | WS | $\beta_1$ | 0.1715 | 0.0477 | 0.1324 | . | 0.24 | -33.3 | Variance weighted as an optimized power of the predicted height (δ = 0.73). |
| 3.1.C | WS | None | 0.1352 | 0.0494 | . | . | 0.30 | 21.2 | Variance weighted as an optimized power of the predicted height (δ = 0.76). |

**Note:** SPP = species; WS = white spruce; $\beta_0/\beta_1$ = linear parameters (Eq. 3-3); $b_0/b_1$ = random-effects (Eq. 3-3); SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; δ = optimized variance parameter (Eq. 3-5); "." = Not Applicable.

Table A-2-2. Summary statistics for the preliminary balsam poplar and black spruce height-diameter models.

| Model | Species | Mixed Effects | $\beta_0$ | $\beta_1$ | $\beta_2$ | $b_0$ SD | $b_1$ SD | $b_2$ SD | RMSE | BIC | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.2.A | BP | $\beta_0/\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.2.B | BP | $\beta_0/\beta_1$ | 11.1234 | 0.0286 | 1.9774 | 3.3834 | 0.0056 | . | 0.77 | 101.3 | Random effects $b_0$ and $b_1$ are correlated. (r = -1) |
| 3.2.C | BP | $\beta_0/\beta_2$ | 10.8157 | 0.0257 | 1.8161 | 2.9298 | . | 0.5607 | 0.63 | 92.4 | Random effects $b_0$ and $b_2$ are correlated. (r = 1) |
| 3.2.D | BP | $\beta_1/\beta_2$ | 16.5999 | 0.0092 | 1.1339 | . | 0.0063 | 0.4999 | 0.71 | 98.2 | Random effects $b_1$ and $b_2$ are correlated. (r = 1) |
| 3.2.E | BP | $\beta_0$ | 12.8345 | 0.0173 | 1.4865 | 2.3354 | . | . | 0.68 | 100.7 | Skewed residual distribution. |
| 3.2.F | BP | $\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.2.G | BP | $\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.2.H | BP | None | 18.3830 | 0.0071 | 0.9891 | . | . | . | 1.82 | 102.4 | Variance weighted as a power of DBH ($\delta$ = 0.81). $\beta_1$ is not significantly different from zero (p-value = 0.15). |
| 3.3.A | BS | $\beta_0/\beta_1/\beta_2$ | 6.5936 | 0.0273 | 1.7506 | 7.04E-09 | 5.90E-14 | 0.0010 | 0.78 | 78.0 | Parameter $\beta_1$ is not significantly different from zero (p-value = 0.07). All random effects are correlated. |
| 3.3.B | BS | $\beta_0/\beta_1$ | 6.4319 | 0.0354 | 2.1586 | 0.9375 | 3.95E-11 | . | 0.43 | 60.1 | Random effects $b_0$ and $b_1$ are correlated. |
| 3.3.C | BS | $\beta_0/\beta_2$ | 6.4315 | 0.0354 | 2.1590 | 0.9375 | . | 6.33E-06 | 0.43 | 60.1 | Random effects $b_0/b_2$ are correlated. |
| 3.3.D | BS | $\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.3.E | BS | $\beta_0$ | 6.4317 | 0.0354 | 2.1591 | 0.9375 | . | . | 0.41 | 53.7 | |
| 3.3.F | BS | $\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.3.G | BS | $\beta_2$ | 6.5903 | 0.0274 | 1.7540 | . | . | 1.37E-05 | 0.68 | 61.9 | Parameter $\beta_1$ is not significantly different from zero. |
| 3.3.H | BS | None | 7.5132 | 0.0194 | 1.4109 | . | . | . | 0.68 | 45.9 | Variance weighted as a power of DBH ($\delta$ = 0.93). |

**Note:** BP = balsam poplar; BS = black spruce; $\beta_0/\beta_1/\beta_2$ = Chapman-Richards parameters (Eq. 3-4); $b_0/b_1/b_2$ = random-effects (Eq. 3-4); SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; $\delta$ = optimized variance parameter (Eq. 3-5); "." = Not Applicable.

Table A-2-3. Summary statistics for the preliminary jack pine and trembling aspen height-diameter models.

| Model | Species | Mixed Effects | $\beta_0$ | $\beta_1$ | $\beta_2$ | $b_0$ SD | $b_1$ SD | $b_2$ SD | RMSE | BIC | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.4.A | JP | $\beta_0/\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.4.B | JP | $\beta_0/\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.4.C | JP | $\beta_0/\beta_2$ | 8.8706 | 0.0341 | 1.6166 | 1.45E-10 | . | 0.0038 | 1.10 | 158.9 | Random effects $b_0$ and $b_2$ are correlated. |
| 3.4.D | JP | $\beta_1/\beta_2$ | 9.0599 | 0.0331 | 1.5753 | . | 0.0089 | 7.76E-05 | 0.64 | 133.1 | Random effects $b_1$ and $b_2$ are correlated. |
| 3.4.E | JP | $\beta_0$ | 8.7149 | 0.0378 | 1.7135 | 0.7631 | . | . | 0.81 | 144.4 | |
| 3.4.F | JP | $\beta_1$ | 9.0601 | 0.0331 | 1.5751 | . | 0.0089 | . | 0.62 | 125.4 | |
| 3.4.G | JP | $\beta_2$ | 8.8706 | 0.0341 | 1.6166 | . | . | 0.0038 | 0.81 | 151.2 | |
| 3.4.H | JP | None | 8.8703 | 0.0341 | 1.6174 | . | . | . | 1.06 | 147.4 | |
| 3.5.A | TA | $\beta_0/\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.5.B | TA | $\beta_0/\beta_1$ | 13.1139 | 0.0199 | 1.2763 | 2.5460 | 0.0018 | . | 0.77 | 290.6 | Random effects $b_0$ and $b_1$ are correlated. (r = -0.995) |
| 3.5.C | TA | $\beta_0/\beta_2$ | 13.4046 | 0.0178 | 1.1874 | 2.3583 | . | 0.0923 | 0.76 | 288.2 | Random effects $b_0$ and $b_2$ are correlated. (r = 0.999) |
| 3.5.D | TA | $\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.5.E | TA | $\beta_0$ | 13.9761 | 0.0151 | 1.0760 | 2.1920 | . | . | 0.76 | 280.2 | |
| 3.5.F | TA | $\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.5.G | TA | $\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.5.H | TA | None | 17.9116 | 0.0083 | 0.9108 | . | . | . | 1.80 | 337.8 | Variance weighted as a power of DBH ($\delta$ = 0.70). |

**Note:** JP = jack pine; TA = trembling aspen; $\beta_0/\beta_1/\beta_2$ = Chapman-Richards parameters (Eq. 3-4); $b_0/b_1/b_2$ = random-effects (Eq. 3-4); SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; $\delta$ = optimized variance parameter (Eq. 3-5); "." = Not Applicable.

Table A-2-4. Summary statistics for the preliminary white birch and white spruce height-diameter models.

| Model | Species | Mixed Effects | $\beta_0$ | $\beta_1$ | $\beta_2$ | $b_0$ SD | $b_1$ SD | $b_2$ SD | RMSE | BIC | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.6.A | WB | $\beta_0/\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.6.B | WB | $\beta_0/\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.6.C | WB | $\beta_0/\beta_2$ | 10.5075 | 0.0226 | 1.0892 | 1.1517 | . | 3.50E-05 | 0.72 | 185.6 | Random effects $b_0$ and $b_2$ appear strongly correlated. |
| 3.6.D | WB | $\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.6.E | WB | $\beta_0$ | 10.5032 | 0.0226 | 1.0901 | 1.1519 | . | . | 0.71 | 177.4 | |
| 3.6.F | WB | $\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.6.G | WB | $\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.6.H | WB | None | 11.6909 | 0.0153 | 0.8992 | . | . | . | 1.07 | 193.2 | |
| 3.7.A | WS | $\beta_0/\beta_1/\beta_2$ | 13.5140 | 0.0086 | 1.1634 | 6.40E-07 | 4.35E-08 | 8.20E-09 | 1.02 | 545.9 | Random effects $b_0$ and $b_2$ are correlated. |
| 3.7.B | WS | $\beta_0/\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.7.C | WS | $\beta_0/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.7.D | WS | $\beta_1/\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.7.E | WS | $\beta_0$ | 13.2890 | 0.0100 | 1.2937 | 1.7291 | . | . | 0.55 | 371.1 | |
| 3.7.F | WS | $\beta_1$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.7.G | WS | $\beta_2$ | . | . | . | . | . | . | . | . | Model failed to converge. |
| 3.7.H | WS | None | 11.1142 | 0.0131 | 1.3798 | . | . | . | 1.01 | 371.9 | Variance weighted as a power of DBH ($\delta$ = 0.80). |

**Note:** WB = white birch; WS = white spruce; $\beta_0/\beta_1/\beta_2$ = Chapman-Richards parameters (Eq. 3-4); $b_0/b_1/b_2$ = random-effects (Eq. 3-4); SD = standard deviation; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion; $\delta$ = optimized variance parameter (Eq. 3-5); "." = Not Applicable.

## Appendix 3. Covariate Inclusion for Height-Estimation Models

Table A-3-1. First round of covariate inclusion for the white spruce height-root collar relationship. BIC = Bayesian Information Criterion; $b_0/b_2$ = random-effects; SD = standard deviation; ε = residual; SE = standard error; LME = linear mixed-effects model; Ht = total height; i = plot; j = tree; $\beta_0/\beta_1/\beta_2/\beta_3$ = linear parameters; RCD = root collar diameter; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Bracke mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E/H= Beckingham et al. (1996) ecosites; DBA = deciduous basal area; GVC = grass visual cover (%).

| Model | BIC | $b_0$ SD | $b_1$ SD | ε SE | Comment |
|---|---|---|---|---|---|
| **3.1.1. LME** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\varepsilon_{ij}$ | 13.6 | 0.1219 | 0.0092 | 0.21 | Model 3.1.A without variance weighting. |
| **3.1.2. LME – BAL** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2BAL_{ij}+\varepsilon_{ij}$ | 18.5 | 0.1103 | 0.0093 | 0.21 | BAL coefficient ($\beta_2$) is not significantly different from zero (p-value = 0.30). |
| **3.1.3. LME – CBAL** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2CBAL_{ij}+\varepsilon_{ij}$ | 18.7 | 0.1171 | 0.0091 | 0.21 | CBAL coefficient ($\beta_2$) is not significantly different from zero (p-value = 0.48). |
| **3.1.4. LME – DBAL** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2DBAL_{ij}+\varepsilon_{ij}$ | 19.1 | 0.1191 | 0.0093 | 0.21 | DBAL coefficient ($\beta_2$) is not significantly different from zero (p-value = 0.68). |
| **3.1.5. LME – MSP** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2DT_i+\beta_3VP_i+\varepsilon_{ij}$ | 23.7 | 0.0822 | 0.0095 | 0.21 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_2$ and $\beta_3$) are not significantly different from zero (p-values = 0.22 and 0.31). |
| **3.1.6. LME – THIN** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2TP_i+\varepsilon_{ij}$ | 16.2 | 0.1098 | 0.0093 | 0.21 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_2$) is not significantly different from zero (p-value = 0.09). |
| **3.1.7. LME –Ecosite** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2D_i+\beta_3E_i+\beta_4H_i+\varepsilon_{ij}$ | 29.8 | 0.1151 | 0.0091 | 0.21 | B, D, E, and H are indicator variables. B is the control variable (0). D, E, and H coefficients ($\beta_2$, $\beta_3$ and $\beta_4$) are not significantly different from zero (p-values = 0.82, 0.50, and 0.72). |
| **3.1.8. LME – DBA** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2DBA_i+\varepsilon_{ij}$ | 17.2 | 0.1268 | 0.0085 | 0.21 | DBA had the strongest positive correlation with the random effect ($b_1$) in Model 3.1.1 (r = 0.64). DBA coefficient ($\beta_2$) is not significantly different from zero (p-value = 0.11). |
| **3.1.9. LME – GVC** $Ht_{ij}=\beta_0+b_{0i}+(\beta_1+b_{1i})RCD_{ij}+\beta_2GVC_i+\varepsilon_{ij}$ | . | . | . | . | Model failed to converge. GVC had the strongest negative correlation with the random effect ($b_1$) in Model 3.1.1 (r = -0.64). |

Table A-3-2. First round of covariate inclusion for the balsam poplar height-diameter relationship. All balsam poplar MS-PSP's were thinned, and no thinning covariate was tested. BIC = Bayesian Information Criterion; $b_0$/$b_2$ = random-effects; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$/$\beta_2$ = Chapman-Richards parameters; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; DT = disc trenching; VP = v-plow scarification; D/E/H = Beckingham et al. (1996) ecosites; DBA = deciduous basal area.

| Model | BIC | $b_0$ SD | $b_2$ SD | ε SE | Comment |
|---|---|---|---|---|---|
| **3.2.1. NLME**<br>$\beta_0=\beta_{00}+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | 92.4 | 2.92 | 0.56 | 0.60 | Equivalent to Preliminary Model 3.2.C. |
| **3.2.2. NLME – BAL**<br>$\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | 95.6 | 2.85 | 0.52 | 0.60 | BAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.78). |
| **3.2.3. NLME – CBAL**<br>$\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | . | . | . | . | Model failed to converge. |
| **3.2.4. NLME – DBAL**<br>$\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$<br>$\beta_2 = \beta_{20}+b_{2i}$ | 92.8 | 2.02 | 0.38 | 0.61 | DBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.06). |
| **3.2.5. NLME – MSP**<br>$\beta_0=\beta_{00}+\beta_{01}DT_i+\beta_{02}VP_i+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | . | . | . | . | Model failed to converge. |
| **3.2.6. NLME – Ecosite**<br>$\beta_0=\beta_{00}+\beta_{01}E_i+\beta_{02}H_i+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | 94.8 | 1.91 | 0.49 | 0.59 | D, E, and H are indicator variables. D is the control variable (0). E coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.16). |
| **3.2.7. NLME – DBA**<br>$\beta_0=\beta_{00}+\beta_{01}DBA_i+b_{0i}$<br>$\beta_2=\beta_{20}+b_{2i}$ | 89.0 | 1.33 | 0.45 | 0.59 | DBA had the strongest correlation with the random effect ($b_0$) in Model 3.2.1 (r = 0.96). |

Table A-3-3. Second round of covariate inclusion for the balsam poplar height-diameter relationship. All balsam poplar MS-PSP's were thinned, and no thinning covariate was tested. BIC = Bayesian Information Criterion; $b_0$/$b_2$ = random-effects; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$/$\beta_2$ = Chapman-Richards parameters; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; DT = disc trenching; VP = v-plow scarification; D/E/H = Beckingham et al. (1996) ecosites; DBA = deciduous basal area.

| Model | BIC | $b_0$ SD | $b_2$ SD | ε SE | Comment |
|---|---|---|---|---|---|
| **3.2.8. NLME – BAL**<br>$\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}BAL_{ij}+b_{2i}$ | 98.6 | 2.92 | 0.74 | 0.58 | BAL coefficients ($\beta_{01}$ and $\beta_{21}$) are not significantly different from zero (p-value = 0.71 and 0.29). |
| **3.2.9. NLME – CBAL**<br>$\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}CBAL_{ij}+b_{2i}$ | 95.0 | 2.78 | 1.12 | 0.53 | |
| **3.2.10. NLME – DBAL**<br>$\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}DBAL_{ij}+b_{2i}$ | 95.6 | 1.69 | 0.27 | 0.63 | DBAL coefficient ($\beta_{21}$) is not significantly different from zero (p-value = 0.53). |
| **3.2.11. NLME – MSP**<br>$\beta_0=\beta_{00}+\beta_{01}DT_i+\beta_{02}VP_i+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}DT_i+\beta_{22}VP_i+b_{2i}$ | . | . | . | . | Model failed to converge. |
| **3.2.12. NLME – Ecosite**<br>$\beta_0=\beta_{00}+\beta_{01}E_i+\beta_{02}H_i+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}E_i+\beta_{22}H_i+b_{2i}$ | 99.4 | 1.47 | 0.32 | 0.59 | D, E, and H are indicator variables. D is the control variable (0). E coefficient ($\beta_{21}$) and H coefficient ($\beta_{22}$) are not significantly different from zero (p-value = 0.18 and 0.31). |
| **3.2.13. NLME – DBA**<br>$\beta_0=\beta_{00}+\beta_{01}DBA_i+b_{0i}$<br>$\beta_2=\beta_{20}+\beta_{21}DBA_i+b_{2i}$ | 87.6 | 0.85 | 0.24 | 0.58 | DBA had the strongest correlation with the random effects ($b_0$ and $b_2$) in Model 3.2.1 (r = 0.96). |

Table A-3-4. First round of covariate inclusion for the black spruce height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E = Beckingham et al. (1996) ecosites; THT = black spruce top height.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.3.1. NLME**<br>$\beta_0=\beta_{00}+b_{0i}$ | 53.7 | 0.94 | 0.40 | Equivalent to Preliminary Model 3.3.E. |
| **3.3.2. NLME – BAL**<br>$\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$ | 52.7 | 0.65 | 0.41 | BAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.10). |
| **3.3.3. NLME – CBAL**<br>$\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$ | 56.9 | 0.93 | 0.40 | CBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.67). |
| **3.3.4. NLME – DBAL**<br>$\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$ | 54.5 | 0.75 | 0.40 | DBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.15). |
| **3.3.5. NLME – MSP**<br>$\beta_0=\beta_{00}+\beta_{01}DT_i+\beta_{02}VP_i+b_{0i}$ | 56.4 | 0.61 | 0.41 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.06 and 0.32). |
| **3.3.6. NLME – THIN**<br>$\beta_0=\beta_{00}+\beta_{01}TP_i+b_{0i}$ | 55.8 | 0.87 | 0.40 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.33). |
| **3.3.7. NLME – Ecosite**<br>$\beta_0=\beta_{00}+\beta_{01}D_i+\beta_{02}E_i+b_{0i}$ | 58.4 | 0.76 | 0.41 | B, D, and E are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.45 and 0.79). |
| **3.3.8. NLME – THT**<br>$\beta_0=\beta_{00}+\beta_{01}THT_i+b_{0i}$ | 50.1 | 0.32 | 0.41 | THT had the strongest correlation with the random effect ($b_0$) in Model 3.3.1 (r = 0.75). |

Table A-3-5. Second round of covariate inclusion for the black spruce height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; THT = black spruce top height; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E = Beckingham et al. (1996) ecosites; TBA = total basal area.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.3.9. NLME – THT+BAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}BAL_{ij}+b_{0i}$ | 45.9 | 7.40E-6 | 0.39 | |
| **3.3.10. NLME – THT+CBAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}CBAL_{ij}+b_{0i}$ | 52.8 | 0.41 | 0.41 | CBAL coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.52). |
| **3.3.11. NLME – THT+DBAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}DBAL_{ij}+b_{0i}$ | 52.4 | 2.64E-5 | 0.44 | DBAL coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.15). |
| **3.3.12. NLME – THT+MSP** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}DT_i+\beta_{03}VP_i+b_{0i}$ | 50.9 | 8.03E-6 | 0.40 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{02}$ and $\beta_{03}$) are not significantly different from zero (p-value = 0.63 and 0.35). |
| **3.3.13. NLME – THT+THIN** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TP_i+b_{0i}$ | 52.9 | 0.34 | 0.41 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.53). |
| **3.3.14. NLME – THT+Ecosite** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}D_i+\beta_{03}E_i+b_{0i}$ | 51.2 | 7.76E-6 | 0.40 | B, D, and E are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{02}$ and $\beta_{03}$) are not significantly different from zero (p-value = 0.83 and 0.07). |
| **3.3.15. NLME – THT + TBA** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TBA_i+b_{0i}$ | 48.0 | 8.46E-6 | 0.40 | TBA had the strongest correlation with the random effect ($b_0$) in Model 3.3.8 (r = 0.74). |

Table A-3-6. First round of covariate inclusion for the jack pine height-diameter relationship. BIC = Bayesian Information Criterion; $b_1$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_1$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; B/D = Beckingham et al. (1996) ecosites; CBA = conifer basal area.

| Model | BIC | $b_1$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.4.1. NLME** $\beta_1=\beta_{10}+b_{1i}$ | 125.4 | 8.90E-3 | 0.64 | Equivalent to Preliminary Model 3.4.F. |
| **3.4.2. NLME – BAL** $\beta_1=\beta_{10}+\beta_{11}BAL_{ij}+b_{1i}$ | . | . | . | Model failed to converge. |
| **3.4.3. NLME – CBAL** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+b_{1i}$ | 124.0 | 1.76E-7 | 0.73 | |
| **3.4.4. NLME – DBAL** $\beta_1=\beta_{10}+\beta_{11}DBAL_{ij}+b_{1i}$ | . | . | . | Model failed to converge. |
| **3.4.5. NLME – MSP** $\beta_1=\beta_{10}+\beta_{11}DT_i+\beta_{12}VP_i+b_{1i}$ | 129.5 | 7.83E-3 | 0.63 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{11}$ and $\beta_{12}$) are not significantly different from zero (p-value = 0.33 and 0.11). |
| **3.4.6. NLME – THIN** $\beta_1=\beta_{10}+\beta_{11}TP_i+b_{1i}$ | . | . | . | Model failed to converge. |
| **3.4.7. NLME – Ecosite** $\beta_1=\beta_{10}+\beta_{11}D_i+b_{1i}$ | 127.6 | 7.74E-3 | 0.64 | B and D are indicator variables. B is the control variable (0). D coefficient ($\beta_{11}$) is not significantly different from zero (p-value = 0.17). |
| **3.4.8. NLME – CBA** $\beta_1=\beta_{10}+\beta_{11}CBA_i+b_{1i}$ | 124.5 | 7.01E-3 | 0.64 | CBA had the strongest correlation with the random effect ($b_0$) in Model 3.4.1 (r = -0.59). CBA coefficient ($\beta_{11}$) is not significantly different from zero (p-value = 0.06). |

Table A-3-7. Second round of covariate inclusion for the jack pine height-diameter relationship. Since CBAL is a derivative of BAL, BAL was not considered. BIC = Bayesian Information Criterion; $b_1$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_1$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; B/D = Beckingham et al. (1996) ecosites; THTD = jack pine top height diameter.

| Model | BIC | $b_1$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.4.9. NLME – CBAL+DBAL** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}DBAL_{ij}+b_{1i}$ | 127.9 | 1.08E-7 | 0.73 | DBAL coefficient ($\beta_{12}$) is not significantly different from zero (p-value = 0.91). |
| **3.4.10. NLME – CBAL+MSP** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}DT_i+\beta_{13}VP_i+b_{1i}$ | 128.0 | 2.97E-7 | 0.70 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{12}$ and $\beta_{13}$) are not significantly different from zero (p-value = 0.15 and 0.11). |
| **3.4.11. NLME – CBAL+THIN** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}TP_i+b_{1i}$ | 127.7 | 1.88E-7 | 0.72 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{12}$) is not significantly different from zero (p-value = 0.73). |
| **3.4.12. NLME – CBAL+Ecosite** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}D_i+b_{1i}$ | 107.1 | 1.42E-3 | 0.55 | B and D are indicator variables. B is the control variable (0). |
| **3.4.13. NLME – CBAL+THTD** $\beta_1=\beta_{10}+\beta_{11}CBAL_{ij}+\beta_{12}THTD_i+b_{1i}$ | 112.5 | 8.43E-6 | 0.61 | THTD had the strongest correlation with the random effect ($b_0$) in Model 3.4.3 (r = -0.75). |

Table A-3-8. First round of covariate inclusion for the trembling aspen height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E/H = Beckingham et al. (1996) ecosites; THT = trembling aspen top height.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.5.1. NLME** $\beta_0=\beta_{00}+b_{0i}$ | 280.2 | 2.19 | 0.80 | Equivalent to Preliminary Model 3.5.E. |
| **3.5.2. NLME – BAL** $\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$ | 277.1 | 2.25 | 0.78 | BAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.15). |
| **3.5.3. NLME – CBAL** $\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$ | 284.2 | 2.21 | 0.80 | CBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.67). |
| **3.5.4. NLME – DBAL** $\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$ | 280.4 | 2.16 | 0.79 | DBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.22). |
| **3.5.5. NLME – MSP** $\beta_0=\beta_{00}+\beta_{01}DT_i+ \beta_{02}VP_i+b_{0i}$ | 288.2 | 2.12 | 0.80 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.77 and 0.49). |
| **3.5.6. NLME – THIN** $\beta_0=\beta_{00}+\beta_{01}TP_i+b_{0i}$ | 284.7 | 2.19 | 0.80 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.87). |
| **3.5.7. NLME – Ecosite** $\beta_0=\beta_{00}+\beta_{01}D_i+\beta_{02}E_i+\beta_{03}H_i+b_{0i}$ | 287.3 | 1.76 | 0.80 | B, D, E, and H are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.61 and 0.45). |
| **3.5.8. NLME – THT** $\beta_0=\beta_{00}+\beta_{01}THT_i+b_{0i}$ | 259.1 | 0.71 | 0.81 | THT had the strongest correlation with the random effect ($b_0$) in Model 3.5.1 (r = 0.90). |

Table A-3-9. Second round of covariate inclusion for the trembling aspen height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; THT = trembling aspen top height; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E/H = Beckingham et al. (1996) ecosites; TBA = total basal area.

| **Model** | **BIC** | **$b_0$ SD** | **ε SE** | **Comment** |
|---|---|---|---|---|
| **3.5.9. NLME – THT+BAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}BAL_{ij}+b_{0i}$ | 256.8 | 0.69 | 0.79 | BAL coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.07). |
| **3.5.10. NLME – THT+CBAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}CBAL_{ij}+b_{0i}$ | 257.4 | 0.54 | 0.81 | |
| **3.5.11. NLME – THT+DBAL** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}DBAL_{ij}+b_{0i}$ | 263.7 | 0.69 | 0.81 | DBAL coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.80). |
| **3.5.12. NLME – THT+MSP** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}DT_i+\beta_{03}VP_i+b_{0i}$ | 267.7 | 0.71 | 0.81 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{02}$ and $\beta_{03}$) are not significantly different from zero (p-value = 0.69 and 0.85). |
| **3.5.13. NLME – THT+THIN** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TP_i+b_{0i}$ | 263.1 | 0.69 | 0.81 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.50). |
| **3.5.14. NLME – THT+Ecosite** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}D_i+\beta_{03}E_i+\beta_{04}H_i+b_{0i}$ | 256.2 | 1.36E-4 | 0.81 | B, D, E, and H are indicator variables. B is the control variable (0). D coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.08). |
| **3.5.15. NLME – THT+TBA** $\beta_0=\beta_{00}+\beta_{01}THT_i+\beta_{02}TBA_i+b_{0i}$ | 247.9 | 1.14E-4 | 0.82 | TBA had the strongest correlation with the random effect ($b_0$) in Model 3.5.8 (r = 0.77). |

Table A-3-10. First round of covariate inclusion for the white birch height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E = Beckingham et al. (1996) ecosites; ln(DTPH) = natural logarithm of deciduous density.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.6.1. NLME** $\beta_0=\beta_{00}+b_{0i}$ | 177.4 | 1.15 | 0.74 | Equivalent to Preliminary Model 3.6.E. |
| **3.6.2. NLME – BAL** $\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$ | 182.5 | 1.15 | 0.73 | BAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.34). |
| **3.6.3. NLME – CBAL** $\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$ | 179.4 | 1.08 | 0.72 | CBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.09). |
| **3.6.4. NLME – DBAL** $\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$ | 179.9 | 1.11 | 0.74 | DBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.45). |
| **3.6.5. NLME – MSP** $\beta_0=\beta_{00}+\beta_{01}DT_i+\beta_{02}VP_i+b_{0i}$ | 181.5 | 0.97 | 0.74 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.38 and 0.06). |
| **3.6.6. NLME – THIN** $\beta_0=\beta_{00}+\beta_{01}TP_i+b_{0i}$ | 181.4 | 1.15 | 0.74 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.72). |
| **3.6.7. NLME – Ecosite** $\beta_0=\beta_{00}+\beta_{01}D_i+\beta_{02}E_i+b_{0i}$ | 181.6 | 1.01 | 0.73 | B, D, and E are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.09 and 0.23). |
| **3.6.8. NLME – ln(DTPH)** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+b_{0i}$ | 174.4 | 0.72 | 0.74 | ln(DTPH) had the strongest correlation with the random effect ($b_0$) in Model 3.6.1 (r = 0.46). Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.62). |

Table A-3-11. Second round of covariate inclusion for the white birch height-diameter relationship. No continuous plot-level covariates were strongly correlated ($r > 0.55$) with random effect $b_0$ in Model 3.6.8. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; $\varepsilon$ SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; ln(DTPH) = natural logarithm of deciduous density; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E = Beckingham et al. (1996) ecosites.

| Model | BIC | $b_0$ SD | $\varepsilon$ SE | Comment |
|---|---|---|---|---|
| **3.6.9. NLME – ln(DTPH)+BAL** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}BAL_{ij}+b_{0i}$ | 178.5 | 0.66 | 0.74 | The intercept and BAL coefficients ($\beta_{00}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.31 and 0.14). |
| **3.6.10. NLME – ln(DTPH) +CBAL** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}CBAL_{ij}+b_{0i}$ | 177.4 | 0.69 | 0.74 | The intercept and CBAL coefficients ($\beta_{00}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.68 and 0.22). |
| **3.6.11. NLME – ln(DTPH) +DBAL** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}DBAL_{ij}+b_{0i}$ | 178.3 | 0.72 | 0.75 | The intercept and DBAL coefficients ($\beta_{00}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.54 and 0.84). |
| **3.6.12. NLME – ln(DTPH) +MSP** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}DT_i+\beta_{03}VP_i+b_{0i}$ | 173.7 | 0.41 | 0.73 | BM, DT, and VP are indicator variables. BM is the control variable (0). Intercept coefficient ($\beta_{00}$) is not significantly different from zero (p-value = 0.12). |
| **3.6.13. NLME – ln(DTPH) +THIN** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}TP_i+b_{0i}$ | 178.3 | 0.72 | 0.75 | TA and TP are indicator variables. TA is the control variable (0). Intercept and TP coefficients ($\beta_{00}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.47 and 0.76). |
| **3.6.14. NLME – ln(DTPH) +Ecosite** $\beta_0=\beta_{00}+\beta_{01}ln(DTPH)_i+\beta_{02}D_i+\beta_{03}E_i+\beta_{04}H_i+b_{0i}$ | 178.3 | 0.60 | 0.74 | B, D, E, and H are indicator variables. B is the control variable (0). Intercept, D, and E coefficients ($\beta_{00}$, $\beta_{02}$, and $\beta_{03}$) are not significantly different from zero (p-value = 0.52, 0.06, and 0.56). |

Table A-3-12. First round of covariate inclusion for the white spruce height-diameter relationship. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E/H = Beckingham et al. (1996) ecosites; TBA = total basal area.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.7.1. NLME** $\beta_0=\beta_{00}+b_{0i}$ | 371.1 | 1.73 | 0.57 | Equivalent to Preliminary Model 3.7.E. |
| **3.7.2. NLME – BAL** $\beta_0=\beta_{00}+\beta_{01}BAL_{ij}+b_{0i}$ | 380.0 | 1.54 | 0.57 | |
| **3.7.3. NLME – CBAL** $\beta_0=\beta_{00}+\beta_{01}CBAL_{ij}+b_{0i}$ | 377.7 | 1.76 | 0.57 | CBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.12). |
| **3.7.4. NLME – DBAL** $\beta_0=\beta_{00}+\beta_{01}DBAL_{ij}+b_{0i}$ | 376.9 | 1.64 | 0.57 | DBAL coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.39). |
| **3.7.5. NLME – MSP** $\beta_0=\beta_{00}+\beta_{01}DT_i+\beta_{02}VP_i+b_{0i}$ | 377.7 | 1.47 | 0.57 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.30). |
| **3.7.6. NLME – THIN** $\beta_0=\beta_{00}+\beta_{01}TP_i+b_{0i}$ | 372.8 | 1.63 | 0.57 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{01}$) is not significantly different from zero (p-value = 0.08). |
| **3.7.7. NLME – Ecosite** $\beta_0=\beta_{00}+\beta_{01}D_i+\beta_{02}E_i+\beta_{03}H_i+b_{0i}$ | 368.9 | 1.00 | 0.57 | B, D, E, and H are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{01}$ and $\beta_{02}$) are not significantly different from zero (p-value = 0.31 and 0.56). |
| **3.7.8. NLME – TBA** $\beta_0=\beta_{00}+\beta_{01}TBA_i+b_{0i}$ | 359.9 | 1.01 | 0.57 | TBA had the strongest correlation with the random effect ($b_0$) in Model 3.7.1 (r = 0.75). |

Table A-3-13. Second round of covariate inclusion for the white spruce height-diameter relationship. No continuous plot-level covariates were strongly correlated (r >0.55) with the random effect ($b_0$) in Model 3.7.8. BIC = Bayesian Information Criterion; $b_0$ = random-effect; SD = standard deviation; ε SE = residual standard error; NLME = nonlinear mixed-effects model; $\beta_0$ = Chapman-Richards parameter; i = plot; j = tree; TBA = total basal area; BAL = basal area larger; CBAL = conifer basal area larger; DBAL = deciduous basal area larger; MSP = mechanical site preparation; BM = Brake mounding; DT = disc trenching; VP = v-plow scarification; TA = thinning absent; TP = thinning present; B/D/E/H = Beckingham et al. (1996) ecosites.

| Model | BIC | $b_0$ SD | ε SE | Comment |
|---|---|---|---|---|
| **3.7.9. NLME – TBA+BAL** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}BAL_{ij}+b_{0i}$ | 361.3 | 0.61 | 0.57 | |
| **3.7.10. NLME – TBA+CBAL** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}CBAL_{ij}+b_{0i}$ | 365.7 | 1.03 | 0.57 | CBAL coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.31). |
| **3.7.11. NLME – TBA+DBAL** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}DBAL_{ij}+b_{0i}$ | 363.1 | 0.84 | 0.57 | |
| **3.7.12. NLME – TBA+MSP** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}DT_i+\beta_{03}VP_i+\beta_{03}VP_i+b_{0i}$ | 368.3 | 0.90 | 0.57 | BM, DT, and VP are indicator variables. BM is the control variable (0). DT and VP coefficients ($\beta_{02}$ and $\beta_{03}$) are not significantly different from zero (p-value = 0.26 and 0.17). |
| **3.7.13. NLME – TBA+THIN** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}TP_i+b_{0i}$ | 364.3 | 1.01 | 0.57 | TA and TP are indicator variables. TA is the control variable (0). TP coefficient ($\beta_{02}$) is not significantly different from zero (p-value = 0.46). |
| **3.7.14. NLME – TBA+Ecosite** $\beta_0=\beta_{00}+\beta_{01}TBA_i+\beta_{02}D_i+\beta_{03}E_i+\beta_{04}H_i+b_{0i}$ | 365.9 | 0.66 | 0.57 | B, D, E, and H are indicator variables. B is the control variable (0). D and E coefficients ($\beta_{02}$ and $\beta_{03}$) are not significantly different from zero (p-value = 0.16 and 0.98). |

## Appendix 4. Alternative Fixed-Effects Height-Estimation Models

Table A-4-1. Summary statistics for the final white spruce height-root collar model (Equation 3-3) under a pure linear fixed-effects fit (Table 3-11: Model 3.1.11). Variance was weighted as an optimized power of the predicted height (Equation 3-5).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_0$ | 0.1352 | 0.0207 | 0.0945 | 0.1759 | <0.0001 |
| | $\beta_1$ | 0.0494 | 0.0013 | 0.0469 | 0.0520 | <0.0001 |
| **varPower** | $\delta$ | 0.7582 | | | | |
| **RMSE** | | 0.2994 | | | | |
| **BIC** | | 21.1541 | | | | |

**Note:** SE = standard error; CI = confidence interval; SD = standard deviation; varPower = variance weighing function (Eq. 3-5); RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

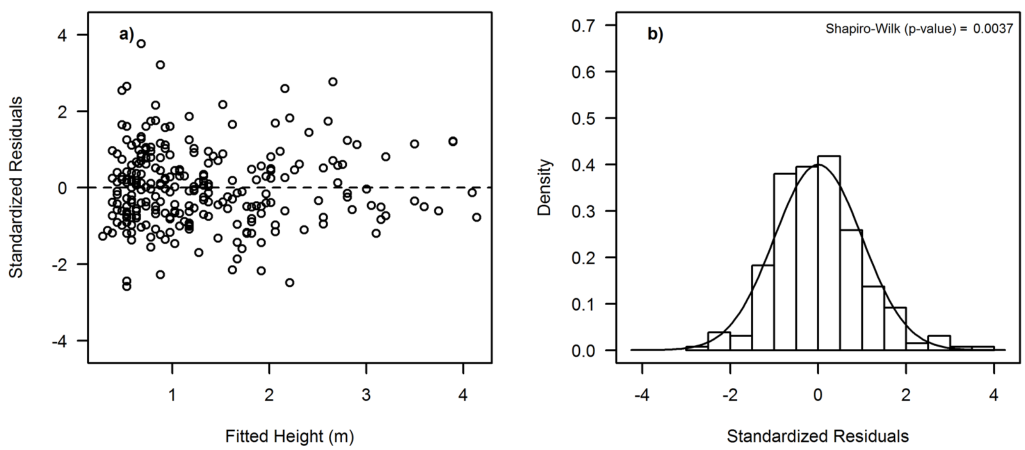


Figure A-4-1. Distribution of residuals and random-effects for the final white spruce height-root collar model (Equation 3-3) under a pure linear fixed-effects fit (Table 3-11: Model 3.1.11): a) standardized residuals against fitted height and b) standardized residual distribution.

Table A-4-2. Summary statistics for the final jack pine height-diameter model (Equation 3-12) under a pure nonlinear fixed-effects fit (Table 3-17: Model 3.4.14).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 8.8702 | 0.3765 | 8.1110 | 9.6294 | <0.0001 |
| | $\beta_{10}$ | 0.0341 | 0.0093 | 0.0154 | 0.0528 | 0.0007 |
| | $\beta_{20}$ | 1.6174 | 0.5180 | 0.5728 | 2.6619 | 0.0032 |
| **RMSE** | | 1.0639 | | | | |
| **BIC** | | 147.3685 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

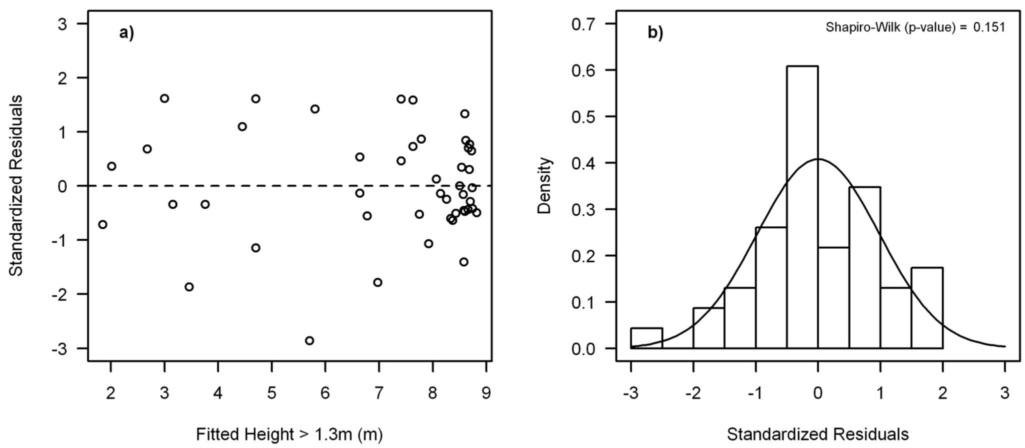


Figure A-4-2. Distribution of residuals and random-effects for the final jack pine height-diameter model (Equation 3-12) under a pure nonlinear fixed-effects fit (Table 3-17: Model 3.4.14): a) standardized residuals against fitted height and b) standardized residual distribution.

Table A-4-3. Summary statistics for the final white birch height-diameter model (Equation 3-14) under a pure nonlinear fixed-effects fit (Table 3-21: Model 3.6.17).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | -4.8037 | 3.3789 | -11.5699 | 1.9625 | 0.1606 |
| | $\beta_{01}$ | 1.9182 | 0.4547 | 1.0077 | 2.8288 | 0.0001 |
| | $\beta_{10}$ | 0.0164 | 0.0066 | 0.0032 | 0.0297 | 0.0160 |
| | $\beta_{20}$ | 0.8750 | 0.1674 | 0.5398 | 1.2101 | <0.0001 |
| **RMSE** | | 0.9116 | | | | |
| **BIC** | | 177.1529 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

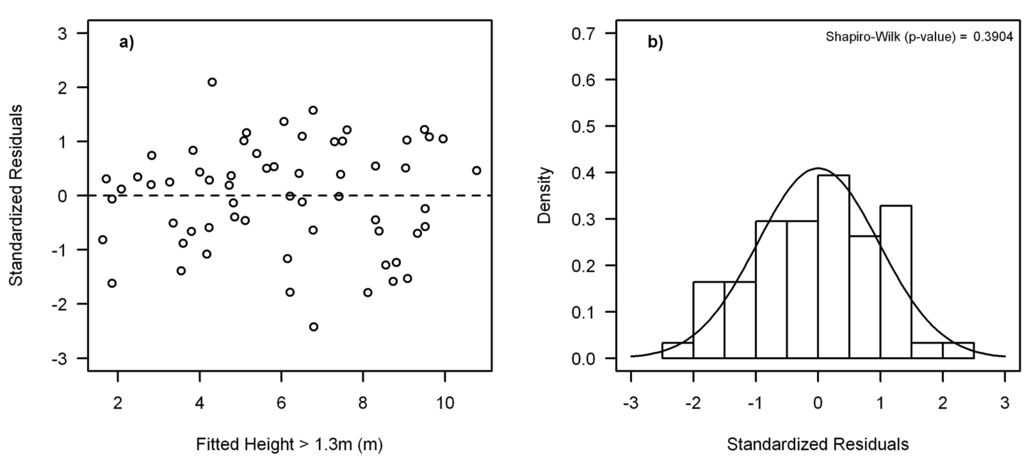


Figure A-4-3. Distribution of residuals and random-effects for the final white birch height-diameter model (Equation 3-14) under a pure nonlinear fixed-effects fit (Table 3-21: Model 3.6.17): a) standardized residuals against fitted height and b) standardized residual distribution.

Table A-4-4. Summary statistics for the final white spruce height-diameter model (Equation 3-15) under a pure nonlinear fixed-effects fit (Table 3-23: Model 3.7.15).

| | | Estimate | SE | Lower 95% CI | Upper 95% CI | p-value |
|---|---|---|---|---|---|---|
| **Fixed Parameters** | $\beta_{00}$ | 6.4930 | 0.7894 | 4.9349 | 8.0511 | <0.0001 |
| | $\beta_{01}$ | 0.2576 | 0.0289 | 0.2005 | 0.3146 | <0.0001 |
| | $\beta_{10}$ | 0.0096 | 0.0018 | 0.0062 | 0.0131 | <0.0001 |
| | $\beta_{20}$ | 1.2688 | 0.0990 | 1.0734 | 1.4643 | <0.0001 |
| **RMSE** | | 0.7004 | | | | |
| **BIC** | | 392.7498 | | | | |

**Note:** SE = standard error; CI = confidence interval; RMSE = root mean square error (Eq. 3-6); BIC = Bayesian Information Criterion.

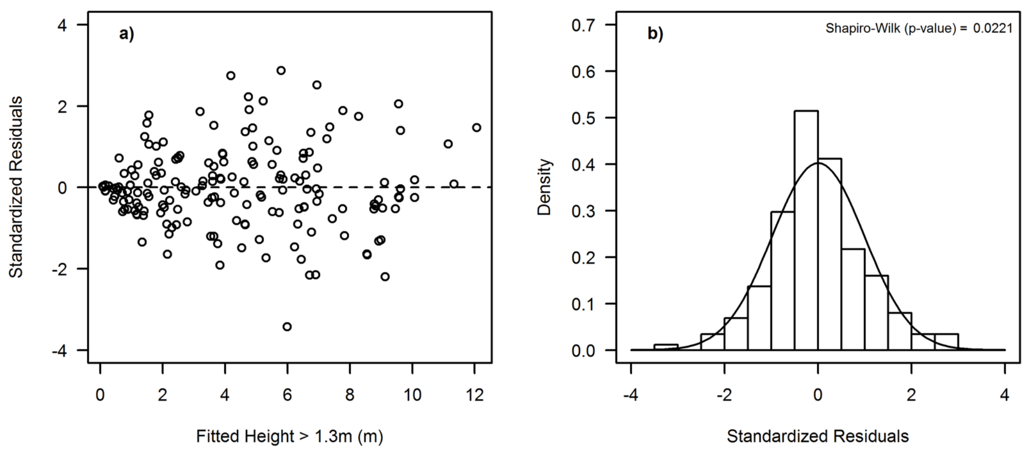


Figure A-4-4. Distribution of residuals and random-effects for the final white spruce height-diameter model (Equation 3-15) under a pure nonlinear fixed-effects fit (Table 3-23: Model 3.7.15): a) standardized residuals against fitted height and b) standardized residual distribution.

## Appendix 5. Juvenile MS-PSP Projections across a Range of Site Indices

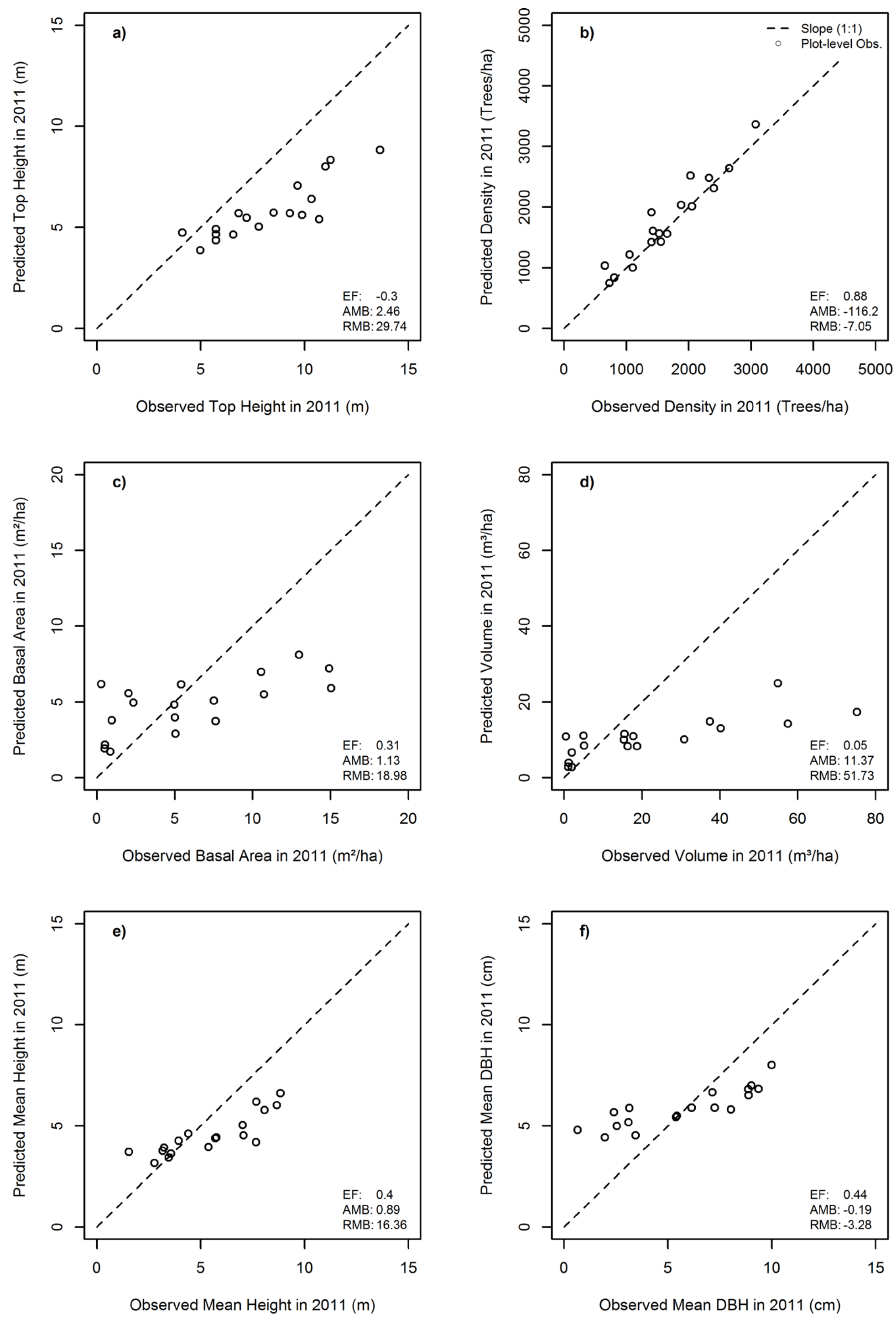


Figure A-5-1. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Individual scatter plots represent white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and submesic site index estimates from Beckingham et al. (1996). Model efficiency (EF), average model bias (AMB), and relative model bias (RMB) are listed in each figure.

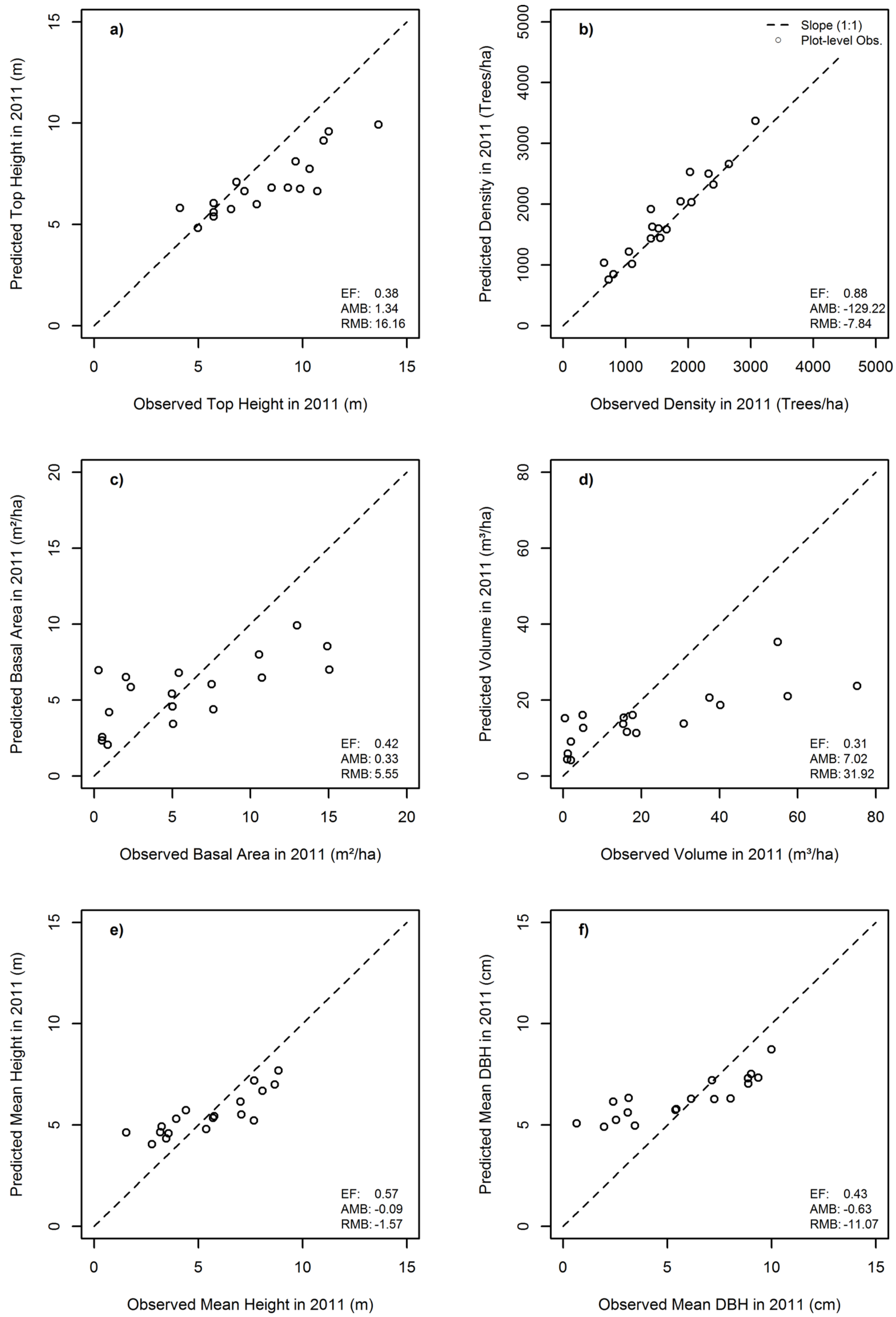


Figure A-5-2. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Individual scatter plots represent white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and mesic site index estimates from Beckingham et al. (1996). Model efficiency (EF), average model bias (AMB), and relative model bias (RMB) are listed in each figure.

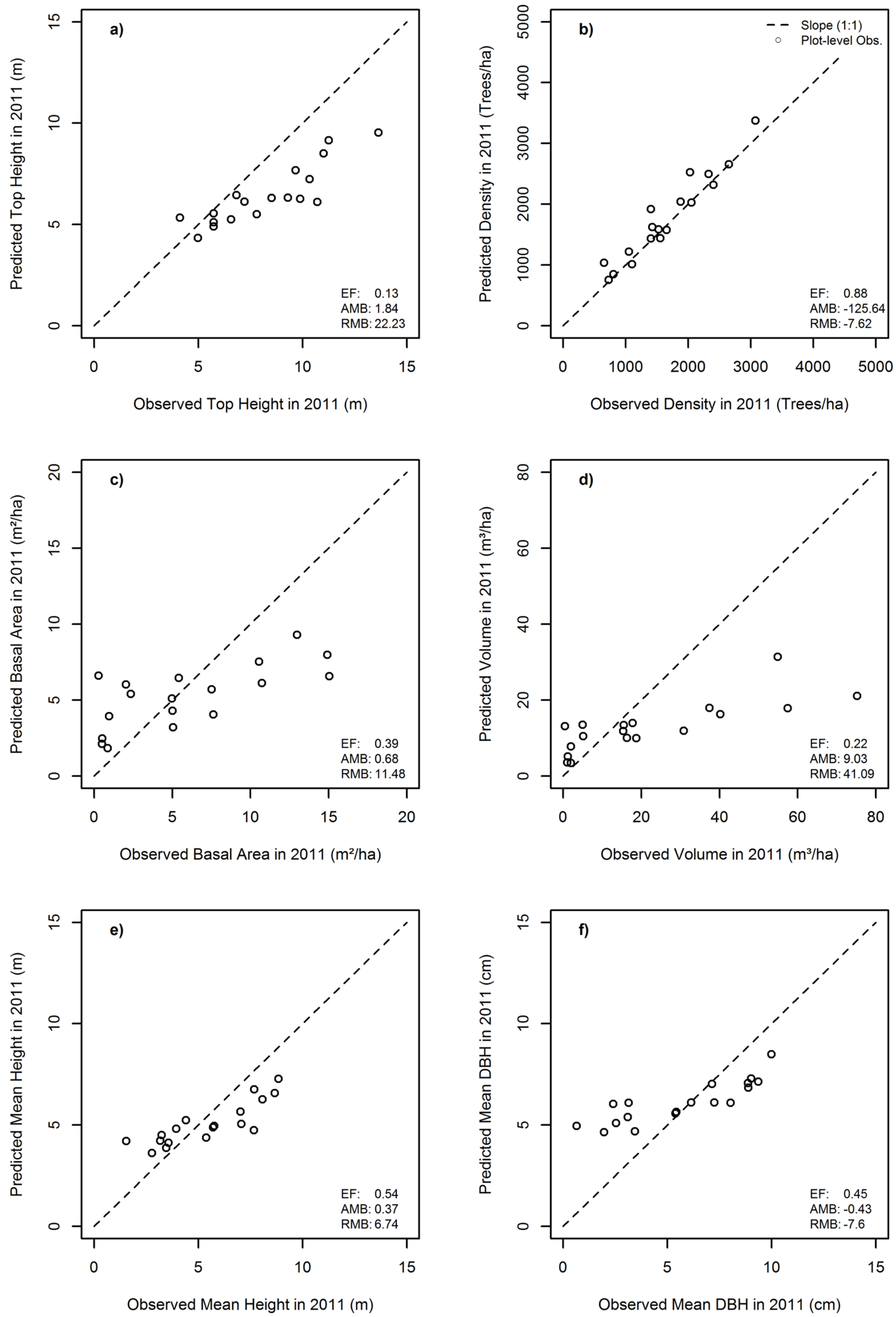


Figure A-5-3. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Individual scatter plots represent white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and subhygric site index estimates from Beckingham et al. (1996). Model efficiency (EF), average model bias (AMB), and relative model bias (RMB) are listed in each figure.

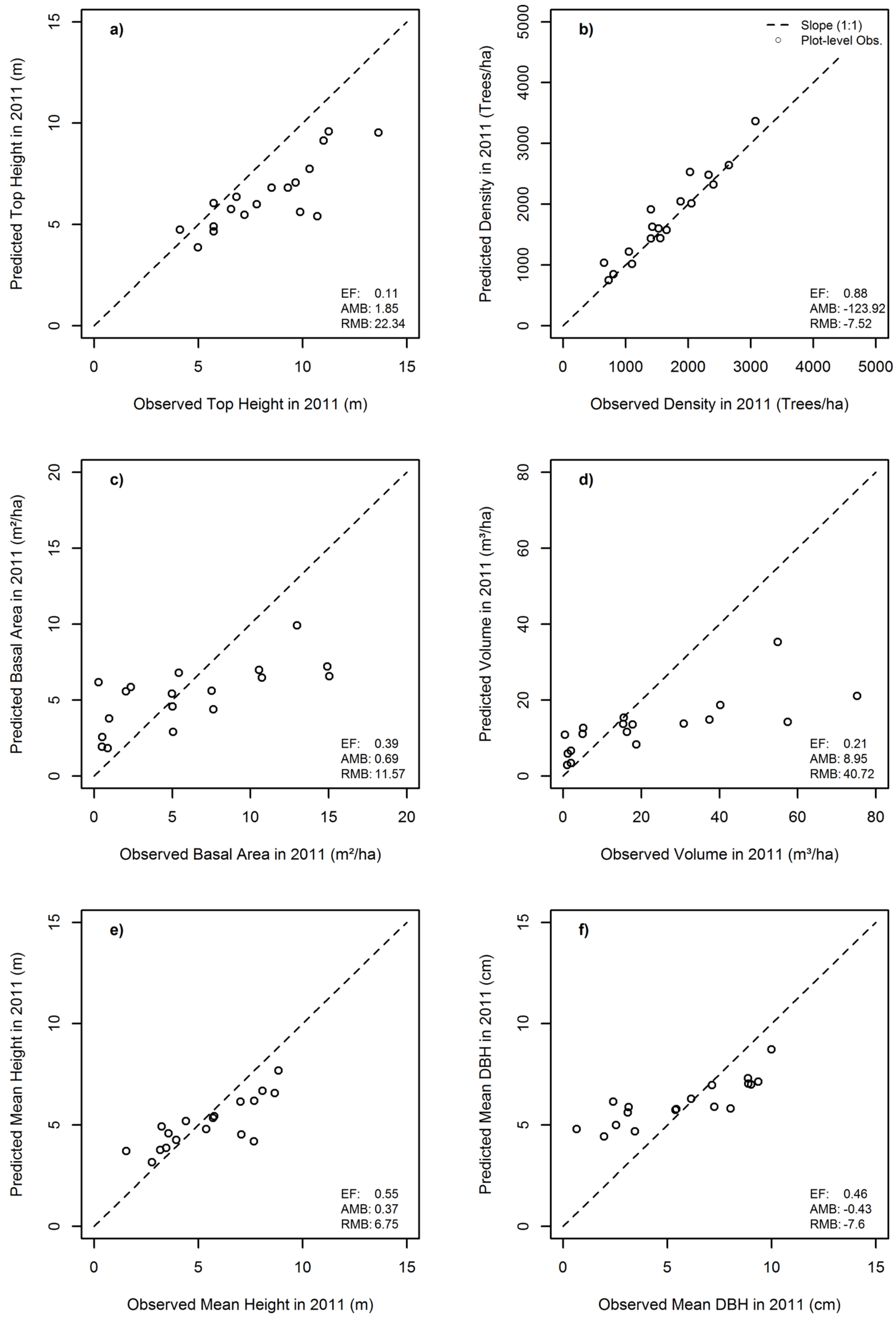


Figure A-5-4. Plot-level MGM predictions versus plot-level observations for the MS-PSP dataset. Individual scatter plots represent white spruce a) top height, b) density, c) basal area, d) volume, e) mean height, and f) mean DBH. All MGM predictions reflect a 15-year projection (i.e. 1996-2011) and site index estimates from plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). Model efficiency (EF), average model bias (AMB), and relative model bias (RMB) are listed in each figure.

Table A-5-1. MGM summary statistics for 18 MS-PSP's modeled under a 15-year projection (i.e. 1996-2011). All MGM predictions reflect submesic ecosite classifications under Beckingham et al. (1996). White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 6731 | 1460 | 10371 | 2799 |
| | Basal Area ($m^2$/ha) | 22.7 | 5.1 | 35.8 | 9.4 |
| | Volume ($m^3$/ha) | 79.6 | 11.1 | 142.2 | 37.1 |
| | Top Height (m) | 10.2 | 5.7 | 11.8 | 1.6 |
| | Height (m) | 5.8 | 4.6 | 7.1 | 0.8 |
| | DBH (cm) | 5.6 | 3.7 | 6.7 | 0.8 |
| BS | Density (Trees/ha) | 10 | 0 | 93 | 30 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.2 | 0.0 |
| | Top Height (m) | 0.4 | 0.0 | 4.1 | 1.1 |
| | Height (m) | 0.4 | 0.0 | 4.1 | 1.1 |
| | DBH (cm) | 0.3 | 0.0 | 3.3 | 0.8 |
| JP | Density (Trees/ha) | 1672 | 0 | 7514 | 2431 |
| | Basal Area ($m^2$/ha) | 7.6 | 0.0 | 25.2 | 10.3 |
| | Volume ($m^3$/ha) | 29.4 | 0.0 | 104.5 | 41.1 |
| | Top Height (m) | 4.6 | 0.0 | 11.8 | 4.8 |
| | Height (m) | 3.6 | 0.0 | 9.2 | 3.8 |
| | DBH (cm) | 3.5 | 0.0 | 10.6 | 3.8 |
| TA | Density (Trees/ha) | 2655 | 29 | 7186 | 2117 |
| | Basal Area ($m^2$/ha) | 9.3 | 0.1 | 21.3 | 6.8 |
| | Volume ($m^3$/ha) | 37.7 | 0.2 | 91.1 | 29.1 |
| | Top Height (m) | 10.0 | 5.9 | 11.4 | 1.6 |
| | Height (m) | 7.1 | 4.8 | 8.2 | 1.0 |
| | DBH (cm) | 5.2 | 2.8 | 7.1 | 1.1 |
| WS | Density (Trees/ha) | 2394 | 1377 | 4022 | 766 |
| | Basal Area ($m^2$/ha) | 5.9 | 3.8 | 9.2 | 1.4 |
| | Volume ($m^3$/ha) | 12.5 | 6.7 | 26.8 | 4.4 |
| | Top Height (m) | 5.9 | 4.6 | 8.8 | 1.3 |
| | Height (m) | 4.4 | 3.4 | 6.2 | 0.9 |
| | DBH (cm) | 5.7 | 4.5 | 7.5 | 0.8 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

Table A-5-2. MGM summary statistics for 18 MS-PSP's modeled under a 15-year projection (i.e. 1996-2011). All MGM predictions reflect mesic ecosite classifications under Beckingham et al. (1996). White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 6755 | 1477 | 10415 | 2697 |
| | Basal Area ($m^2$/ha) | 24.4 | 6.1 | 37.2 | 9.2 |
| | Volume ($m^3$/ha) | 91.6 | 16.3 | 155.0 | 37.9 |
| | Top Height (m) | 10.8 | 6.7 | 12.2 | 1.7 |
| | Height (m) | 6.5 | 5.5 | 7.8 | 0.7 |
| | DBH (cm) | 5.8 | 4.0 | 7.2 | 0.8 |
| BS | Density (Trees/ha) | 10 | 0 | 93 | 30 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Top Height (m) | 0.3 | 0.0 | 3.9 | 1.0 |
| | Height (m) | 0.3 | 0.0 | 3.9 | 1.0 |
| | DBH (cm) | 0.2 | 0.0 | 3.1 | 0.8 |
| JP | Density (Trees/ha) | 1574 | 0 | 6874 | 2268 |
| | Basal Area ($m^2$/ha) | 7.3 | 0.0 | 24.3 | 9.9 |
| | Volume ($m^3$/ha) | 29.0 | 0.0 | 105.1 | 40.5 |
| | Top Height (m) | 4.6 | 0.0 | 12.0 | 4.9 |
| | Height (m) | 3.7 | 0.0 | 9.3 | 3.8 |
| | DBH (cm) | 3.5 | 0.0 | 10.6 | 3.8 |
| TA | Density (Trees/ha) | 2761 | 30 | 7630 | 2230 |
| | Basal Area ($m^2$/ha) | 10.2 | 0.1 | 23.4 | 7.5 |
| | Volume ($m^3$/ha) | 44.9 | 0.2 | 105.4 | 34.6 |
| | Top Height (m) | 10.7 | 6.5 | 12.2 | 1.7 |
| | Height (m) | 7.7 | 5.5 | 8.8 | 1.0 |
| | DBH (cm) | 5.3 | 3.0 | 7.3 | 1.1 |
| WS | Density (Trees/ha) | 2409 | 1395 | 4042 | 765 |
| | Basal Area ($m^2$/ha) | 6.9 | 4.2 | 11.2 | 1.8 |
| | Volume ($m^3$/ha) | 17.7 | 9.1 | 37.9 | 6.2 |
| | Top Height (m) | 7.1 | 5.6 | 9.9 | 1.3 |
| | Height (m) | 5.4 | 4.3 | 7.3 | 0.9 |
| | DBH (cm) | 6.2 | 4.9 | 8.2 | 0.9 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

Table A-5-3. MGM summary statistics for 18 MS-PSP's modeled under a 15-year projection (i.e. 1996-2011). All MGM predictions reflect subhygric ecosite classifications under Beckingham et al. (1996). White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| **Species** | **Variable** | **Mean** | **Min** | **Max** | **SD** |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 6758 | 1476 | 10428 | 2672 |
| | Basal Area ($m^2$/ha) | 24.8 | 5.8 | 36.5 | 9.0 |
| | Volume ($m^3$/ha) | 95.0 | 14.3 | 152.1 | 38.4 |
| | Top Height (m) | 11.3 | 6.5 | 12.9 | 1.9 |
| | Height (m) | 6.4 | 5.2 | 7.8 | 0.8 |
| | DBH (cm) | 5.8 | 4.0 | 7.0 | 0.8 |
| BS | Density (Trees/ha) | 10 | 0 | 93 | 30 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Top Height (m) | 0.3 | 0.0 | 3.6 | 1.0 |
| | Height (m) | 0.3 | 0.0 | 3.6 | 1.0 |
| | DBH (cm) | 0.2 | 0.0 | 2.7 | 0.7 |
| JP | Density (Trees/ha) | 1572 | 0 | 7013 | 2282 |
| | Basal Area ($m^2$/ha) | 7.3 | 0.0 | 24.5 | 9.9 |
| | Volume ($m^3$/ha) | 28.7 | 0.0 | 105.9 | 40.5 |
| | Top Height (m) | 4.6 | 0.0 | 12.0 | 4.9 |
| | Height (m) | 3.7 | 0.0 | 9.3 | 3.8 |
| | DBH (cm) | 3.5 | 0.0 | 10.7 | 3.8 |
| TA | Density (Trees/ha) | 2771 | 34 | 7650 | 2221 |
| | Basal Area ($m^2$/ha) | 11.1 | 0.1 | 25.6 | 8.1 |
| | Volume ($m^3$/ha) | 51.2 | 0.3 | 120.0 | 39.0 |
| | Top Height (m) | 11.3 | 7.2 | 12.9 | 1.8 |
| | Height (m) | 8.2 | 5.9 | 9.3 | 1.0 |
| | DBH (cm) | 5.5 | 3.1 | 7.7 | 1.2 |
| WS | Density (Trees/ha) | 2405 | 1386 | 4032 | 766 |
| | Basal Area ($m^2$/ha) | 6.4 | 4.0 | 10.5 | 1.6 |
| | Volume ($m^3$/ha) | 15.2 | 7.8 | 33.7 | 5.6 |
| | Top Height (m) | 6.6 | 5.1 | 9.5 | 1.3 |
| | Height (m) | 4.9 | 3.9 | 6.8 | 0.9 |
| | DBH (cm) | 6.0 | 4.7 | 8.0 | 0.9 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine; TA = trembling aspen; WS = white spruce.

Table A-5-4. MGM summary statistics for 18 MS-PSP's modeled under a 15-year projection (i.e. 1996-2011). All MGM predictions reflect plot-level ecosite classifications (i.e. submesic-hygric) under Beckingham et al. (1996). White spruce summary statistics include planted and naturally regenerated trees. To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|
| ALL | Density (Trees/ha) | 6799 | 1472 | 10371 | 2770 |
| | Basal Area ($m^2$/ha) | 24.0 | 5.7 | 37.2 | 9.2 |
| | Volume ($m^3$/ha) | 88.1 | 13.8 | 155.0 | 37.8 |
| | Top Height (m) | 10.7 | 6.4 | 12.9 | 1.7 |
| | Height (m) | 6.2 | 4.6 | 7.8 | 0.9 |
| | DBH (cm) | 5.8 | 3.7 | 7.0 | 0.9 |
| BS | Density (Trees/ha) | 10 | 0 | 93 | 30 |
| | Basal Area ($m^2$/ha) | 0.0 | 0.0 | 0.1 | 0.0 |
| | Volume ($m^3$/ha) | 0.0 | 0.0 | 0.2 | 0.0 |
| | Top Height (m) | 0.4 | 0.0 | 4.1 | 1.1 |
| | Height (m) | 0.4 | 0.0 | 4.1 | 1.1 |
| | DBH (cm) | 0.3 | 0.0 | 3.3 | 0.8 |
| JP | Density (Trees/ha) | 1654 | 0 | 7514 | 2419 |
| | Basal Area ($m^2$/ha) | 7.5 | 0.0 | 24.6 | 10.2 |
| | Volume ($m^3$/ha) | 29.5 | 0.0 | 105.1 | 41.1 |
| | Top Height (m) | 4.6 | 0.0 | 12.0 | 4.9 |
| | Height (m) | 3.6 | 0.0 | 9.3 | 3.8 |
| | DBH (cm) | 3.5 | 0.0 | 10.6 | 3.8 |
| TA | Density (Trees/ha) | 2731 | 32 | 7186 | 2158 |
| | Basal Area ($m^2$/ha) | 10.0 | 0.1 | 23.4 | 7.3 |
| | Volume ($m^3$/ha) | 43.2 | 0.2 | 105.4 | 33.5 |
| | Top Height (m) | 10.5 | 6.6 | 12.9 | 1.8 |
| | Height (m) | 7.5 | 4.8 | 8.8 | 1.1 |
| | DBH (cm) | 5.3 | 2.8 | 7.3 | 1.1 |
| WS | Density (Trees/ha) | 2403 | 1395 | 4042 | 764 |
| | Basal Area ($m^2$/ha) | 6.5 | 3.8 | 11.2 | 1.7 |
| | Volume ($m^3$/ha) | 15.4 | 6.7 | 37.9 | 6.7 |
| | Top Height (m) | 6.6 | 4.6 | 9.6 | 1.5 |
| | Height (m) | 5.0 | 3.4 | 7.3 | 1.1 |
| | DBH (cm) | 6.0 | 4.7 | 8.2 | 1.0 |

## Appendix 6. Long-Term MS-PSP Projections across a Range of Site Indices

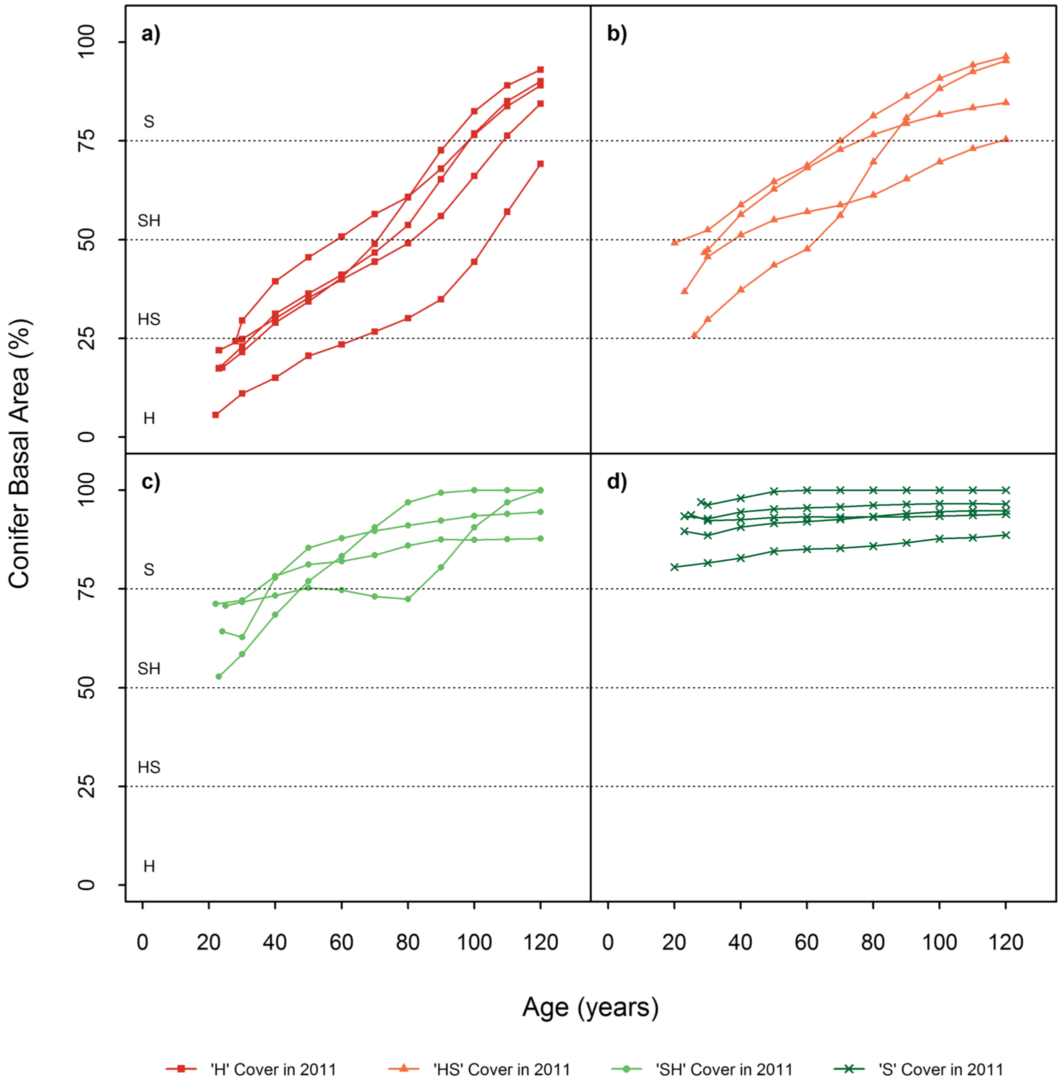


Figure A-6-1. MGM conifer succession across 18 MS-PSP's. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

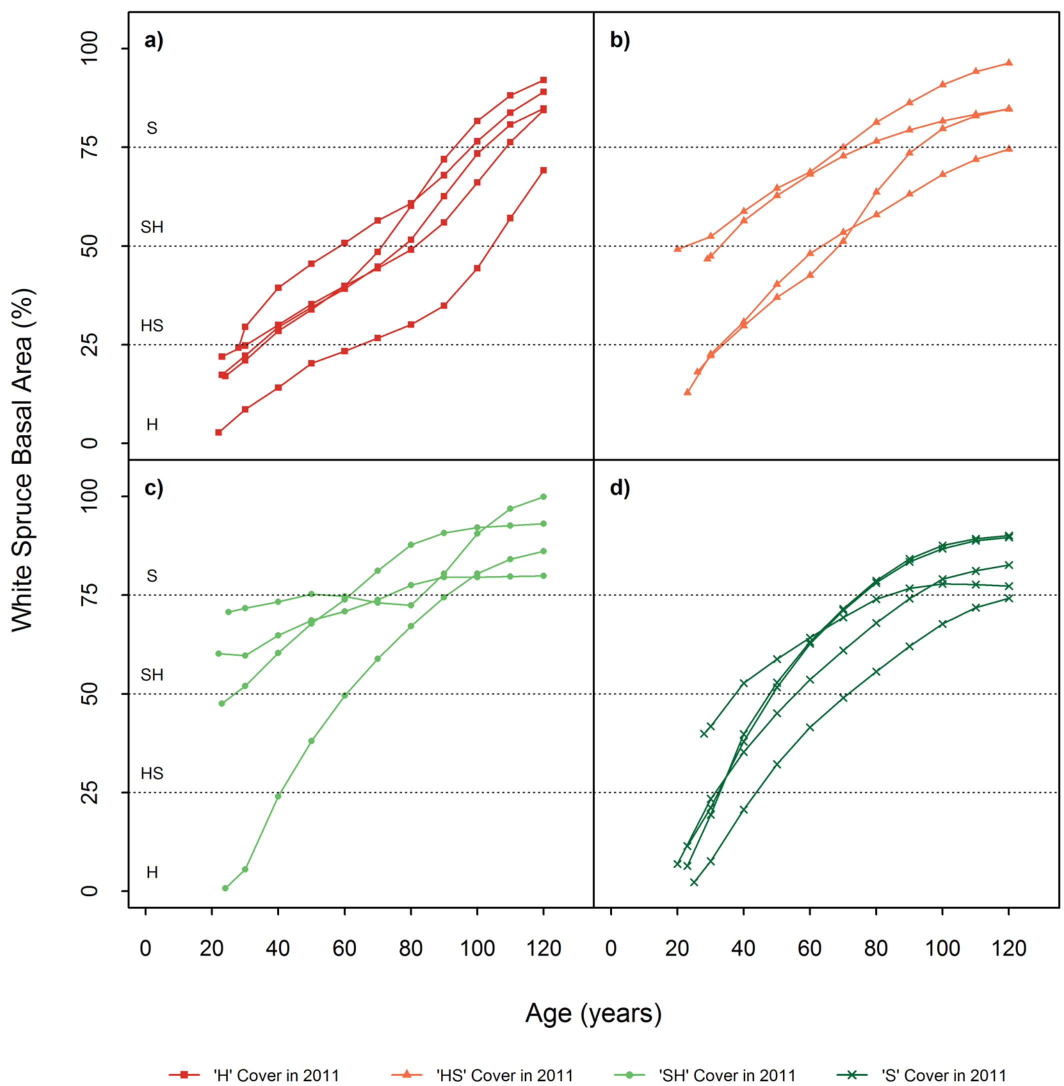


Figure A-6-2. MGM white spruce succession across 18 MS-PSP's. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-6-1. MGM conifer succession across 18 MS-PSP's: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 23 |
| 5.0 | | | | | | | | | | | | | | | 41 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 40 | |
| 5.4 | | | | | | | | | | | | | 40 | | | | | |
| 5.8 | | | | | | | | 57 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 48 | | | | |
| 7.5 | | | | 75 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 51 | | |
| 10.9 | | | | | | | | | | 69 | | | | | | | | |
| 11.9 | | | | | | | | | 83 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 68 | | | | | | |
| 17.6 | | | | | | | 82 | | | | | | | | | | | |
| 20.4 | | 95 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 88 | | | | | | | |
| 25.1 | | | | | | 85 | | | | | | | | | | | | |
| 29.0 | | | 93 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 92 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-2. MGM conifer succession across 18 MS-PSP's: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 35 |
| 5.0 | | | | | | | | | | | | | | | 65 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 73 | |
| 5.4 | | | | | | | | | | | | | 56 | | | | | |
| 5.8 | | | | | | | | 65 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 81 | | | | |
| 7.5 | | | | 80 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 68 | | |
| 10.9 | | | | | | | | | | 86 | | | | | | | | |
| 11.9 | | | | | | | | | 99 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 79 | | | | | | |
| 17.6 | | | | | | | 87 | | | | | | | | | | | |
| 20.4 | | 96 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 92 | | | | | | | |
| 25.1 | | | | | | 87 | | | | | | | | | | | | |
| 29.0 | | | 93 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 94 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-3. MGM conifer succession across 18 MS-PSP's: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 69 |
| 5.0 | | | | | | | | | | | | | | | 90 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 93 | |
| 5.4 | | | | | | | | | | | | | 84 | | | | | |
| 5.8 | | | | | | | | 75 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 95 | | | | |
| 7.5 | | | | 100 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 89 | | |
| 10.9 | | | | | | | | | | 96 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 85 | | | | | | |
| 17.6 | | | | | | | 88 | | | | | | | | | | | |
| 20.4 | | 96 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 94 | | | | | | | |
| 25.1 | | | | | | 89 | | | | | | | | | | | | |
| 29.0 | | | 94 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 95 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-4. MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 2192 | 1395 | 3196 | 494 |
| | | Basal Area ($m^2$/ha) | 36.1 | 27.3 | 39.4 | 3.0 |
| | | Volume ($m^3$/ha) | 261.1 | 167.4 | 330.7 | 41.1 |
| | | Top Height (m) | 21.8 | 17.6 | 26.8 | 2.7 |
| | | Height (m) | 13.5 | 11.4 | 15.8 | 1.3 |
| | | DBH (cm) | 13.4 | 11.3 | 15.7 | 1.3 |
| | 90 | Density (Trees/ha) | 1354 | 817 | 2012 | 339 |
| | | Basal Area ($m^2$/ha) | 37.8 | 31.7 | 42.4 | 3.3 |
| | | Volume ($m^3$/ha) | 334.9 | 283.6 | 395.9 | 32.5 |
| | | Top Height (m) | 25.8 | 22.4 | 30.6 | 2.2 |
| | | Height (m) | 18.6 | 16.1 | 21.2 | 1.5 |
| | | DBH (cm) | 18.0 | 15.1 | 21.4 | 2.0 |
| | 120 | Density (Trees/ha) | 898 | 565 | 1217 | 206 |
| | | Basal Area ($m^2$/ha) | 36.2 | 29.1 | 43.0 | 4.7 |
| | | Volume ($m^3$/ha) | 366.7 | 290.7 | 437.6 | 46.7 |
| | | Top Height (m) | 27.9 | 25.6 | 29.4 | 1.1 |
| | | Height (m) | 23.0 | 19.4 | 25.6 | 1.6 |
| | | DBH (cm) | 22.0 | 17.8 | 25.7 | 2.1 |
| BS | 60 | Density (Trees/ha) | 97 | 0 | 489 | 155 |
| | | Basal Area ($m^2$/ha) | 0.7 | 0.0 | 4.3 | 1.2 |
| | | Volume ($m^3$/ha) | 3.5 | 0.0 | 23.1 | 6.5 |
| | | Top Height (m) | 4.7 | 0.0 | 13.3 | 5.7 |
| | | Height (m) | 4.5 | 0.0 | 12.1 | 5.4 |
| | | DBH (cm) | 4.2 | 0.0 | 13.3 | 5.1 |
| | 90 | Density (Trees/ha) | 61 | 0 | 342 | 112 |
| | | Basal Area ($m^2$/ha) | 0.6 | 0.0 | 3.8 | 1.0 |
| | | Volume ($m^3$/ha) | 3.7 | 0.0 | 28.5 | 7.0 |
| | | Top Height (m) | 6.1 | 0.0 | 17.9 | 7.5 |
| | | Height (m) | 6.0 | 0.0 | 17.9 | 7.4 |
| | | DBH (cm) | 5.7 | 0.0 | 18.5 | 7.0 |
| | 120 | Density (Trees/ha) | 53 | 0 | 341 | 106 |
| | | Basal Area ($m^2$/ha) | 0.7 | 0.0 | 3.6 | 1.2 |
| | | Volume ($m^3$/ha) | 4.6 | 0.0 | 30.2 | 8.3 |
| | | Top Height (m) | 7.4 | 0.0 | 21.0 | 8.9 |
| | | Height (m) | 7.2 | 0.0 | 21.0 | 8.7 |
| | | DBH (cm) | 6.7 | 0.0 | 21.2 | 8.2 |
| JP | 60 | Density (Trees/ha) | 99 | 0 | 334 | 128 |
| | | Basal Area ($m^2$/ha) | 4.6 | 0.0 | 14.2 | 5.9 |
| | | Volume ($m^3$/ha) | 36.6 | 0.0 | 115.8 | 47.5 |
| | | Top Height (m) | 9.2 | 0.0 | 21.8 | 9.9 |
| | | Height (m) | 8.9 | 0.0 | 20.9 | 9.5 |
| | | DBH (cm) | 10.9 | 0.0 | 26.4 | 12.0 |
| | 90 | Density (Trees/ha) | 34 | 0 | 117 | 43 |
| | | Basal Area ($m^2$/ha) | 2.4 | 0.0 | 8.7 | 3.1 |
| | | Volume ($m^3$/ha) | 22.6 | 0.0 | 77.7 | 29.3 |
| | | Top Height (m) | 10.4 | 0.0 | 25.1 | 11.9 |
| | | Height (m) | 10.3 | 0.0 | 25.1 | 11.9 |
| | | DBH (cm) | 13.2 | 0.0 | 32.8 | 15.4 |
| | 120 | Density (Trees/ha) | 19 | 0 | 77 | 26 |
| | | Basal Area ($m^2$/ha) | 1.5 | 0.0 | 8.0 | 2.2 |
| | | Volume ($m^3$/ha) | 15.4 | 0.0 | 78.0 | 21.9 |
| | | Top Height (m) | 11.2 | 0.0 | 26.7 | 12.9 |
| | | Height (m) | 11.2 | 0.0 | 26.7 | 12.9 |
| | | DBH (cm) | 14.2 | 0.0 | 36.3 | 16.6 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-6-4 (continued). MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 353 | 4 | 926 | 292 |
| | | Basal Area ($m^2$/ha) | 11.4 | 0.0 | 28.0 | 8.6 |
| | | Volume ($m^3$/ha) | 101.8 | 0.1 | 239.5 | 85.6 |
| | | Top Height (m) | 20.7 | 11.1 | 26.8 | 4.2 |
| | | Height (m) | 18.8 | 10.6 | 25.7 | 4.5 |
| | | DBH (cm) | 19.8 | 6.1 | 32.1 | 7.1 |
| | 90 | Density (Trees/ha) | 99 | 0 | 358 | 94 |
| | | Basal Area ($m^2$/ha) | 7.6 | 0.0 | 25.6 | 6.6 |
| | | Volume ($m^3$/ha) | 78.5 | 0.0 | 247.2 | 69.2 |
| | | Top Height (m) | 23.8 | 0.0 | 30.6 | 7.5 |
| | | Height (m) | 23.1 | 0.0 | 30.1 | 7.4 |
| | | DBH (cm) | 28.8 | 0.0 | 47.8 | 11.0 |
| | 120 | Density (Trees/ha) | 33 | 0 | 116 | 33 |
| | | Basal Area ($m^2$/ha) | 3.3 | 0.0 | 10.6 | 2.9 |
| | | Volume ($m^3$/ha) | 36.8 | 0.0 | 121.5 | 33.6 |
| | | Top Height (m) | 24.7 | 0.0 | 32.0 | 10.1 |
| | | Height (m) | 24.6 | 0.0 | 32.0 | 10.1 |
| | | DBH (cm) | 32.3 | 0.0 | 52.5 | 15.3 |
| WS | 60 | Density (Trees/ha) | 1642 | 977 | 2782 | 555 |
| | | Basal Area ($m^2$/ha) | 19.4 | 8.5 | 27.9 | 5.1 |
| | | Volume ($m^3$/ha) | 119.2 | 42.4 | 200.0 | 43.6 |
| | | Top Height (m) | 17.5 | 13.9 | 21.4 | 2.2 |
| | | Height (m) | 12.4 | 9.8 | 15.6 | 1.7 |
| | | DBH (cm) | 12.0 | 9.8 | 16.1 | 1.8 |
| | 90 | Density (Trees/ha) | 1159 | 716 | 1881 | 359 |
| | | Basal Area ($m^2$/ha) | 27.3 | 13.7 | 33.6 | 5.4 |
| | | Volume ($m^3$/ha) | 230.2 | 101.4 | 306.7 | 54.8 |
| | | Top Height (m) | 23.6 | 20.0 | 26.3 | 1.7 |
| | | Height (m) | 18.4 | 16.1 | 21.4 | 1.6 |
| | | DBH (cm) | 17.0 | 14.5 | 21.8 | 2.1 |
| | 120 | Density (Trees/ha) | 793 | 508 | 1146 | 196 |
| | | Basal Area ($m^2$/ha) | 30.7 | 20.1 | 36.1 | 3.8 |
| | | Volume ($m^3$/ha) | 309.9 | 191.3 | 362.5 | 40.2 |
| | | Top Height (m) | 27.5 | 25.1 | 29.3 | 1.1 |
| | | Height (m) | 23.3 | 21.4 | 25.8 | 1.2 |
| | | DBH (cm) | 21.9 | 19.4 | 26.1 | 2.0 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

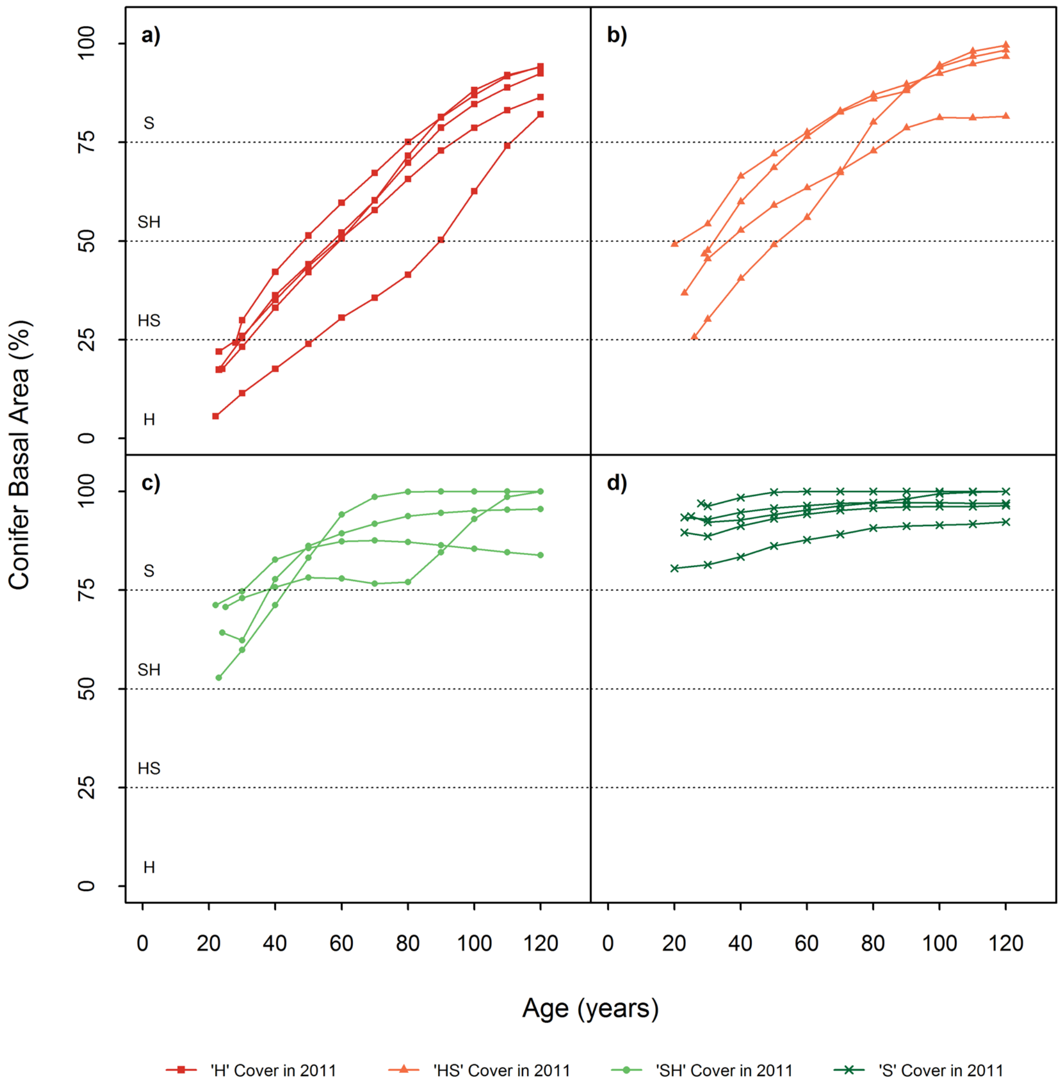


Figure A-6-3. MGM conifer succession across 18 MS-PSP's. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

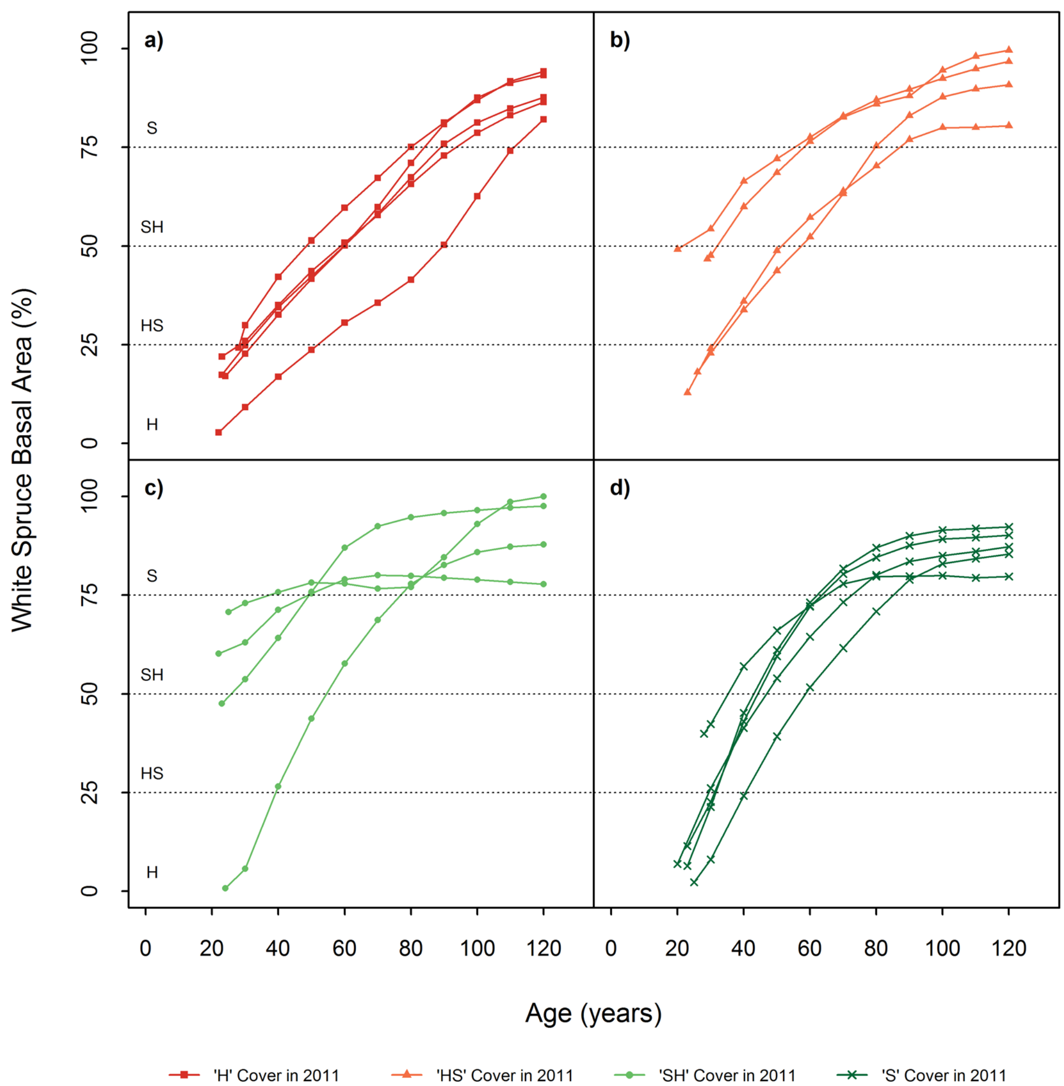


Figure A-6-4. MGM white spruce succession across 18 MS-PSP's. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-6-5. MGM conifer succession across 18 MS-PSP's: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 31 |
| 5.0 | | | | | | | | | | | | | | | 52 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 51 | |
| 5.4 | | | | | | | | | | | | | 51 | | | | | |
| 5.8 | | | | | | | | 63 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 56 | | | | |
| 7.5 | | | | 78 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 60 | | |
| 10.9 | | | | | | | | | | 78 | | | | | | | | |
| 11.9 | | | | | | | | | 94 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 76 | | | | | | |
| 17.6 | | | | | | | 87 | | | | | | | | | | | |
| 20.4 | | 96 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 89 | | | | | | | |
| 25.1 | | | | | | 88 | | | | | | | | | | | | |
| 29.0 | | | 95 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 94 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-6. MGM conifer succession across 18 MS-PSP's: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 50 |
| 5.0 | | | | | | | | | | | | | | | 79 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 81 | |
| 5.4 | | | | | | | | | | | | | 73 | | | | | |
| 5.8 | | | | | | | | 79 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 89 | | | | |
| 7.5 | | | | 85 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 81 | | |
| 10.9 | | | | | | | | | | 90 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 88 | | | | | | |
| 17.6 | | | | | | | 86 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 95 | | | | | | | |
| 25.1 | | | | | | 91 | | | | | | | | | | | | |
| 29.0 | | | 98 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 96 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-7. MGM conifer succession across 18 MS-PSP's: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 82 |
| 5.0 | | | | | | | | | | | | | | | 92 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 94 | |
| 5.4 | | | | | | | | | | | | | 86 | | | | | |
| 5.8 | | | | | | | | 82 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 98 | | | | |
| 7.5 | | | | 100 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 94 | | |
| 10.9 | | | | | | | | | | 97 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 100 | | | | | | |
| 17.6 | | | | | | | 84 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 96 | | | | | | | |
| 25.1 | | | | | | 92 | | | | | | | | | | | | |
| 29.0 | | | 100 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 96 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-8. MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 2081 | 1423 | 3132 | 516 |
| | | Basal Area ($m^2$/ha) | 37.9 | 31.2 | 42.5 | 2.8 |
| | | Volume ($m^3$/ha) | 287.0 | 219.5 | 345.9 | 34.2 |
| | | Top Height (m) | 22.2 | 18.1 | 27.2 | 2.7 |
| | | Height (m) | 14.9 | 13.1 | 17.3 | 1.2 |
| | | DBH (cm) | 14.3 | 12.0 | 16.4 | 1.4 |
| | 90 | Density (Trees/ha) | 1209 | 764 | 1646 | 264 |
| | | Basal Area ($m^2$/ha) | 40.1 | 36.1 | 43.5 | 1.9 |
| | | Volume ($m^3$/ha) | 383.2 | 347.4 | 437.1 | 24.0 |
| | | Top Height (m) | 26.8 | 24.3 | 29.3 | 1.7 |
| | | Height (m) | 20.9 | 18.6 | 23.8 | 1.5 |
| | | DBH (cm) | 19.7 | 16.9 | 23.6 | 2.1 |
| | 120 | Density (Trees/ha) | 772 | 511 | 1032 | 154 |
| | | Basal Area ($m^2$/ha) | 37.8 | 32.7 | 42.4 | 2.8 |
| | | Volume ($m^3$/ha) | 420.1 | 375.5 | 494.8 | 29.5 |
| | | Top Height (m) | 30.1 | 28.2 | 31.6 | 1.0 |
| | | Height (m) | 25.7 | 21.6 | 28.2 | 1.7 |
| | | DBH (cm) | 24.3 | 19.8 | 27.8 | 2.2 |
| BS | 60 | Density (Trees/ha) | 82 | 0 | 468 | 138 |
| | | Basal Area ($m^2$/ha) | 0.5 | 0.0 | 3.4 | 0.9 |
| | | Volume ($m^3$/ha) | 2.6 | 0.0 | 17.2 | 4.8 |
| | | Top Height (m) | 4.5 | 0.0 | 12.8 | 5.4 |
| | | Height (m) | 4.3 | 0.0 | 12.0 | 5.2 |
| | | DBH (cm) | 4.1 | 0.0 | 14.4 | 5.0 |
| | 90 | Density (Trees/ha) | 51 | 0 | 327 | 95 |
| | | Basal Area ($m^2$/ha) | 0.4 | 0.0 | 2.4 | 0.7 |
| | | Volume ($m^3$/ha) | 2.6 | 0.0 | 16.4 | 4.4 |
| | | Top Height (m) | 6.0 | 0.0 | 16.3 | 7.1 |
| | | Height (m) | 5.8 | 0.0 | 16.2 | 7.0 |
| | | DBH (cm) | 5.4 | 0.0 | 18.4 | 6.5 |
| | 120 | Density (Trees/ha) | 47 | 0 | 326 | 93 |
| | | Basal Area ($m^2$/ha) | 0.6 | 0.0 | 2.9 | 0.9 |
| | | Volume ($m^3$/ha) | 3.7 | 0.0 | 20.6 | 6.2 |
| | | Top Height (m) | 7.1 | 0.0 | 18.9 | 8.4 |
| | | Height (m) | 7.0 | 0.0 | 18.9 | 8.3 |
| | | DBH (cm) | 6.3 | 0.0 | 20.8 | 7.6 |
| JP | 60 | Density (Trees/ha) | 81 | 0 | 294 | 105 |
| | | Basal Area ($m^2$/ha) | 3.8 | 0.0 | 12.7 | 5.0 |
| | | Volume ($m^3$/ha) | 30.6 | 0.0 | 101.4 | 40.1 |
| | | Top Height (m) | 9.3 | 0.0 | 21.8 | 9.9 |
| | | Height (m) | 9.0 | 0.0 | 21.1 | 9.6 |
| | | DBH (cm) | 11.0 | 0.0 | 26.8 | 12.1 |
| | 90 | Density (Trees/ha) | 25 | 0 | 89 | 32 |
| | | Basal Area ($m^2$/ha) | 1.7 | 0.0 | 7.7 | 2.4 |
| | | Volume ($m^3$/ha) | 16.7 | 0.0 | 70.0 | 22.4 |
| | | Top Height (m) | 10.4 | 0.0 | 25.4 | 12.0 |
| | | Height (m) | 10.4 | 0.0 | 25.4 | 12.0 |
| | | DBH (cm) | 13.1 | 0.0 | 33.3 | 15.4 |
| | 120 | Density (Trees/ha) | 15 | 0 | 69 | 21 |
| | | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 6.9 | 1.9 |
| | | Volume ($m^3$/ha) | 12.6 | 0.0 | 68.1 | 18.6 |
| | | Top Height (m) | 11.3 | 0.0 | 27.0 | 13.0 |
| | | Height (m) | 11.3 | 0.0 | 27.0 | 13.0 |
| | | DBH (cm) | 13.9 | 0.0 | 35.7 | 16.4 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-6-8 (continued). MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 248 | 2 | 696 | 191 |
| | | Basal Area ($m^2$/ha) | 9.6 | 0.0 | 25.5 | 7.6 |
| | | Volume ($m^3$/ha) | 87.6 | 0.0 | 218.4 | 75.7 |
| | | Top Height (m) | 20.9 | 11.6 | 27.2 | 4.5 |
| | | Height (m) | 19.4 | 9.8 | 26.3 | 4.8 |
| | | DBH (cm) | 21.0 | 6.2 | 34.4 | 8.0 |
| | 90 | Density (Trees/ha) | 60 | 0 | 237 | 58 |
| | | Basal Area ($m^2$/ha) | 5.4 | 0.0 | 19.4 | 4.8 |
| | | Volume ($m^3$/ha) | 56.8 | 0.0 | 190.4 | 50.7 |
| | | Top Height (m) | 23.2 | 0.0 | 31.5 | 9.1 |
| | | Height (m) | 23.0 | 0.0 | 31.5 | 9.1 |
| | | DBH (cm) | 29.8 | 0.0 | 50.9 | 13.4 |
| | 120 | Density (Trees/ha) | 17 | 0 | 63 | 17 |
| | | Basal Area ($m^2$/ha) | 2.4 | 0.0 | 7.4 | 2.5 |
| | | Volume ($m^3$/ha) | 27.2 | 0.0 | 85.0 | 29.6 |
| | | Top Height (m) | 23.5 | 0.0 | 34.6 | 12.0 |
| | | Height (m) | 23.5 | 0.0 | 34.6 | 12.0 |
| | | DBH (cm) | 32.3 | 0.0 | 56.5 | 18.5 |
| WS | 60 | Density (Trees/ha) | 1670 | 1010 | 2797 | 553 |
| | | Basal Area ($m^2$/ha) | 24.0 | 11.3 | 33.6 | 5.8 |
| | | Volume ($m^3$/ha) | 166.3 | 66.2 | 264.5 | 52.5 |
| | | Top Height (m) | 19.6 | 16.2 | 22.7 | 1.9 |
| | | Height (m) | 14.3 | 11.9 | 17.4 | 1.6 |
| | | DBH (cm) | 13.2 | 10.6 | 17.6 | 1.9 |
| | 90 | Density (Trees/ha) | 1073 | 710 | 1548 | 264 |
| | | Basal Area ($m^2$/ha) | 32.5 | 19.6 | 36.4 | 3.8 |
| | | Volume ($m^3$/ha) | 307.2 | 169.0 | 359.5 | 44.4 |
| | | Top Height (m) | 26.3 | 23.2 | 28.4 | 1.4 |
| | | Height (m) | 21.0 | 19.0 | 23.9 | 1.4 |
| | | DBH (cm) | 19.2 | 16.2 | 24.0 | 2.2 |
| | 120 | Density (Trees/ha) | 693 | 483 | 899 | 121 |
| | | Basal Area ($m^2$/ha) | 33.6 | 28.4 | 36.8 | 1.9 |
| | | Volume ($m^3$/ha) | 376.6 | 304.0 | 408.3 | 22.8 |
| | | Top Height (m) | 30.3 | 28.4 | 31.6 | 0.8 |
| | | Height (m) | 26.3 | 24.7 | 28.5 | 1.1 |
| | | DBH (cm) | 24.5 | 22.0 | 28.3 | 1.8 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

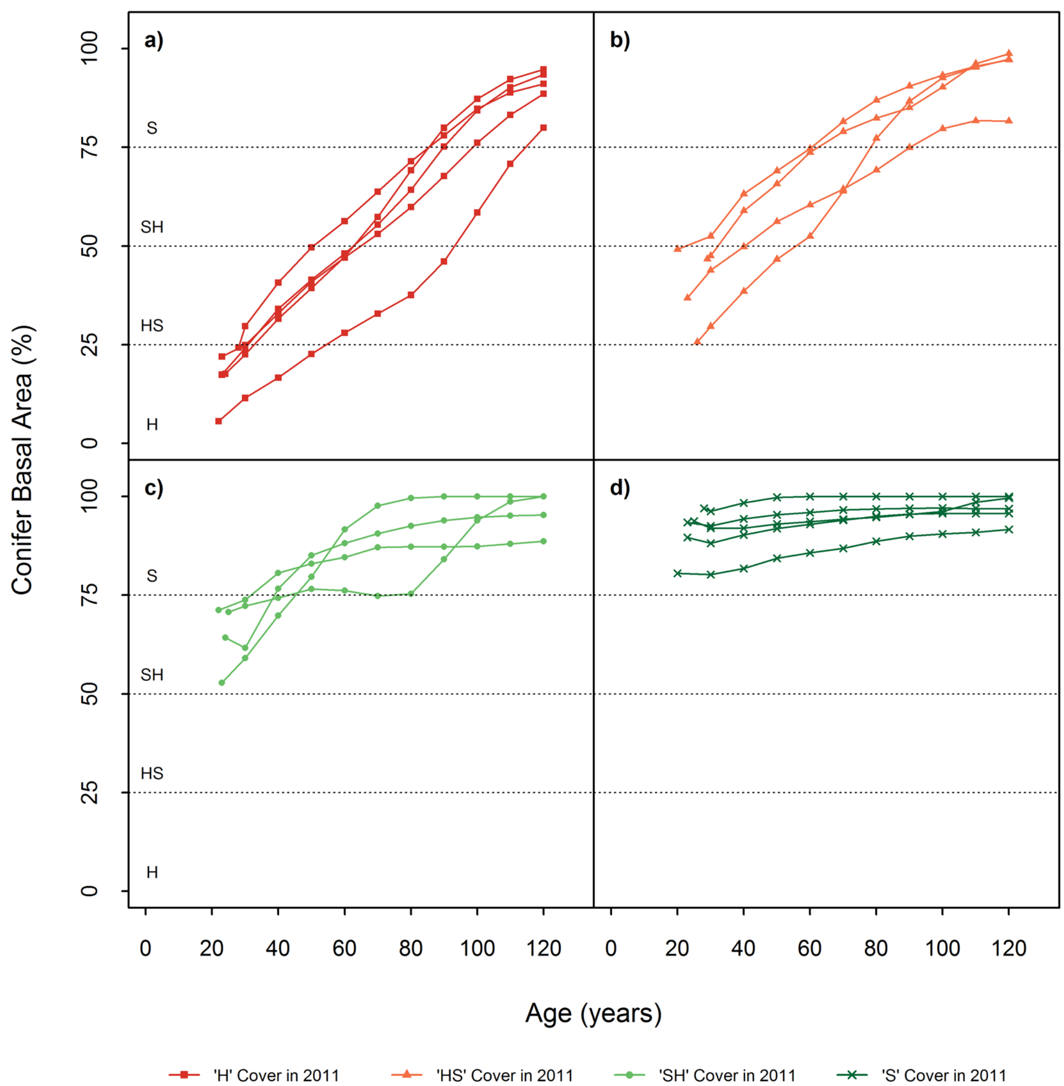


Figure A-6-5. MGM conifer succession across 18 MS-PSP's. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

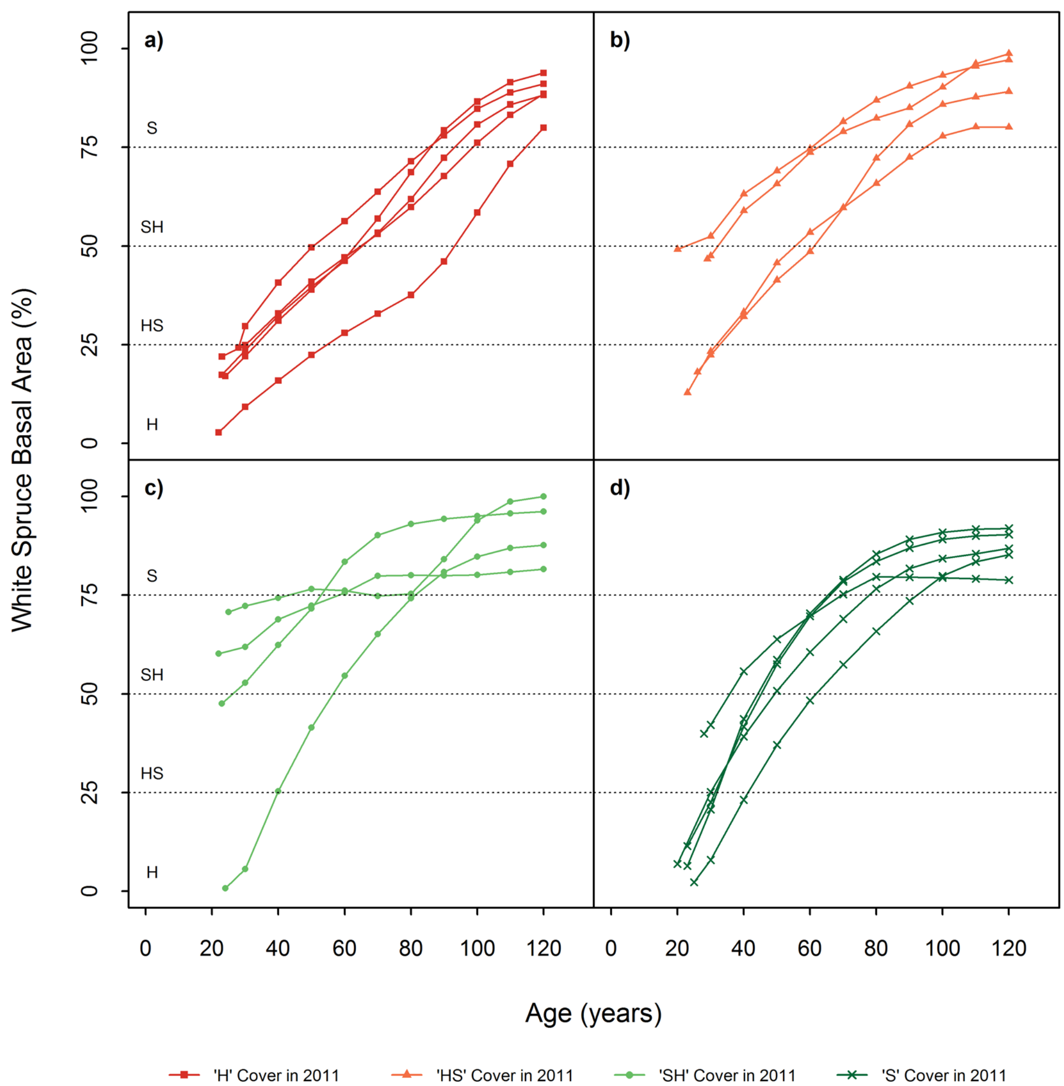


Figure A-6-6. MGM white spruce succession across 18 MS-PSP's. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading MS-PSP's from the 2011 measurement to stand age 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-6-9. MGM conifer succession across 18 MS-PSP's: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 28 |
| 5.0 | | | | | | | | | | | | | | | 48 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 47 | |
| 5.4 | | | | | | | | | | | | | 47 | | | | | |
| 5.8 | | | | | | | | 60 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 52 | | | | |
| 7.5 | | | | 76 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 56 | | |
| 10.9 | | | | | | | | | | 75 | | | | | | | | |
| 11.9 | | | | | | | | | 92 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 74 | | | | | | |
| 17.6 | | | | | | | 85 | | | | | | | | | | | |
| 20.4 | | 96 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 88 | | | | | | | |
| 25.1 | | | | | | 86 | | | | | | | | | | | | |
| 29.0 | | | 94 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 93 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-10. MGM conifer succession across 18 MS-PSP's: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 46 |
| 5.0 | | | | | | | | | | | | | | | 75 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 80 | |
| 5.4 | | | | | | | | | | | | | 68 | | | | | |
| 5.8 | | | | | | | | 75 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 87 | | | | |
| 7.5 | | | | 84 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 78 | | |
| 10.9 | | | | | | | | | | 90 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 85 | | | | | | |
| 17.6 | | | | | | | 87 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 94 | | | | | | | |
| 25.1 | | | | | | 90 | | | | | | | | | | | | |
| 29.0 | | | 95 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 95 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-11. MGM conifer succession across 18 MS-PSP's: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each plot's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous Basal Area ($m^2$/ha) in 2011 | 1.0 | 1.4 | 1.9 | 3.1 | 3.5 | 6.1 | 7.1 | 9.9 | 10.7 | 11.3 | 13.5 | 17.2 | 19.1 | 21.0 | 23.6 | 24.3 | 24.9 | 31.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer Basal Area ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | | | |
| 1.9 | | | | | | | | | | | | | | | | | | 80 |
| 5.0 | | | | | | | | | | | | | | | 93 | | | |
| 5.3 | | | | | | | | | | | | | | | | | 95 | |
| 5.4 | | | | | | | | | | | | | 89 | | | | | |
| 5.8 | | | | | | | | 82 | | | | | | | | | | |
| 7.3 | | | | | | | | | | | | | | 97 | | | | |
| 7.5 | | | | 100 | | | | | | | | | | | | | | |
| 7.8 | | | | | | | | | | | | | | | | 91 | | |
| 10.9 | | | | | | | | | | 97 | | | | | | | | |
| 11.9 | | | | | | | | | 100 | | | | | | | | | |
| 15.1 | | | | | | | | | | | | 99 | | | | | | |
| 17.6 | | | | | | | 89 | | | | | | | | | | | |
| 20.4 | | 97 | | | | | | | | | | | | | | | | |
| 24.2 | | | | | | | | | | | 95 | | | | | | | |
| 25.1 | | | | | | 92 | | | | | | | | | | | | |
| 29.0 | | | 100 | | | | | | | | | | | | | | | |
| 29.8 | | | | | 96 | | | | | | | | | | | | | |
| 31.5 | 100 | | | | | | | | | | | | | | | | | |

Table A-6-12. MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 2111 | 1417 | 3173 | 517 |
| | | Basal Area ($m^2$/ha) | 37.2 | 30.4 | 41.6 | 2.8 |
| | | Volume ($m^3$/ha) | 278.2 | 203.0 | 333.0 | 36.9 |
| | | Top Height (m) | 22.3 | 18.2 | 27.4 | 2.8 |
| | | Height (m) | 14.3 | 12.4 | 16.7 | 1.3 |
| | | DBH (cm) | 14.0 | 11.7 | 16.1 | 1.4 |
| | 90 | Density (Trees/ha) | 1265 | 778 | 1765 | 297 |
| | | Basal Area ($m^2$/ha) | 39.1 | 34.7 | 42.0 | 2.2 |
| | | Volume ($m^3$/ha) | 363.6 | 321.1 | 408.0 | 24.5 |
| | | Top Height (m) | 26.4 | 23.1 | 29.6 | 1.9 |
| | | Height (m) | 20.0 | 17.6 | 23.0 | 1.6 |
| | | DBH (cm) | 19.1 | 16.3 | 23.0 | 2.1 |
| | 120 | Density (Trees/ha) | 817 | 532 | 1077 | 173 |
| | | Basal Area ($m^2$/ha) | 37.2 | 32.2 | 41.4 | 3.2 |
| | | Volume ($m^3$/ha) | 400.1 | 341.8 | 451.4 | 30.9 |
| | | Top Height (m) | 29.2 | 26.3 | 30.8 | 1.2 |
| | | Height (m) | 24.7 | 20.5 | 27.3 | 1.7 |
| | | DBH (cm) | 23.5 | 18.8 | 27.0 | 2.2 |
| BS | 60 | Density (Trees/ha) | 91 | 0 | 503 | 149 |
| | | Basal Area ($m^2$/ha) | 0.5 | 0.0 | 3.1 | 0.9 |
| | | Volume ($m^3$/ha) | 2.4 | 0.0 | 14.8 | 4.4 |
| | | Top Height (m) | 4.3 | 0.0 | 11.9 | 5.1 |
| | | Height (m) | 4.1 | 0.0 | 10.9 | 4.8 |
| | | DBH (cm) | 3.8 | 0.0 | 12.9 | 4.7 |
| | 90 | Density (Trees/ha) | 58 | 0 | 359 | 107 |
| | | Basal Area ($m^2$/ha) | 0.5 | 0.0 | 2.5 | 0.8 |
| | | Volume ($m^3$/ha) | 2.5 | 0.0 | 16.0 | 4.3 |
| | | Top Height (m) | 5.5 | 0.0 | 15.2 | 6.6 |
| | | Height (m) | 5.4 | 0.0 | 14.7 | 6.5 |
| | | DBH (cm) | 5.0 | 0.0 | 16.4 | 6.1 |
| | 120 | Density (Trees/ha) | 52 | 0 | 358 | 103 |
| | | Basal Area ($m^2$/ha) | 0.6 | 0.0 | 3.0 | 0.9 |
| | | Volume ($m^3$/ha) | 3.5 | 0.0 | 18.9 | 5.9 |
| | | Top Height (m) | 6.7 | 0.0 | 17.8 | 7.9 |
| | | Height (m) | 6.6 | 0.0 | 17.8 | 7.8 |
| | | DBH (cm) | 5.9 | 0.0 | 18.5 | 7.1 |
| JP | 60 | Density (Trees/ha) | 85 | 0 | 310 | 111 |
| | | Basal Area ($m^2$/ha) | 4.0 | 0.0 | 13.3 | 5.3 |
| | | Volume ($m^3$/ha) | 32.3 | 0.0 | 105.7 | 42.2 |
| | | Top Height (m) | 9.3 | 0.0 | 21.9 | 9.9 |
| | | Height (m) | 9.0 | 0.0 | 21.1 | 9.6 |
| | | DBH (cm) | 11.0 | 0.0 | 26.8 | 12.1 |
| | 90 | Density (Trees/ha) | 27 | 0 | 88 | 34 |
| | | Basal Area ($m^2$/ha) | 1.9 | 0.0 | 7.7 | 2.5 |
| | | Volume ($m^3$/ha) | 17.8 | 0.0 | 69.9 | 23.5 |
| | | Top Height (m) | 10.4 | 0.0 | 25.3 | 12.0 |
| | | Height (m) | 10.4 | 0.0 | 25.3 | 12.0 |
| | | DBH (cm) | 13.2 | 0.0 | 33.4 | 15.4 |
| | 120 | Density (Trees/ha) | 16 | 0 | 74 | 22 |
| | | Basal Area ($m^2$/ha) | 1.3 | 0.0 | 7.7 | 2.0 |
| | | Volume ($m^3$/ha) | 13.2 | 0.0 | 75.6 | 19.9 |
| | | Top Height (m) | 11.3 | 0.0 | 26.9 | 13.0 |
| | | Height (m) | 11.3 | 0.0 | 26.9 | 13.0 |
| | | DBH (cm) | 14.1 | 0.0 | 36.4 | 16.6 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-6-12 (continued). MGM summary statistics for 18 MS-PSP's projected to ages 60, 90, and 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 272 | 2 | 729 | 210 |
| | | Basal Area ($m^2$/ha) | 10.4 | 0.0 | 26.6 | 7.9 |
| | | Volume ($m^3$/ha) | 95.1 | 0.0 | 228.2 | 80.0 |
| | | Top Height (m) | 21.2 | 11.6 | 27.4 | 4.5 |
| | | Height (m) | 19.6 | 10.1 | 26.4 | 4.8 |
| | | DBH (cm) | 21.2 | 6.2 | 35.1 | 8.0 |
| | 90 | Density (Trees/ha) | 70 | 0 | 255 | 66 |
| | | Basal Area ($m^2$/ha) | 5.9 | 0.0 | 20.4 | 5.1 |
| | | Volume ($m^3$/ha) | 62.1 | 0.0 | 201.2 | 54.7 |
| | | Top Height (m) | 23.4 | 0.0 | 30.9 | 9.1 |
| | | Height (m) | 23.0 | 0.0 | 30.9 | 9.1 |
| | | DBH (cm) | 29.6 | 0.0 | 51.8 | 13.0 |
| | 120 | Density (Trees/ha) | 19 | 0 | 69 | 18 |
| | | Basal Area ($m^2$/ha) | 2.3 | 0.0 | 7.6 | 2.2 |
| | | Volume ($m^3$/ha) | 25.9 | 0.0 | 87.4 | 26.5 |
| | | Top Height (m) | 24.7 | 0.0 | 32.7 | 10.4 |
| | | Height (m) | 24.7 | 0.0 | 32.7 | 10.4 |
| | | DBH (cm) | 32.9 | 0.0 | 56.4 | 16.3 |
| WS | 60 | Density (Trees/ha) | 1663 | 1002 | 2803 | 556 |
| | | Basal Area ($m^2$/ha) | 22.4 | 10.3 | 31.4 | 5.5 |
| | | Volume ($m^3$/ha) | 148.4 | 57.4 | 239.3 | 49.1 |
| | | Top Height (m) | 18.9 | 15.4 | 22.2 | 2.0 |
| | | Height (m) | 13.6 | 11.1 | 16.8 | 1.6 |
| | | DBH (cm) | 12.8 | 10.3 | 17.1 | 1.9 |
| | 90 | Density (Trees/ha) | 1111 | 714 | 1667 | 301 |
| | | Basal Area ($m^2$/ha) | 30.9 | 17.5 | 36.3 | 4.4 |
| | | Volume ($m^3$/ha) | 281.2 | 143.6 | 350.4 | 48.6 |
| | | Top Height (m) | 25.4 | 22.1 | 27.7 | 1.5 |
| | | Height (m) | 20.1 | 17.9 | 23.1 | 1.5 |
| | | DBH (cm) | 18.5 | 15.6 | 23.3 | 2.2 |
| | 120 | Density (Trees/ha) | 730 | 494 | 976 | 143 |
| | | Basal Area ($m^2$/ha) | 33.0 | 25.9 | 36.8 | 2.4 |
| | | Volume ($m^3$/ha) | 357.5 | 267.4 | 400.5 | 27.4 |
| | | Top Height (m) | 29.4 | 27.3 | 30.8 | 0.9 |
| | | Height (m) | 25.3 | 23.5 | 27.6 | 1.1 |
| | | DBH (cm) | 23.6 | 21.1 | 27.6 | 1.9 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

## Appendix 7. Long-Term TSP Projections across a Range of Site Indices

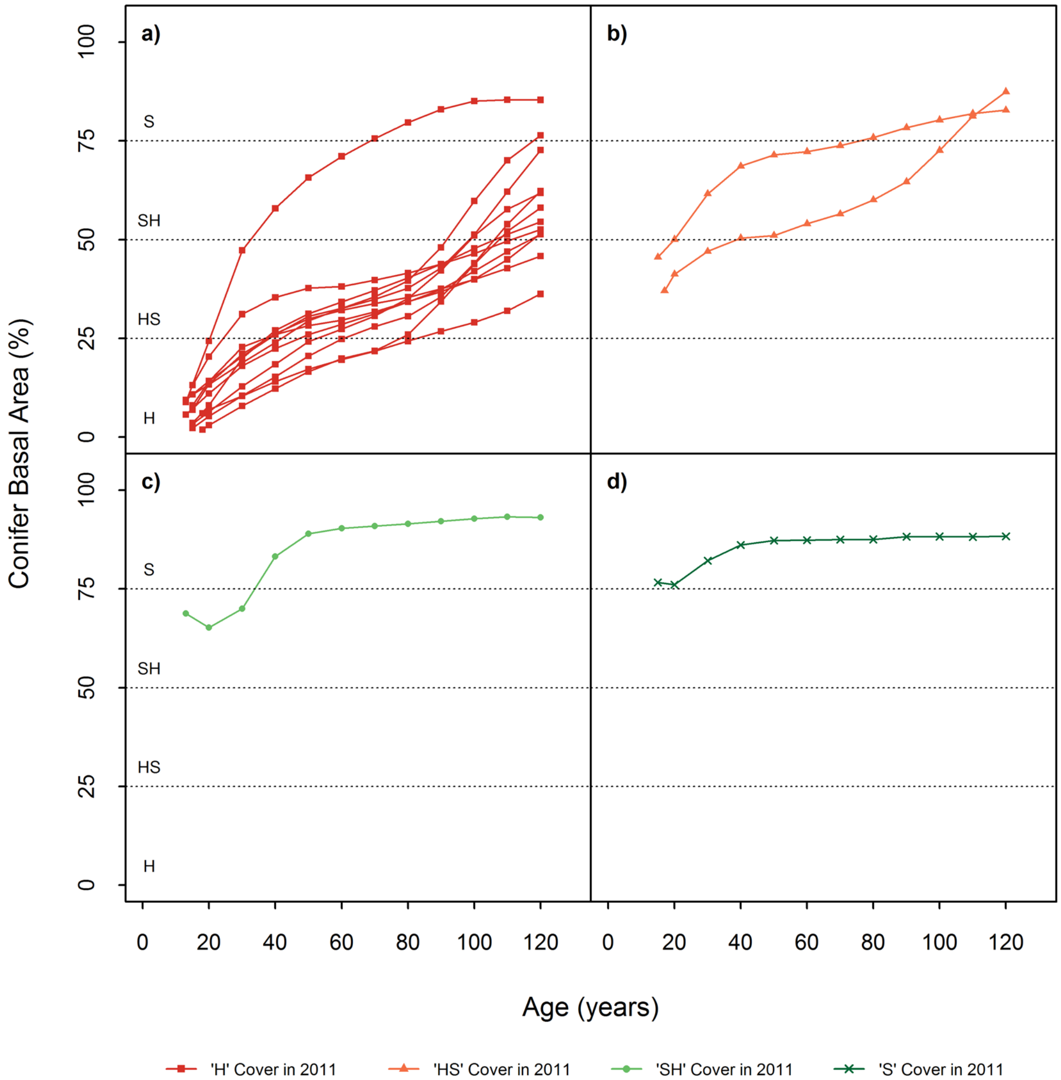


Figure A-7-1. MGM conifer succession across 16 TSP stands. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

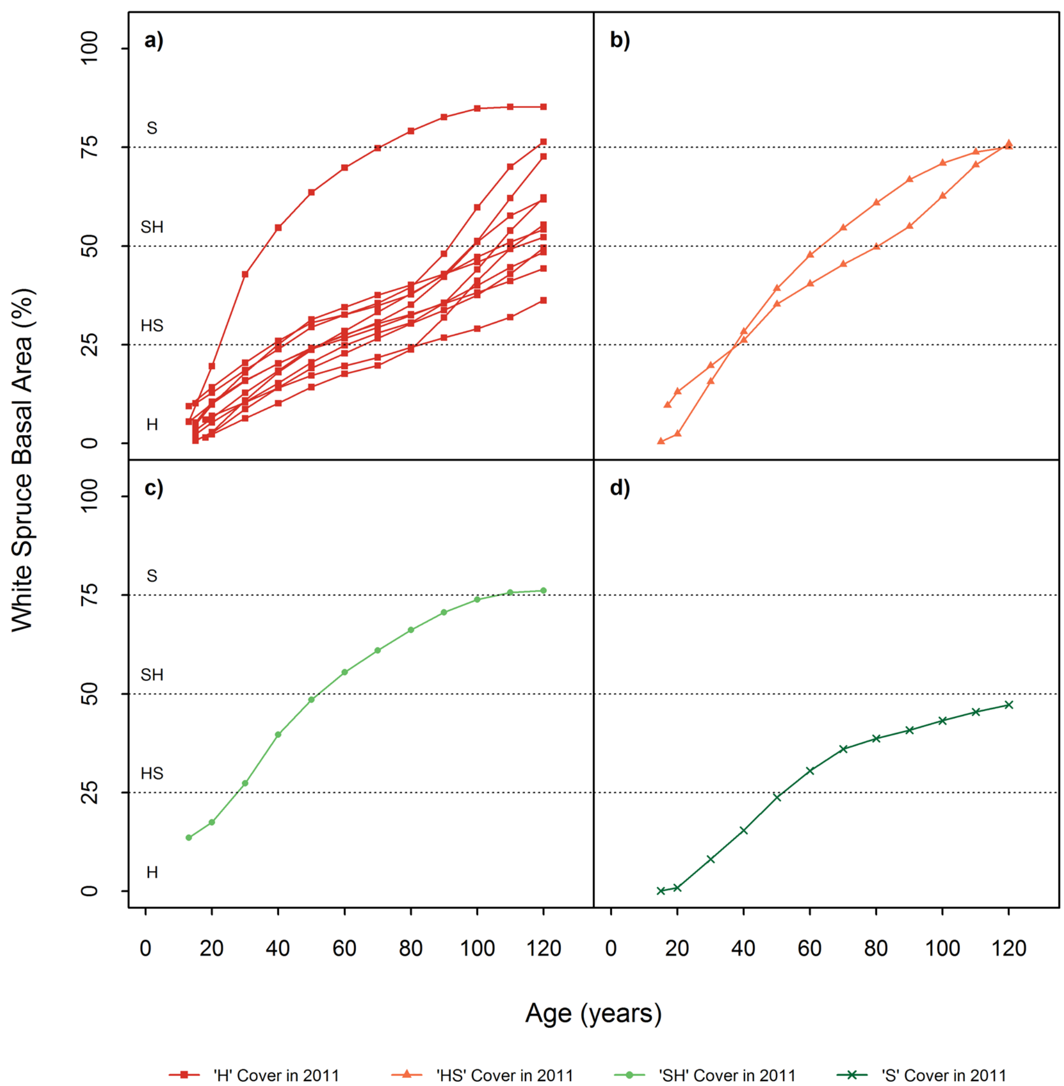


Figure A-7-2. MGM white spruce succession across 16 TSP stands. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-7-1. MGM conifer succession across 16 TSP stands: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 20 | | | |
| 0.5 | | | | | | | | | | | | 25 | | | | |
| 0.6 | | | 32 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 29 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 27 | | |
| 0.8 | | | | | | | | | | | | | | | | 34 |
| 1.1 | | | | | | 33 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 20 | | | | | | |
| 1.5 | | | | | | | | 33 | | | | | | | | |
| 1.8 | | | | | | | | | | | 71 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 30 | |
| 2.0 | | | | | | | | | 38 | | | | | | | |
| 4.2 | 87 | | | | | | | | | | | | | | | |
| 4.9 | | | | 54 | | | | | | | | | | | | |
| 5.9 | | 90 | | | | | | | | | | | | | | |
| 8.1 | | | | | 72 | | | | | | | | | | | |

Table A-7-2. MGM conifer succession across 16 TSP stands: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 34 | | | |
| 0.5 | | | | | | | | | | | | 36 | | | | |
| 0.6 | | | 38 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 37 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 42 | | |
| 0.8 | | | | | | | | | | | | | | | | 44 |
| 1.1 | | | | | | 43 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 27 | | | | | | |
| 1.5 | | | | | | | | 48 | | | | | | | | |
| 1.8 | | | | | | | | | | | 83 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 37 | |
| 2.0 | | | | | | | | | 44 | | | | | | | |
| 4.2 | 88 | | | | | | | | | | | | | | | |
| 4.9 | | | | 65 | | | | | | | | | | | | |
| 5.9 | | 92 | | | | | | | | | | | | | | |
| 8.1 | | | | | 78 | | | | | | | | | | | |

Table A-7-3. MGM conifer succession across 16 TSP stands: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 58 | | | |
| 0.5 | | | | | | | | | | | | 62 | | | | |
| 0.6 | | | 46 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 51 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 62 | | |
| 0.8 | | | | | | | | | | | | | | | | 54 |
| 1.1 | | | | | | 73 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 36 | | | | | | |
| 1.5 | | | | | | | | 76 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 52 | |
| 2.0 | | | | | | | | | 53 | | | | | | | |
| 4.2 | 88 | | | | | | | | | | | | | | | |
| 4.9 | | | | 87 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 83 | | | | | | | | | | | |

Table A-7-4. MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 2097 | 1190 | 4322 | 694 |
| | | Basal Area ($m^2$/ha) | 37.4 | 33.0 | 41.2 | 2.1 |
| | | Volume ($m^3$/ha) | 270.9 | 235.8 | 312.1 | 21.8 |
| | | Top Height (m) | 21.5 | 18.2 | 23.5 | 1.5 |
| | | Height (m) | 13.9 | 10.9 | 15.2 | 1.1 |
| | | DBH (cm) | 14.4 | 10.2 | 17.0 | 1.5 |
| | 90 | Density (Trees/ha) | 1210 | 722 | 2408 | 384 |
| | | Basal Area ($m^2$/ha) | 39.9 | 30.6 | 44.0 | 3.2 |
| | | Volume ($m^3$/ha) | 357.7 | 264.5 | 398.0 | 32.3 |
| | | Top Height (m) | 26.2 | 22.4 | 28.5 | 1.5 |
| | | Height (m) | 18.9 | 16.0 | 20.7 | 1.2 |
| | | DBH (cm) | 19.7 | 13.9 | 21.7 | 2.0 |
| | 120 | Density (Trees/ha) | 759 | 500 | 1295 | 205 |
| | | Basal Area ($m^2$/ha) | 36.6 | 26.2 | 43.3 | 5.3 |
| | | Volume ($m^3$/ha) | 370.7 | 268.0 | 444.7 | 49.6 |
| | | Top Height (m) | 28.1 | 25.2 | 29.5 | 1.1 |
| | | Height (m) | 22.9 | 19.0 | 24.2 | 1.4 |
| | | DBH (cm) | 24.1 | 18.7 | 27.4 | 2.2 |
| BS | 60 | Density (Trees/ha) | 231 | 0 | 1137 | 334 |
| | | Basal Area ($m^2$/ha) | 1.5 | 0.0 | 10.8 | 2.8 |
| | | Volume ($m^3$/ha) | 7.4 | 0.0 | 57.3 | 14.6 |
| | | Top Height (m) | 3.5 | 0.0 | 13.2 | 4.0 |
| | | Height (m) | 3.2 | 0.0 | 11.9 | 3.6 |
| | | DBH (cm) | 3.1 | 0.0 | 11.8 | 3.4 |
| | 90 | Density (Trees/ha) | 112 | 0 | 537 | 167 |
| | | Basal Area ($m^2$/ha) | 1.1 | 0.0 | 9.3 | 2.4 |
| | | Volume ($m^3$/ha) | 6.7 | 0.0 | 63.4 | 16.1 |
| | | Top Height (m) | 4.1 | 0.0 | 16.9 | 5.0 |
| | | Height (m) | 4.0 | 0.0 | 16.1 | 4.8 |
| | | DBH (cm) | 3.9 | 0.0 | 16.3 | 4.7 |
| | 120 | Density (Trees/ha) | 85 | 0 | 359 | 131 |
| | | Basal Area ($m^2$/ha) | 1.0 | 0.0 | 8.0 | 2.1 |
| | | Volume ($m^3$/ha) | 6.6 | 0.0 | 61.4 | 16.2 |
| | | Top Height (m) | 4.6 | 0.0 | 18.6 | 5.6 |
| | | Height (m) | 4.5 | 0.0 | 18.2 | 5.5 |
| | | DBH (cm) | 4.4 | 0.0 | 18.2 | 5.2 |
| JP | 60 | Density (Trees/ha) | 52 | 0 | 218 | 85 |
| | | Basal Area ($m^2$/ha) | 2.2 | 0.0 | 13.5 | 4.5 |
| | | Volume ($m^3$/ha) | 17.7 | 0.0 | 114.3 | 36.6 |
| | | Top Height (m) | 3.9 | 0.0 | 15.7 | 5.7 |
| | | Height (m) | 3.8 | 0.0 | 15.4 | 5.6 |
| | | DBH (cm) | 4.5 | 0.0 | 21.4 | 7.6 |
| | 90 | Density (Trees/ha) | 20 | 0 | 115 | 39 |
| | | Basal Area ($m^2$/ha) | 1.5 | 0.0 | 9.8 | 3.3 |
| | | Volume ($m^3$/ha) | 14.3 | 0.0 | 91.2 | 31.9 |
| | | Top Height (m) | 4.0 | 0.0 | 18.8 | 6.9 |
| | | Height (m) | 4.0 | 0.0 | 18.7 | 6.9 |
| | | DBH (cm) | 5.0 | 0.0 | 26.1 | 9.4 |
| | 120 | Density (Trees/ha) | 12 | 0 | 89 | 27 |
| | | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 8.7 | 2.7 |
| | | Volume ($m^3$/ha) | 12.3 | 0.0 | 86.0 | 28.4 |
| | | Top Height (m) | 4.1 | 0.0 | 20.5 | 7.6 |
| | | Height (m) | 4.1 | 0.0 | 20.5 | 7.6 |
| | | DBH (cm) | 5.2 | 0.0 | 28.6 | 10.3 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-7-4 (continued). MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect submesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 594 | 122 | 1087 | 268 |
| | | Basal Area ($m^2$/ha) | 20.9 | 3.8 | 29.4 | 8.5 |
| | | Volume ($m^3$/ha) | 176.7 | 28.9 | 254.7 | 76.1 |
| | | Top Height (m) | 20.7 | 13.9 | 23.5 | 3.0 |
| | | Height (m) | 18.5 | 13.5 | 22.8 | 2.5 |
| | | DBH (cm) | 20.4 | 13.3 | 27.0 | 3.8 |
| | 90 | Density (Trees/ha) | 225 | 41 | 436 | 109 |
| | | Basal Area ($m^2$/ha) | 18.8 | 3.3 | 28.0 | 8.3 |
| | | Volume ($m^3$/ha) | 190.4 | 31.8 | 278.5 | 89.5 |
| | | Top Height (m) | 24.7 | 11.8 | 28.5 | 4.8 |
| | | Height (m) | 23.5 | 11.8 | 27.9 | 4.5 |
| | | DBH (cm) | 30.8 | 16.1 | 38.8 | 6.7 |
| | 120 | Density (Trees/ha) | 93 | 22 | 194 | 50 |
| | | Basal Area ($m^2$/ha) | 12.1 | 2.9 | 22.2 | 6.6 |
| | | Volume ($m^3$/ha) | 132.9 | 31.1 | 248.3 | 75.8 |
| | | Top Height (m) | 26.3 | 12.7 | 31.1 | 5.6 |
| | | Height (m) | 26.0 | 12.6 | 31.1 | 5.5 |
| | | DBH (cm) | 37.1 | 17.7 | 48.9 | 8.7 |
| WS | 60 | Density (Trees/ha) | 1220 | 488 | 4065 | 838 |
| | | Basal Area ($m^2$/ha) | 12.8 | 5.8 | 28.8 | 5.9 |
| | | Volume ($m^3$/ha) | 69.2 | 30.2 | 144.9 | 31.5 |
| | | Top Height (m) | 14.3 | 10.6 | 17.2 | 1.5 |
| | | Height (m) | 11.8 | 9.3 | 13.0 | 1.0 |
| | | DBH (cm) | 11.6 | 9.3 | 12.6 | 0.9 |
| | 90 | Density (Trees/ha) | 854 | 384 | 2338 | 468 |
| | | Basal Area ($m^2$/ha) | 18.5 | 9.8 | 34.6 | 7.1 |
| | | Volume ($m^3$/ha) | 146.3 | 76.0 | 261.4 | 56.5 |
| | | Top Height (m) | 20.7 | 15.9 | 23.6 | 1.7 |
| | | Height (m) | 17.7 | 14.6 | 18.9 | 1.1 |
| | | DBH (cm) | 16.6 | 13.2 | 18.2 | 1.1 |
| | 120 | Density (Trees/ha) | 570 | 306 | 1260 | 238 |
| | | Basal Area ($m^2$/ha) | 22.3 | 12.2 | 34.6 | 6.5 |
| | | Volume ($m^3$/ha) | 218.9 | 118.0 | 330.4 | 64.3 |
| | | Top Height (m) | 25.4 | 19.6 | 27.7 | 1.7 |
| | | Height (m) | 22.9 | 18.6 | 23.9 | 1.3 |
| | | DBH (cm) | 22.3 | 18.0 | 24.7 | 1.5 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

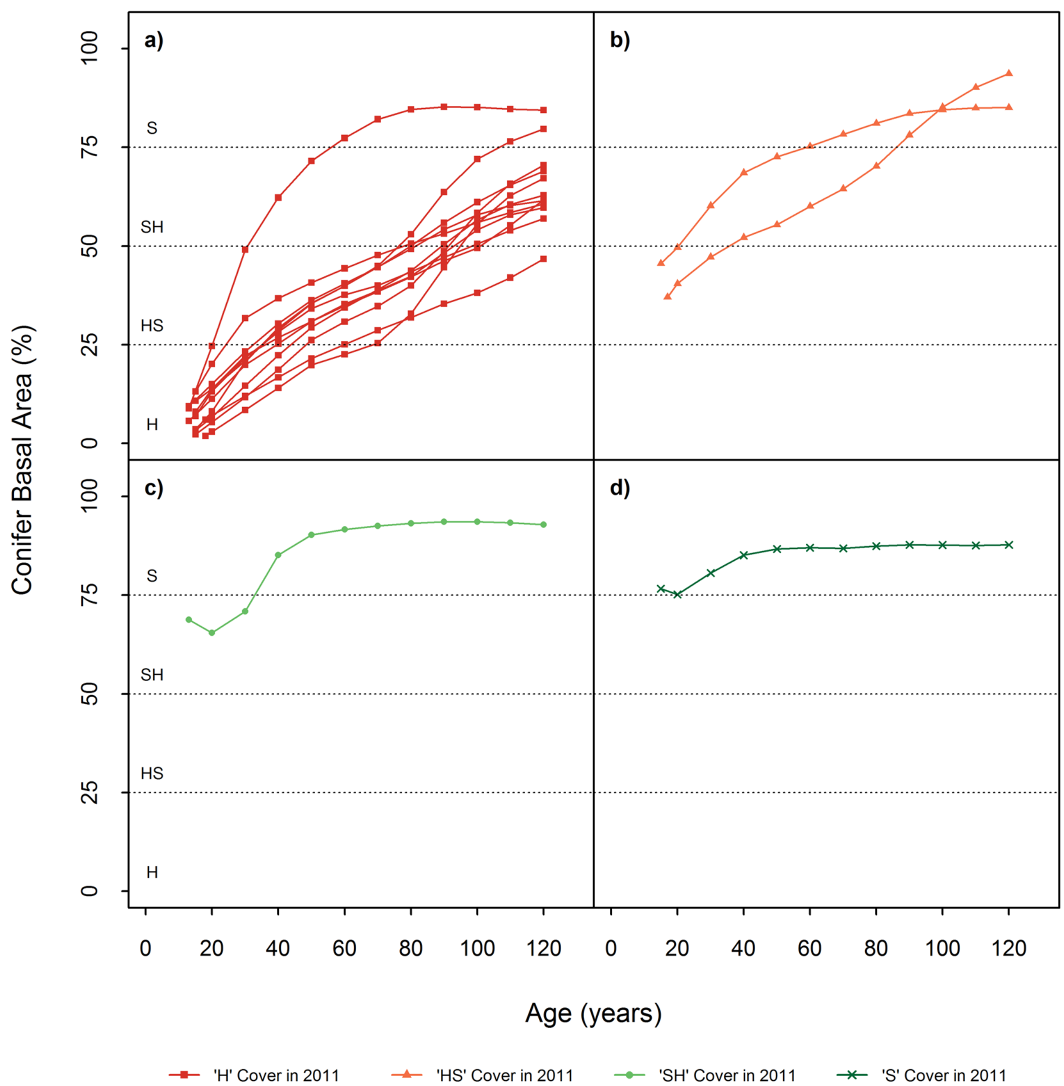


Figure A-7-3. MGM conifer succession across 16 TSP stands. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

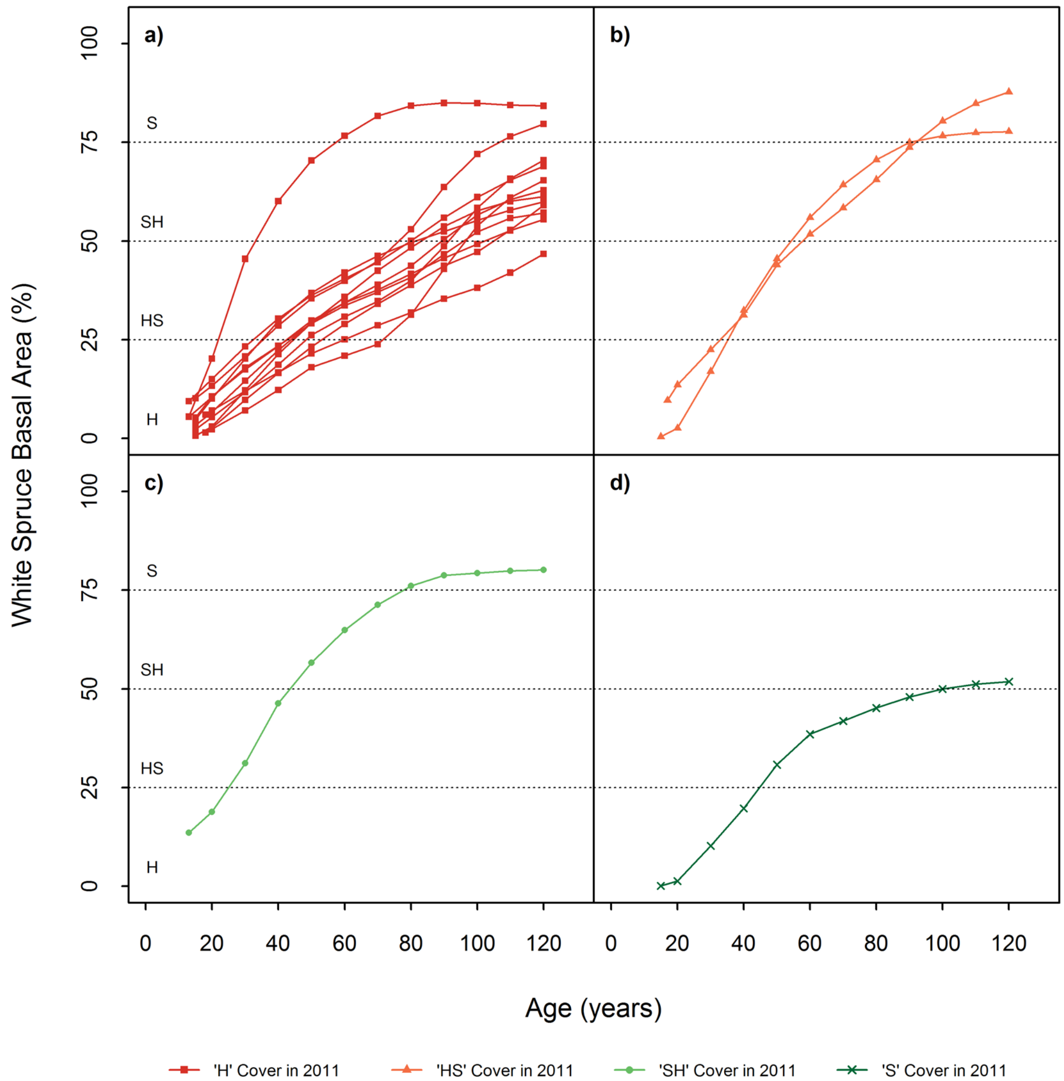


Figure A-7-4. MGM white spruce succession across 16 TSP stands. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-7-5. MGM conifer succession across 16 TSP stands: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 23 | | | |
| 0.5 | | | | | | | | | | | | 31 | | | | |
| 0.6 | | | 38 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 35 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 34 | | |
| 0.8 | | | | | | | | | | | | | | | | 40 |
| 1.1 | | | | | | 41 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 25 | | | | | | |
| 1.5 | | | | | | | | 40 | | | | | | | | |
| 1.8 | | | | | | | | | | | 77 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 35 | |
| 2.0 | | | | | | | | | 44 | | | | | | | |
| 4.2 | 87 | | | | | | | | | | | | | | | |
| 4.9 | | | | 60 | | | | | | | | | | | | |
| 5.9 | | 92 | | | | | | | | | | | | | | |
| 8.1 | | | | | 75 | | | | | | | | | | | |

Table A-7-6. MGM conifer succession across 16 TSP stands: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 45 | | | |
| 0.5 | | | | | | | | | | | | 49 | | | | |
| 0.6 | | | 47 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 48 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 50 | | |
| 0.8 | | | | | | | | | | | | | | | | 54 |
| 1.1 | | | | | | 56 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 35 | | | | | | |
| 1.5 | | | | | | | | 64 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 46 | |
| 2.0 | | | | | | | | | 53 | | | | | | | |
| 4.2 | 88 | | | | | | | | | | | | | | | |
| 4.9 | | | | 78 | | | | | | | | | | | | |
| 5.9 | | 94 | | | | | | | | | | | | | | |
| 8.1 | | | | | 84 | | | | | | | | | | | |

Table A-7-7. MGM conifer succession across 16 TSP stands: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 67 | | | |
| 0.5 | | | | | | | | | | | | 70 | | | | |
| 0.6 | | | 57 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 60 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 63 | | |
| 0.8 | | | | | | | | | | | | | | | | 61 |
| 1.1 | | | | | | 69 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 47 | | | | | | |
| 1.5 | | | | | | | | 80 | | | | | | | | |
| 1.8 | | | | | | | | | | | 84 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 62 | |
| 2.0 | | | | | | | | | 61 | | | | | | | |
| 4.2 | 88 | | | | | | | | | | | | | | | |
| 4.9 | | | | 94 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 85 | | | | | | | | | | | |

Table A-7-8. MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 1967 | 1220 | 3898 | 620 |
| | | Basal Area ($m^2$/ha) | 39.5 | 36.0 | 42.6 | 2.0 |
| | | Volume ($m^3$/ha) | 302.7 | 255.0 | 339.9 | 23.3 |
| | | Top Height (m) | 22.3 | 18.6 | 24.3 | 1.6 |
| | | Height (m) | 15.4 | 12.9 | 17.2 | 1.2 |
| | | DBH (cm) | 15.4 | 10.9 | 17.8 | 1.7 |
| | 90 | Density (Trees/ha) | 1071 | 709 | 1776 | 243 |
| | | Basal Area ($m^2$/ha) | 41.1 | 32.8 | 44.5 | 2.9 |
| | | Volume ($m^3$/ha) | 394.0 | 302.9 | 438.4 | 34.3 |
| | | Top Height (m) | 26.9 | 23.1 | 29.1 | 1.5 |
| | | Height (m) | 21.1 | 18.2 | 22.9 | 1.2 |
| | | DBH (cm) | 21.4 | 15.9 | 23.7 | 1.9 |
| | 120 | Density (Trees/ha) | 674 | 461 | 991 | 143 |
| | | Basal Area ($m^2$/ha) | 38.8 | 30.0 | 44.2 | 4.0 |
| | | Volume ($m^3$/ha) | 424.9 | 331.0 | 497.6 | 41.8 |
| | | Top Height (m) | 29.6 | 26.5 | 30.7 | 1.1 |
| | | Height (m) | 25.5 | 21.3 | 27.4 | 1.6 |
| | | DBH (cm) | 26.5 | 21.7 | 29.1 | 2.1 |
| BS | 60 | Density (Trees/ha) | 220 | 0 | 1218 | 335 |
| | | Basal Area ($m^2$/ha) | 1.2 | 0.0 | 9.6 | 2.4 |
| | | Volume ($m^3$/ha) | 5.6 | 0.0 | 47.3 | 11.7 |
| | | Top Height (m) | 3.2 | 0.0 | 12.4 | 3.7 |
| | | Height (m) | 3.0 | 0.0 | 11.1 | 3.4 |
| | | DBH (cm) | 2.9 | 0.0 | 11.1 | 3.2 |
| | 90 | Density (Trees/ha) | 100 | 0 | 576 | 160 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 8.2 | 2.0 |
| | | Volume ($m^3$/ha) | 5.0 | 0.0 | 51.4 | 12.7 |
| | | Top Height (m) | 3.9 | 0.0 | 15.4 | 4.6 |
| | | Height (m) | 3.8 | 0.0 | 14.6 | 4.5 |
| | | DBH (cm) | 3.6 | 0.0 | 14.5 | 4.2 |
| | 120 | Density (Trees/ha) | 82 | 0 | 427 | 127 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 7.8 | 1.9 |
| | | Volume ($m^3$/ha) | 5.6 | 0.0 | 55.5 | 13.8 |
| | | Top Height (m) | 4.4 | 0.0 | 17.0 | 5.2 |
| | | Height (m) | 4.3 | 0.0 | 16.5 | 5.2 |
| | | DBH (cm) | 4.1 | 0.0 | 16.1 | 4.7 |
| JP | 60 | Density (Trees/ha) | 41 | 0 | 172 | 69 |
| | | Basal Area ($m^2$/ha) | 1.8 | 0.0 | 11.2 | 3.7 |
| | | Volume ($m^3$/ha) | 14.8 | 0.0 | 96.2 | 31.1 |
| | | Top Height (m) | 3.9 | 0.0 | 15.9 | 5.7 |
| | | Height (m) | 3.8 | 0.0 | 15.7 | 5.6 |
| | | DBH (cm) | 4.5 | 0.0 | 21.8 | 7.7 |
| | 90 | Density (Trees/ha) | 13 | 0 | 95 | 29 |
| | | Basal Area ($m^2$/ha) | 1.1 | 0.0 | 8.2 | 2.5 |
| | | Volume ($m^3$/ha) | 10.9 | 0.0 | 76.7 | 24.7 |
| | | Top Height (m) | 4.0 | 0.0 | 19.0 | 6.9 |
| | | Height (m) | 4.0 | 0.0 | 19.0 | 6.9 |
| | | DBH (cm) | 5.0 | 0.0 | 26.4 | 9.5 |
| | 120 | Density (Trees/ha) | 9 | 0 | 70 | 21 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 6.8 | 2.1 |
| | | Volume ($m^3$/ha) | 9.7 | 0.0 | 68.0 | 22.0 |
| | | Top Height (m) | 3.6 | 0.0 | 20.6 | 7.7 |
| | | Height (m) | 3.6 | 0.0 | 20.6 | 7.7 |
| | | DBH (cm) | 4.8 | 0.0 | 28.5 | 10.4 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-7-8 (continued). MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect mesic ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 482 | 91 | 975 | 231 |
| | | Basal Area ($m^2$/ha) | 20.1 | 3.5 | 28.7 | 8.5 |
| | | Volume ($m^3$/ha) | 176.1 | 27.8 | 252.0 | 78.6 |
| | | Top Height (m) | 21.4 | 13.8 | 24.3 | 3.1 |
| | | Height (m) | 19.7 | 13.6 | 23.7 | 2.7 |
| | | DBH (cm) | 22.3 | 13.2 | 28.7 | 4.2 |
| | 90 | Density (Trees/ha) | 171 | 30 | 368 | 92 |
| | | Basal Area ($m^2$/ha) | 15.9 | 2.7 | 24.9 | 7.4 |
| | | Volume ($m^3$/ha) | 165.1 | 26.8 | 251.1 | 81.7 |
| | | Top Height (m) | 25.0 | 11.4 | 29.1 | 5.5 |
| | | Height (m) | 24.1 | 11.3 | 28.7 | 5.2 |
| | | DBH (cm) | 32.6 | 14.3 | 41.0 | 7.7 |
| | 120 | Density (Trees/ha) | 75 | 20 | 158 | 38 |
| | | Basal Area ($m^2$/ha) | 11.0 | 2.4 | 17.7 | 5.3 |
| | | Volume ($m^3$/ha) | 122.6 | 28.2 | 204.5 | 63.1 |
| | | Top Height (m) | 26.9 | 12.9 | 31.7 | 5.7 |
| | | Height (m) | 26.7 | 12.9 | 31.7 | 5.7 |
| | | DBH (cm) | 39.3 | 18.1 | 50.8 | 9.4 |
| WS | 60 | Density (Trees/ha) | 1224 | 511 | 3715 | 752 |
| | | Basal Area ($m^2$/ha) | 16.3 | 7.8 | 32.4 | 6.5 |
| | | Volume ($m^3$/ha) | 106.2 | 48.8 | 198.4 | 42.8 |
| | | Top Height (m) | 17.0 | 12.9 | 20.0 | 1.6 |
| | | Height (m) | 14.2 | 11.6 | 15.4 | 1.0 |
| | | DBH (cm) | 13.1 | 10.2 | 14.2 | 1.0 |
| | 90 | Density (Trees/ha) | 786 | 413 | 1722 | 320 |
| | | Basal Area ($m^2$/ha) | 23.2 | 13.6 | 34.6 | 6.5 |
| | | Volume ($m^3$/ha) | 213.1 | 122.1 | 326.4 | 61.2 |
| | | Top Height (m) | 24.0 | 18.6 | 26.8 | 1.8 |
| | | Height (m) | 20.9 | 17.3 | 22.0 | 1.2 |
| | | DBH (cm) | 19.3 | 15.3 | 21.0 | 1.3 |
| | 120 | Density (Trees/ha) | 508 | 300 | 954 | 166 |
| | | Basal Area ($m^2$/ha) | 26.0 | 15.5 | 34.7 | 5.7 |
| | | Volume ($m^3$/ha) | 287.0 | 169.6 | 378.1 | 63.7 |
| | | Top Height (m) | 28.7 | 22.1 | 30.6 | 1.9 |
| | | Height (m) | 26.2 | 21.2 | 27.2 | 1.5 |
| | | DBH (cm) | 25.4 | 20.7 | 27.9 | 1.7 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.

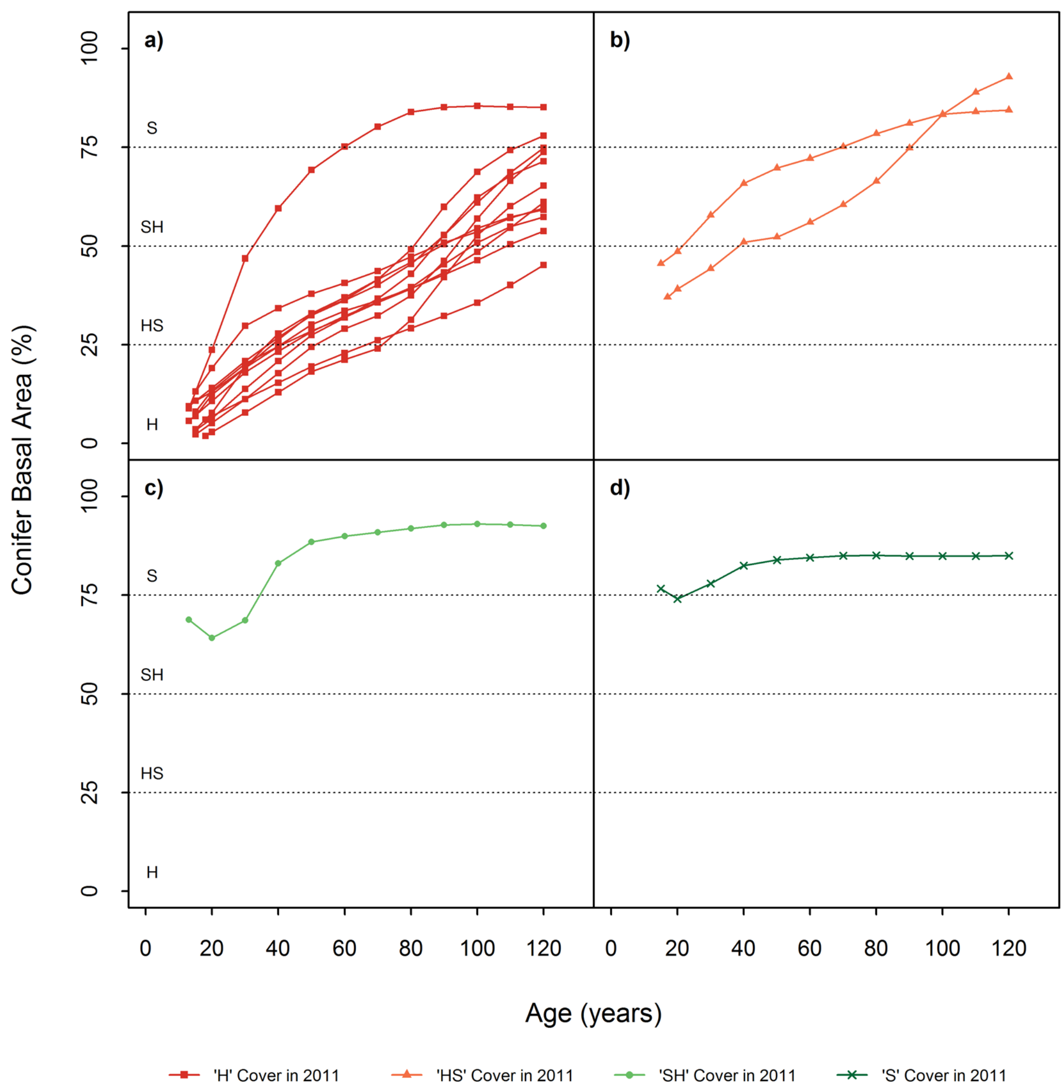


Figure A-7-5. MGM conifer succession across 16 TSP stands. Individual figures represent relative conifer basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

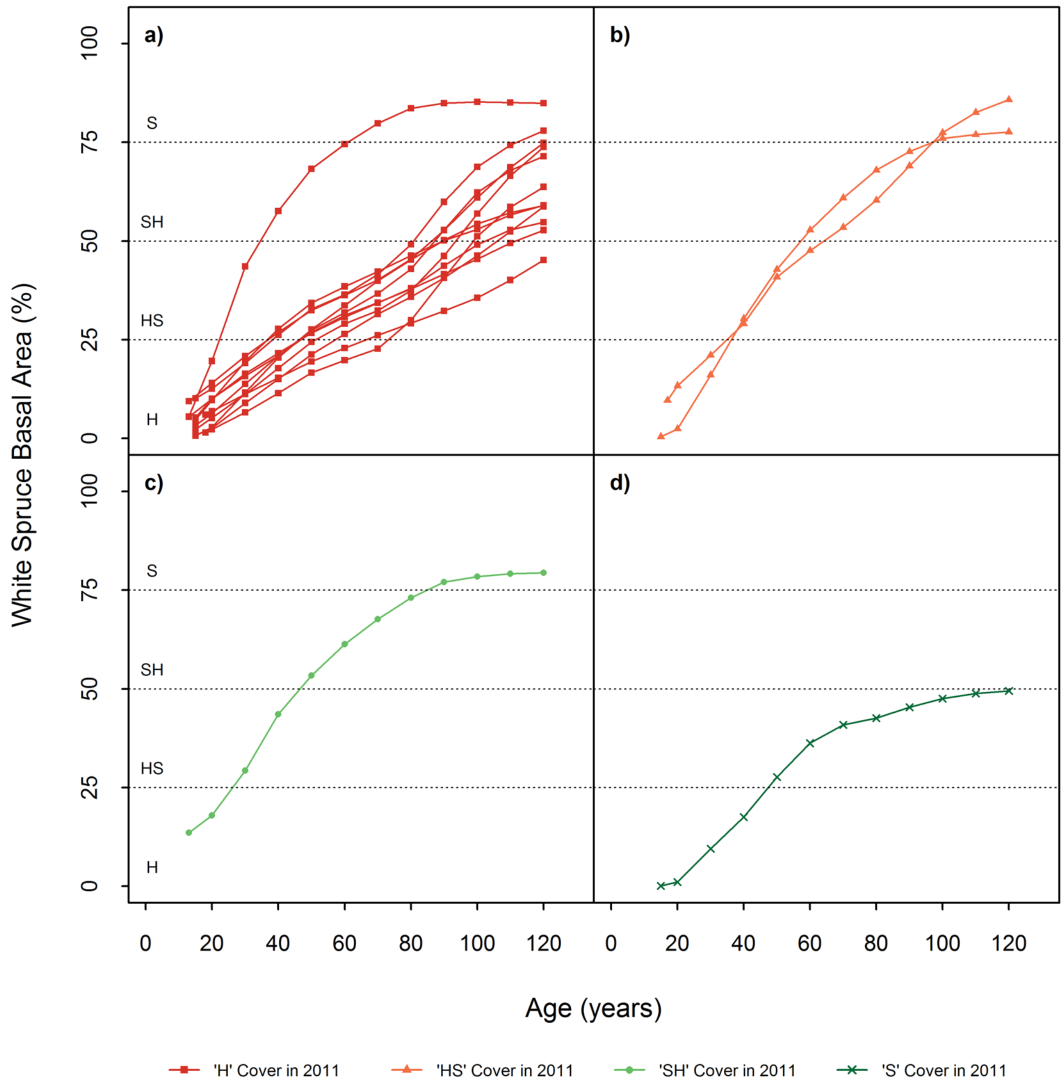


Figure A-7-6. MGM white spruce succession across 16 TSP stands. Individual figures represent relative white spruce basal area for a) hardwood-leading, b) hardwood-leading softwood, c) softwood-leading hardwood, and d) softwood-leading TSP stands from the 2011 measurement to stand age 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). H = Hardwood-leading; HS = Hardwood-leading softwood; SH = Softwood-leading hardwood; S = Softwood-leading.

Table A-7-9. MGM conifer succession across 16 TSP stands: Age 60 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 60: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 21 | | | |
| 0.5 | | | | | | | | | | | | 29 | | | | |
| 0.6 | | | 34 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 32 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 32 | | |
| 0.8 | | | | | | | | | | | | | | | | 37 |
| 1.1 | | | | | | 36 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 23 | | | | | | |
| 1.5 | | | | | | | | 36 | | | | | | | | |
| 1.8 | | | | | | | | | | | 75 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 32 | |
| 2.0 | | | | | | | | | 41 | | | | | | | |
| 4.2 | 84 | | | | | | | | | | | | | | | |
| 4.9 | | | | 56 | | | | | | | | | | | | |
| 5.9 | | 90 | | | | | | | | | | | | | | |
| 8.1 | | | | | 72 | | | | | | | | | | | |

Table A-7-10. MGM conifer succession across 16 TSP stands: Age 90 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 90: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 42 | | | |
| 0.5 | | | | | | | | | | | | 46 | | | | |
| 0.6 | | | 43 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 45 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 53 | | |
| 0.8 | | | | | | | | | | | | | | | | 50 |
| 1.1 | | | | | | 53 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 32 | | | | | | |
| 1.5 | | | | | | | | 60 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 43 | |
| 2.0 | | | | | | | | | 51 | | | | | | | |
| 4.2 | 85 | | | | | | | | | | | | | | | |
| 4.9 | | | | 75 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 81 | | | | | | | | | | | |

Table A-7-11. MGM conifer succession across 16 TSP stands: Age 120 relative conifer basal area (%) plotted against 2011 conifer and deciduous basal area. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). Cell colour indicates each stand's cover group at age 120: Red = Hardwood-leading; Orange/Yellow = Hardwood-leading softwood; Yellow/Green = Softwood-leading hardwood; Green = Softwood-leading.

| Deciduous BA ($m^2$/ha) in 2011 | 1.3 | 2.7 | 8.3 | 8.4 | 9.7 | 10.8 | 11.5 | 12.6 | 13.5 | 18.0 | 18.1 | 20.1 | 21.2 | 21.4 | 21.6 | 22.7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conifer BA ($m^2$/ha) in 2011 | | | | | | | | | | | | | | | | |
| 0.4 | | | | | | | | | | | | | 65 | | | |
| 0.5 | | | | | | | | | | | | 74 | | | | |
| 0.6 | | | 54 | | | | | | | | | | | | | |
| 0.7 | | | | | | | 57 | | | | | | | | | |
| 0.7 | | | | | | | | | | | | | | 71 | | |
| 0.8 | | | | | | | | | | | | | | | | 59 |
| 1.1 | | | | | | 75 | | | | | | | | | | |
| 1.2 | | | | | | | | | | 45 | | | | | | |
| 1.5 | | | | | | | | 78 | | | | | | | | |
| 1.8 | | | | | | | | | | | 85 | | | | | |
| 1.9 | | | | | | | | | | | | | | | 61 | |
| 2.0 | | | | | | | | | 60 | | | | | | | |
| 4.2 | 85 | | | | | | | | | | | | | | | |
| 4.9 | | | | 93 | | | | | | | | | | | | |
| 5.9 | | 93 | | | | | | | | | | | | | | |
| 8.1 | | | | | 84 | | | | | | | | | | | |

Table A-7-12. MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| ALL | 60 | Density (Trees/ha) | 1985 | 1173 | 4018 | 676 |
| | | Basal Area ($m^2$/ha) | 39.1 | 35.6 | 42.1 | 2.0 |
| | | Volume ($m^3$/ha) | 299.4 | 238.7 | 341.1 | 27.4 |
| | | Top Height (m) | 22.7 | 18.8 | 24.8 | 1.7 |
| | | Height (m) | 14.9 | 12.1 | 16.9 | 1.3 |
| | | DBH (cm) | 15.2 | 10.7 | 17.7 | 1.8 |
| | 90 | Density (Trees/ha) | 1118 | 699 | 1946 | 293 |
| | | Basal Area ($m^2$/ha) | 40.2 | 31.0 | 44.4 | 3.5 |
| | | Volume ($m^3$/ha) | 377.7 | 284.3 | 434.0 | 36.5 |
| | | Top Height (m) | 27.1 | 23.2 | 29.2 | 1.6 |
| | | Height (m) | 20.2 | 17.4 | 22.1 | 1.3 |
| | | DBH (cm) | 20.6 | 15.2 | 22.9 | 2.0 |
| | 120 | Density (Trees/ha) | 707 | 464 | 1065 | 171 |
| | | Basal Area ($m^2$/ha) | 37.7 | 28.6 | 44.3 | 4.7 |
| | | Volume ($m^3$/ha) | 401.9 | 308.6 | 489.6 | 46.4 |
| | | Top Height (m) | 29.1 | 26.2 | 30.3 | 1.0 |
| | | Height (m) | 24.5 | 20.6 | 26.3 | 1.6 |
| | | DBH (cm) | 25.5 | 20.8 | 28.5 | 2.1 |
| BS | 60 | Density (Trees/ha) | 248 | 0 | 1424 | 389 |
| | | Basal Area ($m^2$/ha) | 1.1 | 0.0 | 8.8 | 2.2 |
| | | Volume ($m^3$/ha) | 4.7 | 0.0 | 39.1 | 9.8 |
| | | Top Height (m) | 2.9 | 0.0 | 10.7 | 3.3 |
| | | Height (m) | 2.7 | 0.0 | 9.4 | 3.0 |
| | | DBH (cm) | 2.5 | 0.0 | 8.8 | 2.7 |
| | 90 | Density (Trees/ha) | 118 | 0 | 693 | 190 |
| | | Basal Area ($m^2$/ha) | 0.8 | 0.0 | 7.7 | 1.9 |
| | | Volume ($m^3$/ha) | 4.4 | 0.0 | 44.2 | 11.0 |
| | | Top Height (m) | 3.5 | 0.0 | 14.2 | 4.2 |
| | | Height (m) | 3.4 | 0.0 | 13.3 | 4.1 |
| | | DBH (cm) | 3.3 | 0.0 | 13.2 | 3.8 |
| | 120 | Density (Trees/ha) | 92 | 0 | 517 | 148 |
| | | Basal Area ($m^2$/ha) | 0.8 | 0.0 | 7.6 | 1.9 |
| | | Volume ($m^3$/ha) | 5.0 | 0.0 | 49.1 | 12.4 |
| | | Top Height (m) | 4.0 | 0.0 | 15.7 | 4.8 |
| | | Height (m) | 3.9 | 0.0 | 15.2 | 4.7 |
| | | DBH (cm) | 3.7 | 0.0 | 14.8 | 4.3 |
| JP | 60 | Density (Trees/ha) | 40 | 0 | 178 | 69 |
| | | Basal Area ($m^2$/ha) | 1.8 | 0.0 | 11.6 | 3.8 |
| | | Volume ($m^3$/ha) | 15.1 | 0.0 | 100.3 | 32.1 |
| | | Top Height (m) | 3.9 | 0.0 | 15.9 | 5.7 |
| | | Height (m) | 3.8 | 0.0 | 15.7 | 5.6 |
| | | DBH (cm) | 4.5 | 0.0 | 21.7 | 7.6 |
| | 90 | Density (Trees/ha) | 14 | 0 | 98 | 30 |
| | | Basal Area ($m^2$/ha) | 1.1 | 0.0 | 8.3 | 2.6 |
| | | Volume ($m^3$/ha) | 11.2 | 0.0 | 76.8 | 25.5 |
| | | Top Height (m) | 4.0 | 0.0 | 19.0 | 6.9 |
| | | Height (m) | 3.9 | 0.0 | 19.0 | 6.9 |
| | | DBH (cm) | 4.9 | 0.0 | 26.5 | 9.4 |
| | 120 | Density (Trees/ha) | 9 | 0 | 73 | 22 |
| | | Basal Area ($m^2$/ha) | 0.9 | 0.0 | 6.9 | 2.2 |
| | | Volume ($m^3$/ha) | 9.8 | 0.0 | 68.2 | 22.3 |
| | | Top Height (m) | 3.3 | 0.0 | 20.6 | 7.2 |
| | | Height (m) | 3.3 | 0.0 | 20.6 | 7.2 |
| | | DBH (cm) | 4.5 | 0.0 | 28.6 | 10.0 |

**Note:** SD = standard deviation; ALL = all species; BS = black spruce; JP = jack pine.

Table A-7-12 (continued). MGM summary statistics for 16 TSP stands projected to ages 60, 90, and 120. Site index estimates reflect subhygric ecosite classifications under Beckingham et al. (1996). To represent MGM's component species, black spruce includes balsam fir and tamarack, and trembling aspen includes balsam poplar and white birch.

| Species | Age | Variable | Mean | Min | Max | SD |
|---|---|---|---|---|---|---|
| TA | 60 | Density (Trees/ha) | 472 | 102 | 932 | 214 |
| | | Basal Area ($m^2$/ha) | 21.1 | 4.1 | 29.3 | 8.5 |
| | | Volume ($m^3$/ha) | 187.8 | 33.8 | 265.7 | 80.3 |
| | | Top Height (m) | 22.1 | 15.1 | 24.8 | 2.7 |
| | | Height (m) | 20.4 | 15.2 | 24.3 | 2.4 |
| | | DBH (cm) | 23.3 | 15.0 | 30.0 | 4.0 |
| | 90 | Density (Trees/ha) | 171 | 32 | 362 | 89 |
| | | Basal Area ($m^2$/ha) | 16.5 | 3.1 | 26.0 | 7.4 |
| | | Volume ($m^3$/ha) | 172.0 | 31.3 | 265.4 | 82.6 |
| | | Top Height (m) | 26.0 | 12.5 | 29.2 | 4.3 |
| | | Height (m) | 24.9 | 12.5 | 29.2 | 4.1 |
| | | DBH (cm) | 33.8 | 17.7 | 42.6 | 6.6 |
| | 120 | Density (Trees/ha) | 72 | 20 | 152 | 38 |
| | | Basal Area ($m^2$/ha) | 10.7 | 2.6 | 18.7 | 5.4 |
| | | Volume ($m^3$/ha) | 118.7 | 31.1 | 218.3 | 64.2 |
| | | Top Height (m) | 27.4 | 13.9 | 32.1 | 4.8 |
| | | Height (m) | 27.1 | 13.9 | 32.1 | 4.7 |
| | | DBH (cm) | 39.9 | 21.9 | 51.9 | 8.3 |
| WS | 60 | Density (Trees/ha) | 1225 | 504 | 3831 | 780 |
| | | Basal Area ($m^2$/ha) | 15.0 | 7.1 | 31.2 | 6.3 |
| | | Volume ($m^3$/ha) | 91.7 | 42.0 | 179.0 | 38.3 |
| | | Top Height (m) | 16.0 | 12.0 | 18.9 | 1.5 |
| | | Height (m) | 13.3 | 10.7 | 14.5 | 1.0 |
| | | DBH (cm) | 12.6 | 9.9 | 13.6 | 1.0 |
| | 90 | Density (Trees/ha) | 815 | 404 | 1894 | 363 |
| | | Basal Area ($m^2$/ha) | 21.7 | 12.4 | 34.5 | 6.7 |
| | | Volume ($m^3$/ha) | 190.1 | 106.3 | 310.0 | 60.4 |
| | | Top Height (m) | 22.9 | 17.6 | 25.7 | 1.7 |
| | | Height (m) | 19.8 | 16.3 | 20.9 | 1.2 |
| | | DBH (cm) | 18.4 | 14.6 | 20.1 | 1.3 |
| | 120 | Density (Trees/ha) | 533 | 309 | 1030 | 185 |
| | | Basal Area ($m^2$/ha) | 25.2 | 14.6 | 34.5 | 6.0 |
| | | Volume ($m^3$/ha) | 268.4 | 153.6 | 362.1 | 64.0 |
| | | Top Height (m) | 27.6 | 21.2 | 29.6 | 1.8 |
| | | Height (m) | 25.1 | 20.3 | 26.1 | 1.5 |
| | | DBH (cm) | 24.5 | 19.9 | 27.0 | 1.7 |

**Note:** SD = standard deviation; TA = trembling aspen; WS = white spruce.