University of Alberta

Growth and yield implications of site preparation, competition control, and climate in the western boreal forest

by

Francesco Cortini

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Forest Biology and Management

Renewable Resources

Spring 2011
Edmonton, Alberta

Abstract

The main goal of this thesis was to improve our understanding of the long-term effects of establishment treatments and climate change on lodgepole pine and white spruce growth in the western boreal forests. My dissertation also investigated the combined effects of climate and competition on white spruce and trembling aspen growth in boreal mixtures. In the first part of the thesis I evaluated the effects of site preparation treatments on growth of lodgepole pine and white spruce in north-eastern British Columbia. Results indicate that mechanical site preparation can provide yield gains of up-to 10 percent for pine and spruce at 60 and 80 years, respectively. These stands are showing a Type 1 growth response which implies that the treatment effect will eventually cease 90-100 years after planting. In the second part of the thesis I explored pine and spruce growth in relation to past climate and site preparation. Results indicate that up-to 45% and 37% of the respective variation in spruce and pine growth can be explained by selected climatic variables. Future projections indicated that height growth of young pine plantations in the sub-boreal zone could benefit (in the short term) from longer growing seasons by up-to 12% on untreated stands. Untreated young spruce plantations in the boreal zone may suffer height growth decreases of up-to 10% due to increased drought-stress. Vegetation control and mechanical site preparation treatments appear to mitigate effects of climate change to some extent. In the third part of the thesis I explored the combined effects of climate and trembling aspen competition on spruce and aspen growth using data from a long-term study in the boreal zone. Results indicate that climate variables and initial size of the tree can account for significant portions of the annual growth of spruce. Including an estimate of aspen competition in the equations improved the predictive ability of these models. Evidence of the inter-annual variability in aspen competitiveness on spruce and aspen growth indicates that the stress-gradient hypothesis can be applied in boreal mixedwood forests.

Acknowledgments

I would like to gratefully acknowledge my supervisor Dr. Phil Comeau, whose expertise, understanding, and patience, added considerably to my graduate experience. His careful assistance in writing this thesis is very much appreciated. I would also like to thank my other committee members Dr. Andreas Hamann and Dr. Vic Lieffers for the assistance they provided. Special thanks also go to the two external members Dr. Chris Hawkins and Dr. Peter Kershaw.

I would like to express my gratitude to Jacob Boateng, John McClarnon, Allan Powelson, Gordon Nigh, Richard Kabzems, George Harper, Jim Goudie, Greg O’Neill and Dave Spittlehouse of the Ministry of Forests and Range (MFR) of British Columbia (BC), Canada, for their thoughtful and detailed comments on the early drafts of this manuscript. Special thanks also go to Cezary Slugocki, Amanda Nemec, Marvin Grismer, Fred Klassen, Torsten Kaffanke, Ken Polsson, Peter Ott, Susan Salokannel, Stephen Davis, Gurp Thandi, and Alf Kivari for their assistance and support.

Funding for this project was partially provided by the Forests for Tomorrow program within the Forest Practices Branch of the MFR of BC. I would like to express my gratitude to Richard Kabzems and Teresa Newsome of MFR, and the WESBOGY Association for providing the data used to validate the results in the third chapter of this thesis. I would like to thank the WESBOGY Association also for providing the data used in the fourth chapter.

Finally, I would like to thank my family and friends for their continual support and encouragement to pursue this Ph.D. degree.

Table of Contents

Chapter 3. Effects of climate on growth of lodgepole pine and white spruce following site preparation and its implications in a changing climate……....69

Chapter 4. Climate and competition effect on white spruce and trembling aspen growth in mixtures……………………………………………………..136

List of Tables

Chapter 2

Chapter 3

Chapter 4

List of Figures

Chapter 2

Chapter 3

<u>Chapter 4</u>

Chapter 1. Introduction

1.1. General Introduction

Forecasts of forest productivity indicate that the change in the output of global forest products as a consequence of global warming will range from modest increases to a slight decrease with large regional variability around the global trend (Easterling et al., 2007). Given the uncertainty related to the effects of the current climatic changes on forest productivity some silviculturits suggest enhancing the ecological resilience of forest ecosystems by managing for complexity through the maintenance and development of heterogeneity in ecosystem structure, composition and function (Puettmann et al., 2008), as Franklin (1989) also suggested two decades ago. Many scientists concur on the need for more research at the stand level in order to better understand the response of each tree species to climate change and to identify forest management techniques that can mitigate or harness these effects (Kimmins, 2008, Spittlehouse, 2008; Hebda, 2009; Williamson et al., 2009). This Ph.D. thesis endeavours to address some of these questions and provide some practical answers to forest managers on the long term impact of site preparation and climate change on forest productivity in northern British Columbia (Canada).

The establishment of conifers in boreal and sub-boreal forests is often limited by unfavourable soil or microsite conditions and competing vegetation (Lavender et al., 1990; Grossnickle, 2000). Site preparation treatments and the control of competing vegetation (i.e.: manual brushing, herbicide treatments or fire) have the potential to improve growth and survival of the crop tress by inducing changes to soil conditions and vegetation (Boateng and Herring, 1990; Hawkes et al., 1990; Morris and Lowery, 1988). Improvements in seedling survival and growth during the first 10 years after planting following site preparation could result in increased yield at the end of the rotation (Örlander et al., 1990). Management of competing vegetation has already shown to produce significant wood yield gains in Pacific north-western forests (Wagner et al., 2006). Despite these potential benefits increasing areas of the Canadian forests are being established without postharvest site preparation or vegetation control due to a general shift toward less expensive and intensive management techniques (Hawkins et al., 2006; Wang et al., 2003).

Given the uncertainty related to the long term effect of silvicultural treatments, various management options need to be evaluated using growth models, with a firm foundation in science, in order to create sound estimates of growth and yield responses (Snowdon and Waring, 1984; Stage, 2003; Mason and Dzierzon, 2006). Growth models are a very important tool in silviculture and they vary in mechanistic rigor, organization, temporal resolution, spatial explicitness, and scope (Schwalm and Ek, 2001). Models can be divided in three main categories: 1) Process-based (or mechanistic) models; which are defined as the procedure that derives the behaviour of a system from functional components, and their interactions with each other and the environment through physical and mechanistic processes (Mäkelä et al., 2000), 2) Empirical models such as forest yield models, which are built from observations, and 3) Hybrid models, which ideally merge the best features of processed-based physiological model with an empirically based yield model (Monserud, 2003). Yield models assume that the environmental conditions don't change which is in contrast with the recent climate change scenarios, as a result hybrid models have greater potentials in modelling forest growth under the current warming (Monserud, 2003).

To evaluate the growth of lodgepole pine (*Pinus contorta* Dougl. Ex Loud. Var. *latifolia* Engelm.) and white spruce (*Picea glauca* (Moench) Voss) in northern British Columbia the models available, among others, are TASS/TIPSY (Mitchell, 1975; Mitchell et al., 1992), and MGM (Bokalo et al., 2005) which are empirical yield models calibrated for the boreal forests of western Canada, for even aged pure conifer stands and mixedwood stands, respectively. FORECAST (Kimmins et al., 1999) is a hybrid model management-oriented, stand-level forest growth and ecosystem dynamics simulator that will soon incorporate climate parameters (Blanco et al., 2007).

Growth models can provide information on the long-term productivity of our forests and these projections can then be classified according to their 'type' of growth response to treatments. A Type 1 growth response is characteristic of silvicultural treatments that reduce the time needed for the stand to reach a given stage of maturity, and a Type 2 response implies a real gain in volume increment at the end of the rotation period (Snowdon and Waring, 1984). Later models have added complexity to the classification and more ‘types’ of growth responses have been created. For example, a Type C characterizes non effective treatments that lead to an overall decrease in stand volume (Morris and Lowery, 1988; Kyle et al., 2005; South and Miller, 2007). In order to classify the type of growth response the age-shift method, growth multipliers, and site index adjustment have been used to study the long term response of planted conifers to a given silvicultural treatment (Hamilton and Rehfeldt, 1994; Mason and Milne, 1999; South et al., 2006; South and Miller, 2007).

Chapter two investigates the growth response (i.e.: Type 1, Type 2) of various site preparation treatments for lodgepole pine and white spruce in north-eastern British Columbia. Three techniques (i.e.: age-shift, growth multipliers and site index adjustments) have been evaluated coupled with the information on growth and yield provided by the selected growth model TASS/TIPSY (Mitchell, 1975; Mitchell et al., 1992).

Specific objectives include:

1. Evaluate the predictive ability of three modeling techniques (i.e.: the age-shift method, growth multipliers, and site index adjustments).
2. Test and compare results to simulated rotation-length growth responses generated by the Tree and Stand Simulator model (TASS).

3. Compare the simulated growth response to PSP (Permanent Sampled Plot) data and recently harvested blocks within the same biogeoclimatic sub-zone and variant of British Columbia.

The specific research questions that will be answered in Chapter two are:

1. What type of growth response do different site preparation techniques show 20 years after planting and at the end of the rotation period?
2. How do establishment treatments influence future stand volume?
3. What are the implications of different approaches (i.e.: age-shift, growth multiplier, and site index adjustment) on estimation of treatment effects on yield?

Conifer growth is also largely affected by climate (Monserud et al. 2006), and in light of the current global warming it is important to improve our understanding of the relationship between climate and tree growth (IPCC, 2007). The global climatic trend affects a wide range of species and ecosystems (Walther et al., 2002; Parmesan and Yohe, 2003), especially in northern regions (sub-boreal, boreal and sub-arctic) (Zhou et al., 2001; Lloyd and Fastie, 2003). Studies have shown that the inclusion of climatic parameters can improve the predictive ability of growth models (Snowdon et al., 1999; Snowdon, 2001; Woollons et al., 1997), and now that more accurate global climate model simulations are available (Wang et al., 2006; Flato and Boer, 2001) there is an opportunity to explore the growth of future stands (Snowdon, 2001; Chhin et al., 2008).

Chapter three investigates the explanatory capability of various climate parameters on growth of lodgepole pine, and white spruce in north-eastern British Columbia. The baseline information for this study came from data collected on 20-year-old (or more) site preparation trials at several locations in British Columbia: in the sub-boreal region for lodgepole pine and the boreal region for white spruce (Bedford and McMinn, 1990). In addition a large number of trials from British Columbia and Alberta were used to validate the models. ClimateBC software has provided the climate data for the studied sites starting from latitude, longitude and elevation using a scale-free mathematical climate model (Daly et al., 2002; Hamann and Wang, 2005; Mitchell and Jones, 2005; Wang et al., 2006). Moreover the impact of climate change on future conifer productivity has been evaluated by projecting growth using future climate scenarios provided by the most recent global climate model simulations.

Specific objectives include:

1. Evaluate the predictive ability of climate variables divided by time scale (i.e.: annual, seasonal, and monthly) on conifer growth.
2. Evaluate which conifer growth measure (i.e.: height, diameter, basal area, volume) is better correlated to climate variables.
3. Validate the climate-growth modes developed using data from similar trials across a broader latitudinal range.
4. Project future conifer growth according to two scenarios (i.e.: A2 and B2) and evaluate growth responses to climate change.

The specific research questions that will be addressed in Chapter three are:

1. Which growth factor (i.e.: height, diameter, and volume) shows better correlations with climate variables?
2. Which of the selected climatic variable will show the best correlation with growth?
3. How effective are climate variables in predicting conifer growth?
4. How might the growth of lodgepole pine and white spruce be affected by climate change?
5. How could site preparation treatments influence responses of lodgepole pine and white spruce to climate change?

Our ability to estimate the influence of different tending practices on stand development depends on our understanding of key factors such as competition (Comeau et al., 2003), and the effect of climate on conifer growth. Competing vegetation is often considered to be a limiting factor in the process to maximize the yield of selected crop trees, but it has been shown to increase nutrient availability and to provide protection from extreme weather conditions (e.g., Stathers and Spittlehouse 1990; Simard et al. 1997).

In the boreal forests of North America, after a disturbance such as fire or clear-cutting, white spruce seedlings are often mixed with abundant trembling aspen regeneration (Peterson and Peterson, 1992). Aspen tends to dominate the stand for the first six decades while the more shade-tolerant spruce grows slowly under the main canopy layer (Peterson and Peterson, 1992). The frequency of facilitative versus competitive interactions among species across abiotic stress gradients has stimulated a large number of studies (i.e.: stress-gradient hypothesis) (e.g., Callaway and Walker, 1997; Maestre et al. 2005). The basic idea is that facilitation is more common in plant communities developing under high physical stress with high consumer pressure, and where the physical environment is relatively benign and consumer pressure is low positive interactions are less common and competitive interactions are the dominant structuring forces (Bertness and Callaway, 1994).

This chapter will explore in depth the combined effect of climate and trembling aspen competition on white spruce and trembling aspen growth using data from the long-term study established by the Western Boreal Growth and Yield association (WESBOGY). The findings from this study will contribute to a better understanding of the key limiting factors to early growth of mixed spruce and aspen plantations and the combined effects of climate and aspen abundance.

Specific objectives include:

1. Investigate white spruce growth at seven sites in relation to representative climate variables.
2. Evaluate the predictive ability of two methods commonly used to select the climate variables to include in the growth models.

3. Evaluate linear and non-linear equations relating spruce growth to both representative climate variables and competition estimates.
4. Investigate the variability of aspen basal area competitive pressure on spruce growth at the site level.

The specific research questions that will be answered in Chapter four are:

1. Are the local differences in climate able to explain significant portions of the variability in growth of white spruce from year to year?
2. When selecting the most representative climatic variables which method will show the best correlation with growth?
3. Does the inclusion of a competition estimate in predicting spruce growth using climatic variables improve the overall predictive ability of the model?
4. Does the stress gradient hypothesis also apply for the boreal forests of western North America?

1.2. References

Bedford, L., McMinn, R.G., 1990. Trials to appraise the biological effectiveness of mechanical site preparation equipment in British Columbia: FRDA Project 1.10. p. 3±12. In: Titus, B.D., Lavigne, M.B., Newton, P.F., Meades, W.J. (Eds.). The Silvics and Ecology of Boreal Spruces. 1989 IUFRO Working Party S1. 05±12 Proc. Symp. For. Can., St. John's, Newfoundland, Inf. Rep. N-X-271.

Bertness, M., Callaway, R.M., 1994. Positive interactions in communities. Trends in Ecology and Evolution 9: 191-193.

Blanco, J.A., Seely, B., Welham, C., Kimmins, J.P.H., Seebacher, T.M., 2007. Testing the performance of a forest ecosystem model (FORECAST) against 29 years of field data in a Pseudotsuga menziesii plantation. Canadian Journal of Forest Research 37: 1808-1820.

Boateng, J.O., Herring, L.J., 1990. Site preparation: Chemical. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia’s Forests (pp.164-178). University of British Columbia Press. Vancouver 1990.

Bokalo, M., Titus, S.J., Stadt, K.J., 2005. Mixedwood Growth Model. URL: http://www.rr.ualberta.ca/research/mgm/mgm.htm.

Callaway, R.M., Walker, L.R., 1997. Competition and facilitation: a synthetic approach to interactions in plant communities. Ecology 78: 1958-1965.

Chhin, S., Hogg, E.H., Lieffers, V.J., Huang, S., 2008. Potential effects of climate change on the growth of lodgepole pine across diameter size classes and ecological regions. Forest Ecology and Management 256: 1692-1703.

Comeau, P.G., Wang, J.R., Letchford, T., 2003. Influences of paper birch competition on growth of understorey white spruce and subalpine fir following spacing. Canadian Journal of Forest Research 33: 1962-1973.

Daly, C., Gibson, W.P., Taylor, G.H., Johnson, G.L., Pasteris, P., 2002. A knowledge-based approach to the statistical mapping of climate. Climate Research 22(2): 99-113.

Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, J. Schmidhuber, and F.N. Tubiello. 2007. Food, fiber and forest products. In *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental Panel on Climate Change*. Ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J.

van der Linden and C.E. Hanson. Cambridge, U.K.: Cambridge University Press, 273-313.

Flato, G.M., Boer, G.J., 2001. Warming asymmetry in climate change simulations. Geophysical Research Letters 28: 195–198.

Franklin, J.F., 1989. Towards a new forestry. American Forests 95: 37–44.

Grossnickle, S.C., 2000. Ecophysiology of Northern Spruce Species: The Performance of Planted Seedlings. NRC Research Press, Ottawa, Ontario, Canada. 409pp.

Hamann, A., Wang, T.L., 2005. Models of climatic normals for genecology and climate change studies in British Columbia. Agricultural and Forest Meteorology 128(3-4): 211-221.

Hamilton, D.A., Rehfeldt, G. E., 1994. Using individual tree growth projection models to estimate stand-level gain attributable to improved stock. Forest Ecology and Management 68: 189-207.

Hawkes, B.C., Feller, M.C., Meehan, D., 1990. Site preparation: Fire. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia's

Forests (pp.131-149). University of British Columbia Press. Vancouver 1990.

Hawkins, C.B.D., Steele, T.W., Letchford, T., 2006. The economics of site preparation and the impacts of current forest policy: evidence from central British Columbia. Canadian Journal of Forest Research 36: 482-494.

Hebda, R.J., 2009. The future of British Columbia forests requires resilience management. *In:* Drengson, A., and Taylor, D. 2009. Wild Foresting: practising nature's wisdom. New Society Publishers. pp. 202-209.

International Panel on Climate Change (IPCC). Climate change 2007: synthesis report: summary for policymakers: an assessment of the intergovernmental panel on climate change. Valencia, Spain: IPCC; 2007. http://www.ipcc.ch/.

Kimmins, J.P., Mailly, D., Seely, B., 1999. Modelling forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. Ecological Modellling 122: 195–224. doi:10.1016/S0304-3800(99)00138-6.

Kimmins, J.P., 2008. From science to stewardship: Harnessing forest ecology in the service of society. Forest Ecology and Management 256: 1625-1635.

Kyle, K.H., Andrews, L.J., Fox, T.R., Aust, W.M., Burger, J.A., Hansen, G.H., 2005. Long-term effects of drainage, bedding, and fertilization on growth of loblolly pine (*Pinus taeda* L.) in the Coastal Plain of Virginia. Southern Journal of Applied Forestry 29: 205–214.

Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., Winston, D., 1990. Regenerating British Columbia's Forests. University of British Columbia Press. Vancouver 1990.

Lloyd, A.H., Fastie, C.L., 2003. Recent changes in treeline forest distribution and structure in interior Alaska. Ecoscience 10(2): 176-185.

Maestre, F.T., Valladares, F., Reynolds, J.F., 2005. Is the change of plant-plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. Journal of Ecology 93: 748-757.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågen, G.r.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Canadian Journal of Forest Research 20: 289-298.

Mason, E.G., Milne, P.G., 1999. Effects of weed control, fertilization, and soil cultivation on the growth of Pinus radiate at mid-rotation in Canterbury, New Zealand. Canadian Journal of Forest Research 29: 985–992.

Mason, E.G., Dzierzon H. 2006. Applications of modelling to vegetation management. Canadian Journal of Forest Research 36: 2505–2514.

Mitchell, K.J., 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monograph 17. 39 p.

Mitchell, K.J., Grout, S.E., McDonald, R.N., Watmough, C.A., 1992. User's Guide for TIPSY: A Table Interpolation for Stand Yields. BC Ministry of Forests, Victoria, BC, p. 78.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25(6): 693-712.

Monserud, R.A., 2003. Evaluating Forest Models in a sustainable Forest Management context. FBMIS Vol 1, 35-47.

Monserud, R.A., Shongming, H., Yuqing, Y., 2006. Predicting lodgepole pine site index from climatic parameters in Alberta. Forestry Chronicle 82: 562-571.

Morris, L.A., Lowery R.F., 1988. Influence of site preparations on soil conditions affecting stand establishment and tree growth. Southern Journal of Applied Forestry 12(3):170 –178.

Örlander, G., Gemmel, P., Hunt, J., 1990. Site preparation: a Swedish overview. For. Can. and B.C. Min. For., Victoria, BC. FRDA Rep. No. 105.

Peterson E.B., Peterson, N.M., 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces. Can. For. Serv. North. For. Cent. Spec. Rep. 1.

Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918): 37-42.

Puettmann, K.J., Coates, K.D., Messier, C., 2008. A critique of silviculture: managing for complexity. Island Press. 206 p.

Schwalm, C.R., Ek, A.R., 2001. Climate change and site: relevant mechanisms and modeling techniques. Forest Ecology and Management 150: 241-257.

Simard, S., Molina R., Smith J.E., Perry D.A., Jones, M.D., 1997. Shared compatibility of ectomycorrhizae on *Pseudotsuga menziesii* and *Betula papyrifera* seedlings grown in mixture in soils from southern British Columbia. Canadian Journal of Forest Research 27: 331-342.

Snowdon, P., 2001. Short-term predictions of growth of *Pinus radiate* with models incorporating indices of annual climatic variation. Forest Ecology and Management 152: 1-11.

Snowdon, P., Waring, H.D., 1984. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In: Grey, D.C., Shönau, A.P.G., Shutz, C.J. (Eds.), Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations, 30 April–11 May, Pretoria and Pietermaritzberg, South Africa. Forest Research Institute, Pretoria, pp. 701–711.

Snowdon, O., Jovanovic, T., Booth, T.H., 1999. Incorporation of indices of annual climatic variation into growth models for *Pinus radiate*. Forest Ecology and Management 117: 187-197.

Stathers, R.J., Spittlehouse, D.L., 1990. Forest soil temperature manual. Queen's Printer, Victoria, B.C. For. Resour. Dev. Agree. Rep.130.

South, D.B., Miller, J.H., Kimberly, M.O., Vanderschaaf, C.L., 2006. Determining productivity gains from herbaceous vegetation management with 'age-shift' calculations. Forestry 79: 43–56.

South, D.B., J.H. Miller, 2007. Growth response analysis after early control of woody competition for 14 loblolly pine plantations in the southern U.S. Forest Ecology and Management 242: 569–577.

Spittlehouse, D.L., 2008. Climate Change, impacts, and adaptation scenarios: climate change and forest and range management in British Columbia. B.C. Min. For. Range, Res. Br., Victoria, B.C. Tech. Rep. 045.

Stage, A.R., 2003. How forest models are connected to reality: evaluation criteria for their use in decision support. Canadian Journal of Forest Research 33: 410–421.

Wagner, R.G., Little, K.M., Richardson, B., McNabb, K., 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry 79:57-79.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416(6879): 389-395.

Wang, S., van Kooten, G.C., Wilson, B., 2003. Silvicultural practices and costs in coastal British Columbia: a case study. Tree Planters Notes 50: 50–57.

Wang, T., Hamann, A., Spittlehouse, D.L., Aitken, S.N., 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climatology 26(3): 383-397.

Williamson, T.B., Colombo, S.J., Duinken, P.N., Gray, P.A., Hennessey, R.J., Houle, D., Johnston, M.H., Ogden, A.E., Spittlehouse, D.L., 2009. Climate change and Canada's forests: from impacts to adaptation. Sustain. For. Manag. Netw. and Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. 104 p.

Woollons, R.C., Snowdon, P., Mitchell, N.D., 1997. Augmenting empirical stand projection equations with edaphic and climatic variables. Forest Ecology and Management 98: 267-275.

Zhou, L.M., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., Myneni, R.B., 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. Journal of Geophysical Research-Atmospheres 106(D17): 20069-20083.

Chapter 2. Yield implications of site preparation treatments for lodgepole pine and white spruce in northern British Columbia

(A shortened version of this chapter has been published as: *Cortini, F., Comeau, P.G., Boateng, J.O., and Bedford, L., 2010. Forests 2010, 1, 25-48*)

2.1. Introduction

Site preparation and the management of competing vegetation are of primary importance for the successful growth and survival of conifers in the northern regions of Canada (e.g., Bedford and Sutton, 2000; Bedford et al., 2000; Walstad and Kuch, 1987). Improvements in seedling survival and growth during the first 10 years after planting following site preparation can result in a substantial increase in yield (Örlander et al., 1990). Likewise the management of competing vegetation has the potential to produce significant gains in yield (Wagner et al., 2006).

In boreal and sub-boreal forests the establishment of planted conifers is often limited by unfavorable soil or microsite conditions and competing vegetation such as green alder (*Alnus crispa* (Ait.) Pursh.), willow (*Salix* spp.), trembling aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.) (e.g., Grossnickle, 2000; Lieffers et al., 1993; Macadam and Kabzems, 2006; Shropshire et al., 2001; Spittlehouse and Stathers, 1990).

Mechanical site preparation can modify these unfavorable conditions for conifer establishment by: 1) scalping, which removes the organic layer and exposes mineral soil, 2) mixing, which incorporates the organic layer into the underlying mineral soil, and 3) inverted mounds, which turns the surface organic layer upside down and the inverted organic layer may be covered with mineral soil (McMinn and Hedin, 1990).

By modifying the soil surface layer, these treatments can result in earlier warming of soils in the spring which effectively lengthens the growing season (Örlander et al., 1990). Exposure of mineral soil can improve heat exchange between the ground and the surface air, leading to reductions in frost injury to planted seedlings (Örlander et al., 1990). Mounding treatments create planting spots that are raised (higher than the ground level), which reduces the risk of flooding damage (McMinn and Hedin, 1990). Moreover scalping treatments create a vertical profile of planting spots such as berms (raised planting spot favorable on wet sites), hinge (at ground level), and trenches or furrows (depressed planting spots favorable on dry sites) (McMinn and Hedin, 1990). Site preparation treatments can also decrease soil bulk density, improve drainage, accelerate nutrient availability and enhance microsite conditions overall (Örlander et al., 1990).

Burning is used to remove organic material from an area in order to provide a better environment for the growth and survival of crop trees (Hawkes et al., 1990).

This treatment can increase the short term (<5 years) availability of nutrients in the soil and also reduce competing vegetation (Lidenburgh, 1990). However, slash-burning following a harvest may cause long-term nutrition losses on drier nutrient-poor sites (Lidenburgh, 1990).

Control of competing vegetation through manual brushing or herbicide treatments often provides an environment favorable to crop tree establishment (Boateng and Herring, 1990). There are many studies which have demonstrated the benefits of vegetation control in enhancing tree growth (Wagner et al., 2006). However, in some areas vegetation control alone may not be effective in ameliorating unfavorable microsite conditions such as cold soils or frost problems (Stathers, 1989).

The long term effect of site preparation on crop yield at rotation age is still largely unknown, and needs to be addressed so that forest managers will have the ability to estimate growth and yield responses for economic and ecological comparison between various management options (Mason and Dzierzon, 2006; Snowdon and Waring, 1984). While the long term effect of site preparation can be evaluated using growth models (Stage, 2003), few models directly address the effects of site preparation. There are currently no growth models available for northern B.C. that directly incorporate effects of site preparation or vegetation management on tree growth and stand dynamics.

Establishment and tending treatments can have variable effects on long term development and yield of plantations. These growth characteristics are represented in the literature by the concept of Type 1 and 2 growth responses (Snowdon and Waring, 1984). A Type 1 growth response occurs when the establishment treatment, or more generally the silvicultural treatment, reduces the time needed for the stand to reach a given stage of maturity. Type 2 response is obtained when a proportional gain in volume increment is achieved throughout the rotation period (Figure 2.1).

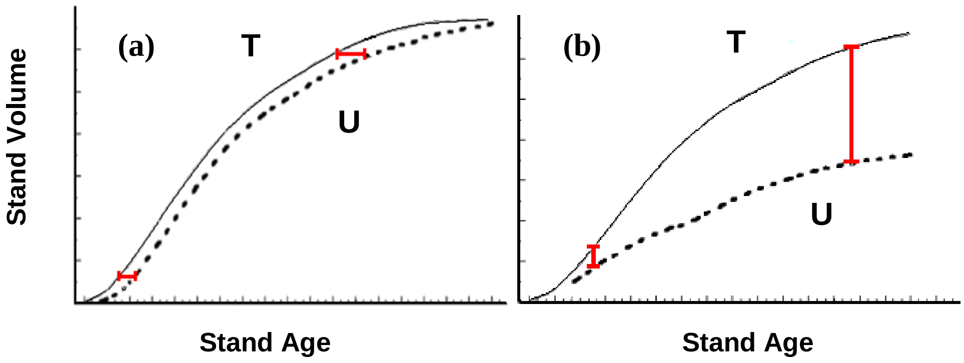


Figure 2.1. Examples of Type 1 **(a)** and Type 2 **(b)** growth response respectively (modified from South and Miller, 2007). The solid line represents the stand that underwent treatment (T) in relation to the untreated stand (U).

Later models have added complexity to the classification, and more ‘types’ of growth response models have been proposed including Type C, which characterizes non effective treatments that lead to an overall decrease in stand yield (South and Miller, 2007; Morris and Lowery, 1988).

In the late 1980s several experiments were established in northern British Columbia (B.C.) to evaluate effects of a variety of mechanical and non-mechanical site preparation techniques on crop tree response (Bedford and McMinn, 1990). Over the past 20 years these trials have provided information not only on early stand development of lodgepole pine (*Pinus contorta* Dougl. Ex Loud. Var. *latifolia* Engelm.), and white spruce (*Picea glauca* (Moench) Voss) plantations but also on plant community composition and diversity (Haeussler et al., 1999; Haeussler et al., 2002).

These trials offer the opportunity to address the long-term effect of site preparation treatments such as fire, mechanical and vegetation control methods on growth of lodgepole pine, and white spruce (e.g., Type 1 or Type 2 growth responses). The objective of this study is to evaluate the ability of three modeling techniques (i.e., the age-shift method, growth multipliers, and site index adjustments) to predict conifer growth which will be tested and compared to simulated rotation-length growth responses generated by the Tree and Stand Simulator model (TASS/TIPSY) (Mitchell, 1975). These projected volumes will be also compared to data from Permanent Sample Plots (PSPs) and recently harvested cut blocks.

2.2. Experimental Design

2.2.1. Study sites, treatments and measurements

The data for this project was obtained from long term trials (20-year-old) in the boreal and sub-boreal forests of British Columbia (B.C.) where various mechanical and non-mechanical site preparation techniques were applied (Bedford and McMinn, 1990).

Data for lodgepole pine was from the Bednesti trial. Bednesti is situated 60 km west of Prince George B.C. (53° $52'$ N, 123° $29'$ W) at an elevation of 850 m in the Stuart Dry Warm variant of the Sub-Boreal Spruce Zone (SBSdw3) (DeLong et al., 1993). It is a mesic site with loamy soil containing 10-20% coarse fragments, and 3-6 cm forest floor at the time of treatment. The previous stand composed of lodgepole pine and black spruce (*Picea mariana* (Mill.) B.S.P) was harvested in 1971. The site was not regenerated with crop trees and was classified as not satisfactorily restocked. Grasses, shrubs, and non-commercial broadleaved trees dominated the site. During the winter of 1986 all vegetation was sheared, piled into windrows, and burned (MacKenzie et al., 2005).

At Bednesti, nine site preparation techniques are compared in a randomized block design. One 750 m^2 plot of each nine treatments was established between burned windrows in each of five blocks. In each plot 48 trees were assessed and monitored. The treatments represented are: 1) control, trees were planted without site preparation, 2) burned windrow, trees planted in well burned areas free of slash, 3) patch shoulder, trees planted into the hinge of relatively deep patches, 4) Bräcke mineral mounds, trees planted into the center of the mound, 5) Delta disk trenching hinge-planting, trees planted in mineral soil at the edge of the berm, 6) Delta disk trenching furrow-planting, trees were planted into the mineral soil at the bottom of the trench, 7) Wadell cone scarifying, trees were planted into the mineral soil between the trench and the berm, 8) breaking plow, trees were planted deeply into berms of mineral soil overlying inverted forest soil, and 9) bedding plow, trees were planted in roughly mixed mineral soil and chunks of forest floor (Bedford and Sutton, 2000). Site preparation treatments were applied between August and October of 1987, and the site was planted with lodgepole pine (PSB 221 1+0) in April of 1988. Trees were measured annually for diameter and height up to 15 years of age and measured again at age 20. Survival rate of planted trees was very good: five years after planting survival ranged between 92% and 100% and 20 years after planting between 80% and 93%.

Data for white spruce comes from the Inga Lake trial located 85 km northwest of Fort Saint John in north-eastern B.C. ($56^\circ\ 37'$ N, $121^\circ\ 38'$ W) at an elevation of 890 m in the Peace variant of the moist warm subzone of the Boreal White and Black Spruce Zone (BWBSmw1) (DeLong et al., 1990). Soils are fine clayey to fine loamy basal till, with a 2-4 cm forest floor at the time of the treatment. The site where the trial was located was never harvested but regularly burned until the

1950s which resulted in a willow-dominated vegetation community that was sheared in winter 1987 (Boateng et al., 2009).

The study has a randomized complete block design with seven treatments randomly allocated to 750 m^2 plots in five blocks. In each plot 48 trees were assessed and monitored. The treatments represented are: 1) control, trees were planted without site preparation, 2) burned windrow, trees planted in well burned areas free of slash, 3) Madge, trees planted in well-mixed layer of surface organic matter and mineral soil, 4) bedding plow, trees were planted in roughly mixed mineral soil and chunks of forest floor, 5) breaking plow, trees were planted deeply into berms of mineral soil overlying inverted forest soil, 6) Delta disk trenching hinge-planting, trees planted in mineral soil at the edge of the berm, 7) vegetation control, three years after shearing and planting, herbicide was applied followed by six manual cuttings (Boateng et al., 2009). Site preparation treatments were applied in July to October 1987 and the site was planted at the end of May to first week of June 1988 with white spruce (PSB 313 2+0). Trees were measured annually for diameter and height up to 15 years of age and measured again at age 20. Survival rate of planted trees was very good: five years after planting survival ranged between 97% and 99% and 20 years after planting between 82% and 98%.

2.2.2. Modeling methods

Three growth variables were used to determine the type of growth response for each treatment: mean height, mean diameter (at ground level), and mean stand volume per hectare. Stem volume (SV, cm^3) was calculated from stem height (HT, cm) and root collar diameter (RCD, cm) using a modified version of Honer's equation (Honer et al., 1983):

$$SV = \frac{RCD^{a}}{b + \frac{c}{HT}}$$

where a, b, and c are parameters calculated by Cortini and Comeau (2008) for lodgepole pine and white spruce plantations in north-western Alberta. By comparing the growth of the control treatment to the growth of the other treatments at any given time, it was possible to analyze the growth characteristics of the two species investigated.

In order to classify the type of growth response three techniques were tested: 1) the age-shift method (acceleration), which quantifies how much sooner a particular size is reached due to the treatment effect, 2) growth multipliers, which represent the treatment effect as the ratio of treated to untreated, and 3) site index adjustments, which imply that the treatment leads to a change in site productivity (South and Miller, 2007; Hamilton and Rehfeldt, 1994; Mason and Milne, 1999; South et al., 2006). The Tree and Stand Simulator (TASS v2.07.61ws) growth model and the Table Interpolation Program for Stand Yields (TIPSY v4.1) growth and yield program provided the growth and yield projections for lodgepole pine and white spruce (Mitchell, 1975; Mitchell et al., 1992).

For the age shift method, a linear regression: $y = a + bx,$ where y is defined by conifer growth and x represents stand age, was fit to data from the untreated plots. This model was then used for each treatment to calculate the stand age relative to the untreated stand for the measured growth value (i.e., $x = (y - a)/b$). The age-shift values were then calculated for each treatment as the difference between stand age values of the measured growth minus the calculated stand age relative to the untreated. When calculating the age-shift value the maximum size (volume per hectare, average diameter or average height) of the untreated stand defines the limit at which the age-shift can be calculated. For example, if the average diameter of the untreated stand is 15 cm at age 20 but the burn treatment reaches 15 cm at age 12, the age-shift value of the burn can be calculated only up-to age 12 in order to avoid extrapolating beyond the available dataset.

The growth multiplier (G.M.) factor was calculated as the ratio between the mean size in the treated block (i*) and the mean size of the untreated (i) (i.e., G.M. = i*/i) (Hamilton and Rehfeldt, 1994). Site index adjustments were calculated using the growth intercept method described by Nigh (1995) for lodgepole pine and Nigh (2004a) for white spruce. The growth intercept method can provide site index estimates for young stands by relating the average height growth rates of trees to site index; accordingly, site index was calculated for each treatment and the control.

The information provided by the three approaches (age-shift method, growth multiplier, and site index adjustments) was analyzed in the TASS/TIPSY growth model to calculate tree growth for the studied sites. The site index values calculated at stand age 19 or 20 were projected in TIPSY to provide estimates of top height for each treatment from age 19 or 20 to the end of the rotation period. This information was then modeled by TASS with customized runs using actual information from the trials. For this study TASS input parameters were customized by using plot data to describe the number of trees per hectare up-to age 20, spatial tree distribution, height-age curves, and site index.

The effect of competing vegetation was also considered. Overall lodgepole pine growth at age 14 was not affected by competing vegetation (Bedford and Sutton, 2000) at the Bednesti site. Therefore the site index value calculated at age 20 for each treatment was used without modifications in the TASS runs.

For white spruce at the Inga site the delta hinge treatment and the untreated plots were affected by competing vegetation through age 20. For the delta hinge treatment the projected growth was not modified from age 20. For the untreated plots, Boateng et al. (2009) indicate that the overtopped white spruce at age 20 is expected to be taller than competing vegetation at stand age 26. Consequentially, growth increments may differ from age 26. Therefore, for the untreated plots, three possible scenarios were tested. Up to age 25 the growth of white spruce for the untreated plots was projected based on the site index value calculated at age

20, and from age 26: for scenario A the top height-age curve of the best treatment (herbicide) was shifted from age 20 to that of the untreated at age 26 (simple age-shift), and for scenario B the top height-age curve of the slower growing treatment (breaking plow) was shifted from age 20 to that of the untreated at age 26. These two scenarios assume that once the untreated trees are above the competing vegetation they will grow faster and follow the curve of either the best site preparation treatment (herbicide) (Scenario A), or the less effective site preparation treatment (breaking plow) (Scenario B). The third scenario (C) projects the growth of the untreated using the site index value at stand age 20 without modifying the growth curve at age 26.

2.2.3. Validation

The information generated by TASS on growth and yield was then compared with inventory data for naturally regenerated stands from PSP data for the same biogeoclimatic sub-zone and variant of British Columbia. Only the PSPs having more than 80% lodgepole pine or white spruce were selected in order to be representative of the experimental trials. Stand age of the PSPs is measured at breast height (1.3 m) therefore it was necessary to estimate stand total age of the PSPs to match that of the TASS outputs. For these untreated plots to reach breast height it takes on average: six years for lodgepole pine at the Bednesti trial and 10 years for white spruce at the Inga Lake trial. In addition the seedlings were 2 years old at planting. These factors required adjusting stand age of the PSPs by 8 years for lodgepole pine, and by 12 years for white spruce.

Smith (1988) reports that the natural regeneration delay for lodgepole pine cut blocks in west central Alberta ranges from seven to 11 years while for white spruce the length of time required to reach breast height under open conditions ranges from 10 to 20 years depending on the site (Nienstaedt and Zasada, 1990). Nigh (2004b) developed juvenile height models for British Columbia which indicate that lodgepole pine reaches breast height in 5-10 years and white spruce in 10-15 years. The information provided by TASS was compared to the PSP data as: 1) total stand volume per hectare versus top height, and 2) total stand volume per hectare versus stand age.

The merchantable volumes projected by TASS were also compared against harvested volumes billed to the Revenue Branch of the B.C. Ministry of Forests and Range for the period 2005-2009 (Personal communication with Stephen Davis, Reporting Analyst of the Revenue Branch. December 16, 2009). The selected cut blocks are located close to the experimental trials within the same forest district (i.e., Prince George for pine and Peace for spruce). Additional information such as harvested area and vegetation survey was acquired from the Reporting Silviculture Updates and Land Status Tracking System (RESULTS, B.C. Ministry of Forests, British Columbia, Canada. Data extracted as of December 17, 2009. Data on RESULTS available at: http://www.for.gov.bc.ca/his/results/). For both lodgepole pine and white spruce only cut blocks with more than 75% of each species were selected. Information relating to the last available survey was also collected including trees per hectare, site index and crown closure which is calculated by photo interpretation and then verified on the ground.

The harvested volumes provided by the Revenue Branch include logs of all grades billed to the Crown. The logs are measured by weight-scaling to inside bark diameter of 10 cm (Scaling Manual of British Columbia, 2008). Merchantable volume is calculated in TASS using 12.5 cm as minimum diameter at breast height, 10 cm as minimum top diameter inside bark, and 30 cm as minimum stump height. Knowing that the merchantable volumes calculated by TASS projected the growth of fully stocked stands (crown closure: 100%) I calculated for the selected cut blocks the relative merchantable volume to that of the TASS runs at age 90 for pine and 130 for spruce (i.e., age-class midpoints of the cut blocks). The relative merchantable volume of the cut blocks was then compared to the average value of crown closure provided by the surveys.

2.3. Results and Discussion

2.3.1. Lodgepole pine results

For lodgepole pine ages 9 and 15 were used to explore age-shift changes over the measured period (Table 2.1).

Table 2.1. Age-shift values calculated for lodgepole pine at stand ages 9 and 15 for volume, diameter, and height.

Treatment	*Age-shift*					
	Volume per ha		Diameter		Height	
	Yr 9	Yr 15	Yr 9	Yr 15	Yr 9	Yr 15
Bedding Plow	1.4	1.9	2.4	3.5	1.4	2.5
Bräcke Mineral Mound	1.1	2.4	0.5	1.3	0.0	0.8
Patch Shoulder	1.0	1.9	0.5	1.4	0.1	0.6
Breaking Plow	0.6	-0.8	1.0	1.5	0.8	1.8
Burn	2.0	4.3	3.1	4.9*	1.8	2.6
Delta Berm Hinge	1.4	2.5	1.3	2.1	0.8	1.4
Delta Furrow	0.1	-1.5	-1.2	-1.2	-1.0	-0.9
Wadell Hinge	1.3	2.8	1.4	2.7	0.8	1.8
Untreated	-	-	-	-	-	-

*Yr 14

The smallest age-shift value calculated is -1.5 years for the delta furrow treatment at age 15, indicating that volume growth in this case is slower than that of the untreated, while the largest age-shift value calculated is 4.9 years for diameter in the burn treatment at age 15, indicating faster diameter growth compared to the untreated. For every treatment, age-shift values calculated from diameter are larger than those related to height, and values calculated at age 15 are substantially larger than values calculated at age 9. The burn treatment is consistently the best treatment while the delta furrow treatment shows the worst performance compared to the untreated.

Growth multipliers were compared at stand ages 9, 15, and 20. Volume multipliers range between 0.9x (delta furrow) and 1.7x (burn) at age 20. For every treatment the growth multipliers for diameter are consistently higher than those related to height. Growth multipliers also indicate that the burn treatment is the more productive compared to the untreated, and the delta furrow is the least productive. Every treatment shows an initial shift in growth compared to the untreated, but after age 5, treatments tend to follow growth patterns similar to that of the untreated (Figure 2.2).

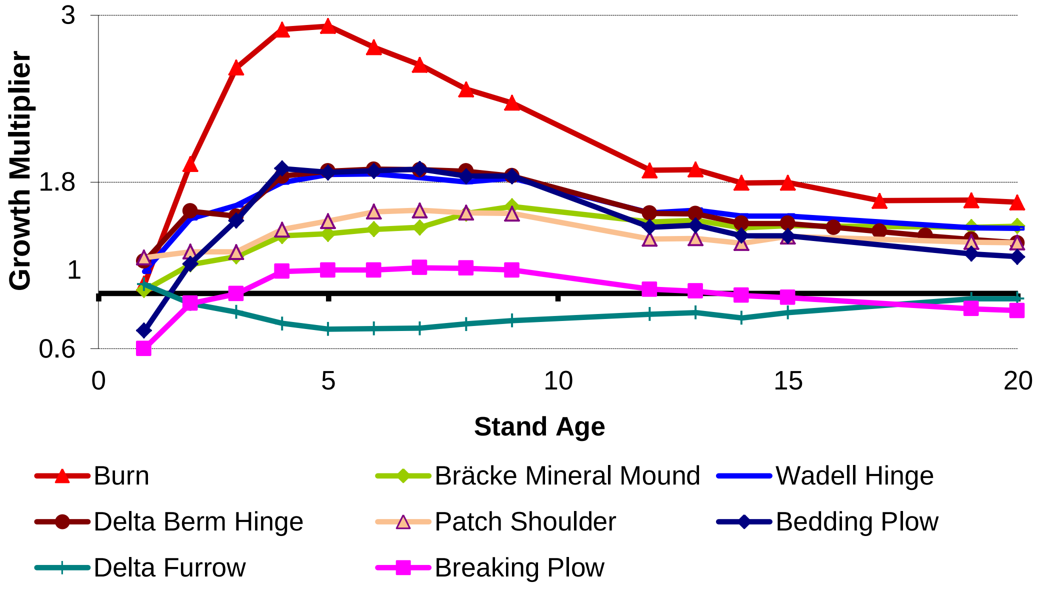


Figure 2.2. Changes in growth multipliers for lodgepole pine stem volume (m^3 ha^{-1}) with age for treatments applied at the Bednesti site.

Every treatment (except the delta furrow treatment) shows a decreasing growth multiplier factor from year 9 to year 20. Growth multipliers calculated at ages 4-8 for all treatments (except the delta furrow treatment) are higher than values obtained at ages 18-20. For the burn treatment the multiplier is 2.9x at age 5 but declines to 1.7x at age 20.

The site index adjustments show that site index values are fairly constant at the treatment level and the changes from age 9 to 20 range from -0.6 (patch shoulder) to 0.7 m (mineral mound and untreated) (Table 2.2). At year 20 the bedding plow treatment shows the highest site index value compared to the untreated (0.8 m difference); and again the delta furrow is the worst performing treatment compared to the untreated (-0.4 m difference).

The growth estimates for lodgepole pine provided by TASS/TIPSY show small differences at age 90 between treatments and untreated. Volume growth multipliers were calculated from age 27 forward and results show that each treatment converges by age 90 to the untreated (Appendix 1).

Table 2.2. Site index adjustments calculated for lodgepole pine at stand ages 9, 15 and 20.

Treatment	*Site Index*			*Difference with Untreated*		
	Yr 9	Yr 15	Yr 20	Yr 9	Yr 15	Yr 20
Bedding Plow	22.4	22.2	22.2	1.6	0.8	0.8
Bräcke Mineral Mound	21.1	21.8	21.8	0.4	0.5	0.4
Patch Shoulder	22.0	21.8	21.4	1.3	0.5	0.0
Breaking Plow	21.6	21.9	21.8	0.9	0.6	0.4
Burn	22.0	21.9	22.1	1.3	0.5	0.7
Delta Berm Hinge	22.0	21.7	21.6	1.2	0.3	0.3
Delta Furrow	21.1	20.4	21.0	0.4	-1.0	-0.4
Wadell Hinge	21.7	22.4	22.0	1.0	1.1	0.6
Untreated	20.7	21.4	21.4	-	-	-

Maximum mean annual increment (MAI) occurs on average at stand age 55.6 and corresponds to average merchantable volume of 284 m^3ha^{-1} and top height of 20 m (Table 2.3). The bedding plow and the breaking plow treatment reach maximum MAI earlier than the untreated and the other treatments with resulting age-shifts of 7 and 2 years, respectively. They are represented in both cases by a 1.1 growth multiplier factor. The narrow range of growth multiplier values (i.e., 0.9-1.1) indicates that model estimates of volume for every treatment at culmination are within 10% of that of the untreated.

Table 2.3. Results from TASS simulations of lodgepole pine at age of maximum mean annual increment (MAI).

Treatment	Age at Max MAI	Merch.Vol. $m^3\ ha^{-1}$	*Age-shift from Untreated*	*Growth Multiplier*	Top Height *m*
Bedding Plow	48	258	7	1.1	18.5
Bräcke Mineral Mound	59	300	-4	1	20.7
Patch Shoulder	62	299	-7	1	20.9
Breaking Plow	53	284	2	1.1	20
Burn	55	292	0	1	20.5
Delta Berm Hinge	56	279	-1	1	20.2
Delta Furrow	56	271	-1	1	18.7
Wadell Hinge	57	296	-2	0.9	20.6
Untreated	55	275	-	-	20.1

For lodgepole pine, the PSP data indicates that the projections provided by TASS/TIPSY are representative of young naturally regenerated stands (up-to stand age 20), but overestimate the growth of natural stands after age 40 (Figure 2.3). According to the projections at stand age 60 every treatment shows a growth multiplier factor of either 1.0 or 1.1 indicating a marginal or small treatment effect (Table 2.4 and Appendix 1).

Lodgepole pine information provided by the recent cut blocks in the same forest district indicates an average merchantable volume of 260 m^3 ha^{-1} (age-class: 81-100) and the latest available survey indicates an average crown closure of 62% (Table 2.5). For these cut blocks the merchantable volume relative to that projected by TASS (at 100% crown closure) is 62% which is the same value as the averaged crown closure for the selected cut blocks.

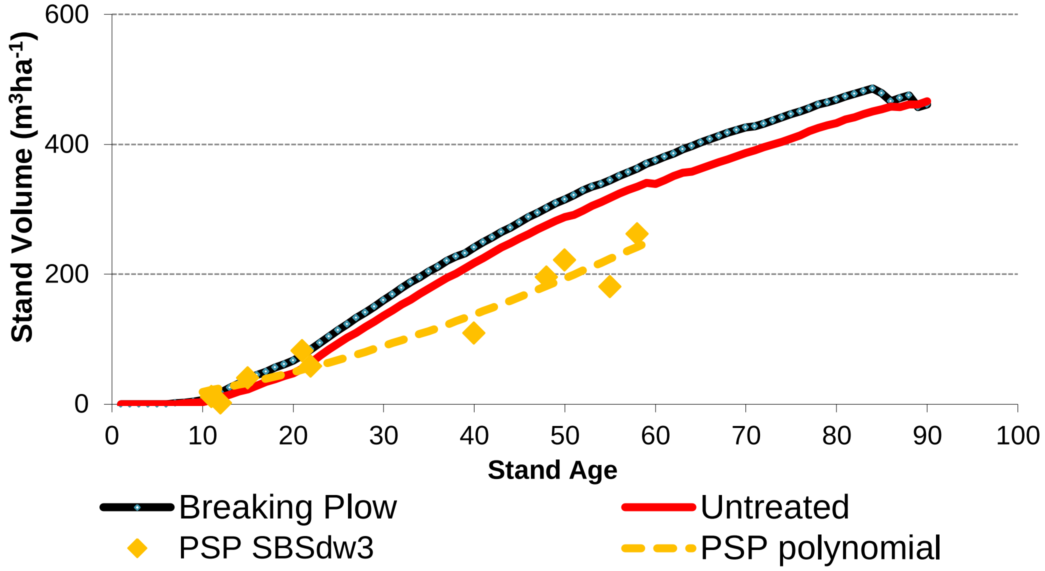


Figure 2.3. Projected stand volume over stand age for lodgepole pine for the best treatment (breaking plow) and the untreated scenario. The PSP data represents measured volume of natural stands in the same biogeoclimatic subzone and variant (SBSdw3). The polynomial fitting the PSP data is represented by: $Y = 1.27554*X+0.06359*X^2-0.00023*X^3$ (n=10; Adj.R2=0.96; P<0.0001).

Table 2.4. Stand yield data from TASS simulations to age 60 for lodgepole pine together with growth multiplier values.

Treatment	Stand Age	Density *Trees ha^{-1}*	Total Volume *m^{3} ha^{-1}*	Merch. Vol. *m^{3} ha^{-1}*	Basal Area *m^{3} ha^{-1}*	Top Height *m*	*Growth Multiplier*
Bedding Plow	60	1185	372	327	47.2	21	1.1
Bräcke Mineral Mound	60	964	344	306	45.3	20.8	1
Patch Shoulder	60	1015	327	288	44.4	20.6	1
Breaking Plow	60	1426	375	324	48.6	21.3	1.1
Burn	60	1073	360	319	46.1	21.5	1.1
Delta Berm Hinge	60	1052	341	301	45.7	21	1
Delta Furrow	60	1060	330	290	44.5	19.4	1
Wadell Hinge	60	1064	353	312	46.1	21.2	1
Untreated	60	1133	339	298	45.1	21	-

Table 2.5. Merchantable volumes from recently harvested cut blocks of pure lodgepole pine for the Prince George Forest District (DPG) (Source: Database of Revenue Branch, and RESULTS database of Forest Practices Branch, BC Ministry of Forests and Range).

									Latest Survey			
Latitude, Longitude	BEC Zone	Merch. Volume *m^3*	Harvested *Year*	Pine *%*	Age-Class	Area *ha*	**Merch. Volume** *m^3 ha^{-1}*	Year	Pine *%*	**Crown Closure** *%*	Trees *ha^{-1}*	Site Index *m*
54° 13' 8.4" N, 123° 16' 4.8" W	SBS	23064	2009	83	81-100	99	**232**	2001	100	60	1042	19
54° 14' 28.2" N, 123° 30' 11" W	SBS	19077	2009	80	81-100	75	**254**	2003	100	70	790	19
54° 13' 17.8" N, 123° 18' 32" W	SBS	28994	2009	86	81-100	105	**276**	2001	100	60	1042	19
54° 14' 47.9" N, 123° 29' 4.3" W	SBS	31917	2009	93	81-100	114	**279**	2001	90	60	1045	18
				Average Values:			**260**			**62**		

2.3.2. White spruce results

For white spruce stand ages 6 and 11 were selected to compare age-shift values over the measured period (Table 2.6). Age-shift values range from 0.3 years for the herbicide treatment at age 6, indicating that height growth in this case is close to that of the untreated, to 10.9 years for the burn treatment at age 11, indicating much faster volume growth compared to that of the untreated. The burn treatment is consistently the best treatment and the delta hinge is by far the worst in comparison to the untreated. For the majority of the treatments age-shift values for diameter are higher than those related to height and values calculated at age 11 are larger than at age 6 except for volume per hectare for the delta hinge treatment.

Table 2.6. Age-shift values calculated for white spruce at stand ages 6 and 11 for volume, diameter, and height.

	Age-shift					
Treatment	Volume per ha		Diameter		Height	
	Yr 6	Yr 11	Yr 6	Yr 11	Yr 6	Yr 11
Bedding Plow	1.9	3.7	1.5	6.4	1.6	7.0
Breaking Plow	2.5	7.1	4.0	9.2*	2.8	10.0
Burn	2.8	10.9	4.3	8.3**	2.4	10.1
Delta Hinge	1.9	1.1	0.7	1.4	0.7	2.5
Herbicide	1.8	9.3	0.6	7.8**	0.3	8.2
Madge	2.3	6.0	2.3	10.4*	1.8	7.8
Untreated	-	-	-	-	-	-

* Year 10 **Year 9

Growth multipliers were compared at ages 6, 11, and 20 and results show that the volume multiplier values range between 2.2x (delta hinge) and 8x (burn) at age

20. For the majority of the treatments, growth multipliers for diameter are larger than those related to height. Growth multipliers increase to age 20 and indicate that the treatment effect steadily enhances spruce growth up to age 20 compared to the untreated (Figure 2.4). The burn is overall the best treatment although the diameter values for the herbicide and the height values for the breaking plow treatment are similar to those for the burn. The delta hinge still represents the worst treatment in relation to the untreated.

The site index adjustments show that site index values decrease from age 11 to age 20 with differences between the two ages ranging from -0.8 (bedding plow) to -2.7 m (herbicide) (Table 2.7). At year 20 the herbicide shows the highest site index value (25.5) which is 6.5 m higher than that of the untreated. The worst treatment is the still the delta hinge with a site index equal to the untreated (19).

For white spruce the growth projections included three scenarios for the untreated plots and volume growth multipliers were calculated from age 27 on. For scenario A and B the growth curve of every treatment (except delta hinge) converges to the untreated scenario by age 85. For scenario C most treatments have a higher volume at age 85 than the untreated (1.3x) although the growth multiplier curve is gradually approaching a value of 1.0x (Appendix 1).

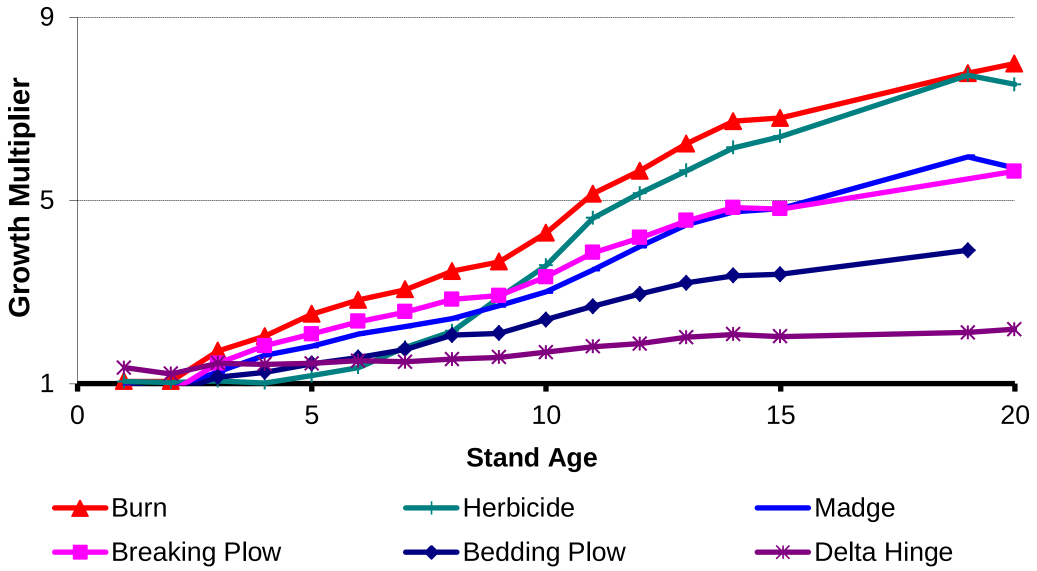


Figure 2.4. Changes in growth multipliers for white spruce stem volume (m^3 ha^{-1}) with age for treatments applied at the Inga Lake site.

Table 2.7. Site index adjustments calculated for white spruce at stand ages 11 and 20.

Treatment	*Site Index*		*Difference with Untreated*	
	Yr 11	Yr 20	Yr 11	Yr 20
Bedding Plow	25.3	24.5*	4.4	5.5
Breaking Plow	25.3	24.1	4.4	5.1
Burn	25.6	24.7	4.7	5.7
Delta Hinge	21.1	19.0	0.2	0.0
Herbicide	28.2	25.5	7.3	6.5
Madge	26.5	24.7	5.6	5.7
Untreated	20.9	19.0	-	-

* Yr 19

The maximum mean annual increment (MAI) for white spruce occurs at stand age 68.5 on average and corresponds to an average merchantable volume of 505 m^{3}ha$^-$

^{1} and a top height of 27.3 m (Table 2.8). The bedding plow treatment reaches maximum MAI earlier (61) than the other treatments and the three projections for the three untreated scenarios; and the worst treatment is the delta hinge that reaches maximum MAI at age 86. The growth multiplier values indicate that a group of treatments (bedding plow, breaking plow, burn, herbicide, and Madge) show similar MAI values while the delta hinge and the untreated (depending on the scenario) have lower MAIs.

The results for white spruce show that the TASS projections and the PSP data from natural stands follows the projections of scenario A and B of the untreated better than the projected growth in scenario C (Figure 2.5). At stand age 80 every treatment except the delta hinge shows a growth multiplier factor of either 1.0 or 1.1 for scenario A and scenario B indicating a marginal or small treatment effect (Table 2.9 and Appendix 1).

Table 2.8. Results from TASS simulations of white spruce at age of maximum mean annual increment (MAI) together with age-shift and growth multiplier values by scenarios.

Treatment	Age at Max MAI	Merch.Vol. $m^3\ ha^{-1}$	*Age-shift from Untreated*			*Growth Multiplier*			Top Height *m*
			Scenario			*Scenario*			
			A	*B*	*C*	*A*	*B*	*C*	
Bedding Plow	61	495	4	9	17	1	1.1	1.5	26.5
Breaking Plow	66	514	-1	4	12	1	1.1	1.4	27.9
Burn	63	513	2	7	15	1	1.1	1.5	28
Delta Hinge	86	485	-21	-16	-8	0.8	0.8	1	26.5
Herbicide	63	544	2	7	15	1.1	1.2	1.6	28.2
Madge	65	524	0	5	13	1	1.1	1.5	28.2
Untreated:									
Scenario A	65	513	-	-	-	-	-	-	27.6
Scenario B	70	513	-	-	-	-	-	-	27.6
Scenario C	78	445	-	-	-	-	-	-	25.2

For white spruce the information provided by the recent cut blocks in the Peace Forest District indicate an average merchantable volume of 364 $m^3\ ha^{-1}$ (age class: 121-140) and the latest available survey indicates an average crown closure of 57% (Table 2.10). The merchantable volume for these cut blocks is 59% of the values estimated by TASS for scenario B (at 100% crown closure) which is similar to the average crown closure value of these cut blocks.

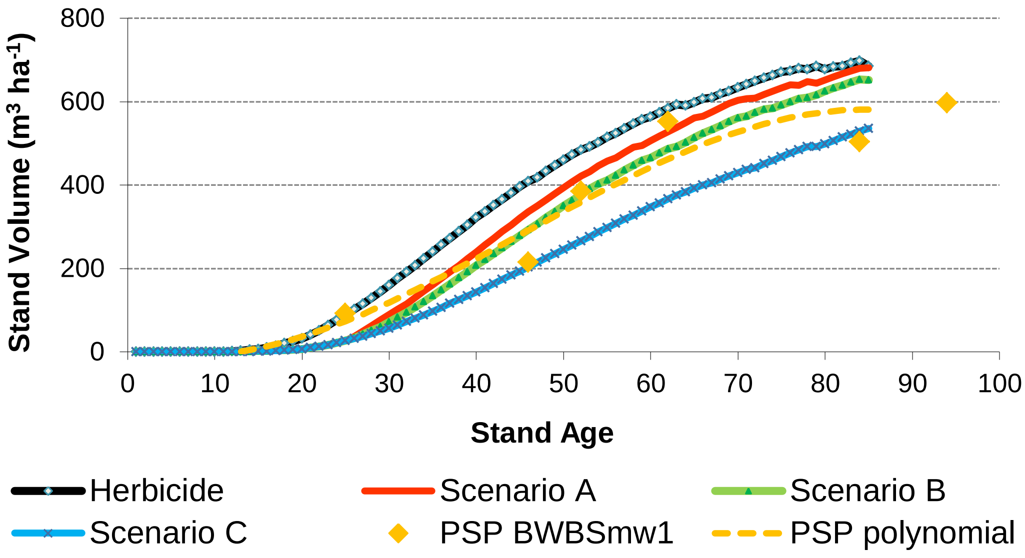


Figure 2.5. Projected stand volume over stand age for white spruce for the best treatment (herbicide) and the untreated scenarios. The PSP data represents measured volume of natural stands in the same biogeoclimatic subzone and variant (BWBSmw1). The polynomial fitting the PSP data is represented by: $Y = -3.9276*X + 0.33743*X^2 - 0.00248*X^3$ (n = 6; Adj.R^2 = 0.96; $P < 0.0048$).

Table 2.9. Stand yield data from TASS simulations to age 80 for white spruce together with growth multiplier values by scenarios.

Treatment	Stand Age	Density *Trees* ha^{-1}	Total Volume $m^3\ ha^{-1}$	Merch.Vol. $m^3\ ha^{-1}$	Basal Area $m^3\ ha^{-1}$	Top Height *m*	*Growth Multiplier* *Scenario* *A*	*B*	*C*
Bedding Plow	80	971	669	619	66.1	31.4	1	1.1	1.3
Breaking Plow	80	922	627	580	61.4	31.3	1	1	1.3
Burn	80	886	661	613	64.9	31.7	1	1.1	1.3
Delta Hinge	80	862	484	442	54.8	25.2	0.7	0.8	1
Herbicide	80	951	681	631	66.8	31.8	1	1.1	1.4
Madge	80	1003	649	598	63.7	31.9	1	1	1.3
Untreated:									
Scenario A	80	885	652	606	63.4	31.6	-	-	-
Scenario B	80	944	625	577	63.2	30.2	-	-	-
Scenario C	80	1062	485	438	55.9	25	-	-	-

Table 2.10. Merchantable volumes from recently harvested cut blocks of pure white spruce for the Peace Forest District (DPC) (Source: Database of Revenue Branch, and RESULTS database of Forest Practices Branch, BC Ministry of Forests and Range).

									Latest Survey			
Latitude, Longitude	BEC Zone	Merch. Volume m^3	Harvested *Year*	Spruce *%*	Age-Class	Area *ha*	**Merch. Volume** $m^3\ ha^{-1}$	Year	Spruce *%*	**Crown Closure** **%**	Trees ha^{-1}	Site Index *m*
56° 46' 17.4" N, 122° 4' 55.9" W	BWBS	1792	2006	87	121-140	5	**381**	2004	75	55	636	16
57° 48' 14" N, 122° 2' 43" W	BWBS	106800	2005	82	121-140	310	**345**	1996	85	65	1142	10
55° 39' 26.8" N, 122° 21' 40" W	ESSF	6247	2006	76	121-140	17	**367**	1969	36	50*****	895	14
56° 33' 38.5" N, 121° 22' 0.1" W	BWBS	46131	2007	85	121-140	127	**364**	2000	80	50	1200	12
				Average Values:			**364**			**57**		

***** Not included in the average value because the last survey was conducted in 1969

2.3.3. General Discussion

For lodgepole pine the best treatments at age 60 are the bedding plow, the breaking plow, and the burn that are showing 10% more productivity than the untreated with an average merchantable volume of 323 m^3ha^{-1}. The other treatments show productivity levels close to that of the untreated plots. Previous studies at the Bednesti site have indicated that the main limiting factors are: low fertility, compact subsoil, and low water-holding capacity with rooting zone as thin as 10 cm (Bedford and Sutton, 2000). While mechanical site preparation typically reduces soil bulk density without reducing nutrient availability, one study reports that the bedding plow treatment had significantly greater total C than the untreated indicating an overall increased level of organic matter (MacKenzie et al., 2005). The fire treatment resulted in higher productivity for lodgepole pine up-to age 60 as a consequence, among the others, of the ash layer that replaces the forest floor and allows more solar radiation to penetrate the soil (MacKenzie et al., 2005; Kimmins, 1996; MacKenzie et al., 2004). The Delta disk trenching furrow-planting is the worst treatment. For this treatment trees were planted into the mineral soil at the bottom of the trench where compact subsoil and low fertility have been shown to affect pine growth (Bedford and Sutton, 2000).

The growth projections for lodgepole pine indicate that the treatments have accelerated growth compared to the untreated but the treatment effect largely ceases by stand age 90 (Figure 2.3). This outcome is characteristic of treated stands following a Type 1 growth response (Snowdon and Waring, 1984). A similar study concluded that enhanced growth following site preparation treatments, which improves soil aeration early in the rotation for *Pinus taeda* L. (i.e., ditching and bedding), decreases over long periods of time (Kyle et al., 2005).

The data from the selected PSPs shows lower volume growth compared to the growth projected by the TASS model for the untreated. Many factors influence this outcome. For example, TASS projects the growth of a plantation under ideal conditions and tends to overestimate its productivity compared to naturally regenerated pine stands (Mitchell 1975; Cummings et al. 2001). Studies in Alberta and British Columbia have concluded that post-harvest lodgepole pine stands grow at a faster rate than mature fire origin stands where stand conditions are different and density is less uniform (Goudie, 1996; Huang et al., 2004). Fire origin stands usually start at higher densities compared to post-harvest pine stands, which may lead to reduced height growth and less vigor (Goudie, 1996; Farnden and Herring, 2002). Information from harvested blocks in the Prince George Forest District corroborates these merchantable volume projections calculated by TASS for the untreated scenario.

For white spruce the best treatments at age 80 are the bedding plow, the burn, and the herbicide which show 10% greater standing volume than the untreated plots (i.e., scenario B) with an average merchantable volume of 621 m^3ha^{-1}at age 80. In boreal forests white spruce establishment is often limited by severe vegetation competition and unfavorable soil conditions. Therefore treatments that affect these factors have proven to increase growth and survival of spruce (e.g., Macadam and Kabzems, 2006; MacKenzie et al., 2005; Boateng et al., 2009; Boateng et al., 2006). Both mechanical site preparation treatments and the removal of competing vegetation, by applying herbicide or fire, result in a shift in the plant community from tall shrubs (e.g., green alder and willow), as in the untreated, to mainly grasses and forbs (Haeussler et al., 1999; Boateng et al., 2009; Forest Practices Branch, 2008). At the Inga Lake, site the treatment effect (e.g., decreased soil density and improved nutrient availability) was still significant 15 years after planting (Macadam and Kabzems, 2006), but a later study at age 20 found that early microsite amelioration caused by the establishment treatments was ceasing and was having less impact on spruce growth than the negative response to competing vegetation (Boateng et al., 2009).

For white spruce, if the untreated follows either scenario A or B, the projected growth of the treated blocks by stand age 85 will result in productivity levels similar to that of the untreated; thus implying a Type 1 growth response (Figure 2.5). If the untreated growth follows scenario C then the best treatments will have 25-30% more volume than the untreated at stand age 85; thus implying a Type 2 growth response. The delta hinge treatment is showing reduced volume growth compared to the other treatments and the untreated as a consequence of hare (*Lepus americanus*) damage and high levels of competing vegetation (Forest Practices Branch 2008). Results from scenario B (untreated) match the curve for the PSP data more closely than Scenario A or C (Figure 2.5). Also the information provided by the harvested blocks in the Peace Forest District corroborates the merchantable volume projections calculated by TASS.

As shown for lodgepole pine, the productivity of spruce stands is also generally overestimated by TASS thus the proximity between the PSP data and the projected growth of scenario B provides a good indication of the potential growth of the untreated. Moreover, in 15-year-old white spruce stands Feng et al., (2006) found that the height of the current top height trees was approximately 14% greater than the height of the top trees that would be selected to calculate site index at breast height age 50. These findings also suggest a Type 1 growth response for white spruce (Snowdon and Waring, 1984).

Results from this study suggest that the age–shift approach is the best method, among the modeling techniques tested, for representing growth differences for a given treatment in relation to the untreated. However, at early stages the age-shift value can be calculated only up to the relative age of the maximum size of the control treatment. This limits its application when the growth of the untreated is significantly slower compared to the treated (Nienstaedt and Zasada, 1990). For this reason, the data for white spruce growth limited calculating age-shift values up to age 11 for the majority of the treatments. For faster growing lodgepole pine (Lotan and Critchfield, 1990) it was possible to calculate age-shift values up to age 14-15 for every treatment.

Age-shift values can also be calculated for older stands using growth and yield information although it is important to consider that age-shift values will fluctuate depending on stand age. For example, at maximum MAI age-shift values indicate that the bedding plow treatment has the potential to shorten the time to reach maximum MAI by 13% compared to the untreated for both lodgepole pine and white spruce, although this gap declines at culmination age.

The growth multiplier method provided valuable information on growth characteristics of treated and untreated plots and also helped in interpreting the growth and yield projections of future stands. Unlike the age-shift method, it is possible to calculate growth multipliers using every growth measurement available (Figure 2.2 and 2.4) (Hamilton and Rehfeldt, 1994). For lodgepole pine the early growth multiplier factors and trends for diameter and height are similar to those calculated for older plantations using the projected growth, which implies that growth multipliers can provide indications on the future development of the stand even at early stages (i.e., stand age 15-20). Nevertheless, at age 20 the growth multiplier values for volume suggest that treated stands could be up-to 70% more productive than untreated (e.g., burn = 1.7x). This outcome is consistent with the findings that slash-burning reduces brush competition and increases short term availability of nutrients in the soil (Lidenburgh, 1990). However, while such early increases in growth are widely observed, it is unlikely that these will translate into yield increases of this magnitude.

Early growth multipliers for white spruce indicate an increasing value of the multiplier with age between treated and untreated stands whereas the values from the projected growth suggest a decreasing trend. In this case the early indications of stand development for any of the growth sizes would not be representative of the stand at the end of the rotation period and could potentially mislead managers regarding the long-term effect of the treatments. For example, at stand age 20 the volume growth multiplier factor for the burn was 800% (i.e., 8x) of the untreated area but at stand age 80 the value drops to 10% (i.e., 1.1x). Differences between pine and spruce in observed relationships between growth multiplier and model estimates of yield are related to differences in patterns of early growth of these two species, number of years to maximum MAI, and the duration of the treatment effects.

This outcome indicates that multipliers calculated up to age 20 do not predict volume gains at stand age 85 or older. For white spruce, vegetation management and forest productivity studies indicate that volume gains compared to the untreated stands at age 10 or 12 range from 194% to 591% (Biring et al., 1999; Biring and Hays-Byl, 2000; Harper et al., 1997), at stand age 19 gains are around 188% (Wood and Dominy, 1988), and at stand age 30 volume gains decline to 53-96% (Wagner et al., 2006; Sutton, 1995). These percentage volume gains are consistent with the range of measured and predicted values for white spruce at the Inga Lake installation. At stand age 15, Simard et al. (2006) indicate that vegetation management increases total lodgepole pine stand volume by 57% which is consistent with the gains measured for pine at the Bednesti Lake installation. These factors corroborate the finding that early estimates of volume gains are more representative of the final yield for lodgepole pine than are those for white spruce.

Age shift values and growth multipliers for lodgepole pine and white spruce indicate that diameter growth was affected more by treatment than height; which is consistent with the findings from many other studies which show that diameter growth is more sensitive than height growth to competing vegetation or site preparation treatments (e.g., Macadam and Kabzems, 2006; Wagner et al., 1999).

The site index adjustments calculated using the growth intercept method provided the base information to create customized growth curves for stands projected with TASS/TISPY. For lodgepole pine, the calculated site index values did not show significant differences between stand age 9, 15 or 20. Huang et al. (2004) have also shown that site index estimates stabilize after stand breast height age 5 in juvenile stands planted after harvesting and drag scarification. The site index estimates at age 20 for white spruce were lower by only 0.4% than the values calculated at age 11.

Growth intercept models which relate the early average height growth of trees to site index, have been shown to provide reasonable site index estimates for young stands (Nigh, 1995; Nigh, 1997; Nigh, 2004a; Huang et al., 2004). Although the growth intercept model has proven to provide significant information on growth and yield of conifers, it still represents an early estimate of the stand productivity. More data, especially for treated stands, is needed in order to validate estimates of the effect of establishment treatments on site productivity.

It is important to mention that this study is based on relatively young stands and that growth models including TASS/TIPSY provide long term growth estimates for the 'average' stand using inventory data of similar locations. For these reasons the projected growth estimates evaluated in this study are only valid for this case study and might not be representative of the future characteristics and development of the stand.

2.4. Conclusions

For lodgepole pine the best treatments at age 60 are the bedding plow, the breaking plow, and the burn and show 10% more productivity than the untreated plots with an average merchantable volume of 323 m^3 ha^{-1}. The other treatments show productivity levels close to that of the untreated plots. This study indicates that before age 60 the best treatments can still result in increased lodgepole pine yield compared to the untreated plots but this gap will likely diminish at stand age 90 and older in accordance to the Type 1 growth response characteristics.

For white spruce the best treatments at age 80 are the bedding plow, the burn, and the herbicide which show 10% higher standing volume than the untreated plots (i.e., scenario B) with an average merchantable volume of 621 $m^3 ha^{-1}$. The other treatments show yield levels close to that of the untreated plots. This study shows that the best treatments can result in an increase in white spruce stand volume up to age 80 compared to the untreated plots but this gap will be likely filled at stand age 85 and older in accordance to the Type 1 growth response characteristics.

Understanding the long-term effect of silvicultural treatments on conifer growth is of fundamental importance in planning sound forest management. In order to project conifer yield at northern latitudes, growth models are needed since the rotation length of conifer plantations generally exceeds 50 years and no experimental trial has been monitored for such a length of time. Growth models such as TASS/TIPSY are developed using inventory data from naturally regenerated forests and tend to provide conservative projections for stands with planted trees with TASS/TIPSY . Moreover climate change adds uncertainty to growth models that do not include a representation of climate effect.

2.6. References

Bedford, L., McMinn, R.G., 1990. Trials to appraise the biological effectiveness of mechanical site preparation equipment in British Columbia: FRDA Project 1.10. In *The Silvics and Ecology of Boreal Spruces*, IUFRO Working Party, St. John's, NL, Canada, 1989; Titus, B.D.; Lavigne, M.B.; Newton, P.F.; Meades, W.J.; Inf. Rep. N-X-271, p.p. 3-12.

Bedford, L., Sutton, R.F., 2000. Site preparation for establishing lodgepole pine in the sub-boreal spruce zone of the interior British Columbia: the Bednesti trial, 10-year results. Forest Ecology and Management 126: 227-238.

Bedford, L., Sutton, R.F., Stordeur, L., Grismer, M., 2000. Establishing white spruce in the Boreal White and Black Spruce Zone. New Forests 20: 213-233.

Biring, B.S., Hays-Byl, W.J., Hoyles, S.E., 1999. Twelve-year conifer and vegetation responses to discing and glyphosate treatments on a BWBSmw backlog site. B.C. Ministry of Forestry, Victoria, BC, Canada; Research Brief, Working Paper No. 43.

Biring, B.S., Hays-Byl, W., 2000. Ten-year conifer and vegetation responses to glyphosate treatment in the SBSdw3. B.C. Ministry of Forestry, Victoria, BC, Canada; Research Brief, Extension Note No. 48.

Boateng, J.O., Herring, L.J., 1990. Site preparation: Chemical. In: *Regenerating British Columbia's Forests*, Lavender, D.P.; Parish, R.; Johnson, C.M.;

Montgomery, G.; Vyse, A.; Willis, R.A.; D. Winston. University of British Columbia Press: Vancouver, Canada, pp.164-178.

Boateng, J.O., Heineman, J.L., McClarnon, J., Bedford, L., 2006. Twenty year responses of white spruce to mechanical site preparation and early chemical release in the boreal region of northeastern British Columbia. Canadian Journal of Forest Research 36: 2386-2399.

Boateng, J.O., Heineman, J.L., Bedford, L., Harper, G.J., Nemec, A.F.L., 2009. Long-term effects of site preparation and postplanting vegetation control on *Picea glauca* survival, growth and predicted yield in boreal British Columbia. Scandinavian Journal of Forest Research 24: 111-129.

Cortini, F., Comeau, P.G., 2008. Evaluation of competitive effects of green alder, willow and other tall shrubs on white spruce and lodgepole pine in Northern Alberta. Forest Ecology and Management 255: 82-91.

Cummings, W., Jones, E., Reed, D., Drummer, T., 2001. Frontier function analysis to estimate the maximum relative growth rate of Red Pine (*Pinus resinosa,* Ait.) in northern Michigan. Proceedings of IUFRO S4.11 conference on Biometry, Modelling and Information Science, 25-29 June 2001, University Of Greenwich, London, UK.

DeLong, C., MacKinnon, A., Jang, L., 1990. A field guide for identification and interpretation of ecosystems of the northeast portion of the Prince George

Forest Region. B.C. Ministry of Forests, Victoria, BC, Canada; Land Manage. Handbook No. 22.

DeLong, C., Tanner, D., Jull, M.J., 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. BC Ministry of Forests, Victoria, BC, Canada; Land Manage. Handbook No. 24.

Farnden, C., Herring, L., 2002. Severely repressed lodgepole pine responds to thinning and fertilization: 19-year results. Forestry Chronicle 78: 404-414.

Feng, Z., Stadt, J.K., Lieffers, V.J., Huang, S., 2006. Linking juvenile growth of white spruce with site index. Forestry Chronicle 82: 819-824.

Forest Practices Branch, 2008. Inga Lake Site: Testing the Biological Effectiveness of Mechanical Site Preparation and Vegetation Control Methods: 20-years Results. Unpublished tour guide. BC. Ministry of Forests, Victoria, BC, Canada.

Goudie, J.W., 1996. The effects of stocking on estimated site index in the Morice, Lakes and Vaderhoof timber supply areas in Central British Columbia. Proceedings of Northern Interior Vegetation Management Association Annual Meeting, Smithers, BC, Canada, 24-25 January 1996; Szauer, T., Ed.; pp. 9-31.

Grossnickle, S.C., 2000. *Ecophysiology of Northern Spruce Species: The Performance of Planted Seedlings*. NRC Research Press: Ottawa, ON, Canada.

Haeussler, S., Bedford, L., Boateng, J.O, MacKinnon, A., 1999. Plant community responses to mechanical site preparation in northern interior British Columbia. Canadian Journal of Forest Research 29: 1084-1100.

Haeussler, S., Bedford, L., Leduc, A., Bergeron, Y., Kranabetter, J.M., 2002. Silvicultural disturbance severity and plant communities of the southern Canadian boreal forest. Silva fennica 36: 307-327.

Hamilton, D.A., Rehfeldt, G. E., 1994. Using individual tree growth projection models to estimate stand-level gain attributable to improved stock. Forest Ecology and Management 68: 189-207.

Harper, G.J., Herring, L.J., Hays-Byl, W.J., 1997. Conifer and vegetation response in the BWBSmw 12 years after mechanical and herbicide site preparation. B.C. Ministry of Forests, Victoria, BC, Canada; Working Paper No. 29.

Hawkes, B.C., Feller, M.C., Meehan, D., 1990. Site preparation: Fire. In: *Regenerating British Columbia's Forests*, Lavender, D.P.; Parish, R.; Johnson, C.M.; Montgomery, G.; Vyse, A.; Willis, R.A.; D. Winston. University of British Columbia Press: Vancouver, Canada, 1990; pp.164-178.

Honer, T.G., Ker, M.F, Alemdag, I.S., 1983. Metric timber tables for the commercial tree species of central and eastern Canada. Can. For. Serv. Inf. Rep. MX-140.

Huang, S., Monserud, R.A., Braun, T., Lougheed, H., Bakowsky, O., 2004. Comparing site productivity of mature fire-origin and post-harvest juvenile lodgepole pine stands in Alberta. Canadian Journal of Forest Research 34: 1181-1191.

Kimmins, J.P., 1996. Importance of soil and role of ecosystem disturbance for sustained productivity of cool temperate and boreal forests. Soil Science Society of America Journal 60: 1643-1654.

Kyle, K.H., Andrews, L.J., Fox, T.R., Aust, W.M., Burger, J.A., Hansen, G.H., 2005. Long-term effects of drainage, bedding, and fertilization on growth of loblolly pine (*Pinus taeda* L.) in the Coastal Plain of Virginia. Southern Journal of Applied Forestry 29: 205-214.

Lidenburgh, S.B., 1990. Effects of prescribed fire on site productivity: a literature review. B.C. Ministry of Forests, Victoria, BC, Canada; Land Manage. Rep. No. 66.

Lieffers, V.I., MacDonald S.E., Hogg, E.H., 1993. Ecology of and control strategies for Calamagrostis-canadensis in boreal forest sites. Canadian Journal of Forest Research 23: 2070-2077.

Lotan, J.E., Critchfield, W.B., 1990. Lodgepole pine. In *Silvics of North America: 1, Cionifers*; Burns R.M.; Honkala, B.H.; U.S. Dep. Agric. Agric. Handb. 654.

Macadam, A., Kabzems, R., 2006. Vegetation management improves early growth of white spruce more than mechanical site preparation treatments. Northern Journal of Applied Forestry 23: 35-46.

MacKenzie, M.D., DeLuca, T.H., Sala, A., 2004. Forest structure and organic matter analysis along a fire chronosequence in the low elevation forests of western Montana. Forest Ecology and Management 203: 331-343.

MacKenzie, M.D., Schmidt, M.G., Bedford, L., 2005. Soil microclimate and nitrogen availability 10 years after mechanical site preparation in northern British Columbia. Canadian Journal of Forest Research 35: 1854-1866.

Mason, E.G., Milne, P.G., 1999. Effects of weed control, fertilization, and soil cultivation on the growth of *Pinus radiata* at mid-rotation in Canterbury, New Zealand. Canadian Journal of Forest Research 29: 985-992.

Mason, E.G., Dzierzon, H., 2006. Applications of modelling to vegetation management. Canadian Journal of Forest Research 36: 2505-2514.

McMinn, R.G., Hedin, I.B., 1990. Site preparation: Mechanical and manual. In: *Regenerating British Columbia's Forests*, Lavender, D.P.; Parish, R.; Johnson, C.M.; Montgomery, G.; Vyse, A.; Willis, R.A.; D. Winston.

University of British Columbia Press: Vancouver, Canada, 1990; pp.150-163.

Mitchell, K.J., 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monograph 17, 39 p.

Mitchell, K.J., Grout, S.E., McDonald, R.N., Watmough, C.A., 1992. User's Guide for TIPSY: A Table Interpolation for Stand Yields. BC Ministry of Forests, Victoria, BC, Canada.

Morris, L.A., and Lowery R.F., 1988. Influence of site preparations on soil conditions affecting stand establishment and tree growth. Southern Journal of Applied Forestry 12: 170-178.

Nienstaedt, H., Zasada, J.C., 1990. White spruce. In *Silvics of North America: 1, Conifers*; Burns R.M.; Honkala, B.H.; U.S. Dep. Agric. Agric. Handb. 654.

Nigh, G.D., 1995. Variable growth intercept models for lodgepole pine in the sub-boreal spruce biogeoclimatic zone, British Columbia. Ministry of Forests, Victoria, BC, Canada; Research Report RR-02.

Nigh, G.D., 1997. Revised growth intercept models for lodgepole pine: comparing northern and southern models. Ministry of Forests, Victoria, BC, Canada; Extension Note 11.

Nigh, G.D., 2004a. Growth intercept and site series-based estimates of site index for white spruce in the Boreal White and Black Spruce biogeoclimatic zone. Ministry of Forests, Victoria, BC, Canada; Tech. Rep. 13.

Nigh, G.D., 2004b. Juvenile height models for lodgepole pine and interior spruce. Ministry of Forests, Victoria, BC, Canada; Research Report. http://www.for.gov.bc.ca/hfd/library/FIA/2004/FSP_R04-037a.pdf.

Örlander, G., Gemmel, P., Hunt, J., 1990. Site preparation: a Swedish overview. For. Can. and B.C. Min. For., Victoria, BC, Canada; FRDA Rep. No. 105.

Scaling Manual of British Columbia. Ministry of Forests, Victoria, BC, Canada; 2008. http://www.for.gov.bc.ca/ftp/hva/external/!publish/web/manuals/scaling/2009/Scaling2009NovMaster.pdf

Shropshire, C., Wagner, R.G., Bell, F.W., Swanton, C.J., 2001. Light attenuation by early successional plants of the boreal forest. Canadian Journal of Forest Research 31: 812-823.

Simard, S.W., Radosevich, S.R., Sachs, D.L., Hagerman, S.M., 2006. Evidence for competition/facilitation trade-offs: effects of Sitka alder density on pine regeneration and soil productivity. Canadian Journal of Forest Research 36: 1286-1298.

Smith, S.M., 1988. Regeneration delays and natural yields on untreated backlog forest land in British Columbia. For. Can. and B.C. Min. For., Victoria, BC, Canada; FRDA Rep. No. 043.

Snowdon, P., Waring, H.D., 1984. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. *Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations*, Pretoria and Pietermaritzberg, South Africa, 30 April-11 May 1984; Grey, D.C., Shönau, A.P.G., Shutz, C.J., Eds.; Forest Research Institute: Pretoria, South Africa; pp. 701-711.

South, D.B., Miller J.H., 2007. Growth response analysis after early control of woody competition for 14 loblolly pine plantations in the southern U.S. Forest Ecology and Management 242: 569-577.

South, D.B., Miller, J.H., Kimberly, M.O., Vanderschaaf, C.L., 2006. Determining productivity gains from herbaceous vegetation management with ‘age-shift’ calculations. Forestry 79: 43-56.

Spittlehouse, D.L., Stathers, R.J., 1990. Seedling microclimate. B.C. Ministry of Forests, Victoria, BC, Canada; Land Manage. Rep. No. 65.

Stage, A.R., 2003. How forest models are connected to reality: evaluation criteria for their use in decision support. Canadian Journal of Forest Research 33: 410-421.

Stathers, R.J., 1989. Summer frost in young forest plantations. For. Can. And B.C. Min. For., Victoria, BC, Canada; FRDA Rep. No. 073.

Sutton, R.F., 1995. White spruce establishment: initial fertilization, weed control, and irrigation evaluated after three decades. New Forests 9: 123-133.

Wagner, R.G., Little, K.M., Richardson, B., McNabb, K., 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry 79: 57-79.

Wagner, R.G., Mohammed, G.H., Noland, T.L., 1999. Critical period of interspecific competition for northern conifers associated with herbaceous vegetation. Canadian Journal of Forest Research 29: 890-897.

Walstad, J.D., Kuch, P.J., 1987. *Forest vegetation management for conifer production*. John Wiley & Sons, Inc., New York, NY, USA.

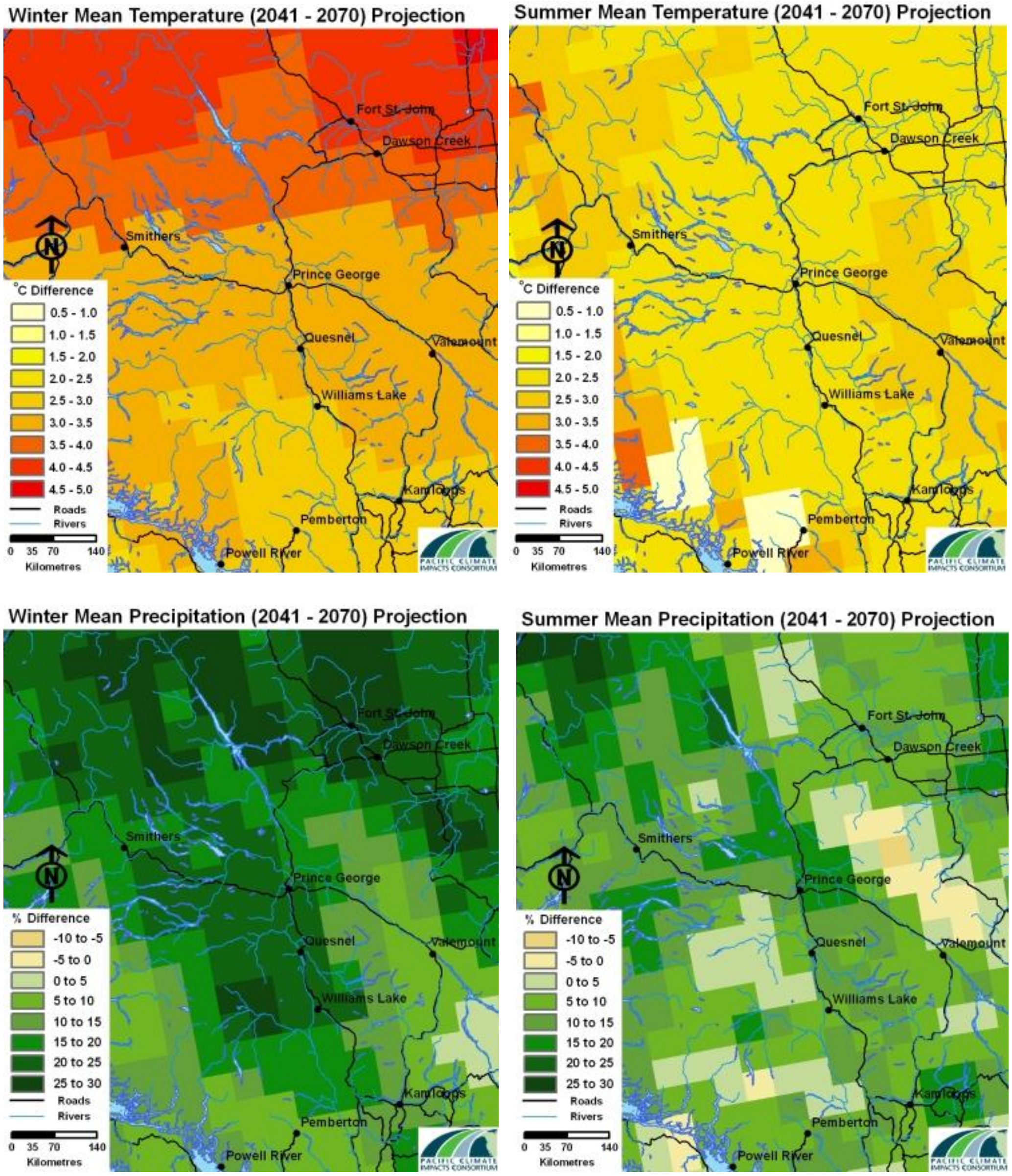
Wood, J.E., Dominy, S.W.J., 1988. Mechanical site preparation and early chemical tending in white spruce: 19-year results. Forestry Chronicle 64: 177-181.

3. Effects of climate on growth of lodgepole pine and white spruce following site preparation and its implications in a changing climate

(a shortened version of this chapter has been accepted for publication as: Cortini, F., Comeau, P.G., Boateng, J.O., Bedford, L., McClarnon, and Powelson, A. 2011. Effects of climate on growth of lodgepole pine and white spruce following site preparation and its implications in a changing climate. Canadian Journal of Forest Research)

3.1. Introduction

Greenhouse gases, such as water vapour (H_2O) and carbon dioxide (CO_2), occur naturally but are influenced either directly or indirectly by human activities, whereas others are purely anthropogenic such as CFCs and HFCs (collectively known as halocarbons) (IPCC, 1997). The Intergovernmental Panel on Climate Change (IPCC) has concluded that the current global warming is the result of increasing greenhouse gas concentration in the atmosphere that is ‘very likely’ due to human activities such as fossil fuel burning and deforestation (IPCC, 2007). Solomon et al. (2009) suggest that the damaging severity of climate change not only depends on the magnitude of the change but also on the potential for irreversibility. Northern British Columbia will undergo a greater warming and changes in precipitation than the global average (IPCC, 2007) (figure 3.1) according to the projected changes (2050s) provided by the Pacific Climate Impacts Consortium (University of Victoria, Victoria, BC).



Winter Mean Temperature (2041 - 2070) Projection

Summer Mean Temperature (2041 - 2070) Projection

Winter Mean Precipitation (2041 - 2070) Projection

Summer Mean Precipitation (2041 - 2070) Projection

Figure 3.1. Projections for north-eastern British Columbia representing differences in temperature and precipitation from the 1961-1990 normal modeled using the Canadian Regional Climate Model (CRCM4) following the A2 emission scenario (http://www.pacificclimate.org/resources/climateimpacts/princegeorge/).

Tree growth is affected by climate and, as average temperature rises, this may result in increased competition from other species better suited to warmer climates (Spittlehouse, 2008). Several studies suggest that a wide range of species and ecosystems are being affected by recent warming (Walther et al., 2002; Parmesan and Yohe, 2003), especially in areas such as the northern sub-boreal, boreal and sub-arctic ecosystems (Zhou et al., 2001). In many regions warming has already been related to changes in the hydrological balance as a consequence of a decline in the fraction of precipitation falling as snow (Knowles et al., 2006), a decline of the water content in the snow pack (Mote et al., 2005), and earlier snowmelt and runoff in the spring (Stewart et al., 2004). These concurrently lead to more severe levels of summer drought (Westerling et al., 2006; van Mantgem et al., 2009).

Even small changes in climate can greatly affect future growth and survival of forest tree populations with magnitude and type of effect (such as beneficial or detrimental) depending on the species (Rehfeldt et al., 1999; Rehfeldt et al., 2002). The rate of climate change is outpacing the rate of natural selection and seed migration with potentially negative consequences to forest productivity (Aitken et al., 2008; O'Neill et al., 2008). Climatic changes will also have economic impacts resulting from increased severity of fire, insect and disease epidemics, and drought-related mortality of forest trees (e.g., Gillett et al., 2004; Ebata, 2004; Woods et al., 2005; Westerling et al., 2006; van Mantgem et al., 2009).

Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) is a ubiquitous species that can grow under a wide variety of climatic and soil conditions and is a common component of the forests in western North America (Lotan and Critchfield, 1990). Lodgepole pine tolerance to minimum temperatures ranges from -7° C on the Pacific Coast to -57° C in the Northern Rocky Mountains and seedlings are relatively resistant to frost injury (Lotan and Perry, 1983). White spruce (*Picea glauca* (Moench) Voss) has a transcontinental range and is also a species able to grow under a wide range of climatic and edaphic conditions (Nienstaedt and Zasada, 1990). However, it is less tolerant of drought than lodgepole pine (Lotan and Critchfield, 1990; Nienstaedt and Zasada, 1990). At the northern limit of the white spruce range temperature extremes are significant (e.g.,-54° C to 34° C); and spruce can grow on sites with a mean annual precipitation between 250 mm in the northern regions and 1270 mm in the eastern part of its range (Nienstaedt and Zasada, 1990).

Competing vegetation and unfavourable soil or microsite conditions can affect the establishment of conifer plantations (Lavender, 1990; Cortini and Comeau, 2008; Macadam and Kabzems, 2006). Site preparation treatments have the potential to improve growth and survival of the crop trees by decreasing soil bulk density, improving soil drainage on wet poorly drained soils, accelerating soil warming in spring and elevating soil temperatures, and increasing nutrient availability (Örlander et al., 1990; Morris and Lowery, 1988).

The management of competing vegetation through herbicide application or prescribed burning is also important for the successful growth and survival of planted conifers in the northern regions of North America (Wagner et al., 2006; Walstad and Kuch, 1987). Conifer plantations are extremely susceptible to competing vegetation during early stages of their establishment because the seedlings are small and generally slow growing (Shropshire et al., 2001). Studies suggest that forest managers are likely to achieve the greatest gain in tree growth from managing vegetation during the first years after planting (Wagner and Radosevich, 1998). In addition to controlling competing vegetation, prescribed burning can increase short term (<5 years) availability of nutrients in the soil (Hawkes et al., 1990).

Recent studies have shown that climatic variables can be used to improve the predictive ability of available growth models (Woollons et al., 1997; Snowdon et al., 1999). While they have proven to be particularly effective for retrospective analysis (i.e., short-term updates of forest inventory), as more global climate model simulations became available, they can also be used for projecting future stand growth (Snowdon, 2001). Many factors are involved when modeling the impact of climate change on tree growth; nonetheless climate is an important factor that needs to be addressed for forest management purposes.

Another important factor when analyzing the growth characteristics of a forest stand is the initial size of the trees. The "initial size advantage" hypothesis states that trees with a larger initial size are more competitive than their smaller cohorts and therefore growth analyses (e.g.: response to competition, treatment effect etc.) could enhance their predictive ability by taking into account the initial size of the trees (e.g.: Harper, 1977; Ford, 1984; Larocque, 1998). A simpler method for analyzing tree and stand growth is represented by the absolute growth rate which is the increment per unit time and a number of studies have investigated the two methodologies (e.g.: Larocque and Marshall, 1993). Nevertheless it is not universally accepted that the relative growth method eliminates size-related differences for seedlings that are growing under similar conditions.

This study evaluates the explanatory capability of various climate variables on growth of lodgepole pine, and white spruce in northern British Columbia following mechanical site preparation and vegetation control treatments. Moreover the impact of climate change on future conifer productivity is evaluated at a forest management level by projecting growth using future climate scenarios provided by the latest climate models.

A number of questions will be addressed in this chapter and include which increment in conifer size such as height, diameter, and volume is better correlated with the climate variables; this will be tested by evaluating the relationships between climate variables and conifer growth over a 20-year period. The standardized growth will be calculated also taking into account the effect of initial size and the two methods will be compared.

Climate variables will be studied at annual, seasonal, and monthly time scales and the results will be used to evaluate which one is better correlated with conifer growth, this will be tested by studying an array of climate variables in relation to conifer growth. The equations developed to link conifer growth to climate variables were also evaluated on an independent dataset.

Moreover this study will explore how the growth of lodgepole pine and white spruce may be affected by climate change; this will be tested by looking at the changes in standardized projected growth over the next 30 years using a global climate model. In addition the study will provide answers on how plantations that underwent site preparation treatments may respond to climate change; and this will be tested by exploring growth responses to climate change at the treatment level.

3.2. Materials and Methods

Data collected during 20 years following establishment of five experiments in the boreal and sub-boreal forests of British Columbia (B.C.) were used to compare various mechanical and non-mechanical site preparation techniques for this study (Bedford and McMinn, 1990; Bedford and Sutton, 2000).

Data for lodgepole pine came from two long-term study sites in B.C. The Bednesti site (53° 52′ N, 123° 29′ W, el. 850 m) is located west of Prince George B.C. in the Stuart Dry Warm variant of the Sub-Boreal Spruce Zone (SBSdw3), and the Tanli site (53° 17′ N, 124° 28′ W, el. 1240 m) located south of Vanderhoof B.C. in the Babine Moist Cold variant of the Sub-Boreal Spruce Zone (SBSmc2) (DeLong et al., 1993; Haeussler et al., 1999; Bedford and Sutton, 2000; Burton et al., 2000; MacKenzie et al., 2005).

Data for white spruce came from three locations in B.C.: Inga Lake (56° 37′ N, 121° 38′ W, el. 890 m), Iron Creek (56° 38′ N, 122° 19′ W, el. 820 m), and Wonowon (56° 37′ N, 121° 49′ W, el. 900 m). These three sites are located north of Fort St. John B.C. in the Peace variant of the moist warm subzone of the Boreal White and Black Spruce Zone (BWBSmw1) (DeLong et al., 1990; Haeussler et al., 1999; Bedford et al., 2000; MacKenzie et al., 2005; Boateng et al., 2006; Boateng et al., 2009).

At each location I selected the most successful (i.e., greater growth) mechanical site preparation treatment and a vegetation control treatment (i.e., fire or herbicide) to be compared against the untreated/control (Table 3.1) (McMinn and Hedin, 1990; Boateng and Herring, 1990; Hawkes et al., 1990). The five experiments each used a randomized complete block design where each treatment was replicated: 4 times (Tanli and Wonowon), or 5 times (Bednesti, Inga Lake, and Iron Creek). One exception is the breaking plow treatment at Iron Creek which was only replicated twice. A minimum of 48 trees were planted in each plot. Trees were measured regularly for diameter and height over the studied 20-year period (1987-2006) and each site was measured: 16 times at Bednesti, Iron Creek, and Wonowon; 18 times at Tanli; and 19 times at Inga Lake. For each site and treatment combination the average growth increment values for height, diameter, and volume were calculated. Stem volume (SV, cm^3) was calculated from stem height (HT, cm) and root collar diameter (RCD, cm) using a modified version of Honer's equation (Honer et al., 1983):

$$SV = \frac{RCD^a}{b + \frac{c}{HT}}$$

where a, b, and c are parameters calculated by Cortini and Comeau (2008) using non-linear least squares from lodgepole pine and white spruce plantations in north-western Alberta.

Table 3.1. Summary of treatments applied and species planted (Sp) at each experimental trial for lodgepole pine (Pl) and whites spruce (Sw).

Treatment	**Description of Technique**	**Site**	**Sp**
Mechanical Preparation (MP)			
Bedding plow	Eden relief bedding plow pulled by a tractor that provided a raised, rough-mixed planting bed of mineral soil and chunks of organic matter	Bednesti	Pl
Disc trenching	Wadell powered scarifier that provided continuous shallow furrows and berms composed of mixed forest floor and mineral soil material	Tanli	Pl
Madge	Madge rotoclear pulled by a tractor that provided a well-mixed layer of surface organic matter and mineral soil, about 15 cm deep	Inga Lake	Sw
Breaking Plow	Double-bottom agricultural breaking plow that provides a side-by-side furrow slices to produce a raised mineral soil berm over a single layer of inverted humus	Iron Creek	Sw
20 cm Mound	Bräcke Mounder that provided mounds with 20 cm of mineral soil cap	Wonowon	Sw
Vegetation Control (VC)			
Fire	Slash and some mineral soil were piled in long rows and burned creating a uniform ash bed where the conifer were planted	Bednesti & Tanli	Pl
Herbicide	Glyphosate (Vision® or Roundup®) applications followed by manual brushing*	Inga Lake, Iron Creek, & Wonowon	Sw
Untreated (UN)			
Untreated	No site preparation or vegetation control	All	Pl Sw

* No manual brushing at Wonowon

Other studies have indicated initial size is an important factor to include in growth analyses and it can improve the overall significance of the model (e.g., Comeau et al. 1993). Consequently, I use relative growth rates (RGR) calculated as the increment divided by the initial size of the tree averaged at the plot level (i.e., Relative Growth Rate = Growth/Initial Size) (Hunt 1982). Preliminary analysis also tested the Relative Production Rate as described by Brand et al. (1986) but the results did not show significant improvements to the models.

Further standardization is necessary to provide measurements of growth that are not dependent on crop tree size considering that RGR changes with initial size of tree. This involved a two-step process similar to that used by Chhin et al. (2008). First, a smoothing spline was fit to RGR data, with the year of the increment as the independent variable, using Proc Glimmix in SAS (SAS Institute, Cary, NC). Then, the relative growth index (RGI) was calculated as the ratio between observed RGR and the RGR value predicted by the smoothing spline.

The spatial climate model ClimateBC, modified following Mbogga et al. (2009), was used to provide monthly data for the sites based on their latitude, longitude and elevation (Wang et al., 2006). Several climatic variables, including mean annual temperature, mean summer precipitation, and growing degree days were tested as predictors of each of the relative growth indexes. ClimateBC provided past climate data for three different time scales (annual, seasonal and monthly). Standard meteorological seasons are: spring - March, April, and May; summer - June, July, and August; autumn - September, October, and November; and winter - December, January and February. For both species we included climate variables spanning from July of the previous year to August of the current growth year.

For each climate variable I calculated the normal values (average over the 20 year period from 1987 to 2006) and then the anomalies relative to normal values (e.g., year 2000 Temperature minus 1987-2006 Temperature). I tested for co-linearity of climate variables (anomalies) using Proc CORR in SAS software (SAS Institute, Cary, NC) and if Pearson's correlation coefficient was higher than 0.7 only one (randomly selected) of the two climate variables was retained for further calculations.

In the RGI model, height increment, diameter increment, and volume increment were used as response (dependent) variables. Explanatory (independent) variables were the climatic variables expressed as anomalies (i.e., *Conifer growth = f(Climate anomalies)*). The climate variables that were used as candidates also included monthly, seasonal and annual values for the preceding year. Relationships between RGI and the climate anomalies were modeled with multiple linear regression analysis using Proc Reg (SAS Institute, Cary, NC). Preliminary analysis (i.e., examination of scatter plots, testing of non-linear and linear models, and evaluation of residuals) investigating the relationship between RGI and the climate variables found that linear models were as valid as more complex non-linear models.

Preliminary analyses also screened the climate variables using the 'forward' selection technique that adds variables at a specified significant level (i.e.: slentry=0.25) to the model one by one until no remaining variable produces a significant F statistic; once a variable is in the model it stays (SAS Institute Inc., 2004). In the final models the number of variables selected by the 'forward' selection technique ranged from 1 to 19 ($\overline{X} = 9.41$). The partial R-square contributions to the model of each climate variable dropped to values lower than 0.1 for any addition after the second variable and likewise it decreased the significance relative to the variable. Preliminary analyses also screened the variables using the 'stepwise' method, that similarly to the 'forward' selection technique, adds variables one by one to the model at the significant level (i.e.: slentry=0.25), but also checks the F statistic of the added variables and deletes any variable that is not significant at the specified level (i.e.: slstay=0.10) (SAS Institute Inc., 2004). In the final models following the more conservative 'stepwise' technique the number of selected variables ranged from 1 to 7 ($\overline{X} = 3.75$). Also in this case the first two climate variables were able to explain the majority of the variation in conifer growth and minor improvements to the final model were represented by adding more variables.

The preliminary analyses indicated that the selection of models with few explanatory variables only would reduce the 'noise' related to the large dataset of climate variables analyzed and the related co-linearity issues between similar variables. Thus for this study the models were restricted to the two best climate variables. This also avoids over parameterizing the model given the restricted number of observations of conifer growth available. Accordingly, in the process of identifying the most representative climate variables influencing the growth of lodgepole pine and white spruce I used the 'R^2' selection technique in Proc Reg with results restricted to two variables (SAS Institute, Cary, NC). This technique finds subsets of independent variables that best predict a dependent variable by linear regression and allows specifying the number of independent variables to appear in a subset (SAS Institute Inc., 2004). Keeping the number of variables constant in each model also allows comparing the results across the sub-sets to identify the more representative models. Preliminary analysis also tested models with only one climate variable relative to a climate index (i.e. Summer Heat Moisture Index) but the results indicated that the models where not significant.

At each climate scale (i.e., annual, seasonal, and monthly) the models were calculated for the three relative growth indices in order to provide a total of six climate variables candidates for the final model. The relationship between the selected climate anomalies and each relative growth index was modeled again in SAS to provide the best final model with only two independent variables (i.e., climate variables). Multicollinearity of the climate variables in the final models was re-evaluated after final model fitting.

ClimateBC also provided information on future climate based on recent global climate model simulations (CGCM2) from the Canadian Centre for Climate Modelling and Analysis (CCCma) (Flato and Boer, 2001). Out of the 40 possible scenarios of future climate provided by the IPCC, scenario A2 and scenario B2 were selected based on their widely available output data and because they have received the most scientific peer review (IPCC, 2007). These model runs and scenarios were chosen to evaluate sensitivity to change in temperature and precipitation that are forecast by most global climate models (GCM) for the area. The projected greenhouse gas emissions in scenario A2 will steadily increase in the future, while scenario B2 projects lower levels of greenhouse gasses by the middle of the century; nonetheless both scenarios predict similar warming trends over the next 20 years (IPCC, 2007).

I evaluated the sensitivity of the species to typical changes in temperature and precipitation forecast for the study area using ClimateBC to produce the site-specific temperature and precipitation data forecasts for 2020s (2005-2035).

Three extremely warm years (1992, 1998, and 2006) within the climate normal period (1987-2006) were selected and annual climate values are shown in Tables 3.2 and 3.3 for lodgepole pine and white spruce respectively. In most cases the three selected years show annual climate variables such as SHM (i.e.: Summer Heat Moisture Index = Mean Warmest Month Temperature/(Mean Summer Precipitation/1000)) with values representing a warmer and drier climate than the projected climate for scenario A2 and B2 up-to year 2035. SHM values for lodgepole pine for the three selected warm years averaged 55.6 versus 43.6 for the average across the future projections and for white spruce the warm years indicate an SHM average value of 62.9 versus an average value of 48.5 for the future projections. This information is presented to suggest that past climate data is representative of the projected climate under the two selected scenarios. Nevertheless the projected climate variables are averaged over the next 30-year period (i.e.: 2020s), thus overall these means represent a warmer climate compared to the selected years 1992, 1998, and 2006 considered independently.

Table 3.2. Climate normal of representative annual climate variables for the studied period 1987-2006 and selection of warm years for the lodgepole pine sites (i.e.: Bednesti and Tanli) in comparison to the projections of future scenarios A2 and B2 for the period 2005-2035 (2020s).

Lodgepole Pine	Bednesti					Tanli				
Year	MAT	MAP	MSP	AHM	SHM	MAT	MAP	MSP	AHM	SHM
1992	4.4	785.0	277.0	18.4	51.6	2.5	541.0	245.0	23.0	52.9
1998	4.6	842.0	311.0	17.3	50.6	2.4	586.0	280.0	21.1	49.0
2006	3.9	739.0	256.0	18.8	58.5	1.9	459.0	185.0	26.0	71.3
Climate Normal	**3.7**	**853.5**	**366.2**	**16.2**	**39.7**	**1.8**	**556.9**	**282.3**	**21.6**	**45.2**
2020s A2	3.9	875.0	360.0	15.9	39.7	2.0	567.0	266.0	21.2	47.2
2020s B2	3.9	853.3	360.0	16.3	39.9	2.1	553.7	265.7	21.8	47.7

MAT=Mean Annual Temperature; MAP=Mean Annual Precipitation; MSP=Mean Summer Precipitation;

AHM=Annual Heat Moisture Index (MAT+10)/(MAP/1000);

SHM=Summer Heat Moisture Index ((Mean Warmest Month Temperature)/(MSP/1000))

Table 3.3. Climate normal of representative annual climate variables for the studied period 1987-2006 and selection of warm years for the white spruce sites (i.e.: Inga Lake, Iron Creek and Wonowon) in comparison to the projections of future scenarios A2 and B2 for the period 2005-2035(2020s).

White spruce	Inga Lake					Iron Creek					Wonowon				
Year	MAT	MAP	MSP	AHM	SHM	MAT	MAP	MSP	AHM	SHM	MAT	MAP	MSP	AHM	SHM
1992	1.6	387.0	235.0	29.8	59.6	1.9	438.0	275.0	27.0	51.9	1.5	380.0	228.0	30.2	60.6
1998	2.4	417.0	239.0	29.8	67.1	2.9	459.0	286.0	28.1	57.6	2.4	410.0	237.0	30.3	67.2
2006	1.9	441.0	228.0	27.0	68.7	2.2	456.0	249.0	26.8	63.8	1.8	429.0	220.0	27.5	70.1
Climate Normal	**1.6**	**490.9**	**311.7**	**24.0**	**48.2**	**2.0**	**525.2**	**345.4**	**23.2**	**44.3**	**1.6**	**477.3**	**300.8**	**24.6**	**49.2**
2020s A2	1.9	500.0	312.0	23.8	49.0	2.3	533.0	345.0	23.1	45.4	1.9	486.0	301.0	24.4	50.2
2020s B2	2.1	498.3	310.3	24.2	49.8	2.4	532.3	346.0	23.4	45.6	2.0	485.0	300.7	24.7	50.8

MAT=Mean Annual Temperature; MAP=Mean Annual Precipitation; MSP=Mean Summer Precipitation;

AHM=Annual Heat Moisture Index (MAT+10)/(MAP/1000);

SHM=Summer Heat Moisture Index ((Mean Warmest Month Temperature)/(MSP/1000))

The previously selected models from the growth-climate analysis allowed projecting standardized growth in the future. Only the increment (diameter, height or volume) with the highest predictive ability was selected for the projections. Future conifer growth was then expressed as percentage change relative to the mean growth ratio of the 20-year-old conifer plantations (Chhin et al. 2008). For each observed value of relative growth index (1987-2007) the standard error of the mean was used to calculate the width of the confidence interval expressed as a percentage.

The final models were validated with independent datasets from other studies in northern B.C. and western Alberta (Figure 3.2 and Table 3.4). For each of these study sites climate anomalies relative to the studied period (1987-2006) were determined from climate data by ClimateBC and used to calculate relative growth of white spruce and lodgepole pine by substituting the climate variables into the final models previously calculated.

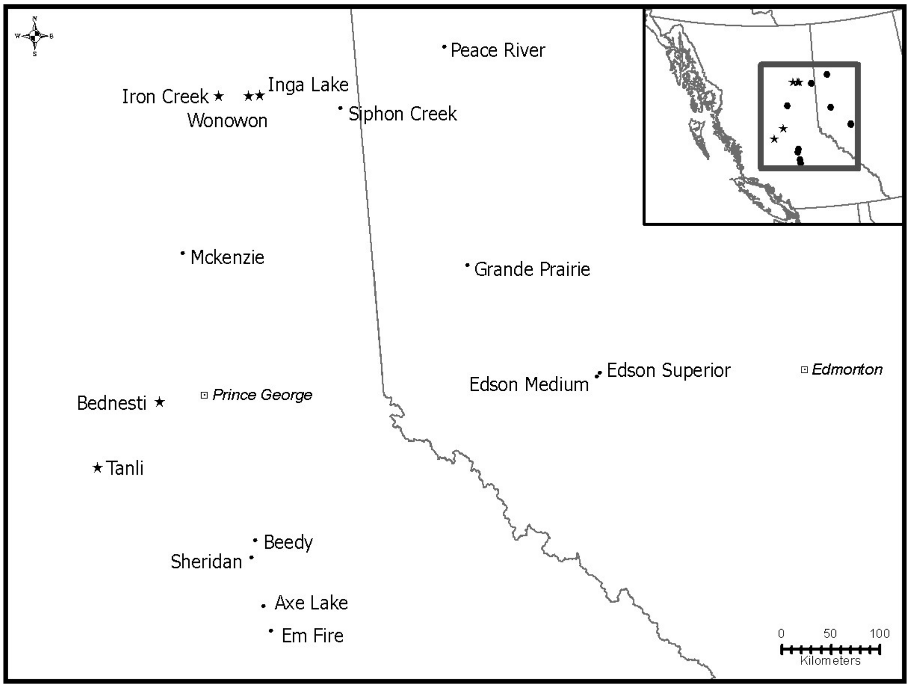


Figure 3.2. Distribution of the five main sites (stars) and the 10 validation sites (circles) included in the study.

Validation data for lodgepole pine came from four sites in the Interior Region of B.C. Two sites were located 60 km northeast of Williams Lake in the Horsefly variant of the dry warm subzone of the Sub-Boreal Spruce Zone (SBSdw1) and two sites were located 70 km southwest of Williams Lake in the Fraser variant of the dry cool subzone of the Interior Douglas-fir (IDFdk3) (Table 3.4) (DeLong et al. 1990). These trials are part of a long term study that compares growth and survival of lodgepole pine following various site preparation treatments. The sites in the SBS zone were harvested in 1981 and had well-developed covers of herbs, grasses and low shrubs, while the sites in the IDF zone were backlog areas (not satisfactorily restocked) with a well-developed cover of pinegrass (*Calamagrostis rubescens*).

This lodgepole pine study used a split plot design with each of six site preparation treatments replicated three times (once in each of three blocks) at each site. In 1985, 50 seedlings were planted in each plot and measurements were made 12 times within the 1987-2006 period. The mechanical site preparation treatments selected for this study are the ripper plow in the SBS, which created a deep and wide continuous trench with large berms, and the ripper teeth in the IDF, which created a narrow deep continuous trench. The untreated/control was also selected for the analysis.

Validation data for white spruce was obtained from two sites in B.C. and four sites in Alberta. The sites in B.C. are located south of Mackenzie in the Finlay-Peace variant of the wet cool subzone of the Sub-Boreal Spruce Zone (SBSwk2), and at Siphon Creek located 45 km northeast of Fort St. John in the Peace variant of the Boreal White and Black Spruce biogeoclimatic zone (BWBSmw1) (DeLong et al., 1990; Forest Practices Branch, 1999) (Table 3.4). For Alberta, the sites are part of a long term study of growth and development of white spruce and trembling aspen by the Western Boreal Growth and Yield (WESBOGY) association (WESBOGY, 2007) and were established in the Boreal mixedwood sub-region near Peace River and Grande Prairie, and in the Lower foothills sub-region near Edson (Beckingham and Archibald, 1996; Beckingham et al., 1996).

The Mackenzie experiment used a randomized complete block design where mechanical site preparation and untreated controls were replicated 5 times and the herbicide 4 times. A minimum of 48 trees were planted in each replicate (Sutton et al., 2001). Trees were measured regularly for diameter and height over the 20 year period (1987-2006). At this site trees were measured between seven and nine times although the first three years of growth were not included in the calculations.

The mechanical site preparation treatment selected for the validation analysis is the blading treatment. This was carried out in 3 m wide strips by a D7-mounted V-blade and trees were planted into exposed mineral soil 10 cm from the edge of the strip. The vegetation control treatment was created applying glyphosate (Vision®) at a rate of 2.7 Kg ai/ha pre-planting (Sutton et al., 2001). Observed values of the relative growth indices were calculated for height, diameter, and volume similarly to the other site preparation trials and these were then compared to the predicted values generated by the final models.

The Siphon Creek site was planted in May 1985 with 3-year-old bare root white spruce seedlings at 1480 stems per hectare. In 1990, the plots were thinned to aspen (*Populus tremuloides* Michx) densities of 0, 5000, and 10 000 stems per hectare. Aspen was manually thinned to the target densities, and balsam poplar (*Populus balsamifera* L.), willow (*Salix* spp.), green alder (*Alnus crispa* [Ait]

Pursh), and paper birch (*Betula papyrifera* Marsh.) were removed to maintain treatment densities (Kabzems et al., 2007). Spruce height was measured in 1994 to 1998 and in 2001 and 2002.

The treatment selected for the validation analysis is the ‘zero aspen density’ and the observed relative height growth index was calculated and compared with the predicted values generated using the model for spruce relative height growth index for the vegetation control treatment and the untreated.

The WESBOGY sites were planted in 1991 and 1992 with white spruce at 500 or 1000 stems per hectare and aspen (*Populus tremuloides* Michx) at densities ranging from 0 to 4000 stems per hectare (WESBOGY, 2007). Spruce height was measured regularly and the data used for validation are from years 1996 to 2004. The ‘zero aspen density’ treatment with 1000 white spruce per hectare was selected for this analysis. The observed relative height growth index was calculated and compared with the predicted values generated using the model for spruce based on relative height growth index for the vegetation control treatment and the untreated.

A number of methods were explored to validate the models including visual/graphical inspection, standard deviation and mean absolute difference between predicted and observed values, and the two on-sided test strategy (TOST) (Huang et al., 2003; Robinson et al., 2005). The TOST test computes the confidence interval for the upper and lower difference between observed and predicted at alpha=0.05 in relation to a given region of equivalence (e.g.,10%) (Robinson et al., 2005). If the two one-sided confidence intervals around the mean difference are entirely contained within the 10% region of equivalence than the predictions are considered significantly similar to the observations (Huang et al., 2003; Robinson et al., 2005). Confidence interval values that are within 10% and 20% indicate that additional data may be needed to help reach a more definitive answer while values higher than 20% should be rejected regardless of the theory (Huang et al. 2003).

Scatter plots of observed versus predicted values calculated for the validation analysis are presented in Appendix 4.

Table 3.4. List of locations for data used to validate the models for pine and spruce. MAT=Mean Annual Temperature; MAP=Mean Annual Precipitation; MSP=Mean Summer Precipitation; SHM=Summer Heat Moisture Index ((Mean Warmest Month Temperature)/(MSP/1000)).

Sp Location	Latitude and Longitude	Elevation (s.l.m.)	Biogeoclimatic Zone Or Natural sub-region	Year planted	MAT (C°)	MAP (mm)	MSP (mm)	SHM
Pine								
Beedy	52° 34' N, 122° 07' W	910	Sub-boreal spruce	1985	4.1	491	260	61
Sheridan	52° 25' N, 122° 11' W	980	Sub-boreal spruce	1985				
Em Fire	51° 44' N, 121° 57' W	930	Interior Douglas-fir	1985	3.6	505	260	60
Axe Lake	51° 58' N, 122° 03' W	1150	Interior Douglas-fir	1985				
Spruce								
Mckenzie	55° 13' N, 123° 01' W	760	Sub-boreal spruce	1987	2.8	790	299	51.7
Siphon Creek	56° 27' N, 120° 19' W	760	Boreal white and black spruce	1985	1.5	473	269	58.8
Peace River	56° 55' N, 118° 30' W	800	Boreal Mixedwood	1992	1.2	484	328	45.7
Grande Prairie	54° 55' N, 118° 30' W	762	Boreal Mixedwood	1991	2.2	491	323	50.4
Edson Medium	53° 46' N, 116° 41' W	1060	Lower Foothills	1992	2.9	570	417	36.8
Edson Superior	53° 48' N, 116° 38' W	1120	Lower Foothills	1992	2.8	580	422	36.1

3.3. Results

3.3.1. Growth indices and Climate variables

Growth of lodgepole pine and white spruce was evaluated for each selected treatment: mechanical preparation (MP), vegetation control (VC), and untreated controls (UN). For each treatment, the relative growth indices were calculated for diameter increment (D), height increment (H), and volume increment (V). For lodgepole pine relative growth indices the number of observations ranged from 20 to 30 with an average value of 25, and the relative growth index values range from 0.99 to 1.01 with an average value of 1.00. The number of observations ranges from 23 to 39 for white spruce relative growth indices with a range from 1.00 to 1.03 and an average across the growth indexes of 1.01 (Appendix 2). The growth indices calculated without the inclusion of the initial size of the tree performed slightly worse than the Relative Growth Indices and were not included in the balance of this chapter (Appendix 3).

In Table 3.5 I present the selected climate variables for each time scale including annual, seasonal, and monthly data that were tested for co-linearity. For every selected climate variable the value of the year prior to the increment was also included as an explanatory variable for the model calculations, which were indicated by a small letter ‘p’ before the variable name (e.g., pMAT).

Table 3.5. List of selected climate variables for each time scale. The value of the year prior to the increment is indicated by a small letter ‘p’ before the variable name (e.g., pMAT).

Annual Variables	
MAT and pMAT	mean annual temperature (°C)
MSP and pMSP	mean annual summer (May to September) precipitation (mm)
DD>5 and pDD>5	degree-days above 5°C, growing degree-days
eFFP and peFFP	the day of year on which frost-free period ends
PAS and pPAS	precipitation as snow
Seasonal variables	
pTAV_sm	summer mean temperature of the previous year (°C)
pTAV_wt	winter mean temperature of the previous year (°C)
TAV_sp	spring mean temperature (°C)
TAV_sm	summer mean temperature (°C)
pPPT_sm	summer mean precipitation of the previous year (mm)
pPPT_at	autumn mean precipitation of the previous year (mm)
pPPT_wt	winter mean precipitation (mm) of the previous year
PPT_sp	spring mean precipitation (mm)
PPT_sm	summer mean precipitation (mm)
Monthly variables	
pTAV07 - pTAV12	July - December mean temperature of the previous year (°C)
pPPT07 - pPPT12	July - December mean precipitation of the previous year (mm)
TAV01 – TAV08	January - December mean temperature (°C)
PPT01 – PPT08	January - December mean precipitation (mm)

3.3.2. Growth-climate relationships

The first selection process identified the best two climate variables at each time scale (annual, seasonal, and monthly) for each relative growth index and treatment (Tables 3.6 and 3.7). For the relative growth index, the R^2 values of the annual climate variables range from 0.165 to 0.293 for lodgepole pine, and from 0.182 to 0.370 for white spruce with peFFP (previous year end of frost free period) being the most reoccurring climate variable for pine (six times out of nine possible equations) and PAS (precipitation falling as snow) for spruce (eight times out of nine possible equations). For the seasonal climate variables R^2 values range from 0.064 to 0.300 for lodgepole pine, and from 0.202 to 0.475 for white spruce with TAV_sp (spring mean temperature) being the most reoccurring climate variable for pine (four times out of nine possible equations) and TAV_sp (spring mean temperature) for spruce (six times out of nine possible equations). For the monthly climate variables R^2 values range from 0.353 to 0.503 for lodgepole pine and from 0.295 to 0.575 for white spruce with pPPT_07 (previous year July precipitation) being the most reoccurring climate variable for pine (five times out of nine possible equations) and TAV_06 (June average temperature) being the most reoccurring climate variable for spruce (four times out of nine possible equations).

Table 3.6. Climate variable candidates for lodgepole pine for each relative growth index (RGI) and treatment (Tr.). Previous year climate variables are defined by a letter 'p' in front of the climate variable (e.g.: pMAT = Mean Annual Temperature of the previous year). See Table 3.3 for explanation of variable labels.

RGI	Tr.	Annual		R^2	Seasonal		R^2	Monthly		R^2
D	**MP**	MAT	peFFP	0.216	pPPT_sm	pPPT_at	0.157	pPPT07	pPPT10	0.456
	VC	MAT	peFFP	0.293	PPT_sp	pTAV_sm	0.283	PPT04	pPPT10	0.353
	UN	MAT	peFFP	0.177	TAV_sp	pPPT_sm	0.064	PPT01	pPPT07	0.382
H	**MP**	peFFP	pPAS	0.211	TAV_sp	pPPT_wt	0.208	PPT03	pTAV09	0.401
	VC	peFFP	pPAS	0.290	TAV_sp	pPPT_wt	0.205	PPT08	pTAV09	0.376
	UN	peFFP	pPAS	0.281	pTAV_wt	pTAV_sm	0.300	PPT06	pTAV07	0.503
V	**MP**	eFFP	pPAS	0.165	TAV_sm	pPPT_sm	0.158	PPT06	pPPT07	0.434
	VC	MAT	pPAS	0.209	TAV_sp	PPT_sp	0.242	PPT06	pPPT07	0.446
	UN	MAT	pPAS	0.220	TAV_sm	pPPT_wt	0.137	pPPT07	pPPT08	0.397

Table 3.7. Climate variable candidates for white spruce for each relative growth index (RGI) and treatment (Tr.). Previous year climate variables are defined by a letter ‘p’ in front of the climate variable (e.g.: pMAT = Mean Annual Temperature of the previous year). See Table 3.3 for explanation of variable labels.

RGI	Tr.	Annual		R^2	Seasonal		R^2	Monthly		R^2
D	**MP**	peFFP	pPAS	0.354	TAV_sp	pPPT_sm	0.433	PPT03	pPPT07	0.457
	VC	PAS	peFFP	0.274	pTAV_wt	PPT_sm	0.202	PPT01	pTAV09	0.393
	UN	PAS	pMSP	0.369	TAV_sp	pPPT_sm	0.421	pTAV12	pPPT11	0.575
H	**MP**	PAS	pMSP	0.327	TAV_sp	TAV_sm	0.355	TAV06	pTAV08	0.398
	VC	PAS	pMSP	0.370	pPPT_sm	pPPT_at	0.370	TAV06	pTAV08	0.492
	UN	pDD5	peFFP	0.309	TAV_sp	pTAV_sm	0.308	TAV06	pTAV08	0.465
V	**MP**	PAS	peFFP	0.182	TAV_sp	pPPT_at	0.284	PPT03	pPPT10	0.388
	VC	PAS	pDD5	0.267	pTAV_wt	pPPT_at	0.252	pPPT11	pPPT12	0.295
	UN	PAS	peFFP	0.245	TAV_sp	PPT_sp	0.475	TAV04	TAV06	0.522

The six final candidate explanatory variables for each relative growth index and treatment were evaluated in the final models using two climate variables each and results are presented in Tables 3.8 and 3.9 for lodgepole pine and white spruce respectively.

Monthly climate variables for lodgepole pine were selected in the final model 15 times out of 18 possible variables, annual climate variables were selected two times, and only one seasonal variable was selected. For white spruce monthly climate variables were selected 12 times out of 18 possible variables, seasonal climate variables were selected five times, and only annual variable was selected. Climate variables for the year prior to the growth are represented in the final models 12 times out of the 18 possible variables for pine and eight times for spruce.

For lodgepole pine the climate variables for diameter relative growth index include precipitation levels four out of six times, for height the climate variables selected are a mix of temperature and precipitation while for volume only precipitation levels are represented. For white spruce the relative growth index for diameter includes five precipitation variables (out of the six possible combinations) while height growth is predicted only by temperature variables. The relative volume index presents a mix of four temperature variables and two precipitation variables.

Statistical significance, Akaike's information criterion values (AIC), Mallows' Cp values, and co-linearity test of the best models were calculated for lodgepole pine and white spruce (Tables 3.8 and 3.9). AIC values and Mallows' Cp values are measures of the goodness of fit of the estimated statistical models. The averaged adjusted R-square values for the relative growth index are 0.370 for pine and 0.432 for spruce.

All models shown in Tables 3.8 and 3.9 are significant ($P<0.05$) and the adjusted R^2 (Adj-R^2) values range from 0.311 to 0.467 for pine, and from 0.326 to 0.566 for white spruce. For pine, Adj-R^2 values averaged by growth index show that height growth index is predicted best (Adj-R^2=0.375), followed by volume (Adj-R^2=0.371), and diameter (Adj-R^2=0.365). For spruce Adj-R^2 results show that height growth index is best predicted (Adj-R^2=0.461), followed by diameter (Adj-R^2=0.455), and volume (Adj-R^2=0.381). AIC values, Mallows' Cp values, and co-linearity test results do not indicate any statistical problem with the models.

Table 3.8. Description of final selected models using climate variables to estimate lodgepole pine relative growth index (RGI) for diameter (D), height (H), and volume (V) by treatment (Tr): mechanical preparation (MP), vegetation control (VC), and untreated (UN). Number of observations, predictive ability, statistical significance, Akaike's information criterion values (AIC), Mallows' Cp values, and co-linearity test of the best models for lodgepole pine. Climate variables abbreviations are described in Table 3.5.

RGI	Tr								*Significance test*						*Co-linearity test*	
		Obs #	Adj-R^2	Intercept	Variable A		Variable B		Model	Intercept	Var. A	Var. B	AIC	Cp	Coeff	Prob.
D	**MP**	25	0.407	1.01119	-0.00325	pPPT07	-0.00332	pPPT10	0.001	<.0001	0.002	0.008	-102	3	0.133	0.428
	VC	21	0.315	0.99974	-0.0054	peFFP	-0.00174	PPT_sp	0.013	<.0001	0.031	0.009	-96	3	-0.191	0.251
	UN	29	0.372	1.00869	-0.00725	peFFP	-0.00374	pPPT07	0.001	<.0001	0.017	0.001	-113	3	-0.253	0.125
H	**MP**	26	0.348	1.02657	0.00561	PPT03	0.09163	pTAV09	0.003	<.0001	0.009	0.001	-105	3	-0.407	0.011
	VC	22	0.311	1.00309	0.00288	PPT08	0.05969	pTAV09	0.011	<.0001	0.034	0.016	-90	3	-0.051	0.759
	UN	30	0.467	1.03653	-0.00163	PPT06	0.12483	pTAV07	<.0001	<.0001	0.010	<.0001	-132	3	0.394	0.015
V	**MP**	24	0.380	1.03238	-0.00149	PPT06	-0.0038	pPPT07	0.002	<.0001	0.028	0.001	-102	3	-0.008	0.962
	VC	20	0.381	1.0317	-0.00138	PPT06	-0.00273	pPPT07	0.007	<.0001	0.014	0.004	-96	3	-0.008	0.962
	UN	29	0.351	1.02187	-0.004	pPPT07	0.00296	pPPT08	0.001	<.0001	0.001	0.032	-130	3	0.481	0.002

Table 3.9 Description of final selected models using climate variables to estimate white spruce relative growth index (RGI) for diameter (D), height (H), and volume (V) by treatment (Tr): mechanical preparation (MP), vegetation control (VC), and untreated (UN). Number of observations, predictive ability, statistical significance, Akaike's information criterion values (AIC), Mallows' Cp values, and co-linearity test of the best models for white spruce. Climate variables abbreviations are described in Table 3.5.

RGI	Tr								*Significance test*						*Co-linearity test*	
		Obs #	Adj-R^2	Intercept	Variable A		Variable B		Model	Intercept	Var. A	Var. B	AIC	Cp	Coeff	Prob.
D	**MP**	23	0.484	1.03472	-0.00205	PPT_sm	0.00755	PPT03	0.001	<.0001	0.001	0.001	-97	3	0.070	0.603
	VC	31	0.380	1.05346	0.00605	pPPT_at	0.01323	PPT01	0.001	<.0001	0.004	0.001	-88	3	-0.151	0.263
	UN	23	0.532	0.92046	-0.05361	pTAV12	0.00697	pPPT11	0.001	<.0001	<.0001	0.016	-74	3	-0.158	0.241
H	**MP**	30	0.353	1.02715	0.1418	TAV06	-0.09262	pTAV08	0.001	<.0001	0.001	0.007	-117	3	0.384	0.003
	VC	39	0.463	1.00802	0.13439	TAV06	-0.09188	pTAV08	<.0001	<.0001	<.0001	0.001	-155	3	0.384	0.003
	UN	33	0.566	0.98131	-0.22178	pTAV_sm	0.1503	TAV06	<.0001	<.0001	<.0001	<.0001	-120	3	0.055	0.685
V	**MP**	23	0.326	1.0385	0.00506	PPT03	0.00368	pPPT10	0.007	<.0001	0.009	0.025	-110	3	-0.246	0.065
	VC	31	0.326	1.04799	0.00402	PAS	0.00366	pPPT_at	0.002	<.0001	0.001	0.005	-117	3	-0.370	0.005
	UN	23	0.491	1.00437	-0.02414	TAV_sp	0.03653	TAV06	0.001	<.0001	0.001	0.017	-124	3	0.022	0.871

3.3.3 Model validation

Figures 3.3, 3.4, and 3.5 illustrate the correspondence between predicted and observed relative growth indices of both species for the validation datasets. Table 3.10 summarizes the mean absolute differences (MAD) and standard deviation (σ) between model predictions and observed values for all sites and species, and Table 3.11 summarizes the TOST test results.

Lodgepole pine results for the Sub-Boreal Spruce and Interior Douglas-fir biogeoclimatic zones show satisfactory correspondence between observed and predicted values based on visual inspection for the relative height growth index (Figure 3.3). The model for the mechanical preparation treatment shows a better predictive ability than the untreated based on MAD and standard deviation (Table 3.10). In the Sub-Boreal Spruce zone the TOST test indicates that two out of the three confidence intervals fall within the 10% region of equivalence and one falls in the 20% region of equivalence, while in the Interior Douglas-fir zone one out of the four confidence intervals falls within the 10% region of equivalence and two in the 20% region of equivalence (Table 3.11).

For white spruce the results of the visual inspection shows satisfactory correlations for: Siphon Creek, Peace River and mechanical preparation at Mackenzie, while correlations are limited for: Grande Prairie, Edson Medium, Edson Superior and vegetation control and untreated at Mackenzie (Figures 3.4 and 3.5). Across all sites the model for the vegetation control treatment shows higher predictive ability than mechanical preparation and untreated based on the MAD and standard deviation values (Table 3.10). The TOST test indicates that the majority of the confidence intervals fall within the 10% region of equivalence at Siphon Creek, and Peace River and half of the confidence interval values fall within the 10% region of equivalence at the Grande Prairie and Edson Superior sites (Table 3.11). Less than half of the confidence interval values fall within the 10% region of equivalence at Mackenzie and Edson Medium sites for spruce although the majority of the remaining interval values are smaller than 20%.

Table 3.10. Residual values (number of observations (n), mean absolute difference (MAD) and standard deviation (σ)), for lodgepole pine (Pl) and white spruce (Sw) presented by: species (Spp), site, relative growth index (RGI), and treatment (mechanical preparation (MP), vegetation control (VC) and untreated (UN)).

Spp	Site	RGI	Treatment	n	MAD	σ
Pl	SBS	Height	MP	6	0.12	0.09
			UN	6	0.29	0.17
Pl	IDF	Height	MP	6	0.18	0.12
			UN	6	0.15	0.16
Sw	MacKenzie	Diam.	MP	3	0.08	0.03
			VC	3	0.32	0.16
			UN	3	0.32	0.27
		Height	MP	4	0.16	0.10
			VC	4	0.17	0.12
			UN	4	0.25	0.16
		Volume	MP	3	0.03	0.05
			VC	3	0.43	0.14
			UN	3	0.15	0.10
Sw	Siphon Creek	Height	VC	5	0.08	0.09
			UN	5	0.03	0.07
Sw	Peace River	Height	VC	6	0.15	0.14
			UN	6	0.06	0.10
Sw	Grande Prairie	Height	VC	7	0.17	0.20
			UN	7	0.13	0.21
Sw	Edson Medium	Height	VC	8	0.14	0.19
			UN	8	0.17	0.23
Sw	Edson Superior	Height	VC	8	0.15	0.18
			UN	8	0.15	0.21

Table 3.11. TOST test results for lodgepole pine (Pl) and white spruce (Sw) presented by: species (Spp), site, relative growth index (RGI), and treatment (mechanical preparation (MP), vegetation control (VC) and untreated (UN)). For positive and negative residuals the information presented is: number of observations (n), mean, standard deviation (σ), and confidence intervals (CI). Confidence intervals values are in bold when the percentage is contained in the region of equivalence (10%).

				Positive				Negative			
Spp	Site	RGI	Treatment	n	Mean	σ	CI (%)	n	Mean	σ	CI (%)
Pl	SBS	Height	MP	5	0.10	0.08	**7**	1	-	-	**-**
			UN	3	0.42	0.13	15	3	-0.16	0.09	**10**
Pl	IDF	Height	MP	2	0.21	0.17	23	3	-0.15	0.08	**9**
			UN	4	0.18	0.19	18	2	-0.08	0.1	14
Sw	MacKenzie	Diam.	MP	2	0.06	0.07	**10**	1	-	-	**-**
			VC	3	0.33	0.16	18	-	-	-	**-**
			UN	-	-	-	-	3	-0.32	0.27	30
		Height	MP	4	0.16	0.1	**10**	0	-	-	-
			VC	4	0.17	0.12	12	0	-	-	-
			UN	4	0.25	0.16	15	0	-	-	-
		Volume	MP	-	-	-	**-**	3	-0.03	0.05	**6**
			VC	-	-	-	-	3	-0.43	0.14	16
			UN	1	-	-	-	2	-0.10	0.09	12
Sw	Siphon Creek	Height	VC	2	0.06	0.04	**5**	3	-0.09	0.01	**2**
			UN	1	-	-	-	4	-0.09	0.08	**8**
Sw	Peace River	Height	VC	4	0.14	0.08	**7**	2	-0.14	0.05	**6**
			UN	4	0.14	0.12	12	2	-0.09	0.07	**10**
Sw	Grande Prairie	Height	VC	3	0.26	0.15	17	4	-0.1	0.05	**5**
			UN	5	0.17	0.25	22	2	-0.27	0.06	**8**
Sw	Edson Medium	Height	VC	5	0.18	0.21	19	1	-	-	-
			UN	3	0.34	0.34	39	5	-0.1	0.08	**7**
Sw	Edson Superior	Height	VC	5	0.19	0.17	15	3	-0.08	0.07	**8**
			UN	4	0.25	0.3	30	4	-0.11	0.07	**6**

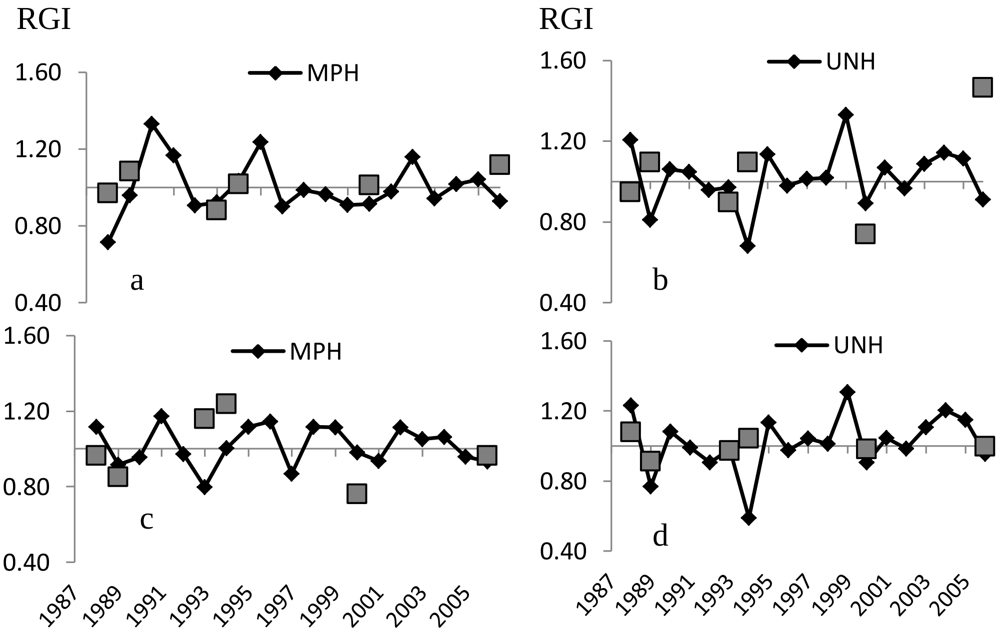


Figure 3.3. Validation results for lodgepole pine using data from the Sub-Boreal Spruce (a, b) and the Interior Douglas-fir (c, d) biogeoclimatic zones. Relative Growth Index (RGI) for predicted (diamond) and observed height values (square) calculated using the models developed for mechanical preparation (MPH), and untreated (UNH).

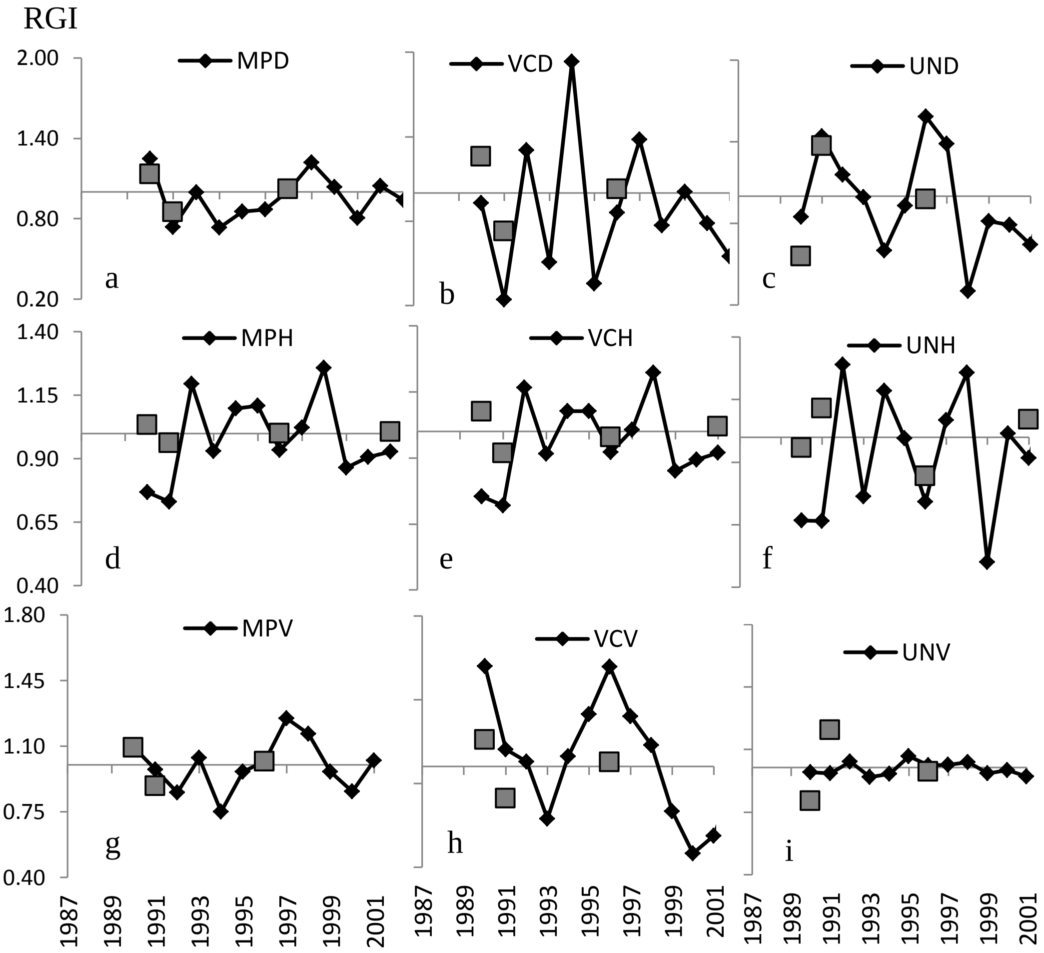


Figure 3.4. Validation results for white spruce using data from the Mackenzie site. Relative Growth Index (RGI) predicted (diamond) and observed values (square) for diameter (a,b,c), height (d,e,f), and volume (g,h,i) were calculated using the models developed for mechanical preparation (MP), vegetation control (VC) and untreated (UN).

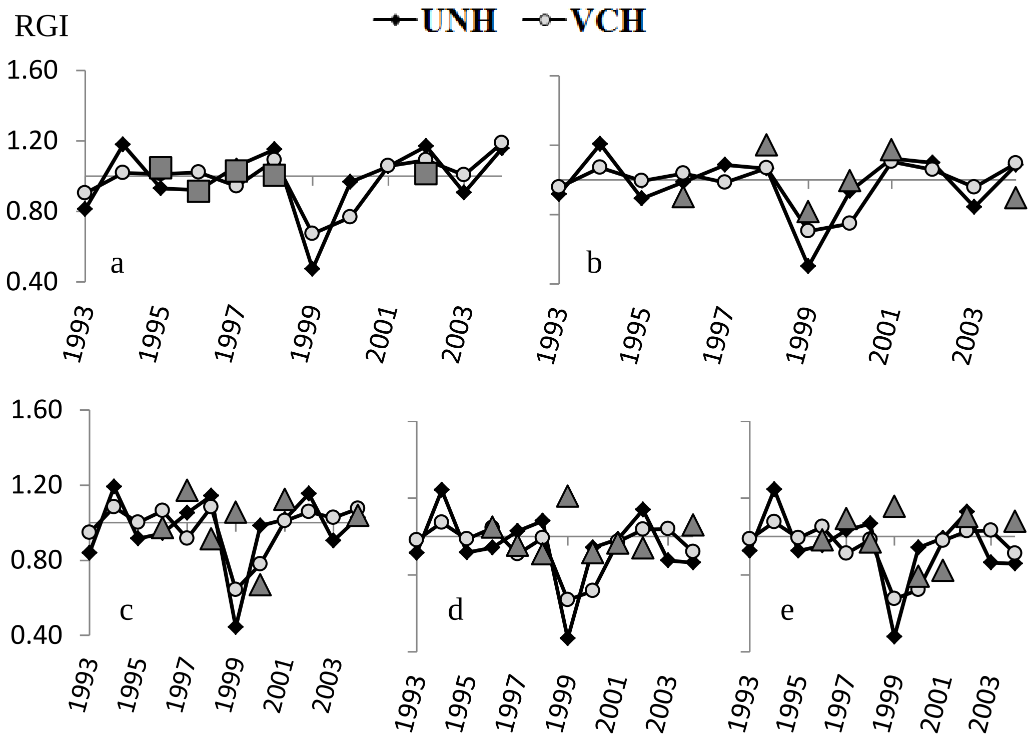


Figure 3.5. Validation results for white spruce using data from the Siphon creek site (a), and from the WESBOGY sites near: Peace River (b), Grande Prairie (c), Edson Medium (d) and Superior site (e). Relative Growth Index (RGI) for predicted (diamond and circle) and observed height values (squares for the Siphon Creek trial and triangles for the WESBOGY sites) were calculated using the models developed for vegetation control (VCH) and untreated (UNH).

3.3.4. Growth projections

Under two climate change scenarios (i.e., A2 and B2) projected growth was calculated for the 2020s future period (2005-2035) for lodgepole pine and white spruce for the best increment among the relative growth index models (Figures 3.6 and 3.7).

For pine, height growth shows that the untreated has the highest growth potential under the two future scenarios (A2: 11.9% and B2: 12.4%), followed by the mechanical preparation treatment (A2: 8.1% and B2: 8.2%), and the vegetation control treatment (A2: 1.8% and B2: 2.6%). For spruce results for height growth show a potential growth increase for the mechanical preparation treatment (A2: 4.0% and B2: 3.5%), and the vegetation control treatment (A2: 2.2% and B2: 1.6%); and a potential growth decrease for the untreated (A2: -8.7% and B2: -4.8%).

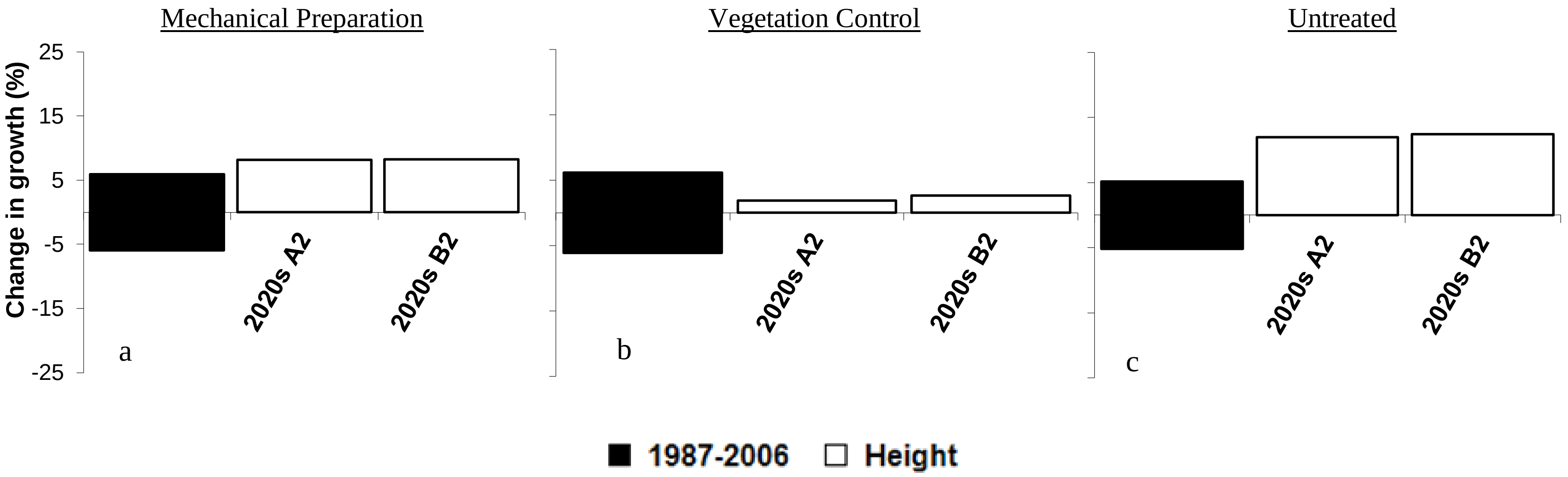


Figure 3.6. Projected percent change of relative growth indices for height of lodgepole pine for the 2020s future period (2005-2035) according to scenarios: A2 and B2 compared to the averaged past growth. The black bar indicates the 95% confidence interval limits of the mean past growth for the studied period (1987-2006) (and approximate the confidence interval for future years).

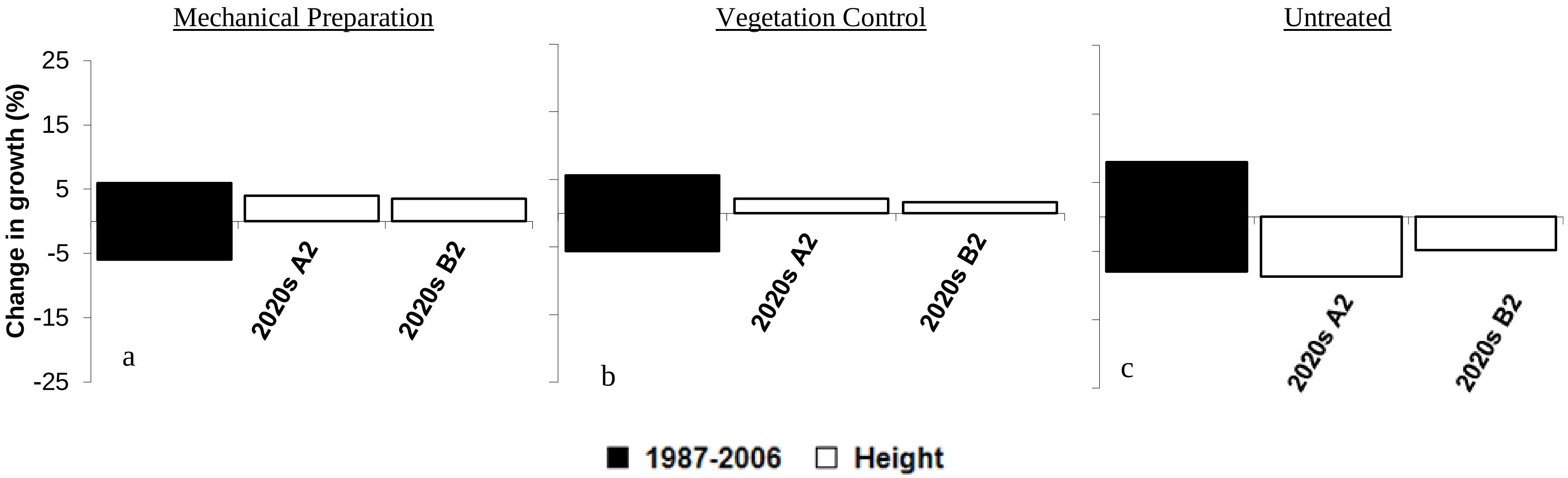


Figure 3.7. Projected percent change of relative growth indices for diameter of white spruce for the 2020s future period (2005-2035) according to scenarios: A2 and B2 compared to the averaged past growth. The black bar indicates the 95% confidence interval limits of the mean past growth for the studied period (1987-2006) (and approximate the confidence interval for future years).

3.4. Discussion

3.4.1. Growth-climate relationships

Monthly climate variables are better predictors of pine and spruce growth than seasonal or annual variables. This is consistent with existing knowledge indicating that monthly or bimonthly average precipitation and temperature for selected months are major factors controlling growth rates (e.g., Chhin et al. 2008). Thomson and Parker (2008) used data from a provenance test of jack pine to screen a total of 65 climate variables at annual, seasonal, and monthly levels and found that monthly values (i.e., August minimum temperature and January maximum temperature) were better correlated with pine growth than seasonal and annual averages. Similar analysis for black and white spruce have also shown that monthly variables are better predictors of spruce growth (Cherry and Parker 2003; Thomson et al. 2009). Our study also suggests that the finer climatic scale of the monthly variables makes them more effective than seasonal and annual averages at capturing the factors limiting the growth of conifer plantations.

Previous studies of jack pine and lodgepole pine have found that air temperature is a better predictor of height growth than precipitation (e.g., Thomson and Parker 2008; Rehfeldt et al. 1999) we found that monthly temperature and precipitation are equally effective in predicting lodgepole pine growth. Chhin et al. (2008) found that precipitation was better correlated than temperature to basal area of lodgepole pine in north-western Alberta whereas Miyamoto et al. (2010) found a stronger relationship between growth and temperature in B.C. Results for lodgepole pine in our study show that both temperature and precipitation should be used for explaining variation in relative diameter growth. Cherry and Parker, (2003) report a strong relationship with both temperature (i.e., mean maximum January temperature) and precipitation (i.e., mean May precipitation) for white spruce growth and survival. Our results for white spruce also indicate that temperature and precipitation are the best predictors of growth suggesting that at these northern latitudes both factors are important (Barber et al. 2000).

Lodgepole pine and white spruce manifest lagged responses to climate of the previous year. Other studies indicate that the most influential predictor variables were related to the prior growing season (Chhin et al. 2008; Miyamoto et al. 2010). For conifers with determinant growth patterns (such as lodgepole pine and white spruce) the climatic conditions in the year of bud formation determine the size of the bud and the number of needle or fascicle bundle internodes and stem initials that will grow during the following growing season (O'Reilly and Owens 1987). In species with determinant growth characteristics total annual elongation is the result of the number of internodes set during the previous growing season and their average length achieved during the current year (Chuine et al. 2006). Thus growth rates are highly dependent on the number of internodes set the previous growing season which is consistent with the good correlation found in this study between growth and climate conditions of the previous year. In addition, the amount (leaf area) and condition of foliage at the end of the preceding year will have a substantial effect on net photosynthesis by a tree and its growth rate. Chuine et al. (2006) found that the number of internodes set the preceeding summer was highly correlated to lodgepole pine height growth. Subsequent growth of the buds, needles and stem initials is strongly influenced by conditions during the season of growth.

3.4.2. Model validation

For both lodgepole pine and white spruce, models developed in this study effectively predict tree growth on a range of other sites. However, the best predictions were obtained for sites located near those used for model development. Other studies have indicated the importance of regional and site specific studies given the large variability between each population and its response to climatic factors (e.g., Miyamoto et al., 2010; O'Neill et al., 2008).

3.4.3. Growth projections

Results indicate that future growth of lodgepole pine in the sub-boreal spruce zone of B.C. might benefit from the future climate conditions in plantations up to 20 years old. In the Canadian Yukon, Johnstone and Chapin (2003) examined the distribution of lodgepole pine and concluded that pine is not in equilibrium with current climate and they found evidence of a rapid population expansion northward. Studies have also indicated that lodgepole pine productivity will increase in central B.C. as temperature increases (Wang et al. 2006; Miyamoto et al. 2010). In Alberta, a study on site index variations modeled with climate variables has shown that lodgepole pine site index could potentially increase in the future by 3 m for each 30-year period (Monserud et al. 2008). In areas with similar climatic conditions to this study Chhin et al. (2008) have also shown that lodgepole pine growth could increase in the future. Smithwick et al. (2009) also concluded that lodgepole pine production could potentially increase by 22-36% by 2100 in the Yellowstone National Park (USA).

For the untreated lodgepole pine control plots in this study the projections for the future period 2020s indicate a growth increase of approximately 12% whereas the vegetation control treatment and the mechanical preparation treatment will increase on average by 5%. This difference could be related to the fact that the treated pines are already growing at a rate close to their full potential whereas the untreated can benefit from growth improvement provided by a warmer climate. Our study indicates that lodgepole pine could increase its productivity in north-eastern B.C. based on the assumption that the mean conditions represent how pine will respond to the variation around the mean growth, and assuming that climate change will not trigger other negative ecological responses such as insect or disease outbreaks, increased competition levels or result in maladaptation of these provenances (e.g., Nigh et al. 2004).

For white spruce the results show that future growth in the boreal zone of B.C. could be negatively affected by the future climatic conditions for untreated stands. Another study in the Alaskan boreal forest using mature and old stands concluded that temperature-induced drought stress is reducing white spruce productivity at northern latitudes (Barber et al. 2000). Similarly Lloyd and Fastie (2003) found that growth declines were more common in warmer and drier parts of the boreal forest. Cherry and Parker (2003) also report that white spruce populations will survive at their present locations but productivity will be negatively affected by the climatic changes. Drought stress related to warmer and drier summers could also make other vegetation (e.g.,*Calamagrostis canadensis* (Michx.) Beauv., *Salix* spp.) stronger competitors for water in spruce stands (e.g., Lieffers et al. 1993; Man et al. 2008).

Our study indicates height growth of white spruce for the future period 2005-2035 could potentially increase by approximately 3% on average where mechanical site preparation or vegetation control is applied while spruce growth could potentially decrease on untreated sites by up-to 10%.

Plant community analyses at Inga Lake highlight that, even 20 years after planting, tall shrubs deciduous were still a major component of the untreated plots whereas grasses and forbs were more common in the mechanical site preparation and vegetation control treatments (Haeussler et al. 1999; Forest Practices Branch 2008). In boreal region stands, Matsushima and Chang (2006) also found that white spruce would not benefit from N fertilization unless the grass layer is removed. The effect of the competing vegetation suggests that drought-stress levels could increase in the future for young untreated white spruce plantations up to age 20. Thus the application of proper site preparation could potentially offset the negative impact of climate change on early spruce growth (i.e., drought-stress) by decreasing competition from tall shrubs (e.g., willow and alder), and grass, improving soil temperature, reducing limitations from excess spring moisture, increasing nutrient availability, and accelerating early root growth of white spruce to make it better able to overcome competition. These projections are valid if other ecological factors remain within the tolerance limits of this provenance of white spruce under the current climatic changes (e.g., temperature, moisture and nutrient requirements); and also if insect and disease problems do not increase with climate change (e.g., Huberty and Denno 2004; Laubhann et al. 2009).

Mechanical preparation and competing vegetation control can potentially ease the competitive effect of unwanted vegetation in a changing climate although every treatment needs to be planned carefully at the stand level and more studies are required to explore the impact of these treatments in relation to climate change. Nitrogen fixing species (e.g., *Alnus viridis* spp. *Sinuata* (Regel) Á. Löve & D. Löve) have the capability to enhance site fertility with potential benefit to the crop trees thus their complete removal from the stand would not be indicated on poor sites or given the uncertainty related to the current climatic changes (Brockley and Sanborn 2003; Laubhann et al. 2009). Maintenance of some woody vegetation cover may also afford protection of trees from cold injury during winters with low snow cover (Krasowski et al. 1993).

Other studies have indicated that high variability should be expected in regard to species response to climate change based on their geographic location and provenance (e.g., Spittlehouse 2008). A study on conifer growth across a wide range of geographic and climate ranges in B.C. and Yukon indicated that lodgepole pine shows positive correlations with growing season temperature, while white spruce growth may show increased growth on cooler sites due to higher growing season temperatures but may be negatively affected on warmer sites (Miyamoto et al. 2010). For spruce, interactions between temperature, soil moisture, microsite and competing vegetation are likely to have strong influences on climate change responses.

Establishment practices including mechanical site preparation and vegetation control should be considered as important tools for improving growth and survival of lodgepole pine and white spruce under changing climates. However, the potential benefits of these and other silvicultural treatments will vary by species and climate conditions.

3.5. Conclusions

Tree species interactions with abiotic and biotic factors can lead to variable levels of forest productivity under the current climatic changes compared to past growth. This study reinforces the importance of climate variables when studying the growth of conifer plantations and provides some indications regarding the climatic factors that have more effect on growth of lodgepole pine and white spruce.

For the sub-boreal zone of British Columbia (Canada) young lodgepole pine plantations will potentially benefit in the short term from longer growing seasons as a result of global warming. The untreated plots are showing greater potential in relative growth increase and smaller increases can be observed for the mechanical site preparation treatment and the vegetation control treatment. For the boreal zone of British Columbia young white spruce plantations may suffer from drought stress as the climate warms. Potentially, there will be more negative effects on untreated stands while vegetation management and mechanical preparation might result beneficial for spruce growth in the short term.

The most recent literature on forest management in a climate change era indicates the need for an enhanced capacity to undertake integrated assessments of vulnerability to climate change at various scales (e.g., Campbell et al. 2009; Spittlehouse, 2008 Williamson et al., 2009; Hebda, 2009). The stand level scale of this study offered the unique opportunity to explore different forest management techniques in relation to climate. Nevertheless, a larger number of long term studies are necessary in order to expand the range of indications to more ecological zones and to other species.

3.6. References

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. Evolutionary Applications 1: 95–111.

Barber, V.A., Juday, G.P., Finner, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405: 668-673.

Beckingham, J.D., Archibald, J.H., 1996. Field guide to ecosites of northern Alberta. Can. For. Serv. North. For. Cent. Spec. Rep. 5.

Beckingham, J.D., Corns, I.G.W., Archibald, J.H., 1996. Field guide to ecosites of west-central Alberta. Can. For. Serv. North. For. Cent. Spec. Rep. 9.

Bedford, L., McMinn, R.G., 1990. Trials to appraise the biological effectiveness of mechanical site preparation equipment in British Columbia: FRDA Project 1.10. p. 3±12. In: Titus, B.D., Lavigne, M.B., Newton, P.F., Meades, W.J. (Eds.). The Silvics and Ecology of Boreal Spruces. 1989 IUFRO Working Party S1. 05±12 Proc. Symp. For. Can., St. John's, Newfoundland, Inf. Rep. N-X-271.

Bedford, L., Sutton, R.F., 2000. Site preparation for establishing lodgepole pine in the sub-boreal spruce zone of the interior British Columbia: the Bednesti trial, 10-year results. Forest Ecology and Management 126: 227-238.

Bedford, L., Sutton, R.F., Stordeur, L., Grismer, M., 2000. Establishing white spruce in the Boreal White and Black Spruce Zone. New Forests 20: 213-233.

Boateng, J.O., Herring, L.J., 1990. Site preparation: Chemical. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia’s Forests (pp.164-178). University of British Columbia Press. Vancouver 1990.

Boateng, J.O., Heineman, J.L., McClarnon, J., Bedford, L., 2006. Twenty year responses of white spruce to mechanical site preparation and early chemical release in the boreal region of northeastern British Columbia. Canadian Journal of Forest Research 36: 2386-2399.

Boateng, J.O., Heineman, J.L., Bedford, L., Harper, G.J., Nemec, A.F.L., 2009. Long-term effects of site preparation and postplanting vegetation control on *picea glauca* survival, growth and predicted yield in boreal British Columbia. Scandinavian Journal of Forest Research 24(2): 111-129.

Brand, D.G., Weetman, G.F., and Rehsler, P. 1987. Growth analysis of perennial plants: the relative production rate and its yield components. Annals of Botany (London), **59**: 45–53.

Brockley, R.P., Sanborn, P., 2003. Effects of Sitka alder on the growth and foliar nutrition of young lodgepole pine in central interior of British Columbia. Canadian Journal of Forest Research 33:1761-1771.

Burton, P., Bedford, L., Goldstein, M., Osberg, M., 2000. Effects of disk trench orientation and planting spot position on the ten-year performance of lodgepole pine. New Forests 20: 23-44.

Campbell, E.M., S.C. Saunders, K.D., Coates, D.V., Meidinger, A., MacKinnon, G.A., O'Neill, D.J., MacKillop, S.C. DeLong, and D.G. Morgan. 2009. Ecological resilience and complexity: a theoretical framework for understanding and managing British Columbia's forest ecosystems in a changing climate. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. Tech. Rep. 055. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr055.htm

Cherry, M., Parker, W.H., 2003. Utilization of genetically improved stock to increase carbon sequestration. For. Res. Rep. 160. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ont.

Chhin, S., Hogg, E.H., Lieffers, V.J., Huang, S., 2008. Potential effects of climate change on the growth of lodgepole pine across diameter size classes and ecological regions. Forest Ecology and Management 256: 1692-1703.

Chuine, I., Rehfeldt, G.E., Aitken, S.N., 2006. Height growth determinants and adaptation to temperature in pines: a case study of Pinus contorta and Pinus monticola. Canadian Journal of Forest Research 36:1059-1066.

Comeau, P.G., Braudmandl, T.F., Xie, C.Y., 1993. Effects of overtopping vegetation on light availability and growth of Engelmann spruce (*Picea* *engelmannii*) seedlings. Canadian Journal of Forest Research 23: 2044–2048.

Cortini, F., Comeau, P.G., 2008. Evaluation of competitive effects of green alder, willow and other tall shrubs on white spruce and lodgepole pine in Northern Alberta. Forest Ecology and Management 255: 82-91.

DeLong, C., MacKinnon, A., Jang, L., 1990. A field guide for identification and interpretation of ecosystems of the northeast portion of the Prince George Forest Region. B.C. Ministry of Forests Land Manage. Handb. No. 22. Victoria, B.C. 108 p.

DeLong, C., Tanner, D., Jull, M.J., 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. BC Min. For., Victoria, BC, Land Manage. Handb. 24, 290 pp.

Ebata, T., 2004. Current status of mountain pine beetle in British Columbia. Pages 52–56 in T. L. Shore, J. E. Brooks, and J. E. Stone, editors. Mountain Pine Beetle Symposium: Challenges and Solutions. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, British Columbia, Canada.

Flato, G.M., Boer, G.J., 2001. Warming asymmetry in climate change simulations. Geophysical Research Letters 28: 195–198.

Ford, E.D., 1984. The Dynamics of Plantation Growth. In: G.D. Bowen and E.K.S. Nambiar, Editors, *Nutrition of Plantation Forests*, Academic Press, London (1984), pp. 17–52.

Forest Practices Branch, 1999. Settling of Mechanically Prepared Munds in Northern BC: 10-year Summary. Silviculture Nore: 22. BC. Min. For., Victoria, B.C. 6 pp.

Forest Practices Branch, 2008. Inga Lake Site: Testing the Biological Effectiveness of Mechanical Site Preparation and Vegetation Control Methods: 20-years Results. Unpublished tour guide. BC. Min. For., Victoria, B.C. 84 pp.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., Flanning, M.D., 2004. Detecting the effect of climate change on Canadian forest fires. Geophysical research letters, 31: L18211.

Haeussler, S., Bedford, L., Boateng, J.O., MacKinnon, A., 1999. Plant community responses to mechanical site preparation in northern interior British Columbia. Canadian Journal of Forest Research 29: 1084-1100.

Harper, J.L., 1977. Population Biology of Plants, Academic Press, New York (1977).

Hawkes, B.C., Feller, M.C., and Meehan, D. 1990. Site preparation: Fire. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia's

Forests (pp.131-149). University of British Columbia Press. Vancouver 1990.

Hebda, R.J., 2009. The future of British Columbia forests requires resilience management. *In:* Drengson, A., and Taylor, D. 2009. Wild Foresting: practising nature's wisdom. New Society Publishers. pp. 202-209.

Honer, T.G., Ker, M.F, Alemdag, I.S., 1983. Metric timber tables for the commercial tree species of central and eastern Canada. Can. For. Serv. Inf. Rep. MX-140.

Huang, S., Yang, Y., Wang. Y., 2003. A critical look at procedures for validating growth and yield models. *In:* Amaro, A., Reed, D., and P. Soares. Modelling Forest Systems. CAB International 2003. pp. 271-293.

Huberty, A.F., Denno R.F., 2004. Plant water stress and its consequences for herbivorous insects: a new synthesis. Ecology 85: 1383-1398.

Hunt, R., 1982. Plant Growth Curves – The Functional Approach to Plant Growth Analysis. Edward Arnold (Publishers) Ltd., London, pp. 248.

International Panel on Climate Change (IPCC). 1997. An introduction to simple climate models used in the IPCC second assessment report. IPCC Technical paper II. http://www.ipcc.ch/.

International Panel on Climate Change (IPCC). 2007. Climate change 2007: synthesis report: summary for policymakers: an assessment of the intergovernmental panel on climate change. Valencia, Spain: IPCC; 2007.

Kabzems, R., Nemec, A.L., Farnden, C., 2007. Growing trembling aspen and white spruce intimate mixtures: Early results (13–17 years) and future projections. BC Journal of Ecosystems and Management 8(1): 1–15.

Knowles, N., Dettinger, M.D., Cayan, D.R., 2006. Trends in snowfall versus rainfall in the Western United States. Journal of Climate 19: 4545-4559.

Krasowski, M.J., Herring, L.J., Letchford, T., 1993. Winter freezing injury and frost acclimation in planted coniferous seedlings. For. Can. and B.C. Min. For., Victoria, BC. FRDA Rep. No. 206.

Johnstone, J.F., Chapin, F.S., 2003. Non-equilibrium succession dynamics indicate continued northern migration of lodgepole pine. Global Change Biology 9: 1401-1409.

Larocque, G.R., Marshall, P.L., 1993. Evaluating the impact of competition using relative growth rate in red pine (*Pinus resinosa* Ait.) stands. Forest Ecology and Management 58: 65–83.

Larocque, G.R., 1998. Functional growth analysis of red pine trees under variable intensities of competition. Forestry Chronicle 74: 728–735.

Lavender, D.P., 1990. Physiological principles of regeneration. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia’s Forests (pp: 30-44). University of British Columbia Press. Vancouver 1990.

Laubhann, D., Sterba, H., Reinds, G.J., De Vries, W., 2009. The impact of atmospheric deposition and climate on forest growth in European monitoring plots: An individual tree growth model. Forest Ecology and Management 258: 1751-1761.

Lieffers, V.I., MacDonald, S.E., Hogg E.H., 1993. Ecology of and control strategies for Calamagrostis-canadensis in boreal forest sites. Canadian Journal of Forest Research 23: 2070-2077.

Lloyd, A.H., Fastie, C.L., 2003. Recent changes in treeline forest distribution and structure in interior Alaska. Ecoscience 10(2): 176-185.

Lotan, J.E., Perry, D.A., 1983. Ecology and regeneration of lodgepole pine. U.S. Dep. Agric. Agric. Handb. 606. Washington, DC. 51 p.

Lotan, J.E., Cricthfield, W.B., 1990. Lodgepole pine. *In* Silvics of North America: 1, Cionifers. *Edited by* R.M. Burns and B.H. Honakala. U.S. Dep. Agric. Agric. Handb. 654.

Macadam, A., Kabzems, R., 2006. Vegetation management improves early growth of white spruce more than mechanical site preparation treatments. Northern Journal of Applied Forestry 23(1): 35-46.

MacKenzie, M.D., Schmit, M.G., Bedford, L., 2005. Soil microclimate and nitrogen availability 10 years after mechanical site preparation in northern British Columbia. Canadian Journal of Forest Research 35: 1854-1866.

Man, C.D., Comeau, P.G., Pitt, D., 2008. Competitive effects of woody and herbaceous vegetation in a young boreal mixedwood stand. Canadian Journal of Forest Research 38: 1817–1828.

Matsushima, M., Chang, S.X., 2006. Vector analysis of understory competition, N fertilization, and litter layer removal effects on white spruce growth and nutrition in a 13-year-old plantation. Forest Ecology and Management 236: 332–341.

Mbogga, S.M., Hamann, A., Wang, T., 2009. Historical and projected climate data for natural resource management in western. Agricultural and Forest Meteorology 149: 881-890.

McMinn, R.G., Hedin, I.B., 1990. Site preparation: Mechanical and manual. *In:* Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., and D. Winston. 1990. Regenerating British Columbia's Forests (pp.150-163). University of British Columbia Press. Vancouver 1990.

Miyamoto, Y, Griesbauer, H.P., Green, D.S., 2010. Growth responses of three coexisting conifer species to climate across wide geographic and climate ranges in Yukon and British Columbia. Forest Ecology and Management 259: 514-523.

Monserud, R.A., Yuqing, Y., Shongming, H., Tchebakova N., 2008. Potential change in lodgepole pine site index and distribution under climatic change in Alberta. Canadian Journal of Forest Research 38: 343–352.

Morris, L.A., Lowery R.F., 1988. Influence of site preparations on soil conditions affecting stand establishment and tree growth. Southern Journal of Applied Forestry 12(3): 170-178.

Mote, P.W, Hamlet, A.F., Clark, Lettenmaier, D.P., 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86: 39-49.

Nienstaedt, H., Zasada, J.C., 1990. White spruce. *In* Silvics of North America: 1, Cionifers. *Edited by* R.M. Burns and B.H. Honakala. U.S. Dep. Agric. Agric. Handb. 654.

Nigh, G.D., Cheng, C.Y., Qian, H., 2004. Climate and productivity of major conifer species in the interior of British Columbia, Canada. Forest Science 50: 659-671.

O’Neill, G.A., N.K. Ukrainetz, M.R. Carlson, C.V. Catwright, B.C. Jaquish, J.N. King, J. Krakowski, J.H. Russel, M.U. Stoehr, C. Xie, and A.D. Yanchuk. 2008. Assisted migration to address climate change in British Columbia: recommendations for interim seed transfer standards. B.C. Min. For. Range, Res. Br., Victoria, B.C. Tech. Rep. 048.

O'Reilly, C., Owens, J.N., 1987. Long-shoot bud development, shoot growth, and foliage production in provenance of lodgepole pine. Canadian Journal of Forest Research 17: 1421-1433.

Örlander, G., Gemmel, P., Hunt, J., 1990. Site preparation: a Swedish overview. For. Can. and B.C. Min. For., Victoria, BC. FRDA Rep. No. 105.

Örlander, G., 1993. Shading reduces both visible and invisible frost damage to Norway spruce seedlings in the field. Forestry 66 (1): 27–36.

Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918): 37-42.

Rehfeldt, G.E., Ying, C.C., Spittlehouse, D.L., Hamilton, D.A., 1999. Genetic responses to climate in Pinus contorta: niche breadth, climate change, and reforestation. Ecological Monographs 69: 375–407.

Rehfeldt, G.E., Tchebakova, N.M., Parfenova, Y.I., Wykoff, W.R., Kuzmina, N.A., and Milyutin, L.I., 2002. Intraspecific responses to climate in Pinus sylvestris. Global Change Biology 8(9): 912-929.

Robinson, A.P., Duursma, R.A., Marshall, J.D., 2005. A regression-based equivalence test for model validation: shifting the burden of proof. Tree Physiology 25: 903-913.

SAS Institute Inc. 2004. SAS OnlineDoc® 9.1.3**.** Cary, NC: SAS Institute Inc.

Shropshire, C., Wagner, R.G., Bell, F.W., Swanton, C.J., 2001. Light attenuation by early successional plants of the boreal forest. Canadian Journal of Forest Research 31: 812-823.

Smithwick, E.A.H., Ryan, M.G., Kashians, D.M., Romme, W.H., Tinker, D.B., and Turner, M.G., 2009. Modeling the effects of fire and climate change on carbon and nitrogen storage in lodgepole pine (*Pinus contorta*) stands. Global Change Biology 15: 535-548.

Snowdon, O., Jovanovic, T., Booth, T.H., 1999. Incorporation of indices of annual climatic variation into growth models for *Pinus radiata.* Forest Ecology and Management 117: 187-197.

Snowdon, P., 2001. Short-term predictions of growth of *Pinus radiata* with models incorporating indices of annual climatic variation. Forest Ecology and Management 152: 1-11.

Solomon, S., Platter, G.K., Knutti, R., Friedlingstein, P., 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106(6): 1704–1709.

Spittlehouse, D.L., 2008. Climate Change, impacts, and adaptation scenarios: climate change and forest and range management in British Columbia. B.C. Min. For. Range, Res. Br., Victoria, B.C. Tech. Rep. 045.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2004. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18: 1136-1155.

Sutton, R.F., Bedford, L., Stordeur, L., Grismer, M., 2001. Site preparation for establishing interior spruce in British Columbia: trials at upper Coalmine and Mackenzie. Western Journal of Applied Forestry 16: 9–17.

Thomson, A.M., Parker, W.H., 2008. Boreal forest provenance tests used to predict optimal growth and response to climate change: 1. Jack pine. Canadian Journal of Forest Research 38: 157-170.

Thomson, A.M., Riddel, C.L., Parker, W.H., 2009. Boreal forest provenance tests used to predict optimal growth and response to climate change: 2. Black spruce. Canadian Journal of Forest Research 39: 143-153.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fulé, P.Z., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., and Veblen. T. 2009. Widespread increase of tree mortality rates in the western United States. Science 323: 521–524.

Wagner, R.G., Radosevich, S.R., 1998. Neighborhood approach for quantifying interspecific competition in coastal Oregon forests. Ecological Applications 8: 779-794.

Wagner, R.G., Little, K.M., Richardson, B., McNabb, K., 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry 79: 57-79.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., and Bairlein, F. 2002. Ecological responses to recent climate change. Nature 416(6879): 389-395.

Walstad, J.D., Kuch, P.J., 1987. Forest vegetation management for conifer production. John Wiley & Sons, Inc., New York.

Wang, T., Hamann, A., Spittlehouse, D.L., Aitken, S.N., 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climatology 26(3): 383-397.

WESBOGY, 2007. Long term study of growth and development of mixed stands of spruce and aspen. Experimental design, Data collection and Database Maintenance Manual [online]. http://www.uofaweb.ualberta.ca/rr//pdfs/2007DataCollectionManualSept2007.pdf

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science, 18: 940-943.

Williamson, T.B., Colombo, S.J., Duinken, P.N., Gray, P.A., Hennessey, R.J., Houle, D., Johnston, M.H., Ogden, A.E., Spittlehouse, D.L., 2009.

Climate change and Canada's forests: from impacts to adaptation. Sustain. For. Manag. Netw. and Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. 104 p.

Woods, A., Coates, K.D., Hamann, A., 2005. Is an unprecedented dothistroma needle blight epidemic related to climate change? Bioscience 55(9): 761-769.

Woollons, R.C., Snowdon, P., Mitchell, N.D., 1997. Augmenting empirical stand projection equations with edaphic and climatic variables. Forest Ecology and Management 98: 267-275.

Zhou, L.M., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., Myneni, R.B., 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. Journal of Geophysical Research-Atmospheres 106(D17): 20069-20083.

Chapter 4. Climate and competition effect on white spruce and trembling aspen growth in mixtures

4.1. Introduction

Chapter two and three of the thesis have dealt with growth of lodgepole pine and white spruce plantations following site preparation; and the combined effects of climate and site preparation. The main findings in chapter three indicated that, for pure white spruce plantations, uncontrolled competition resulted in a strong negative response to climate change in northeastern B.C., likely due to increasing levels of drought stress. Nevertheless validation of the models indicated that: 1) the equations developed for B.C. had weaker predictive ability as we moved farther from the studied sites, and 2) during particularly warm and dry years (e.g., 1998) growth of spruce at the WESBOGY (Western Boreal Growth and Yield association) site near Edson Alberta was poorly predicted by the equations developed using B.C. data.

Competing vegetation is often considered to be a limiting factor in the process to maximize the yield of selected crop trees, but it has been shown to increase nutrient availability and to provide protection from extreme weather conditions (e.g., Stathers and Spittlehouse 1990; Simard et al. 1997). Many studies have also shown the importance of retaining nitrogen fixing species such as alder (*Alnus* spp.) in order to enrich (or not deplete) the soil of nitrogen, calcium and other nutrients (Binkley et al. 1992; Sanborn et al. 2002; Cortini and Comeau 2008b).

In the boreal forests of North America, after a disturbance such as fire or clear-cutting, white spruce seedlings are often mixed with abundant trembling aspen regeneration (Peterson and Peterson, 1992). Aspen tends to dominate the stand for the first six decades while the more shade-tolerant spruce grows slowly under the main canopy layer (Peterson and Peterson, 1992). Although spruce growth can be greatly affected by aspen competition for light, mixedwood stands have been shown to increase spruce resistance to pests and climate extremes, and to reduce understory competition (Lieffers and Stadt, 1994; Comeau, 1996; Pritchard and Comeau, 2004; Voicu and Comeau, 2004). In theory, mixedwood stands should be more productive than pure stands (e.g., Man and Lieffers, 1999; MacPherson et al., 2001), particularly in the case where an intolerant overstory species such as aspen is growing in combination with a shade tolerant understory species such as white spruce. However, the influence of stocking, site, history, age and other factors on stand productivity makes it difficult to clearly demonstrate beneficial effects of species mixtures in these stands.

The frequency of facilitative versus competitive interactions among species across abiotic stress gradients has stimulated a large number of studies (i.e.: stress-gradient hypothesis) (e.g., Callaway and Walker, 1997; Maestre et al. 2005). The basic idea is that facilitation is more common in plant communities developing under high physical stress with high consumer pressure, and where the physical environment is relatively benign and consumer pressure is low positive interactions are less common and competitive interactions are the dominant structuring forces (Bertness and Callaway, 1994).

Although this hypothesis has been quite controversial given the variability related to the large number of biotic and abiotic factors that affect plant community development (e.g, Lortie and Callaway, 2006; Maestre et al. 2006), it has been recently supported and validated by numerous studies in many ecosystems (e.g., Maestre et al. 2009; Kikvidze and Callaway, 2009). While the focus of the stress-gradient hypothesis is on semi-arid and arid environments the same concept can potentially apply to boreal and sub-boreal forests. Facilitation is more important at high levels of abiotic stress (e.g., extremely low temperatures), and one of the primary mechanisms for facilitation in boreal and sub-boreal forests is protection from frost and winter injury (e.g., Stathers and Spittlehouse, 1990; Krasowski et al. 1993).

Our ability to estimate the influence of different tending practices on stand development depends on our understanding of key factors such as competition (Comeau et al., 2003), and the effect of climate on conifer growth. Competition indices are one of the available tools commonly used to quantify competition in conifer plantations (e.g., Weigelt and Jolliffe, 2003). Competition indices can be calculated from simple measurements such as visual estimates of competing vegetation cover or from tree and stand measurements used to calculate basal area, which can be collected quickly and consistently in the field (Cortini and Comeau 2008a). Many studies on the effect of aspen competition on spruce growth have indicated that simple competition indices such as aspen basal area and density can be as effective as more complex indices (e.g., Filipescu and Comeau, 2007a; Stadt et al. 2007).

Results in chapter three showed that both climate and site preparation treatments influence growth of white spruce. In particular, abundant vegetation (grass and tall shrubs) resulted in suppression of growth with climate warming in pure spruce plantations. Filipescu and Comeau (2007a and 2007b) found that the relationships between aspen competition and spruce growth vary with site location presumably due to changes in climate (particularly frost) and other factors. This chapter will explore the combined effects of climate and trembling aspen competition on white spruce growth using data from the long-term study established by the Western Boreal Growth and Yield association (WESBOGY).

I will further explore the relationship between climate and tree growth using data from seven selected locations of the WESBOGY long-term study. These data provide up-to six years of annual increments during the period from 1997 to 2006. I will also evaluate the competitive effects of trembling aspen (*Populus Tremuloides* Michx.) on spruce and aspen growth and wether these change with changes in climate. The findings from this study contribute to a better understanding of the key limiting factors to early growth of spruce plantations and the combined effects of climate and trembling aspen abundance.

4.2. Materials and Methods

4.2.1. Study description

Data for this study comes from field installations established by the Western Boreal Growth and Yield association (WESBOGY) for a long term study of growth and development of tended mixtures of white spruce and trembling aspen (Bokalo et al. 2007).

The WESBOGY long term study uses a randomized block design where each block consists of two installations, one on a superior site and one on a median site and each installation has two replications of a series of 15 plots (WESBOGY, 2007). Plots are square with 20 m sides and, at each installation, the data I used relate to present three levels of spruce density (0, 500 and 1000 stems per hectare), and five levels of aspen density (0, 200, 500, 1500, and 4000 stems per hectare) (Table 4.1).

Table 4.1. Spruce and aspen density combinations (i.e., trees per hectare). The circles identify the density combinations represented in the study.

Aspen **Spruce**	**0**	**200**	**500**	**1500**	**4000**
1000	O	O	O	O	O
500	O	O	O	O	O
0	X	X	X	O	O

The WESBOGY long term study also includes natural densities of aspen, and plots with no spruce; however these were not used in the present study due to: 1) the use of very small plots for aspen measurements (2 m x 2 m) in the unthinned natural density plots; and 2) the lack of spruce in the plots without planted spruce. On the selected WESBOGY sites white spruce was planted starting in 1990 and aspen (naturally regenerated) was thinned to treatment densities around age 5. Treatment location, planting year and main climate information are presented in Table 4.2 and Figure 4.1.

Table 4.2. Information relating the selected WESBOGY sites and climate normals for the period 1987-2006 (MAT = mean annual temperature, MAP = mean annual precipitation, and MSP = mean summer precipitation).

Agency	Inst.	Repl.	Lat.	Long.	Elevation	Year Spruce Planted	MAT	MAP	MSP
ALP	Superior	1,2	55.00	-112.00	567	1994	1.7	418.2	305.8
DMI	Medium	1,2	56.39	-118.59	781	1992	1.3	409.1	263.6
DMI	Superior	1,2	56.41	-117.73	728	1992	1.1	399.2	261.2
SBR	Medium	1,2	54.09	-107.07	505	1992	1.2	431.3	288.7
SBR	Superior	1,2	54.05	-106.98	515	1992	1.1	433.7	289.5
SPA	Medium	1,2	53.76	-105.51	548	1990	0.6	453.9	293.9
SPA	Superior	1,2	53.68	-105.94	535	1990	1.0	441.1	288.8
SRD	Medium	1,2	55.30	-114.10	640	1992	1.6	459.5	322.3
WFR	Medium	1,2	53.77	-116.69	1056	1993	2.9	556.8	411.3
WFR	Superior	1	53.80	-116.64	1106	1993	2.9	570.5	417.7
WFR	Superior	2	53.80	-116.61	1085	1994	2.9	564.7	414.9
WGP	Medium	1	54.89	-118.90	701	1991	2.6	493.3	328.9
WGP	Superior	1,2	54.91	-118.92	709	1991	2.6	486.1	323.8

Figure 4.1. Map of the selected WESBOGY sites (© 2010 Google-Map data).

Spruce and aspen have been measured regularly since planting. To avoid confounding results with undocumented competitive effects or initial responses to aspen thinning, I utilized data starting two years after thinning treatments. The data used for this study were from two years following thinning to 2006 and cover the period from years 1997 to 2006. For ALP, DMI, SRD there are four annual increments available; for SBR, SPA, WFR there are five annual increments available; and for WGP there are six annual increments available. Trees with negative or null annual increments were excluded from the analysis as well as trees that had form problems resulting from frost, insect injuries, and browsing.

4.2.*2. Data analysis*

Spruce stem volume (SV, cm^3) was calculated from stem height (HT, cm) and root collar diameter (RCD, cm) using a modified version of Honer's equation (Honer et al., 1983):

$$SV = \frac{RCD^{a}}{b + \frac{c}{HT}}$$

where a, b, and c are parameters calculated by Cortini and Comeau (2008a) for white spruce plantations in north-western Alberta. Aspen volume was calculated as the volume of a cylinder from basal area and height. Preliminary analysis modeled tree growth and climate variables either at the tree level or at the plot level and indicated that plot averages were better suited for the statistical analysis (e.g., higher predictive ability) and will be used in the balance of this study.

The spatial climate model ClimateWNA modified following Mbogga et al. (2009), was used to provide climate data for each site based on their latitude, longitude and elevation (Wang et al., 2006). For each WESBOGY installation I calculated climate data for three different time scales (annual, seasonal and monthly). Standard meteorological seasons are: spring - March, April, and May; summer - June, July, and August; autumn - September, October, and November; and winter - December, January and February, and I included only those climate variables spanning from July of the previous year to August of the current growth year (Table 4.3).

Table 4.3. List of climate variables evaluated for each time scale. The value of the year prior to the increment is indicated by a small letter 'p' before the variable name (e.g., pMAT).

Annual Variables	
MAT and pMAT	mean annual temperature (°C)
MSP and pMSP	mean annual summer (May to September) precipitation (mm)
DD>5 and pDD>5	degree-days above 5°C, growing degree-days
eFFP and peFFP	the day of year on which frost-free period ends
PAS and pPAS	precipitation as snow
Seasonal variables	
pTAVsm	summer mean temperature of the previous year (°C)
pTAVat	autumn mean temperature of the previous year (°C)
pTAVwt	winter mean temperature of the previous year (°C)
TAVsp	spring mean temperature (°C)
TAVsm	summer mean temperature (°C)
pPPTsm	summer mean precipitation of the previous year (mm)
pPPTat	autumn mean precipitation of the previous year (mm)
pPPTwt	winter mean precipitation (mm) of the previous year
PPTsp	spring mean precipitation (mm)
PPTsm	summer mean precipitation (mm)
Monthly variables	
pTAV07 - pTAV12	July - December mean temperature of the previous year (°C)
pPPT07 - pPPT12	July - December mean precipitation of the previous year (mm)
TAV01 - TAV08	January - December mean temperature (°C)
PPT01 - PPT08	January - December mean precipitation (mm)

Multiple linear regressions (similar to chapter 3) were used to select the most representative climate variable at the study level and at the agency level. Thus I used the 'R^2' selection technique in Proc REG with results restricted to two variables in Proc REG (SAS Institute, Cary, NC) where volume increment represent the dependent variable and the pool of climate variables plus initial volume represents the predictors. The best models always include volume initial together with one climate variable. For this study, I selected only the climate variable with the highest predictive ability of volume increment similarly to Thompson and Parker (2008 and 2009).

A second screening process selected two climate variables that are most representative of climatic conditions during the growing season. The pool of climate variables was restricted to spring and summer temperature and precipitation of the current growth year. This selection process found that average summer temperature (TAVsm) and mean summer precipitation (MSP) were the climate variables with the highest predictive ability across the seven agencies. Co-linearity between these two variables was evaluated and proved not to be a problem (Pearson correlation coefficient = -0.37; p<.0001).

Spruce volume increments (VI) were then analyzed together with the selected climate variable/s (Clim. Var.) using linear and non-linear regressions in Proc REG and Proc NLIN, respectively (SAS Institute, Cary, NC). Initial spruce (Vol. Initial), was used as additional explanatory variable similarly to Comeau et al. (2003). Non-linear models proved to be the best fit between spruce growth, and climate variables. An estimate of competition (i.e., aspen basal area per hectare) was then added to the selected equations relating spruce growth to climate variables. The non-linear equations investigated were:

a) $VI = b_0 + b_1 * C\lim.Var + b_2 * C\lim.Var.^2 + \epsilon$

b) $VI = b_0 + b_1 * e^{(b_2 * C\lim.Var.)} * Vol.Initial^{b_3} + \epsilon$

c) $VI = b_0 + b_1 * e^{(b_2 * C\lim.Var.)} * Vol.Initial^{b_3} * AspenBasalArea^{b_4} + \epsilon$

d) $VI = b_0 + b_1 * e^{(b_2 * TAVsm + b_3 * MSP)} * Vol.Initial^{b4} + \epsilon$

e) $VI = b_0 + b_1 * e^{(b_2 * TAVsm + b_{3*} * MSP)} * Vol.Initial^{b4} * AspenBasalArea^{b5} + \epsilon$

In order to investigate if the seven agencies could be pooled into a single equation I carried extra sum of squares testing with indicator variables (i.e., dummy variables) as described by Ott (1997) and Draper and Smith (1998).

Repeated measures analysis was also applied using Proc NLIN (SAS Institute, Cary, NC) for the equations developed in this study but given the complexity of the models (high number of predictive variables) SAS did not provide meaningful results. However, the effect of repeated measurements in this study is reduced by using plot averages calculated from a large number of trees per plot.

I also calculated the relative growth rate (RGR) as the annual volume increment for spruce and aspen divided by the initial volume of the tree (i.e., Relative Growth Rate = Growth/Initial Size) to provide an estimate of growth that is not dependent on crop tree size (Hunt 1982). I then selected for each agency and installation only the data relative to those years with either the highest or the lowest values of volume RGR.

For the selected years, I then fitted at the tree level a non-linear regression in Proc NLIN (SAS Institute, Cary, NC) to predict spruce and aspen volume increment

(VI) using initial spruce and aspen volume (Vol. Initial) together with aspen basal area per hectare as explanatory variables:

f) $VI = b_0 + b_1 * e^{(b_2 * AspenBasalArea)} * Vol.Initial^{b_3}$

I then investigated the significance and magnitude of the parameter value related to aspen basal area in equation *f* (i.e. B2) by calculating the difference between the parameter values (i.e., B2 for the low RGR year minus B2 for the high RGR year). When B2 was not significantly different from zero I substituted the parameter value with zero. If the difference between the two years is a positive value this implies that competition increased on the high RGR year. The calculated differences in the parameter value relative to aspen basal area were also plotted against the respective differences in SHM (i.e.: Summer Heat Moisture Index = Mean Warmest Month Temperature/(Mean Summer Precipitation/1000)) between the high RGR year and the low RGR year for each combination of agency and installation. This provided a visual representation of the relationship between the changes in growth and the changes in climate between high and low RGR years.

Graphs representing main climatic characteristics at each agency and the annual variation in relative volume growth are presented in Appendix 5.

4.3. Results

When investigating if the seven agencies could be pooled into a single equation the following climate variable was selected at the study level for equations *a, b*, and *c*: temperature average in February. In equation *d* and *e* average summer temperature (TAVsm) and mean summer precipitation (MSP) were used in the equation as independent variables.

Extra sum of squares analysis indicated that the seven agencies could not be pooled into one single equation. The starting formulas used for the tests were equation *b*, *c*, *d* and *e* as described in the methods and the results indicated that the intercepts and other parameter values were significantly different between agencies.

Since the analysis could not be carried at the study level I re-selected the best climate variables at the agency level. This provided more sensitive climate variables that are better able to capture the variation in growth at each agency. The results indicated that for spruce, six out of the seven cases resulted in selection of a monthly value and the remaining was mean annual temperature (i.e., MAT). Monthly precipitation was selected at five of the seven agencies and monthly temperature one time. Two of the monthly values selected represented precipitation levels of the year previous to the current increment.

Non-linear models described in the methods as equations *a*, *b* and *c* were then calculated and results are presented in Table 4.4.

The spruce models are always significant. For equation *a* the adjusted R^2 values range from 0.045 to 0.767 and for equation *b*, the adjusted R^2 values range from 0.823 to 0.938 and for equation *c*, adjusted R^2 values range from 0.846 and 0.950. The majority of the parameter values related to the climate variables do not include zero in their 95% confidence interval indicating that they are significant. At five out of the seven agencies available, the parameter value corresponding to aspen basal area is significant and the inclusion of aspen basal area in the models results in an overall increase in adjusted R^2 of 2%. Figure 4.2 presents the relationship between spruce volume increment (i.e., observed and predicted values) for those agencies where the parameter related to the climate variable is significant for model *c*.

Table 4.4. Parameter values and statistical information for non-linear models of white spruce stem volume increment. The table shows by agency and equation: number of observations (obs. #), model P values, adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (B0, B1, B2, B3, B4) for intercept, climate variable, volume initial and aspen basal area. Parameter values which are significantly different from zero are shown in bold type. Equations *a*, *b*, and *c* are described in the methods and climate variables are described in Table 4.3.

						Intercept	Climate Variable			Volume Initial	Aspen Basal Area
Agency	Equation	# obs	Model P	Adj.R^2	RMSE	B0	B1	Var.	B2	B3	B4
	a	80	<.0001	0.639	0.715	-0.5565	**0.3229**	pPPT12	**-0.0062**		
ALP	b	80	<.0001	0.887	0.400	-1.1578	**1.7457**	pPPT12	**0.00854**	**0.4631**	
	c	80	<.0001	0.888	0.397	-0.9646	**1.5729**	pPPT12	**0.00867**	**0.5027**	0.00696
	a	159	<.0001	0.407	1.260	-422.6	**57.74**	TAVE07	**-1.954**		
DMI	b	159	<.0001	0.838	0.659	0.1747	0.2122	TAVE07	0.0962	**0.8301**	
	c	159	<.0001	0.846	0.642	-0.025	0.4057	TAVE07	0.0645	**0.7551**	**-0.0152**
	a	158	<.0001	0.701	22.546	0.122	0.0075	PPT03	0.00379		
SBR	b	158	<.0001	0.823	17.292	-0.4321	1.0214	PPT03	0.0196	**0.5132**	
	c	158	<.0001	0.868	14.883	-0.0799	0.6116	PPT03	0.0235	**0.6418**	**-0.0478**
	a	186	<.0001	0.767	2.568	**7.2621**	**-0.2746**	pPPT08	**0.00266**		
SPA	b	186	<.0001	0.884	1.833	0.2453	**0.6568**	pPPT08	-0.00372	**1.1066**	
	c	186	<.0001	0.884	1.829	0.2455	**0.6467**	pPPT08	-0.00339	**1.0973**	-0.00765
	a	80	<.0001	0.637	1.124	**2.6042**	**-0.259**	PPT01	**0.00732**		
SRD	b	80	<.0001	0.929	0.496	0.1886	**0.524**	PPT01	**-0.0127**	**1.2101**	
	c	80	<.0001	0.950	0.416	0.0864	**0.5997**	PPT01	-0.00571	**1.0184**	**-0.0287**
	a	189	0.005	0.045	0.954	**-11.949**	**10.0942**	MAT	**-1.8902**		
WFR	b	189	<.0001	0.938	0.243	0.00608	**0.3861**	MAT	**0.2694**	**0.8848**	
	c	189	<.0001	0.948	0.223	0.0286	**0.375**	MAT	**0.2531**	**0.9008**	**-0.0218**
	a	178	<.0001	0.242	0.649	**3.095**	**-0.363**	PPT03	**0.0104**		
WGP	b	178	<.0001	0.930	0.196	0.0736	**0.4303**	PPT03	**0.0139**	**1.067**	
	c	178	<.0001	0.933	0.193	**0.0821**	**0.4238**	PPT03	**0.013**	**1.0981**	**-0.0127**

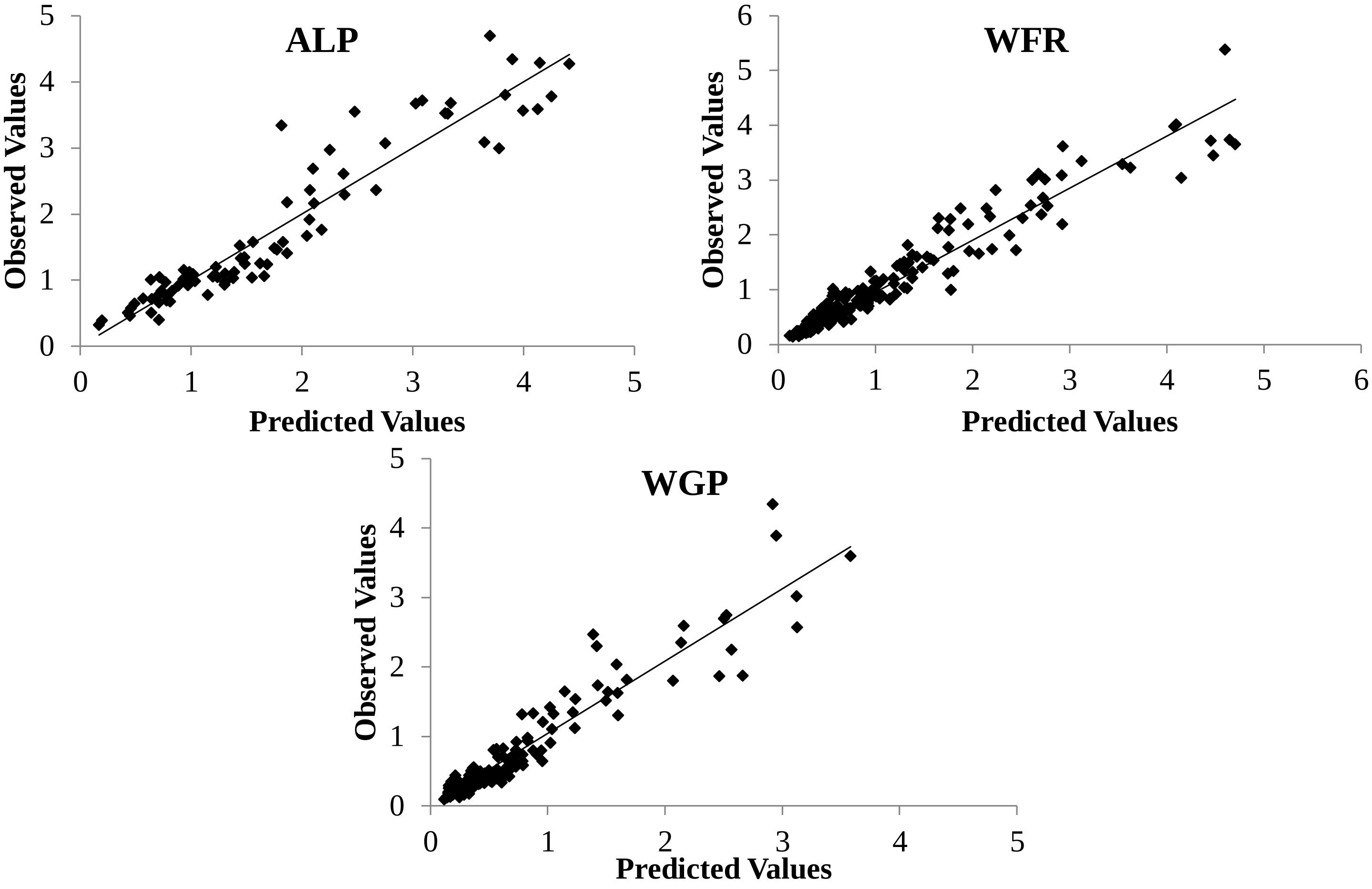


Figure 4.2. Relationship between observed and predicted values of spruce volume increment ($cm^3 * 10^{-2}$) for those agencies where climate was significant. Predicted values are calculated from equation *c*. Parameters and climate variables information is provided in Table 4.4.

The results indicate that all the spruce models calculated are significant when using the climate variables related to the growing season (Table 4.5). Overall, for equation *d* the adjusted R^2 values range from 0.822 to 0.935 for spruce; for equation *e*, adjusted R^2 values range between 0.794 and 0.950. Less than half of the parameter values related to the climate variables do not include zero in their 95% confidence interval. At five out of the seven agencies the parameter value corresponding to the aspen basal area is significant and the inclusion of aspen basal area in the models results in an overall increase in adjusted R^2 of 2.3%. The graph in Figure 4.4 presents the relationship between spruce volume increment (i.e., observed and predicted values) and the relative climate variable/s for those agencies where the parameter representing the climate variable was significant for model *e*.

Table 4.5. Parameter values and statistical information for non-linear models of white spruce stem volume increment. The table shows by agency and equation: number of observations (obs. #), model P values, adjusted R^2 (Adj. R^2), root mean square error (RMSE) and equation parameters (B0, B1, B2, B3, B4, B5) for intercept, climate variables, volume initial and aspen basal area. Parameter values which are significantly different from zero are shown in bold type. Equations *d*, and *e* are described in the methods and climate variables are described in Table 4.3.

						Intercept	Climate Variable					Volume Initial	Aspen Basal Area
Agency	Equation	# obs	Model P	Adj.R^2	RMSE	B0	B1	Var.	B2	Var.	B3	B4	B5
ALP	d	80	<.0001	0.887	0.403	-1.1241	0.1195	TAVsm	-0.0566	MSP	**0.0115**	**0.4668**	
	e	80	<.0001	0.888	0.400	-0.9388	0.1015	TAVsm	-0.0564	MSP	**0.0117**	**0.506**	0.00703
DMI	d	159	<.0001	0.836	0.665	-0.1839	1.7986	TAVsm	-0.0405	MSP	0.000624	**0.7491**	
	e	159	<.0001	0.845	0.647	-0.3904	2.0509	TAVsm	-0.0302	MSP	0.000061	**0.6788**	**-0.0144**
SBR	d	158	<.0001	0.822	17.323	-1.0627	0.0556	TAVsm	0.2079	MSP	0.00121	**0.4715**	
	e	158	<.0001	0.866	14.973	-0.2682	0.00204	TAVsm	0.3279	MSP	0.00385	**0.6246**	**-0.0463**
SPA	d	186	<.0001	0.884	1.839	0.233	6.5777	TAVsm	-0.062	MSP	-0.00512	**1.0825**	
	e	186	<.0001	0.884	1.834	0.2293	5.3749	TAVsm	-0.0563	MSP	-0.00471	**1.0732**	-0.00777
SRD	d	80	<.0001	0.917	0.541	0.2921	0.000915	TAVsm	0.3982	MSP	0.000789	**1.1309**	
	e	80	<.0001	0.950	0.418	0.2182	0.000585	TAVsm	0.4081	MSP	0.00278	**0.9824**	**-0.0327**
WFR	d	189	<.0001	0.918	0.281	0.034	0.0827	TAVsm	0.1323	MSP	**0.00141**	**0.8792**	
	e	189	<.0001	0.930	0.258	0.0571	0.1007	TAVsm	0.1146	MSP	**0.00128**	**0.8984**	**-0.0254**
WGP	d	178	<.0001	0.935	0.191	**0.0878**	0.00476	TAVsm	**0.2817**	MSP	**0.00191**	**1.0405**	
	e	178	<.0001	0.936	0.188	**0.0922**	0.00612	TAVsm	**0.2667**	MSP	**0.00175**	**1.0676**	**-0.0109**

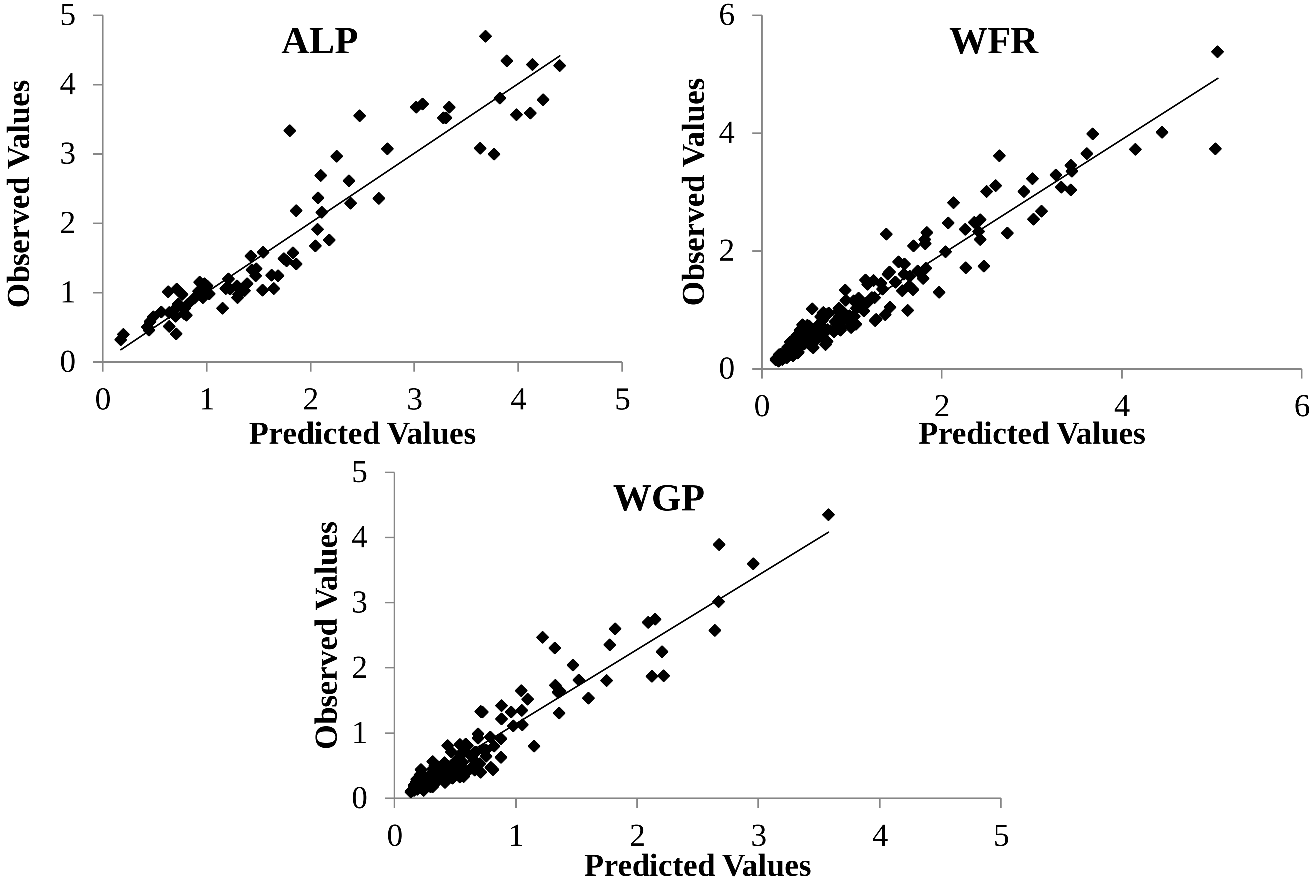


Figure 4.3. Relationship between observed and predicted values of spruce volume increment ($cm^3 * 10^{-2}$) for those agencies where climate was significant. Predicted values are calculated from equation *e*. Parameters and climate variables information are provided in Table 4.5.

Relationships between spruce volume growth and aspen basal area are significant at five out of seven agencies (for equation *c* and *e*); with several being negatively related to increasing levels of aspen competition. However, the averaged parameter value is relatively low for equation *c* (B4 = -0.13) and equation *e* (B4 = -0.03) (Tables 4.4 and 4.5).

Based on the average values of volume relative growth ratio (RGR), those increment years with the highest and the lowest RGR were selected at the agency level and used in model *f* for spruce and aspen separately (Table 4.6). Results from model *f* for spruce indicate that every model is significant ($P < 0.0001$) and that the adjusted R^2 value ranges from 0.177 to 0.843 with the parameter relative to aspen basal area significant at 18 of the 24 models (Table 4.7). The results for aspen show that every model is significant ($P < 0.0001$) and that the adjusted R^2 value ranges from 0.291 to 0.785 with the parameter relative to aspen basal area significant at 14 of the 24 models (Table 4.8).

Table 4.6. Averaged values of volume RGR and representative climate information for each agency. Bold font highlight the years with the highest RGR value and in italic font the year with the lowest RGR value for each agency.

AGCY	Year	Spruce VR	Aspen VR	MAT	MAP	MSP	SHM	DD>5
ALP	2002	0.796914	**0.78789**	0.7	369	309	53.4	1209.0
ALP	2003	0.667001	0.57117	1.2	467	312	55.1	1374.0
ALP	2004	*0.65077*	0.35428	1.2	460	308	54.9	1126.0
ALP	2005	**0.870219**	*0.34866*	2.6	418	326	48.8	1234.0
DMI	1999	**1.081347**	0.77938	1.8	318	203	75.2	1139.0
DMI	2000	0.990659	**0.98096**	0.8	315	246	63.1	1044.5
DMI	2001	0.835974	0.51073	1.5	336	241	65.0	1253.5
DMI	2002	*0.74433*	*0.50513*	0.9	302	203	74.2	1135.5
SBR	1998	0.998289	**1.11157**	2.6	320	187	99.5	1692.5
SBR	1999	0.841871	0.55096	2.3	343	248	66.9	1378.5
SBR	2000	*0.73296*	0.54004	0.7	420	350	50.4	1269.0
SBR	2006	**1.08556**	*0.28465*	2.2	488	303	61.1	1607.0
SPA	1997	0.996656	**0.67092**	1.2	443	255	69.4	1468.0
SPA	1998	**1.080386**	0.56524	2.3	391	216	83.4	1610.5
SPA	1999	0.989685	0.56627	1.9	373	257	62.5	1316.0
SPA	2000	0.836148	0.34794	0.5	415	334	52.1	1268.5
SPA	2006	*0.72941*	*0.25091*	1.9	522	318	57.4	1558.5
SRD	1999	0.570599	0.59405	2.2	298	205	77.6	1228.0
SRD	2000	0.653117	**0.70738**	0.9	419	340	47.4	1128.0
SRD	2001	**0.730993**	0.50157	2.3	316	243	66.7	1341.0
SRD	2004	*0.55127*	*0.39779*	1.1	521	344	48.0	1090.0
WFR	1998	1.050172	0.62907	3.1	468	289	58.1	1372.3
WFR	1999	**1.2228**	**0.7703**	3.2	439	331	44.1	1005.3
WFR	2000	0.717344	0.4258	2.2	537	434	33.7	999.1
WFR	2001	0.870652	*0.30306*	3.3	460	374	39.0	1155.3
WFR	2002	*0.68225*	0.34685	2.5	415	310	48.1	1076.0
WGP	1997	**1.295689**	0.52517	2.6	547	396	37.9	1266.3
WGP	1998	0.969121	**0.59968**	2.9	384	195	89.3	1604.3
WGP	1999	0.541737	*0.42281*	2.8	403	271	56.1	1137.3
WGP	2000	*0.48922*	0.4955	2.0	428	329	48.0	1149.8
WGP	2001	0.689525	0.50326	2.7	431	318	49.1	1296.3
WGP	2004	0.828224	0.49756	2.6	576	385	41.7	1213.3

MAT = mean annual temperature (°C); MAP = mean annual precipitation (mm); MSP = mean annual summer (May to September) precipitation (mm); SHM = Summer Heat Moisture Index = Mean Warmest Month Temperature/(Mean Summer Precipitation/1000); DD>5 = degree-days above 5°C, growing degree-days.

Table 4.7. Parameter values and statistical information for non-linear models of white spruce stem volume increment. The table shows by agency, RGR value and installation (Inst.): number of observations (obs. #), model P values, adjusted R^2 (Adj. R^2), and equation parameters (B0, B1, B2, B3) for intercept, aspen basal area (Asp. BA), and volume initial. Parameter values which are significantly different from zero are shown in bold type. Equation *f* is described in the methods.

Spruce						Intercept		Asp BA	Vol. Initial
Agency	Inst.	RGR	# obs.	Model P	Adj. R^2	B0	B1	B2	B3
ALP	Superior	Low	564	<.0001	0.635	**0.4538**	**0.3281**	**-0.0143**	**1.2993**
		High	522	<.0001	0.576	-0.2777	**1.2413**	**0.0261**	**0.6943**
DMI	Medium	Low	589	<.0001	0.513	-1.701	**2.3579**	-0.00205	**0.5669**
		High	548	<.0001	0.260	0.229	**0.8821**	**-0.1706**	**0.7018**
	Superior	Low	554	<.0001	0.476	-1.59	**2.5314**	**-0.0256**	**0.4811**
		High	519	<.0001	0.536	-0.1174	**1.3727**	**-0.0897**	**0.7094**
SBR	Medium	Low	442	<.0001	0.635	-0.138	**0.9841**	**-0.0267**	**0.7219**
		High	224	<.0001	0.604	1.5945	**0.3013**	**-0.0615**	**1.3401**
	Superior	Low	367	<.0001	0.583	**0.1586**	**0.376**	**0.0871**	**2.2133**
		High	277	<.0001	0.219	**5.376**	0.003	**-0.112**	**2.696**
SPA	Medium	Low	356	<.0001	0.399	1.1398	1.1087	**-0.036**	**0.8352**
		High	558	<.0001	0.761	-0.0743	**1.092**	**-0.0153**	**0.7296**
	Superior	Low	246	<.0001	0.177	**6.4301**	0.0713	**-0.0596**	**1.422**
		High	524	<.0001	0.678	**-0.2175**	**1.1312**	0.00601	**0.5816**
SRD	Medium	Low	473	<.0001	0.554	0.0442	**0.8913**	**-0.0197**	**0.8083**
		High	557	<.0001	0.626	-0.2671	**1.0142**	0.00588	**0.7439**
WFR	Medium	Low	562	<.0001	0.712	-0.015	**0.7708**	**-0.0672**	**0.9477**
		High	613	<.0001	0.762	-0.0478	**1.1081**	**-0.0534**	**0.8138**
	Superior	Low	560	<.0001	0.804	-0.1798	**1.0021**	**-0.0577**	**0.7693**
		High	571	<.0001	0.843	0.0381	**1.2135**	**-0.0399**	**0.971**
WGP	Medium	Low	136	<.0001	0.509	0.068	**0.3913**	-0.00545	**1.0899**
		High	251	<.0001	0.550	0.0188	**0.9347**	**0.1008**	**1.0228**
	Superior	Low	341	<.0001	0.622	0.00716	**0.4386**	0.00495	**0.8681**
		High	492	<.0001	0.542	-0.086	**1.0924**	-0.00474	**0.6845**

Table 4.8. Parameter values and statistical information for non-linear models of trembling aspen stem volume increment. The table shows by agency, RGR value and installation (Inst.): number of observations (obs. #), model P values, adjusted R^2 (Adj. R^2), and equation parameters (B0, B1, B2, B3) for intercept, aspen basal area (Asp. BA), and volume initial. Parameter values which are significantly different from zero are shown in bold type. Equation *f* is described in the methods.

Aspen						Intercept		Asp. BA	Vol. Initial
Agency	Inst.	RGR	# obs.	Model P	Adj. R^2	B0	B1	B2	B3
ALP	Superior	Low	1198	<.0001	0.532	1.7354	**0.386**	-0.00312	**0.9718**
		High	1146	<.0001	0.599	**-12.2551**	**5.1079**	-0.00015	**0.5978**
DMI	Medium	Low	1198	<.0001	0.400	8.6565	2.1745	**-0.0152**	**0.7068**
		High	1328	<.0001	0.549	**-14.6326**	**5.0589**	-0.0003	**0.6587**
	Superior	Low	999	<.0001	0.291	1.7229	1.6333	-0.00505	**0.7065**
		High	1334	<.0001	0.538	2.5165	**0.8759**	0.00792	**0.9906**
SBR	Medium	Low	1157	<.0001	0.763	**-18.3826**	**0.4242**	**-0.00296**	**0.9455**
		High	1313	<.0001	0.588	**-11.9073**	**5.022**	**-0.0263**	**0.7236**
	Superior	Low	1185	<.0001	0.542	-15.2435	**2.6426**	**-0.017**	**0.7198**
		High	1326	<.0001	0.641	**-5.835**	**2.523**	0.004	**0.810**
SPA	Medium	Low	1107	<.0001	0.716	2.314	**0.4323**	**-0.00803**	**0.9138**
		High	1192	<.0001	0.551	**-5.8265**	**2.8619**	**-0.0618**	**0.6942**
	Superior	Low	1099	<.0001	0.785	-0.9481	**0.2032**	-0.00139	**1.0348**
		High	1359	<.0001	0.667	**-6.1763**	**2.8845**	**-0.0232**	**0.7145**
SRD	Medium	Low	1442	<.0001	0.371	-25.1024	7.5535	**0.0121**	**0.4744**
		High	1709	<.0001	0.644	0.1491	**2.0492**	**-0.0356**	**0.7956**
WFR	Medium	Low	535	<.0001	0.545	4.862	0.1244	**0.0947**	**1.0435**
		High	836	<.0001	0.496	**-10.3549**	**7.0956**	-0.0103	**0.493**
	Superior	Low	188	<.0001	0.426	**9.7077**	0.00887	0.1285	**1.4447**
		High	526	<.0001	0.594	-7.2299	**4.2372**	**-0.0407**	**0.6226**
WGP	Medium	Low	592	<.0001	0.590	**-12.2137**	**5.2922**	**-0.0219**	**0.5022**
		High	622	<.0001	0.537	0.6888	**1.0362**	**-0.0534**	**0.8882**
	Superior	Low	1219	<.0001	0.638	-1.5958	**0.7302**	0.00142	**0.8799**
		High	1189	<.0001	0.601	0.8515	**1.0181**	**-0.0554**	**0.8785**

Further investigation into the parameter related to aspen basal area in model *f* (i.e., B2) indicated that the difference in the parameter value between the low and high RGR years is positive for spruce 4 times out of the 12 possible combinations of agency and installations with an average value of 0.02 (Figure 4.4), and for aspen the parameter value is positive 8 times out of the 12 possible combinations with an average values of 0.03 (Figure 4.5). The differences calculated were also plotted against the differences in summer heat moisture index values (SHM) relative to the selected years for each agency and installation (Figure 4.6). The scatter plot shows a larger concentration of data points within and around the first quadrant of the plot which indicates that positive changes between low and high volume RGR years correspond to positive differences in SHM relative to the selected years for each agency and installation.

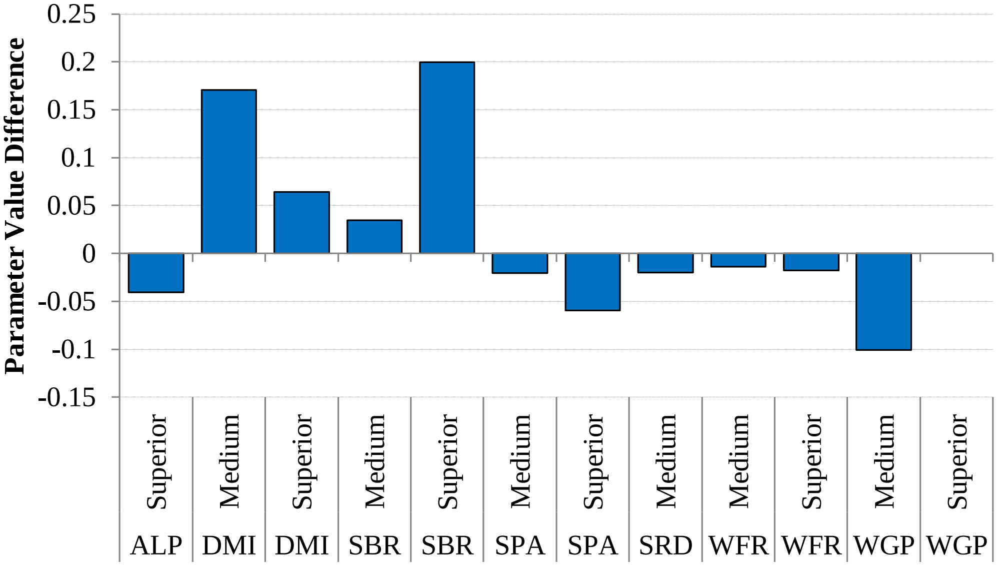


Figure 4.4. Representation of the differences in the parameter value related to aspen basal area between low and high volume RGR years for white spruce. Model information and parameter values are presented in Table 4.7.

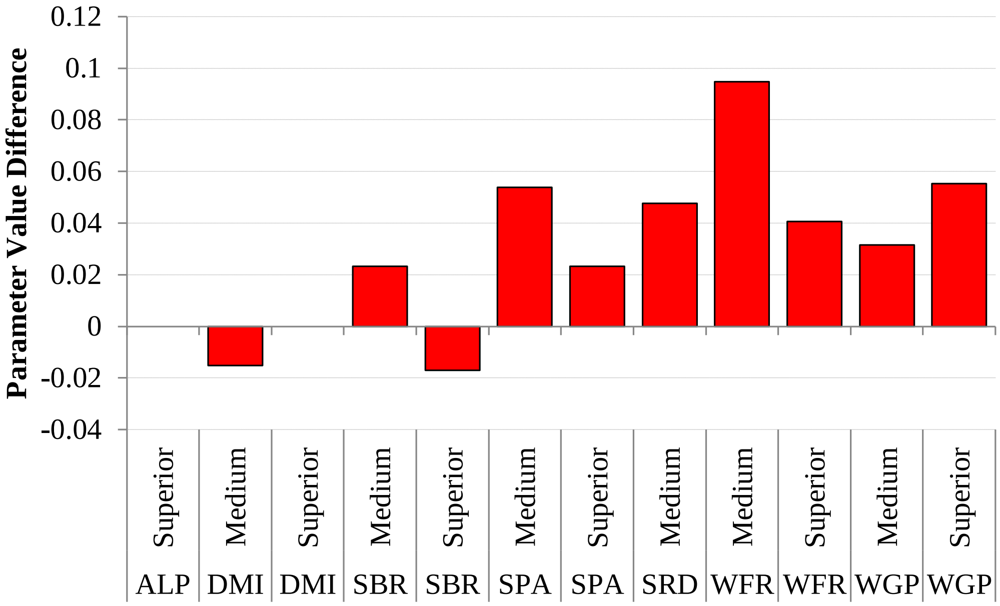


Figure 4.5. Representation of the differences in the parameter value related to aspen basal area between low and high volume RGR years for trembling aspen. Model information and parameter values are presented in Table 4.8.

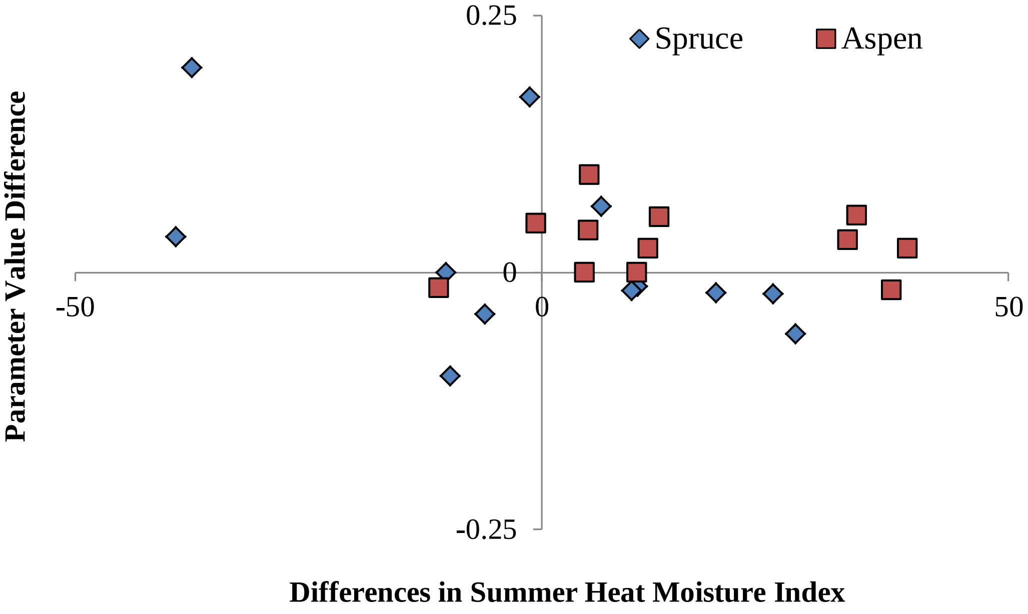


Figure 4.6. Representation of the differences in the parameter value related to aspen basal area between low and high volume RGR years for white spruce and trembling aspen plotted against the differences in summer heat moisture index values (SHM) relative to the selected years for each agency and installation.

4.4. Discussion

The extra sum of squares test carried for the models relating spruce volume increment to the climate variable/s and tree size indicated that the seven agencies could not be pooled into a single equation. The same results were obtained for the models that included aspen basal area as well. This outcome suggests that climate effect on spruce and aspen growth varies between locations similarly to the variability reported by Filipescu and Comeau (2007a) on the same sites for the effect of competition on spruce growth. However, other important factors have not been taken into account in this study and need to be evaluated carefully. These factors include frost and winter injuries that have a strong influence on white spruce growth in boreal forests (e.g., Stathers and Spittlehouse, 1990; Krasowski et al. 1993) and which are not well explained by the climate data used in this study.

Studies have also shown a relationship between the temperature sum needed by certain phenological events and the total length of the growing season of the original growing site of different tree provenances (e.g. Sarvas 1967). Moreover, spring temperatures, which are related to the risk of spring frost damage, have been linked to the differences in the timing of bud burst among different geographical origins (e.g. Burley 1966). For this study each agency used local seed to grow the planted trees which resulted in genetic differences across the WESBOGY long-term study. However the confounding effect of the seed provenance cannot be taken into account in the models that I developed because it is not possible to isolate its effect on tree growth.

This study indicated that climate variables and initial size of the tree can account for 89% of the annual increment in volume growth of spruce. Other studies have indicated that the predictive ability of the available growth models improves when taking into account climate variables (e.g., Snowdon, 2001). The outcome of this study also indicates that adding to the model an estimate of competition further improves the strength of the model. The parameter related to the estimate of competition was often significant in the studied models and the coefficient of determination was 2.2% higher (on average) for spruce in comparison to models without an estimate of aspen competition.

February average temperature was the climate variable with the highest predictive ability of spruce growth across the seven agencies. Cherry and Parker, (2003) also found that white spruce growth and survival was strongly related with maximum temperature in January; and Thomson et al. (2009) found that February maximum temperature was highly significant for black spruce. This finding is consistent with existing knowledge indicating that extreme winter temperatures are important limiting factors for white spruce growth in the boreal forests of Canada (Nienstaedt and Zasada, 1990). However, the results also indicated that precipitation, particularly during the summer of the previous year and the winter, has a significant impact on spruce growth because of its relationship with the water content in the soil during the growing season. Also Barber et al. (2000) concluded that for white spruce both temperature and precipitation levels are important limiting factors.

The comparison between the two sets of selected climate variables indicated that when using climate variables related to the growing season instead of variables with the highest coefficient of determination, the number of significant climate variables in the final spruce models dropped by 14% and the predictive ability of the final models with aspen basal area (i.e., equation *c* and *e*) dropped by less than 1% on average. This outcome indicates that when using climate variables expressing the climatic conditions of the growing season fewer agencies are significant. However, the final models (i.e., equation *c* and *e*) are able to capture on average 76% of the variability in spruce volume growth independently from the method used to select the climate variables.

When investigating the relationship between tree growth and climate the selection of the climate variable plays a pivotal role. A large number of studies use linear and non-linear functions to identify the climate variables with the highest predictive ability (e.g., Cherry and Parker, 2003; Thomson and Parker, 2008) while others select climate indicators that are more biologically meaningful in relation to tree growth (e.g., Hogg, 1997; Refheldt et al. 1999; Hogg et al. 2005; Hogg et al. 2008; Chen et al. 2010). Likewise, the first selection process in this study found that more than half (64%) of the climate variables selected were represented by monthly levels of precipitation and temperature. These variables had a greater statistical significance than the seasonal climate variables that were selected to represent the climatic conditions during the growing season. However, since the overall strength of the models developed in this study was not largely affected by the selection process it appears that the selection of climate variables should be based: firstly on the biological meaning of the climate variable, and then on its statistical value.

The results also indicate that aspen density has a negative effect on spruce growth but the reduction in growth appears to be modest. The strength of the competition measure used (i.e., aspen basal area per hectare) is probably weakened by the lack of spatial information within each plot (e.g., tree-level competition estimates). However, the low competitive effect of aspen density on spruce growth may be related to the many beneficial effects related to mixedwood forests composed by white spruce and trembling aspen (e.g., Örlander, 1993; Man and Lieffers, 1999; Pritchard and Comeau, 2004).

Examination of competitive effect during years when growth rates are either the highest and lowest within each agency and installation indicated that for both spruce and aspen the competitive effect of aspen density overall increases when conditions are more favourable for growth. Moreover, the difference in competitiveness within each agency and installation appears to be related to changes in the climatic conditions during the growing season. These results corroborate the stress-gradient hypothesis that indicates that facilitation is more common in plant communities developing under high environmental stress, and where the physical environment is relatively benign positive interactions are less common and competitive interactions are the dominant structuring forces (e.g.: Bertness and Callaway, 1994; Callaway and Walker, 1997; Maestre et al. 2005). In boreal and sub-boreal forests, where extremely low temperatures are an important limiting factor, mixedwood stands offer protection from frost and winter injury (e.g.: Stathers and Spittlehouse, 1990; Krasowski et al. 1993). This factor represents one of the primary mechanisms for facilitation with studies showing that the chance of frost injuries for conifer seedlings increases in large gaps where limited shading is provided by the surrounding vegetation (Örlander, 1993; Pritchard and Comeau, 2004).

Other studies have indicated that mixedwood stands can increase spruce resistance to climate extremes, and can reduce understory competition (Lieffers and Stadt, 1994; Comeau, 1996; Voicu and Comeau, 2004). These and other factors have a facilitative effect on spruce growth when the abiotic conditions are not favourable by providing shade which reduces evapo-transpiration, and by reducing competition from grass and shrubs which can be aggressive competitors for water (Cortini and Comeau 2008a; Man and Comeau 2008).

4.5. Conclusion

In this chapter I explored the combined effect of climate and trembling aspen competition on white spruce and trembling aspen growth using data from the long-term study established by the Western Boreal Growth and Yield association (WESBOGY).

Results indicate that climate variables and initial size of the tree can account for 89% of the annual increment in spruce volume growth. Including an estimate of competition in the models was often significant and the coefficient of determination was 2.2% higher (on average). The predictive ability of the final models with aspen basal area dropped by less than 1% on average when comparing two different sets of climate variables (i.e., variables spanning from July of the previous year to August of the current growth year or solely based on the climate during growing season). Since the overall strength of the models developed in this study was not largely affected by the selection process it appears that the selection of climate variables should be based: firstly on the biological meaning of the climate variable, and then on its statistical value.

The stress gradient hypothesis test indicates that: 1) for both spruce and aspen the competitive effect of aspen density overall increases when conditions are more favourable for growth, and 2) the difference in competitiveness within each combination of agency and installation appears to be related to the changes in the climatic conditions during the growing season. These results corroborate the stress-gradient hypothesis indicating that facilitation is more common in plant communities developing under high physical stress, and where the physical environment is relatively benign positive interactions are less common and competitive interactions are the dominant structuring forces

Although the original dataset comes from a well-designed and replicated long term study the analysis in this chapter would have benefitted from tree-level estimates of competition and micro-site level information on climate (e.g., frost events). This study also provides good evidence that the stress gradient hypothesis is also important in the boreal forests of North America. This outcome should be explored further using long term studies in order to better understand the changes in competitive pressure over multiple years and across climate gradients.

4.6. References

Barber, V.A., Juday, G.P., Finner, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405: 668-673.

Bertness, M., Callaway, R.M., 1994. Positive interactions in communities. Trends in Ecology and Evolution 9: 191-193.

Binkley, D., Sollins P., Bell R., Sachs D., Myrold, D., 1992. Biogeochemistry of adjacent conifer and alder/conifer stands. Ecology 73:2022-2033.

Bokalo, M., Comeau, P.G., Titus, S.J., 2007. Early development of tended mixtures of aspen and spruce in western Canadian boreal forests. Forest Ecology and Management 242: 175-184.

Burley, J. 1966. Genetic variation in seedling development of Sitka spruce, Picea sitchensis (Bong.) Carr. Forestry 39: 68–94.

Callaway, R.M., Walker, L.R., 1997. Competition and facilitation: a synthetic approach to interactions in plant communities. Ecology 78: 1958-1965.

Chen, P., Welsh, C., Hamann, A., 2010. Geographic variation in growth response of Douglas-fir to inter-annual climate variability and projected climate change. Global Change Biology. Accepted article online: Jan 5 2010.

Cherry, M., Parker, W.H., 2003. Utilization of genetically improved stock to increase carbon sequestration. For. Res. Rep. 160. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ont.

Comeau, P.G., 1996. Why mixedwoods? In: Comeau, P.G., Thomas, K.D. (Eds.), Silviculture of Temperate and Boreal Broadleaf-Conifer Mixtures. B.C. Min. For. Victoria, B.C., Land Manage. Handb. 36, pp. 1-5.

Comeau, P.G., Wang, J.R., Letchford, T., 2003. Influences of paper birch competition on growth of understorey white spruce and subalpine fir following spacing. Canadian Journal of Forest Research 33: 1962-1973.

Cortini, F., Comeau, P.G., 2008a. Evaluation of competitive effects of green alder, willow and other tall shrubs on white spruce and lodgepole pine in Northern Alberta. Forest Ecology and Management 255: 82-91.

Cortini, F., Comeau, P.G., 2008b. Effects of red alder and paper birch competition on juvenile growth of three conifer species in south-western British Columbia. Forest Ecology and Management 256: 1795-1803.

Draper, N.R., and Smith, H. 1981. Applied regression analysis. Wiley, New York.

Fililpescu, C., Comeau, P.G., 2007a. Aspen competition affects light and white spruce growth across several boreal sites in western Canada. Canadian Journal of Forest Research 37: 1701 1713.

Fililpescu, C., Comeau, P.G., 2007b. Competitive interactions between aspen and white spruce vary with stand age in boreal mixedwoods. Forest Ecology and Management 247: 175-184.Hogg, E.H. 1997. Temporal scaling of moisture and the forest grassland boundary in western Canada. Agric. For. Meteorol. **84**: 115–122.

Hogg, E.H. (Ted), Brandt, J.P., Kochtubajada, B., 2005. Factors affecting interannual variation in growth of western Canadian aspen forests during 1951-2000. Can. J. For. Res. 35, 610-622.

Hogg, E.H. (Ted), Brandt, J.P., Michaelian, M., 2008. Impacts of a regional drought on the productivity, dieback, and biomass of western Canadian aspen forests. Can. J. For. Res. 38, 1373-1384.

Honer, T.G., Ker, M.F, Alemdag, I.S., 1983. Metric timber tables for the commercial tree species of central and eastern Canada. Can. For. Serv. Inf. Rep. MX-140.

Hunt, R., 1982. Plant Growth Curves – The Functional Approach to Plant Growth Analysis. Edward Arnold (Publishers) Ltd., London, pp. 248.

Kikvidze, Z., Callaway, R.M., 2009. Ecological facilitation may drive major evolutionary transitions. Bioscience 59: 399-404.

Krasowski, M.J., Herring, L.J., Letchford, T., 1993. Winter freezing injury and frost acclimation in planted coniferous seedlings. For. Can. and B.C. Min. For., Victoria, BC. FRDA Rep. No. 206.

Lieffers, V.J., Stadt, K.J., 1994. Growth of understory *Picea Glauca, Calamagrostis Canadiensis,* and *Epilobium angustifolium* in relations to overstory light transmission. Canadian Journal of Forest Research 24, 1193-1198.

Lortie, C.J., Callaway, R.M., 2006. Re-analysis of meta-analysis: support for the stress-gradient hypothesis. Journal of Ecology 94: 7-16.

MacPherson, D.M., Lieffers, V.J., Blenis, P.V., 2001. Productivity of aspen stands with and without a spruce understory in Alberta’s boreal mixedwood forests. Forestry Chronicle 77, 351-356.

Maestre, F.T., Valladares, F., Reynolds, J.F., 2005. Is the change of plant-plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. Journal of Ecology 93: 748-757.

Maestre, F.T., Valladares, F., Reynolds, J.F., 2006. The stress-gradient hypothesis does not fit all relationships between plant-plant interactions and abiotic stress: further insights from arid environments. Journal of Ecology 94: 17-22.

Maestre, F.T., Callaway, R.M., Valladares, F., Lortie, C.J., 2009. Refining the stress-gradient hypothesis for competition and facilitation in plant communities. Journal of Ecology 97: 199-205.

Man, C.D., Comeau, P.G., Pitt, D., 2008. Competitive effects of woody and herbaceous vegetation in a young boreal mixedwood stand. Canadian Journal of Forest Research **38**: 1817–1828.

Man, R., Lieffers, V.J., 1999. Are mixtures of aspen and white spruce more productive than single species stands? Forestry Chronicle 75, 505-513.

Mbogga, S.M., Hamann, A., Wang, T., 2009. Historical and projected climate data for natural resource management in western. Agricultural and Forest Meteorology 149: 881-890.

Nienstaedt, H., Zasada, J.C., 1990. White spruce. *In* Silvics of North America: 1, Cionifers. *Edited by* R.M. Burns and B.H. Honakala. U.S. Dep. Agric. Agric. Handb. 654.

Örlander, G., 1993. Shading reduces both visible and invisible frost damage to Norway spruce seedlings in the field. Forestry 66 (1): 27–36.

Ott, P. 1997. The use of indicator variables in non-linear regression. B.C. Minist. For. Biom. Inf. Pamphlet No. 56.

Peterson E.B., Peterson, N.M., 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces. Can. For. Serv. North. For. Cent. Spec. Rep. 1.

Pritchard, J.M, Comeau, P.G., 2004. Effects of opening size and stand characteristics on light transmittance and temperature under young trembling aspen stands. Forest Ecology and Management 200:119-128.

Rehfeldt, G.E., Ying, C.C., Spittlehouse, D.L., Hamilton, D.A., 1999. Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation. Ecological Monographs 69: 375-407.

Sanborn, P., Preston, C., Brockley, R., 2002. N2-fixation by Sitka alder in a young lodgepole pine stand in central interior British Columbia, Canada. Forest Ecology and Management 167: 223-231.

Sarvas, R. 1967. The annual period of development of forest trees. Proceedings of the Finnish Academy of Science and Letters 1965: 211–231.

SAS Institute Inc. 2004. SAS OnlineDoc® 9.1.3**.** Cary, NC: SAS Institute Inc.

Simard, S., Molina R., Smith J.E., Perry D.A., Jones, M.D., 1997. Shared compatibility of ectomycorrhizae on *Pseudotsuga menziesii* and *Betula papyrifera* seedlings grown in mixture in soils from southern British Columbia. Canadian Journal of Forest Research 27: 331-342.

Snowdon, P., 2001. Short-term predictions of growth of *Pinus radiata* with models incorporating indices of annual climatic variation. Forest Ecology and Management 152: 1-11.

Stadt, K.J., Huston, K.D., Coates, K.D., Feng, Z., Dale, M.R.T., Lieffers, V.J., 2007. Evaluation of competition and light estimation indices for predicting diameter growth in mature boreal mixed forests. Annals of Forest Science 64: 477-490.

Stathers, R.J., Spittlehouse, D.L., 1990. Forest soil temperature manual. Queen's Printer, Victoria, B.C. For. Resour. Dev. Agree. Rep.130.

Thomson, A.M., and Parker, W.H. 2008. Boreal forest provenance tests used to predict optimal growth and response to climate change: 1. Jack pine. Can. J. For. Res. **38**, 157-170.

Thomson, A.M., Riddel, C.L., and Parker, W.H. 2009. Boreal forest provenance tests used to predict optimal growth and response to climate change: 2. Black spruce. Can. J. For. Res. **39**, 143-153.

Hogg, E.H., 1997. Temporal scaling of moisture and the forest-grassland boundary in western Canada. Agricultural and Forest Meterology 84, 115-122.

Voicu, M., Comeau, P.G., 2006. Microclimatic and spruce growth gradients adjacent to young aspen stands. Forest Ecology and Management 221:13-26.

Wang, T., Hamann, A., Spittlehouse, D.L., Aitken, S.N., 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climate 26(3): 383-397.

Weigelt, A., Jolliffe, P. 2003. Indices of plant competition. Journal of Ecology 91: 707-720.

WESBOGY, 2007. Long term study of growth and development of mixed stands of spruce and aspen. Experimental design, Data collection and Database Maintenance Manual [online]. http://www.uofaweb.ualberta.ca/rr//pdfs/2007DataCollectionManualSept2007.pdf

Chapter 5. Summary and Conclusions

This thesis had the ambitious goal of improving our understanding of long term effects of site preparation and climate change on lodgepole pine and white spruce growth in northern British Columbia and the combined effect of climate and aspen density on white spruce and trembling aspen growth in boreal mixtures. In Chapter two I examined the long-term effect of silvicultural treatments such as mechanical preparation, vegetation control, and fire on growth of lodgepole pine and white spruce using data from experimental trials established in north-eastern British Columbia in the late 1980s. The objectives of this study were to evaluate the predictive ability of three modelling techniques (age-shift method, growth multipliers and site index adjustments) which were tested and compared to simulated rotation-length growth responses generated by the Tree and Stand Simulator model (TASS) (Mitchell, 1975). The information provided by the growth model together with the modelling techniques tested allowed identifying the ‘type’ of growth response shown by the various treatments for lodgepole pine and white spruce. Results were also validated by comparing the simulated growth response to PSP (Permanent Sampled Plot) data and recently harvested blocks within the same biogeoclimatic zones of British Columbia.

For lodgepole pine the data came from the Bednesti site located west of Prince George B.C. in the Stuart Dry Warm variant of the Sub-Boreal Spruce Zone (SBSdw3) (DeLong et al., 1993). For white spruce the data was provided by the

Inga Lake site located northwest of Fort Saint John B.C. in the Peace variant of the moist warm subzone of the Boreal White and Black Spruce Zone (BWBSmw1) (DeLong et al., 1990). At these locations various site preparation treatments such as mechanical preparation, vegetation control, and fire were applied in 1987 (Bedford and McMinn, 1990).

Two of the key research questions addressed in this chapter were:

1. What type of growth response do different site preparation techniques show 20 years after planting and at the end of the rotation period?
2. How do establishment treatments influence future stand volume?

The results indicate that up to age 20 the treatment effect steadily enhances spruce growth compared to the untreated (i.e., Type 2 growth response) while for lodgepole pine the treatment effect is less significant after two decades. The growth projections indicate that at age 60 lodgepole pine plantations that underwent silvicultural treatments (i.e.: mechanical and non-mechanical site preparation) in the Sub-Boreal zone of B.C. show increased yield of 10% compared to untreated stands but this gap is likely to be filled by the end of the rotation (stand age 100+) in accordance to the Type 1 growth response characteristic. Also white spruce plantations in the Boreal zone of B. C. result in 10% more stand volume up to age 80 where proper silvicultural treatments are applied compared to untreated stands. However, this gap will gradually disappear by the end of the rotation (stand age 100+) in accordance to the Type 1 growth response characteristics.

In chapter two I also addressed the following research question:

3. What are the implications of different approaches (age-shift, growth multiplier, and site index adjustment) on estimation of treatment effects on yield?

Results from this study indicate that, among the modeling techniques tested, the age–shift approach is the best method for representing growth differences for a given treatment in relation to the untreated. This study also indicates that growth multipliers calculated up to age 20 do not predict volume gains at stand age 85 or older. Both age-shift and growth multipliers values up to age 20 are more representative of the long-term growth for a shade-intolerant species like lodgepole pine than for the slow growing white spruce. The site index values calculated using the growth intercept model become quite stable after year 11-15 for planted stands. However, these values still represent early estimates of stand productivity and might not be as accurate as later estimates.

It is important to mention that this study is based on relatively young stands and that growth models including TASS/TIPSY provide long term growth estimates for the ‘average’ stand using inventory data of similar locations. For these reasons the projected growth estimates are only valid for this case study and might not be representative of the future characteristics and development of the stand. In order to enhance the predictive ability of this type of studies the analyses should be extended to a larger number of species and ecological zone. It is also suggested that the same methodology would be applied to other growth models (e.g., MGM).

In chapter three I examined the explanatory capability of various climate variables on growth of lodgepole pine and white spruce in northern B.C. following mechanical site preparation and vegetation control treatments. The equations developed to relate conifer growth and climate variables were also tested using additional data on conifer growth from sites across a broad latitudinal range. I also explored the impact of climate change by projecting conifer growth using the latest climate models and future climate scenarios.

The base data used for this study came from five experiments in the boreal and sub-boreal forests of B.C. where various mechanical and non-mechanical site preparation techniques were applied 20 or more years ago (Bedford and McMinn, 1990; Bedford and Sutton, 2000). At each location I selected the best mechanical site preparation treatment, and a vegetation control treatment (i.e. fire or herbicide) to be compared against the untreated/control. Various growth indices were evaluated in order to provide measurements of conifer growth that are not dependent on crop tree size considering that the annual increment is proportionally related to the initial size of the tree. ClimateBC provided climate data over the past two decades for these locations based on latitude, longitude and elevation using a scale-free mathematical climate model (e.g.: Wang et al., 2006). Various climatic variables were tested as predictors of each of the growth indexes. ClimateBC also provided information on future climate based on the latest global climate model simulations (CGCM2) from the Canadian Centre for Climate Modelling and Analysis (CCCma) for scenario A2 and scenario B2.

Two of the key research questions addressed in this chapter were:

1. Which growth factor (i.e., height, diameter, and volume) shows better correlations with climate variables?
2. Which of the selected climatic variables will show the best correlation with growth?

The results indicate that the predictive ability of the growth indices improves when the initial size of the trees is taken into account (i.e., relative growth index) which is indicated not only by the higher adjusted R-square values but also by the enhanced significance of the final models. For lodgepole pine the final models for the relative growth index show that among the increments the best correlations with the climate variables are represented by height. Lodgepole pine is very intolerant of shade and competition from other species thus it allocates a significant amount of energy into height growth (e.g.: Lotan and Cricthcfield, 1990). For white spruce the relative growth index with the best correlations with climate variables is height as well. Monthly climate variables are better predictors of pine and spruce growth compared to seasonal and annual variables respectively showing that monthly average precipitation and temperature are important driving factors (Lotan and Critchfield, 1990; Nienstaedt and Zasada, 1990). Climate variables related to the preceding year accounted for more than half of the variables in the final equations indicating a lagged response in conifer growth.

In Chapter three I also addressed the following research questions:

3. How might growth of lodgepole pine and white spruce be affected by climate change?
4. How could site preparation treatments respond to climate change?
5. How effective are climate variables in predicting conifer growth?

The results indicate that for the Sub-Boreal zone of B.C. young lodgepole pine plantations will potentially benefit from longer growing seasons as the result of global warming. The untreated control plots are showing the highest potential for future growth by up-to 12% height increase compared to the mechanical site preparation treatment and the vegetation control treatment. For the Boreal zone of B.C. untreated young white spruce plantations in the boreal zone may suffer height growth decreases of up-to 10% due to increased drought-stress. Vegetation control and mechanical site preparation treatments appear to mitigate effects of climate change to some extent. The additional sites used to validate the equations developed to relate conifer growth and climate variables indicated a good predictive ability. The best growth predictions were obtained for those sites located near the original trials.

Although this study is based on sound data from well replicated long term trials the indications provided should be considered valid only for the studied regions of B.C. and only for young conifer plantations up to stand age 20. It is yet to be proven that the same relationships between growth and climate variables will be maintained after age 20 thus these findings cannot be generalized to mature stands.

The most recent literature on forest management in a climate change era indicate the need for an enhanced capacity to undertake integrated assessments of vulnerability to climate change at various scales (Spittlehouse, 2008; Williamson et al., 2009; Hebda, 2009). The stand level scale of this study offered the unique opportunity to explore different forest management techniques in relation to climate change. However a larger number of long term trials would be necessary in order to expand the range of indications to more ecological zones and to other species.

The outcome of this study shows the potential to expand this findings to quasi-physiological models such as 3-PG (Landsberg and Waring, 1997) which uses weather data as one of the main driving factors (monthly time steps) to calculate photosynthesis and allocate resources to tree growth. A recent study used 3-PG to project Douglas-fir growth based on site index and PSP data which tend to provide poor results for young conifer plantations (Coops et al. 2010). This thesis provides sound results on the correlation between juvenile growth and climate variables.

In chapter four I evaluated the combined effect of climate and trembling aspen competition on white spruce and trembling aspen growth using data from the long-term study established by the Western Boreal Growth and Yield association (WESBOGY).

The WESBOGY long term study uses a randomized block design where each block consists of two installations, one on a superior site and one on a median site and each installation has two replications of a series of 15 plots (WESBOGY, 2007). Plots are square with 20 m sides and, at each installation, the data I used relate to present three levels of spruce density (0, 500 and 1000 stems per hectare), and five levels of aspen density (0, 200, 500, 1500, and 4000 stems per hectare). Spruce and aspen stem volume were calculated and multiple linear regressions (similarly to chapter 3) were used to select the most representative climate variable at the study level and at the agency level.

For each WESBOGY installation I calculated climate data for three different time scales (annual, seasonal and monthly) spanning from July of the previous year to August of the current growth year. A second screening process selected two climate variables that are most representative of climatic conditions during the growing season. The pool of climate variables was restricted to spring and summer temperature and precipitation of the current growth year.

Spruce volume increments were then analyzed together with the selected climate variable/s using linear and non-linear regressions. Initial spruce and aspen size, was used as additional explanatory variable similarly to Comeau et al. (2003). Non-linear models proved to be the best fit between spruce growth, and climate variables. An estimate of competition (i.e., aspen basal area per hectare) was then added to the selected equations relating spruce growth to climate variables.

For selected years with either the highest or the lowest growth rates, I also fitted at the tree level a non-linear regression to predict spruce and aspen volume increment using initial spruce and aspen volume together with aspen basal area per hectare as explanatory variables in order to investigate the stress gradient hypothesis.

Three of the key research questions addressed in this chapter were:

1. Are the local differences in climate able to explain significant portions of the variability in growth of white spruce from year to year?
2. When selecting the most representing climatic variables which method will show the best correlation with growth?

3. Does the inclusion of a competition estimate in predicting spruce growth using climatic variables improve the overall predictive ability of the model?

The results indicated that climate variables and initial size of the tree can account for 89% of the annual increment in volume growth of spruce. Other studies have indicated that the predictive ability of the available growth models improves when taking into account climate variables (e.g., Snowdon, 2001). The outcome of this study also indicated that adding to the model an estimate of competition further improves the strength of the model. The parameter related to the estimate of competition was often significant in the studied models and the coefficient of determination was 2.2% higher (on average) in comparison to models without an estimate of aspen competition.

When investigating the relationship between tree growth and climate the selection of the climate variable plays a pivotal role. A large number of studies use linear and non-linear functions to identify the climate variables with the highest predictive ability (e.g., Cherry and Parker, 2003) while others select climate indicators that are more biologically meaningful in relation to tree growth (e.g., Hogg, 1997). Likewise, the first selection process in this study found that more than half (64%) of the climate variables selected were represented by monthly levels of precipitation and temperature. These variables had a higher statistical significance than the seasonal climate variables that were selected to represent the climatic conditions during the growing season. However, since the overall strength of the models developed in this study was not largely affected by the selection process it appears that the selection of climate variables should be based: firstly on the biological meaning of the climate variable, and then on its statistical value.

In Chapter four I also addressed the following research questions:

4. Does the stress gradient hypothesis also apply for the boreal forests of North America?

The calculations carried for a selected number of years when growth rates are either the highest or lowest within each agency and installation indicated that for both spruce and aspen the competitive effect of aspen density overall increases when conditions are more favourable for growth. Moreover, the difference in competitiveness within each agency and installation appears to be related to changes in the climatic conditions during the growing season. These results corroborate the stress-gradient hypothesis that indicates that facilitation is more common in plant communities developing under high physical stress, and where the physical environment is relatively benign positive interactions are less common and competitive interactions are the dominant structuring forces (e.g.: Maestre et al. 2009). In boreal and sub-boreal forests, where extremely low temperatures are an important limiting factor, mixedwood stands offer protection from frost and winter injury (e.g.: Stathers and Spittlehouse, 1990). This factor represents one of the primary mechanisms for facilitation with studies showing that the chance of frost injuries for conifer seedlings increases in large gaps where limited shading is provided by the surrounding vegetation (Pritchard and Comeau, 2004).

Other studies have indicated that mixedwood stands can increase spruce resistance to climate extremes, and can reduce understory competition (e.g., Lieffers and Stadt, 1994). These and other factors have a facilitative effect on spruce growth when the abiotic conditions are not favourable by providing shade which reduces evapo-transpiration, and by reducing competition from grass and shrubs which can be aggressive competitors for water (Cortini and Comeau, 2008a; Man and Comeau, 2008).

Although the original dataset comes from a well-designed and replicated long term study the analysis in this chapter would have benefitted from tree-level estimates of competitions and micro-site level information on climate (e.g., frost events). This study also provides good evidence that the stress gradient hypothesis is important also for the boreal forests of North America. This outcome should be explored further using long term studies in order to better understand the changes in competitive pressure over multiple years and across latitudinal gradients.

5.2. References

Bedford, L., McMinn, R.G., 1990. Trials to appraise the biological effectiveness of mechanical site preparation equipment in British Columbia: FRDA Project 1.10. p. 3±12. In: Titus, B.D., Lavigne, M.B., Newton, P.F., Meades, W.J. (Eds.). The Silvics and Ecology of Boreal Spruces. 1989 IUFRO Working Party S1. 05±12 Proc. Symp. For. Can., St. John's, Newfoundland, Inf. Rep. N-X-271.

Bedford, L., Sutton, R.F., 2000. Site preparation for establishing lodgepole pine in the sub-boreal spruce zone of the interior British Columbia: the Bednesti trial, 10-year results. Forest Ecology and Management 126: 227-238.

Cherry, M., Parker, W.H., 2003. Utilization of genetically improved stock to increase carbon sequestration. For. Res. Rep. 160. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ont.

Coops, N.C., Hember, R.A., Waring, R.H., 2010. Assessing the impact of current and projected climates on Douglas-fir productivity in British Columbia, Canada, using a process-based model (3-PG). Canadian Journal of Forest Research 40: 511-524.

Comeau, P.G., Wang, J.R., Letchford, T., 2003. Influences of paper birch competition on growth of understorey white spruce and subalpine fir following spacing. Canadian Journal of Forest Research 33: 1962-1973.

Cortini, F., Comeau, P.G., 2008a. Evaluation of competitive effects of green alder, willow and other tall shrubs on white spruce and lodgepole pine in Northern Alberta. Forest Ecology and Management 255: 82-91.

DeLong, C., MacKinnon, A., Jang, L., 1990. A field guide for identification and interpretation of ecosystems of the northeast portion of the Prince George Forest Region. B.C. Ministry of Forests Land Manage. Handb. No. 22. Victoria, B.C. 108 p.

DeLong, C., Tanner, D., Jull, M.J., 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. BC Min. For., Victoria, BC, Land Manage. Handb. 24, 290 pp.

Hebda, R.J., 2009. The future of British Columbia forests requires resilience management. *In:* Drengson, A., and Taylor, D. 2009. Wild Foresting: practising nature's wisdom. New Society Publishers. pp. 202-209.

Hogg, E.H. 1997. Temporal scaling of moisture and the forest grassland boundary in western Canada. Agric. For. Meteorol. **84**: 115–122.

Landsberg, J.J., Waring, R.H., 1997. A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 172(2-3): 209-228.

Lieffers, V.J., Stadt, K.J., 1994. Growth of understory *Picea Glauca, Calamagrostis Canadiensis,* and *Epilobium angustifolium* in relations to overstory light transmission. Canadian Journal of Forest Research 24, 1193-1198.

Lotan, J.E., Cricthfield, W.B., 1990. Lodgepole pine. *In* Silvics of North America: 1, Cionifers. *Edited by* R.M. Burns and B.H. Honakala. U.S. Dep. Agric. Agric. Handb. 654.

Macadam, A., Kabzems, R., 2006. Vegetation management improves early growth of white spruce more than mechanical site preparation treatments. Northern Journal of Applied Forestry 23(1): 35-46.

Maestre, F.T., Callaway, R.M., Valladares, F., Lortie, C.J., 2009. Refining the stress-gradient hypothesis for competition and facilitation in plant communities. Journal of Ecology 97: 199-205.

Man, C.D., Comeau, P.G., Pitt, D., 2008. Competitive effects of woody and herbaceous vegetation in a young boreal mixedwood stand. Canadian Journal of Forest Research **38**: 1817–1828.

Mitchell, K.J., 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monographs 17. 39 p.

Nienstaedt, H., Zasada, J.C., 1990. White spruce. *In* Silvics of North America: 1, Cionifers. *Edited by* R.M. Burns and B.H. Honakala. U.S. Dep. Agric. Agric. Handb. 654.

Pritchard, J.M, Comeau**,** P.G., 2004. Effects of opening size and stand characteristics on light transmittance and temperature under young trembling aspen stands. Forest Ecology and Management 200:119-128.

Snowdon, P., 2001. Short-term predictions of growth of *Pinus radiata* with models incorporating indices of annual climatic variation. Forest Ecology and Management 152: 1-11.

Spittlehouse, D.L., 2008. Climate Change, impacts, and adaptation scenarios: climate change and forest and range management in British Columbia. B.C. Min. For. Range, Res. Br., Victoria, B.C. Tech. Rep. 045.

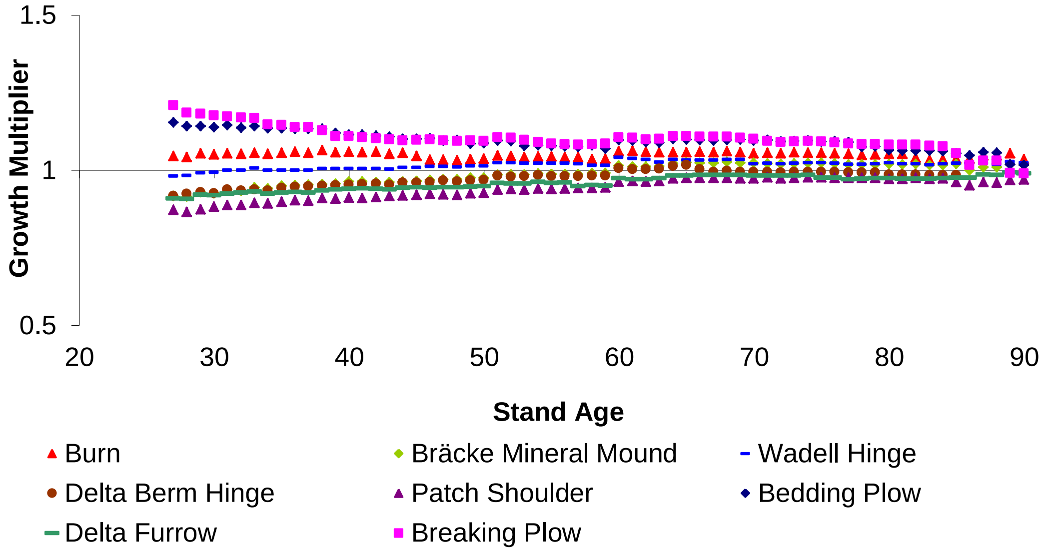
Stathers, R.J., Spittlehouse, D.L., 1990. Forest soil temperature manual. Queen's Printer, Victoria, B.C. For. Resour. Dev. Agree. Rep.130.

Wang, T., Hamann, A., Spittlehouse, D.L., Aitken, S.N., 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climatology 26(3): 383-397.

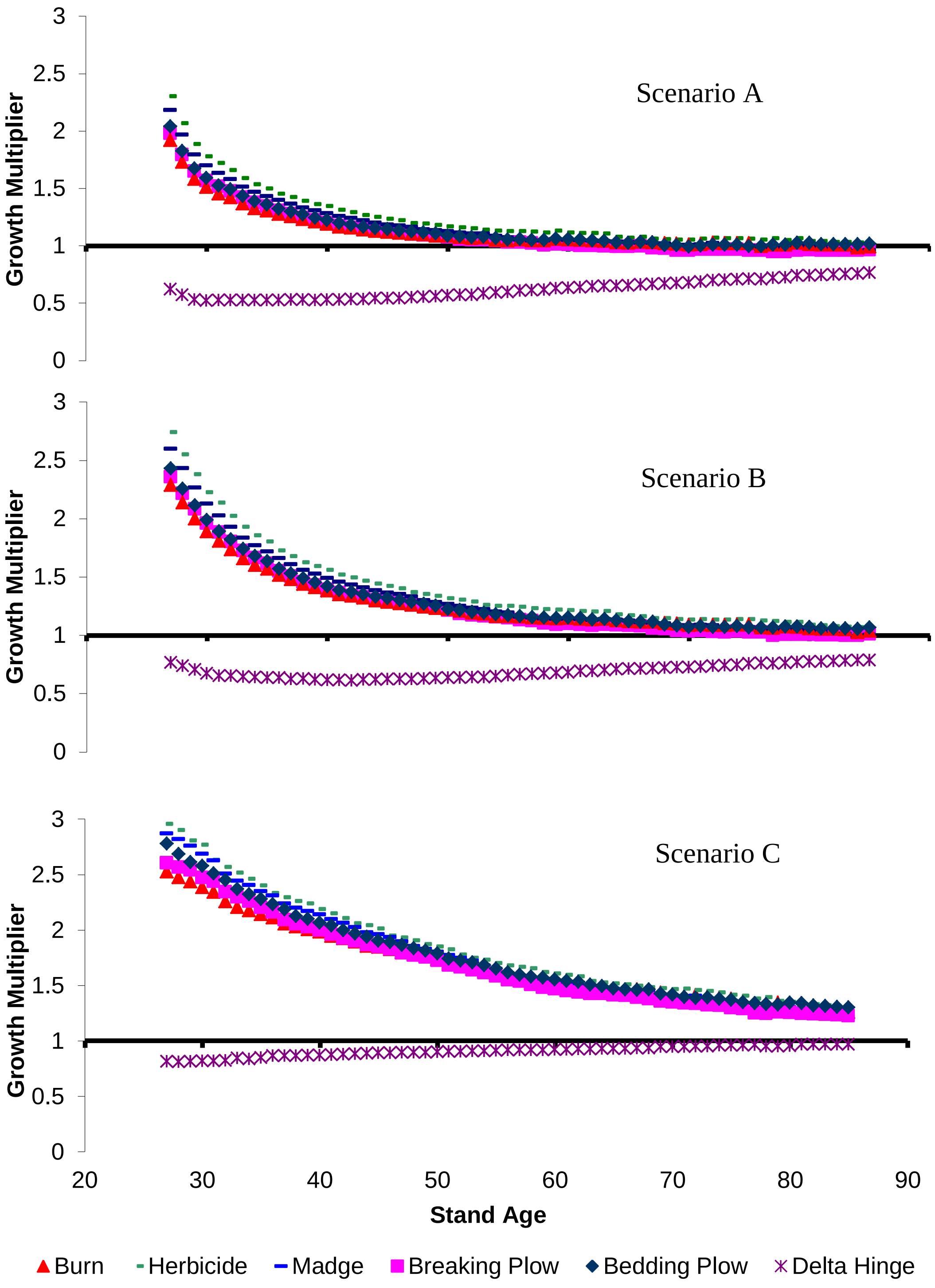
WESBOGY, 2007. Long term study of growth and development of mixed stands of spruce and aspen. Experimental design, Data collection and Database Maintenance Manual [online]. http://www.uofaweb.ualberta.ca/rr//pdfs/2007DataCollectionManualSept2007.pdf

Williamson, T.B., Colombo, S.J., Duinken, P.N., Gray, P.A., Hennessey, R.J., Houle, D., Johnston, M.H., Ogden, A.E., Spittlehouse, D.L., 2009. Climate change and Canada's forests: from impacts to adaptation. Sustain. For. Manag. Netw. and Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. 104 p.

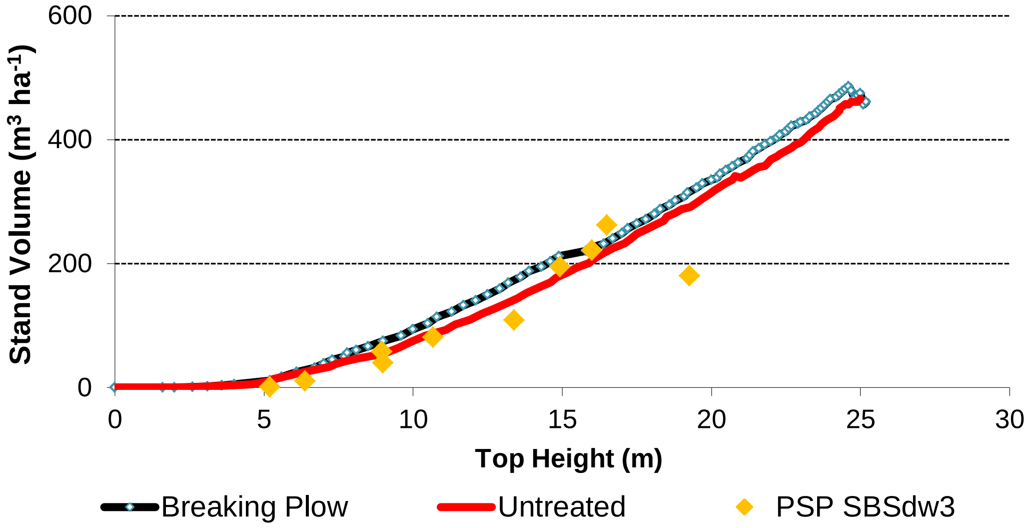
Appendix 1.



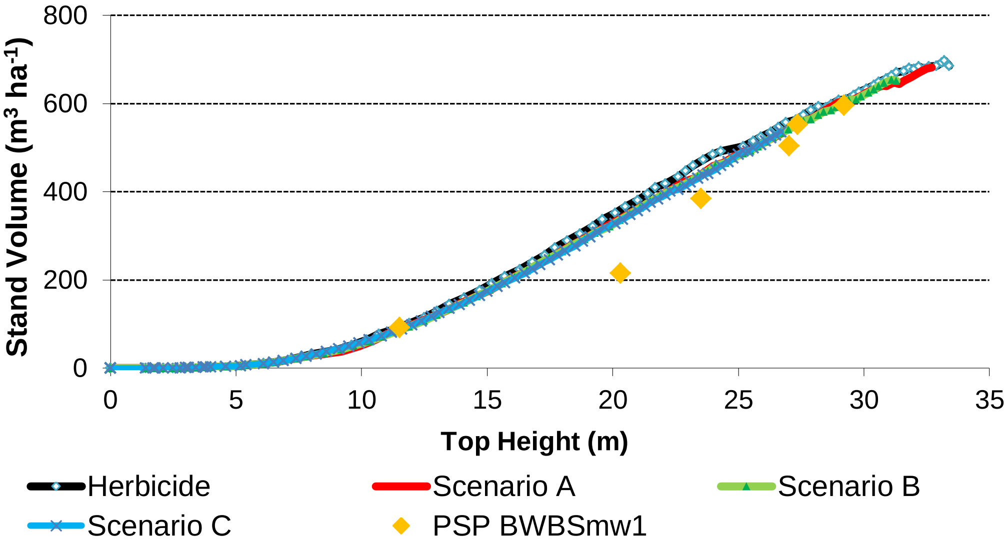
Projected growth multiplier results for lodgepole pine volume per hectare for each treatment in relation to the untreated from age 27 up-to age 90.



Projected growth multiplier results according to three scenarios for white spruce volume per hectare for each treatment in relation to the untreated from age 27 up-to age 85.



Projected stand volume versus top height for lodgepole pine for the best treatment (breaking plow) and the untreated. The PSP data represent measured volume of naturally regenerated stands in the same biogeoclimatic sub-zone and variant.



Projected stand volume versus top height for white spruce for the best treatment (herbicide) and the untreated. The PSP data represent measured volume of naturally regenerated stands in the same biogeoclimatic sub-zone and variant.

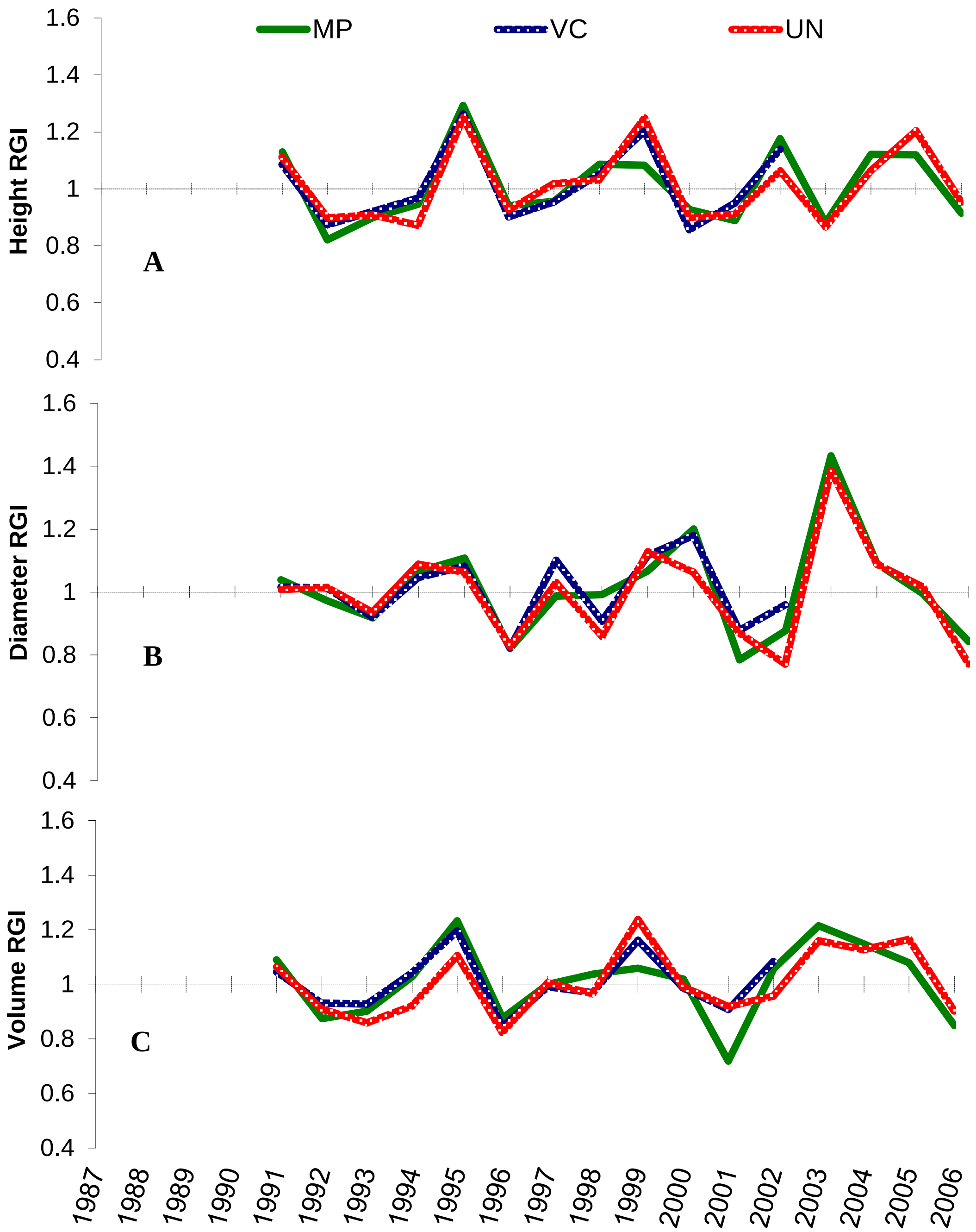
Appendix 2.

Statistical information on lodgepole pine relative growth index (RGI) such as diameter (D), basal area (B), height (H), and volume (V) by treatment: mechanical preparation (MP), vegetation control (VC), and untreated (UN).

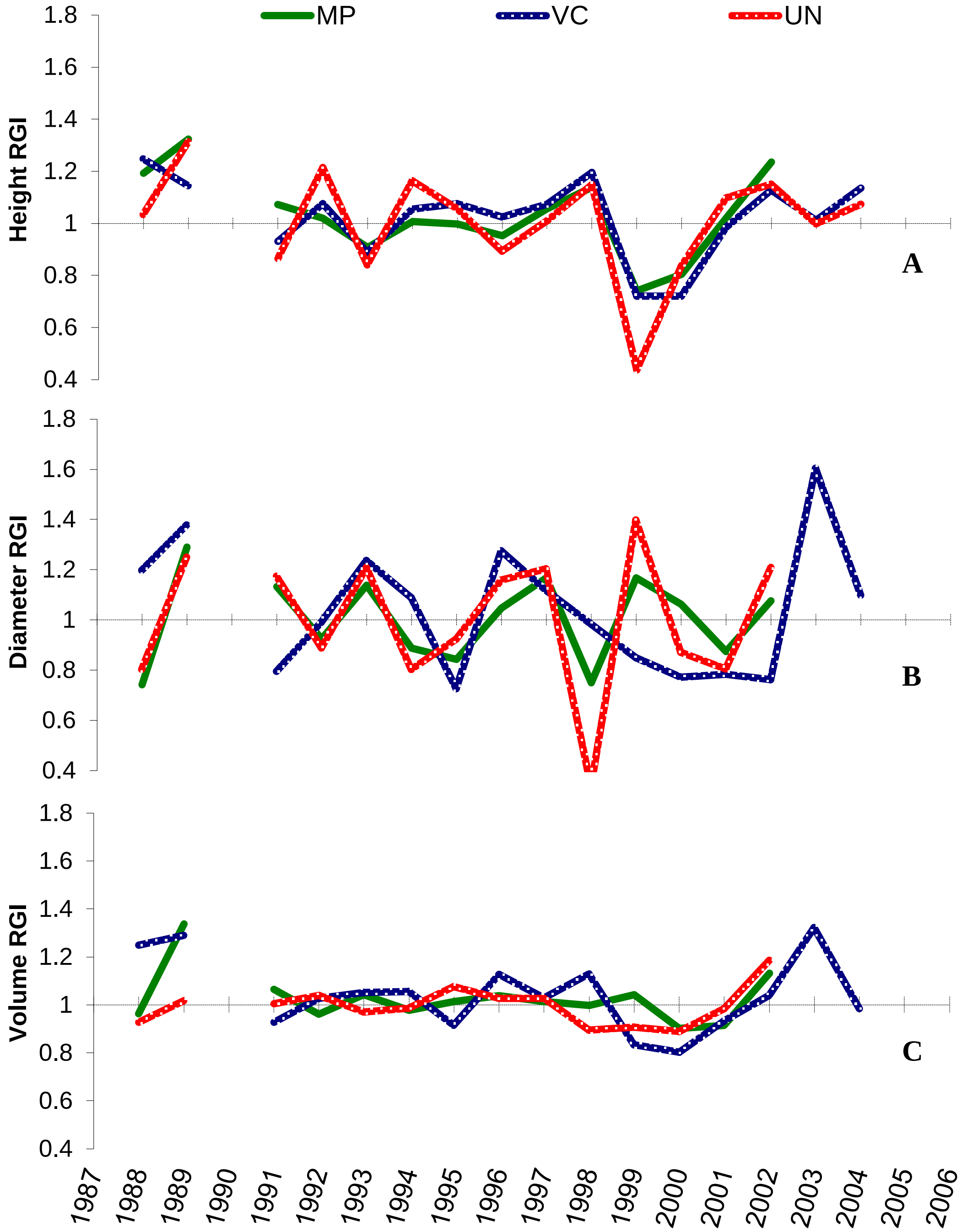
RGI	Treat.	# of Obs.	Mean	Variance	Standard Deviation	Standard Error	Coeff. of Variation	95% Conf. Interval (+/-)
D	**MP**	25	1.00	0.03	0.16	0.03	15.96	0.06
	VC	21	1.00	0.01	0.11	0.02	11.45	0.05
	UN	29	0.99	0.03	0.17	0.03	17.15	0.06
B	**MP**	25	1.00	0.03	0.17	0.03	16.92	0.07
	VC	21	1.00	0.01	0.12	0.03	11.77	0.05
	UN	29	0.99	0.03	0.18	0.03	18.24	0.07
H	**MP**	26	1.01	0.02	0.16	0.03	15.41	0.06
	VC	22	1.00	0.02	0.15	0.03	14.73	0.06
	UN	30	1.01	0.02	0.15	0.03	14.45	0.05
V	**MP**	24	1.01	0.02	0.14	0.03	14.06	0.06
	VC	20	1.01	0.01	0.11	0.02	10.62	0.05
	UN	29	1.00	0.02	0.13	0.02	12.48	0.05

Statistical information on white spruce relative growth index (RGI) such as diameter (D), basal area (B), height (H), and volume (V) by treatment: mechanical preparation (MP), vegetation control (VC), and untreated (UN).

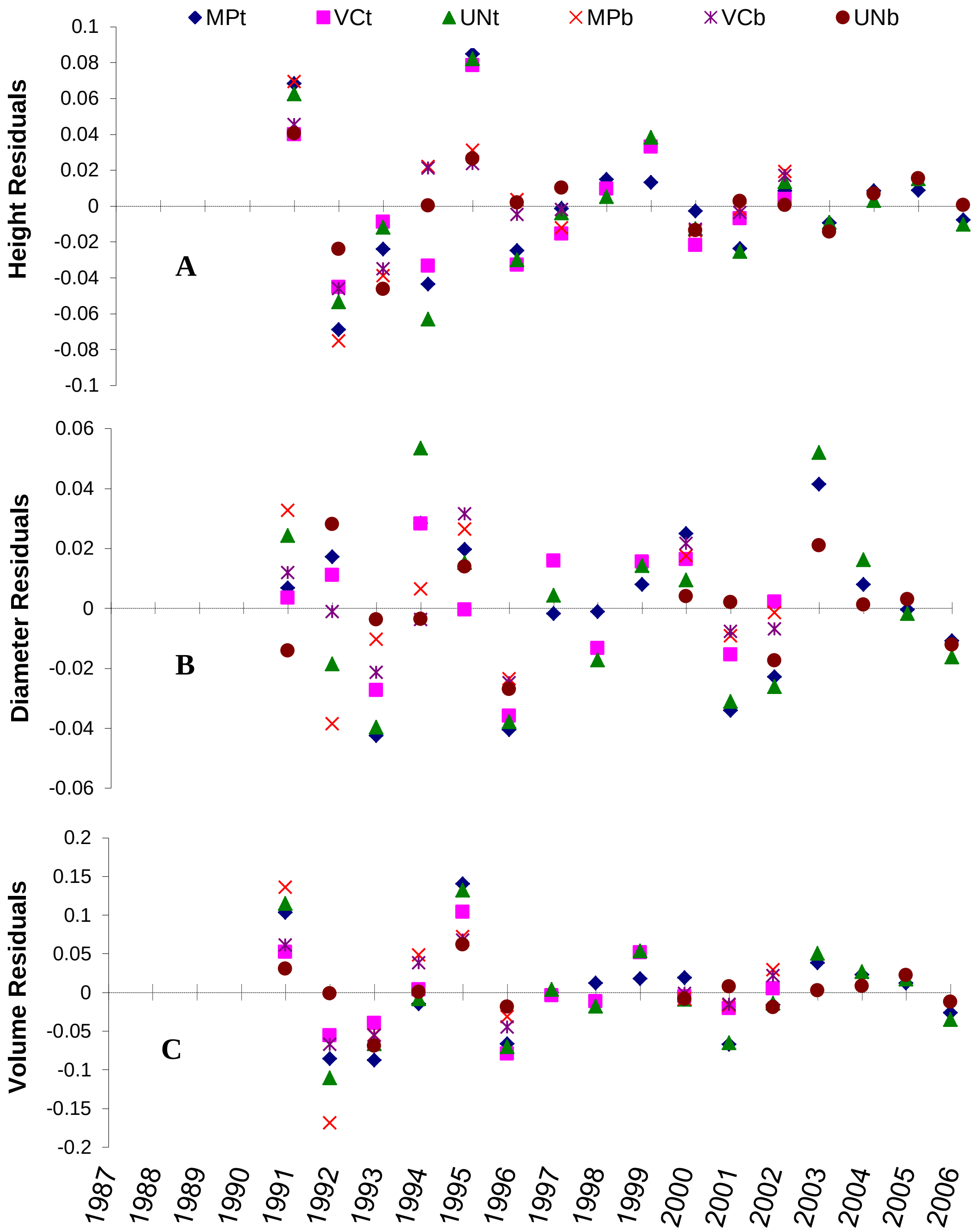
RGI	Treat.	# of Obs.	Mean	Variance	Standard Deviation	Standard Error	Coeff. of Variation	95% Conf. Interval (+/-)
D	**MP**	23	1.01	0.02	0.16	0.03	15.65	0.07
	VC	31	1.03	0.09	0.29	0.05	28.59	0.10
	UN	23	1.00	0.07	0.27	0.06	27.39	0.15
B	**MP**	23	1.01	0.03	0.17	0.04	17.20	0.09
	VC	29	1.03	0.10	0.32	0.06	31.28	0.12
	UN	23	1.00	0.08	0.29	0.06	28.73	0.15
H	**MP**	30	1.01	0.03	0.17	0.03	16.61	0.07
	VC	39	1.01	0.03	0.18	0.03	17.80	0.07
	UN	33	1.00	0.06	0.23	0.04	23.38	0.09
V	**MP**	23	1.01	0.01	0.11	0.02	10.35	0.06
	VC	31	1.02	0.03	0.17	0.03	17.19	0.08
	UN	23	1.00	0.01	0.09	0.02	8.90	0.09



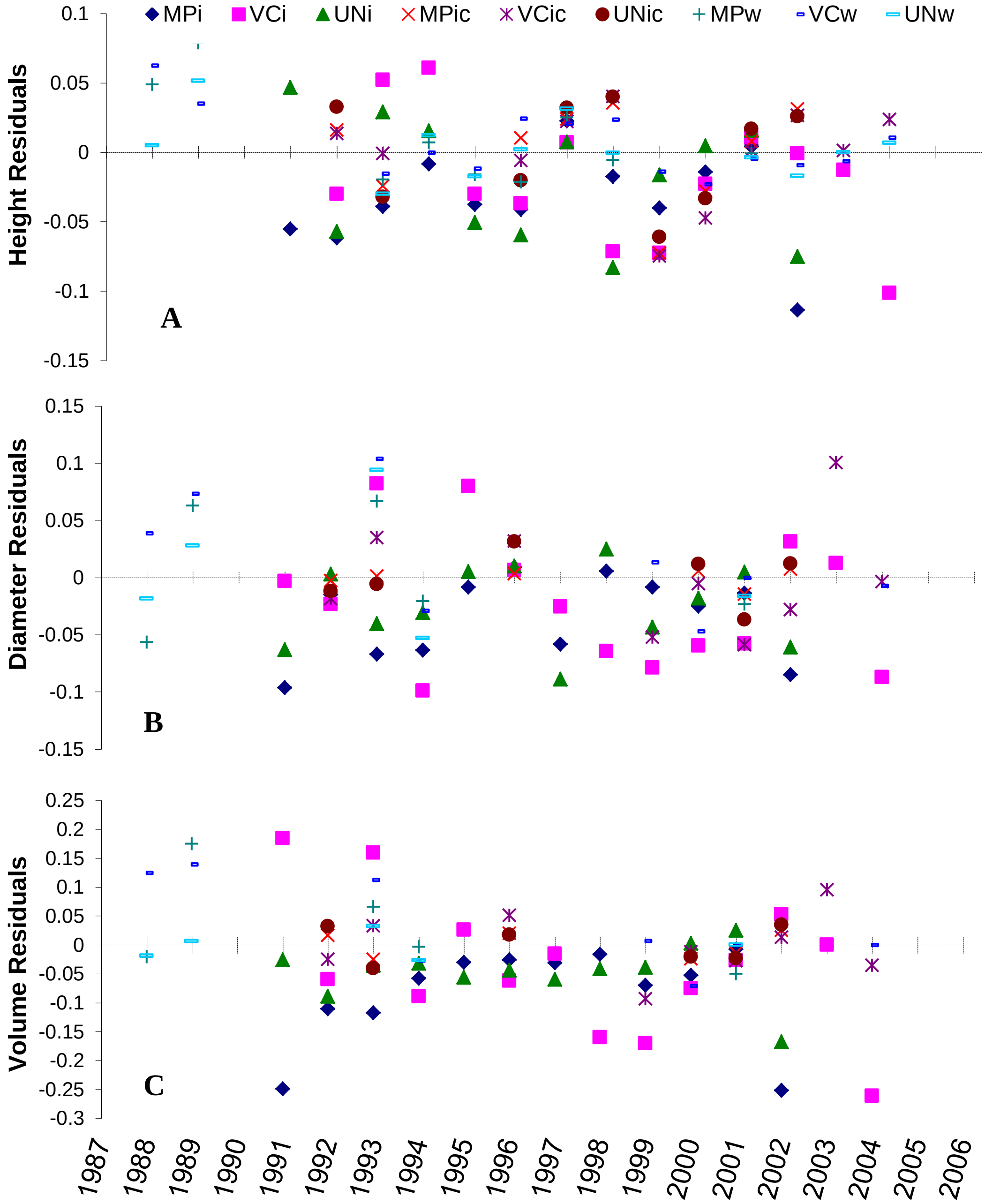
Lodgepole pine averaged relative growth indexes (RGI) such as height (A), diameter (B), and volume (C) for mechanical preparation (MP), vegetation control (VC), and untreated (UN) over the period 1987-2006.



White spruce averaged relative growth indexes (RGI) such as height (A), diameter (B), and volume (C) for mechanical preparation (MP), vegetation control (VC), and untreated (UN) over the period 1987-2006.



Lodgepole pine residuals of observed relative growth minus predicted relative growth for height (A), diameter (B), and volume (C) for mechanical preparation (MP), vegetation control (VC), and untreated (UN); for Tanli '-t' and Bednesti '-b' over the period 1987-2006.



White spruce residuals of observed relative growth minus predicted relative growth for height (A), diameter (B), and volume (C) for mechanical preparation (MP), vegetation control (VC), and untreated (UN); for Inga Lake ‘-i’, Iron Creek ‘-ic’, and Wonowon ‘-w’ over the period 1987-2006.

Appendix 3.

Growth Index Analysis

For lodgepole pine the number of observations ranges from 21 to 30 with an average value of 26, and the growth index values range from 0.99 to 1.03 with an average value of 1.00 (Table A and Figure A). For white spruce the number of observations ranges from 21 to 39 where the average value is 27; and the growth index values range from 0.97 to 1.03 with an average across the growth indexes of 1.00 (Table B and Figure B).

For every treatment (i.e.: MP, VC, and UN) residuals of observed growth minus predicted growth (i.e.: height, diameter, and volume) were calculated over the studied period (1987-2006) at each trial and plotted against age (x); and results are presented for lodgepole pine and white spruce in Figures C and D respectively.

Table A. Statistical information on lodgepole pine growth index such as diameter (D), basal area (B), height (H), and volume (V) by treatment: mechanical preparation (MP), vegetation control (VC), and untreated (UN).

Growth Index	Treatment	Number of Obs.	Mean	Variance	Standard Deviation	Standard Error	Coeff. of Variation	95% Conf. Interval (+/-)
D	**MP**	25	1.00	0.03	0.17	0.03	17.34	0.07
	VC	21	1.00	0.02	0.13	0.03	13.19	0.06
	UN	29	1.00	0.03	0.19	0.03	18.65	0.07
B	**MP**	23	1.01	0.05	0.21	0.04	21.31	0.09
	VC	19	0.99	0.02	0.14	0.03	14.45	0.06
	UN	27	1.01	0.05	0.22	0.04	21.39	0.08
H	**MP**	26	1.00	0.01	0.11	0.02	11.45	0.04
	VC	22	1.00	0.02	0.14	0.03	14.43	0.06
	UN	30	1.00	0.02	0.13	0.02	13.34	0.05
V	**MP**	24	1.00	0.02	0.12	0.03	12.45	0.05
	VC	21	1.03	0.04	0.19	0.04	18.58	0.08
	UN	28	1.01	0.02	0.14	0.03	13.61	0.05

Table B. Statistical information on white spruce growth index such as diameter (D), basal area (B), height (H), and volume (V) by treatment: mechanical preparation (MP), vegetation control (VC), and untreated (UN).

Growth Index	Treatment	Number of Obs.	Mean	Variance	Standard Deviation	Standard Error	Coeff. of Variation	95% Conf. Interval (+/-)
D	**MP**	23	0.99	0.02	0.13	0.03	13.21	0.05
	VC	31	1.03	0.06	0.24	0.04	23.53	0.09
	UN	23	1.00	0.07	0.27	0.06	26.85	0.11
B	**MP**	21	0.98	0.02	0.13	0.03	13.27	0.06
	VC	26	1.03	0.11	0.34	0.07	32.69	0.13
	UN	21	0.97	0.09	0.29	0.06	30.34	0.13
H	**MP**	30	1.01	0.02	0.15	0.03	15.38	0.06
	VC	39	1.00	0.03	0.17	0.03	17.17	0.05
	UN	33	1.00	0.05	0.22	0.04	22.29	0.08
V	**MP**	23	1.01	0.01	0.07	0.02	7.43	0.03
	VC	29	1.02	0.04	0.21	0.04	20.56	0.08
	UN	23	1.00	0.01	0.12	0.02	11.50	0.05

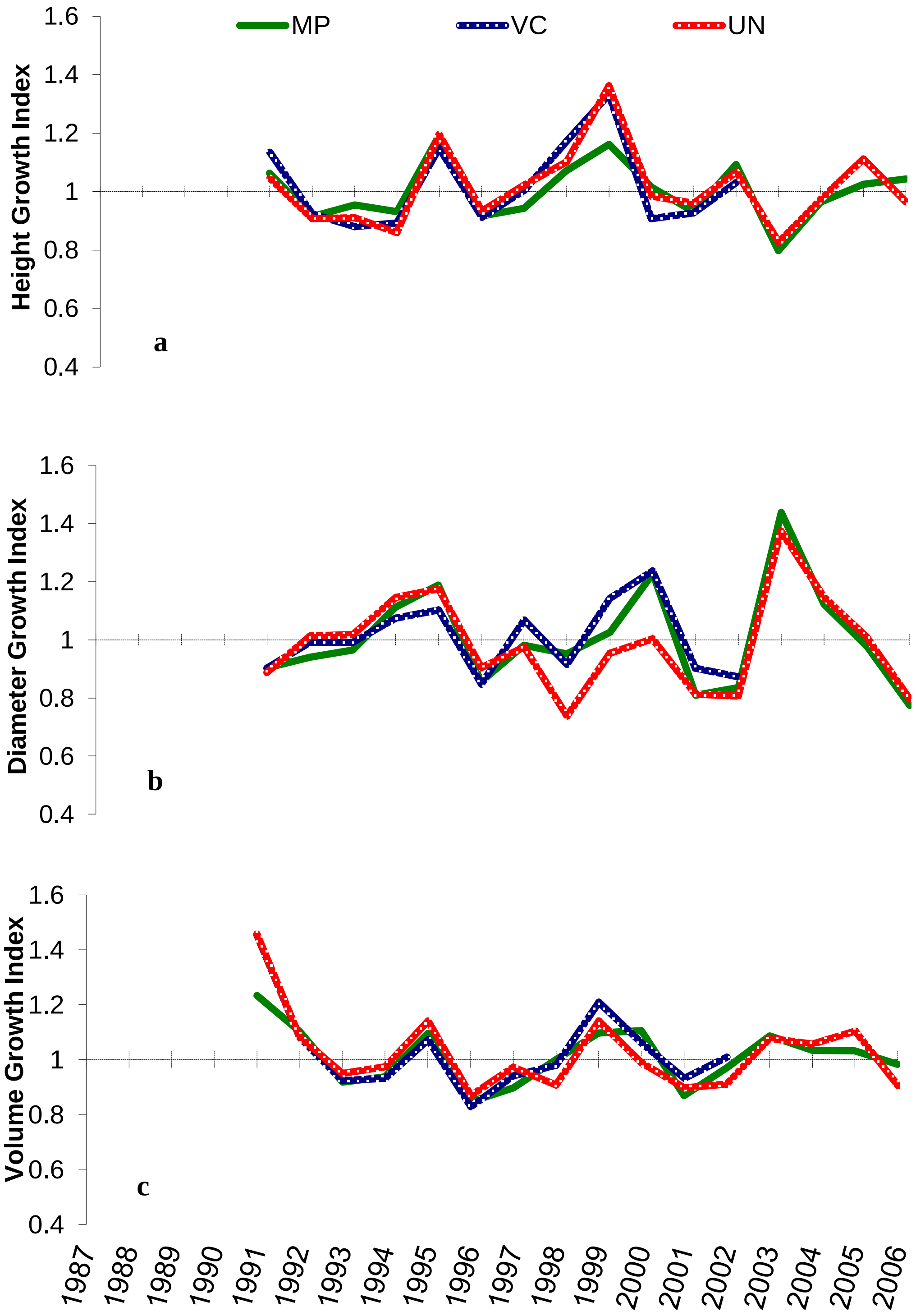


Figure A. Lodgepole pine averaged growth indexes such as height (a), diameter (b), and volume (c) for mechanical preparation (MP), vegetation control (VC), and untreated (UN) over the period 1987-2006.

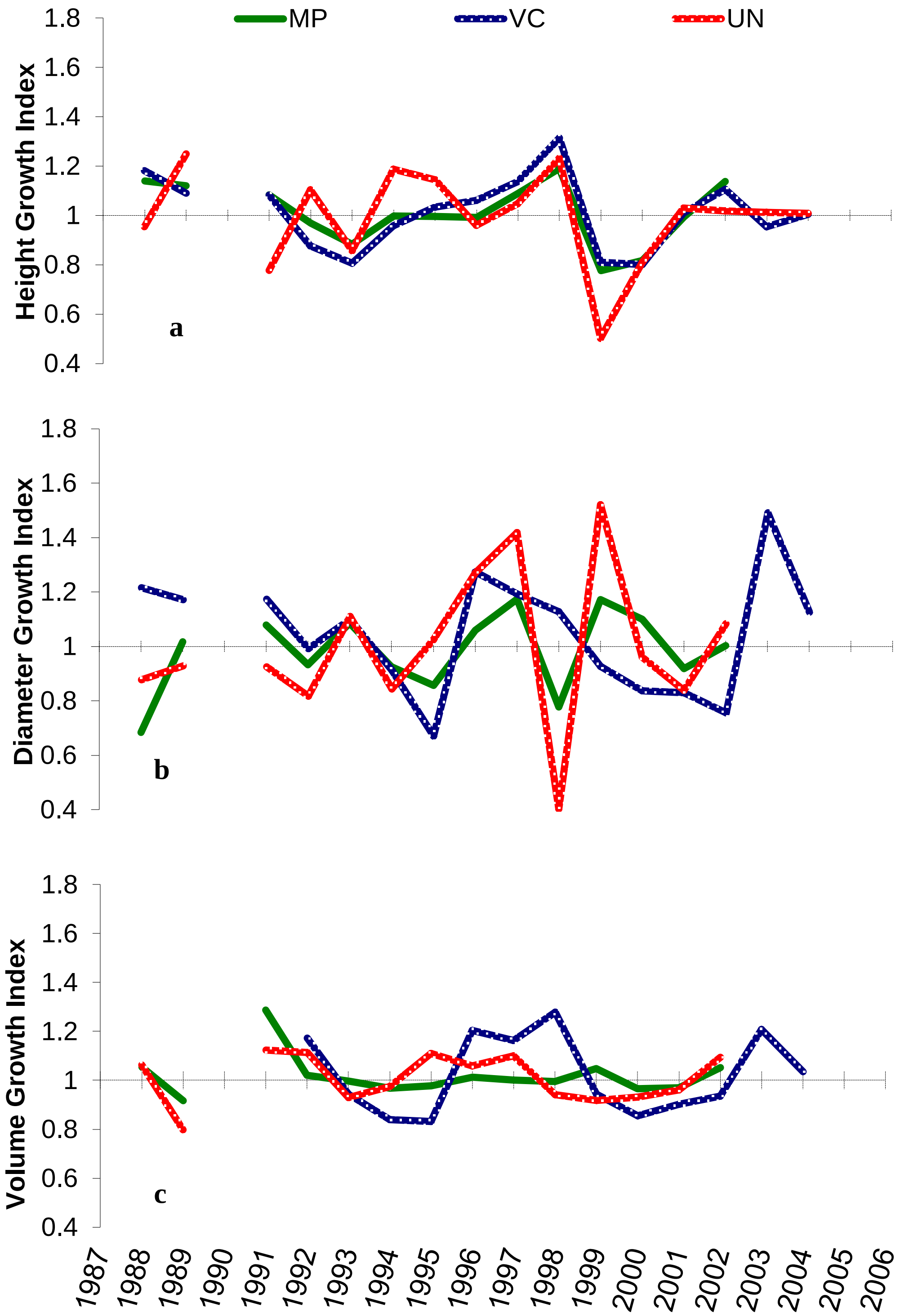


Figure B. White spruce averaged growth indexes such as height (a), diameter (b), and volume (c) for mechanical preparation (MP), vegetation control (VC), and untreated (UN) over the period 1987-2006.

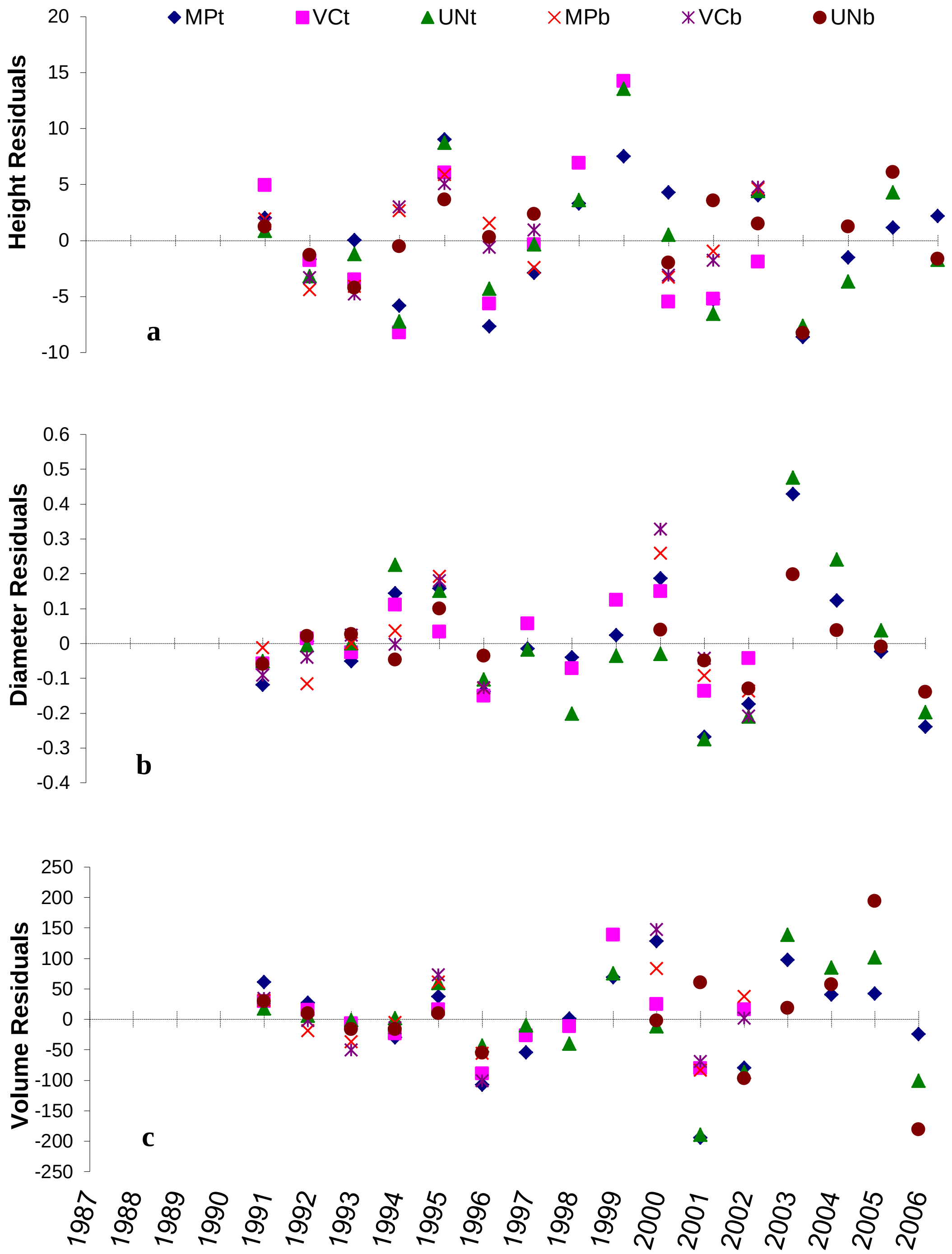


Figure C. Lodgepole pine residuals of observed growth minus predicted growth for height (a), diameter (b), and volume (c) for mechanical preparation (MP), vegetation control (VC), and untreated (UN); for Tanli '-t' and Bednesti '-b' over the period 1987-2006.

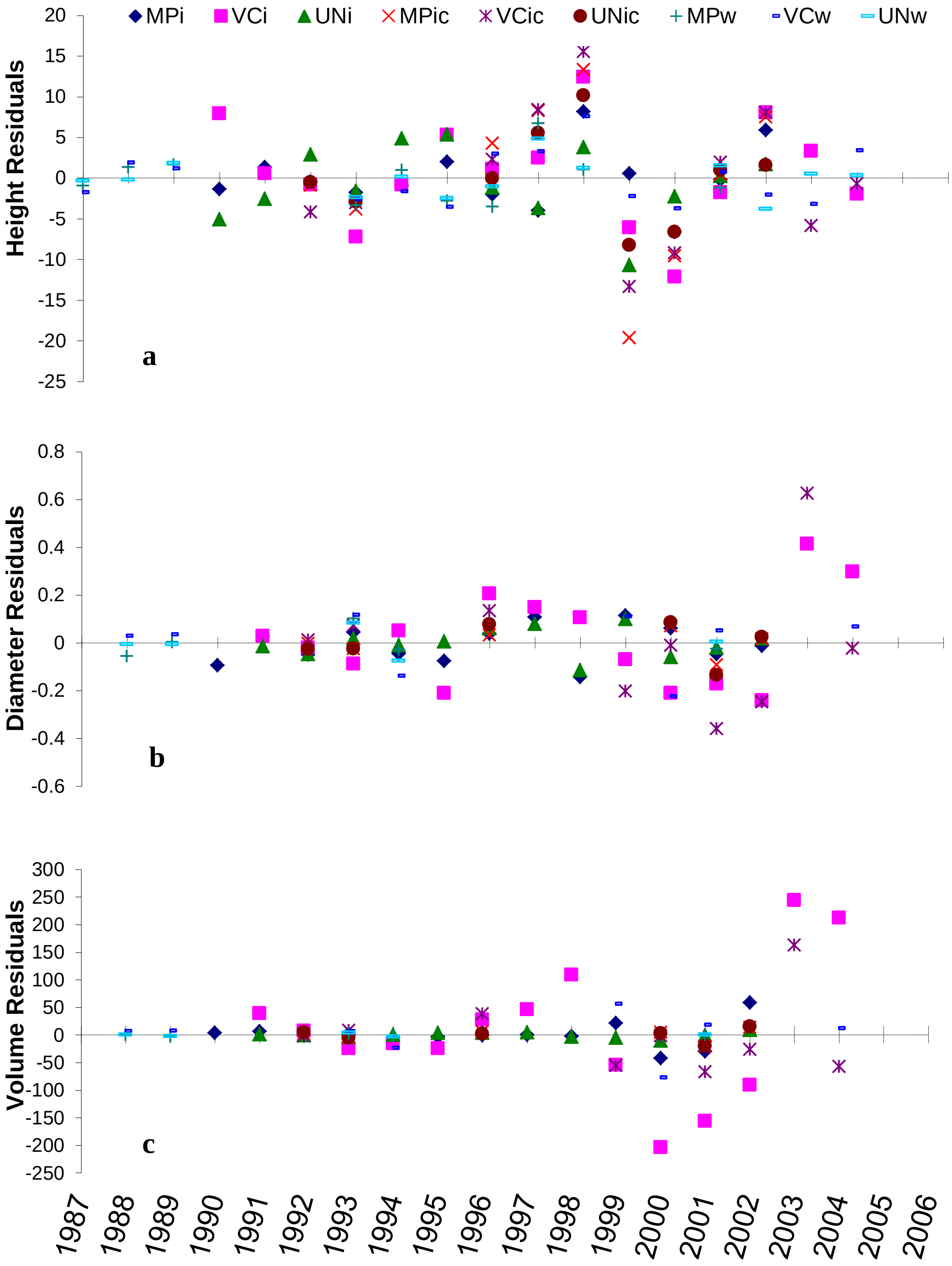
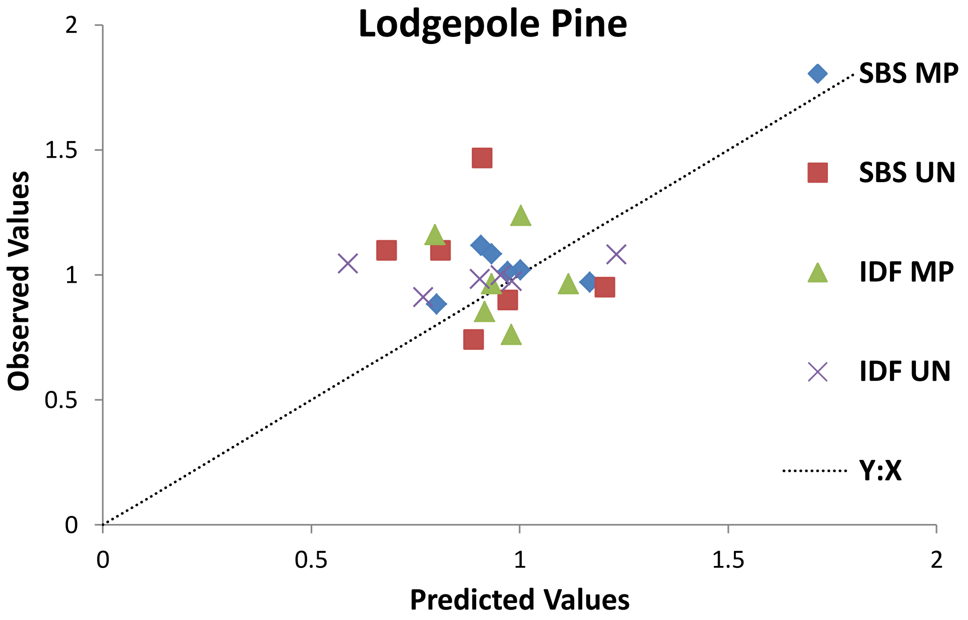
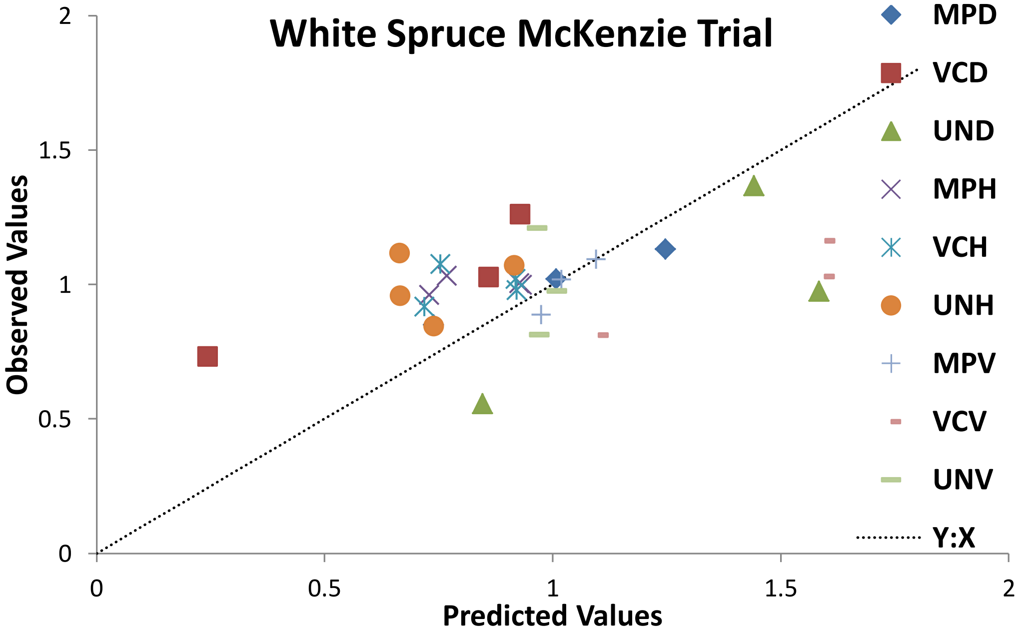


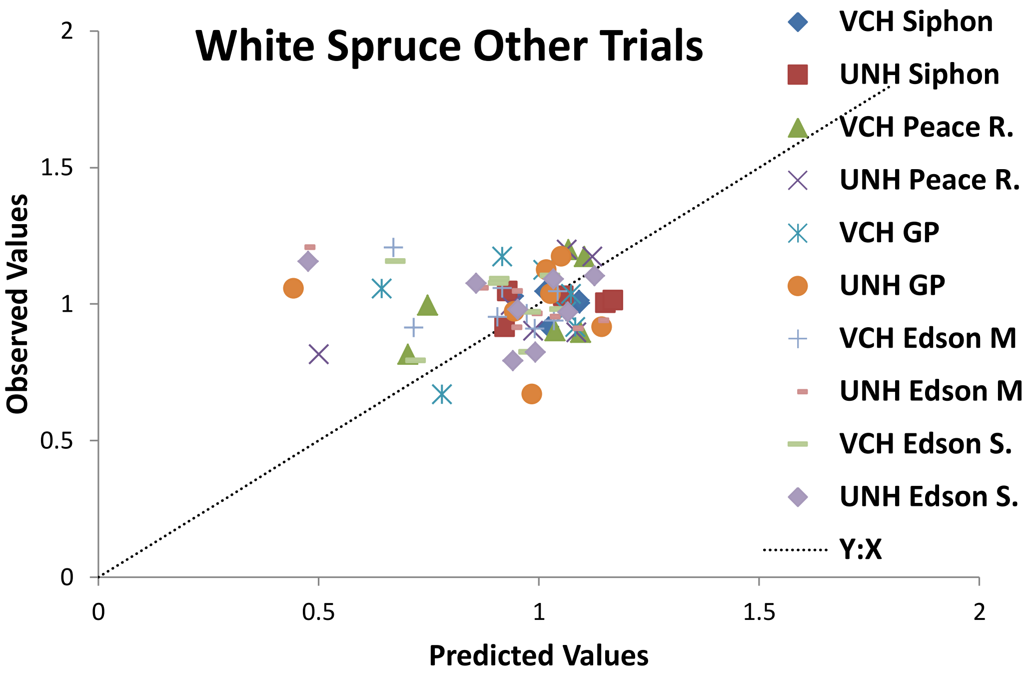
Figure D. White spruce residuals of observed growth minus predicted growth for height (a), diameter (b), and volume (c) for mechanical preparation (MP), vegetation control (VC), and untreated (UN); for Inga Lake '-i', Iron Creek '-ic', and Wonowon '-w' over the period 1987-2006.

APPENDIX 4.

Validation Analysis – Observed versus Predicted values

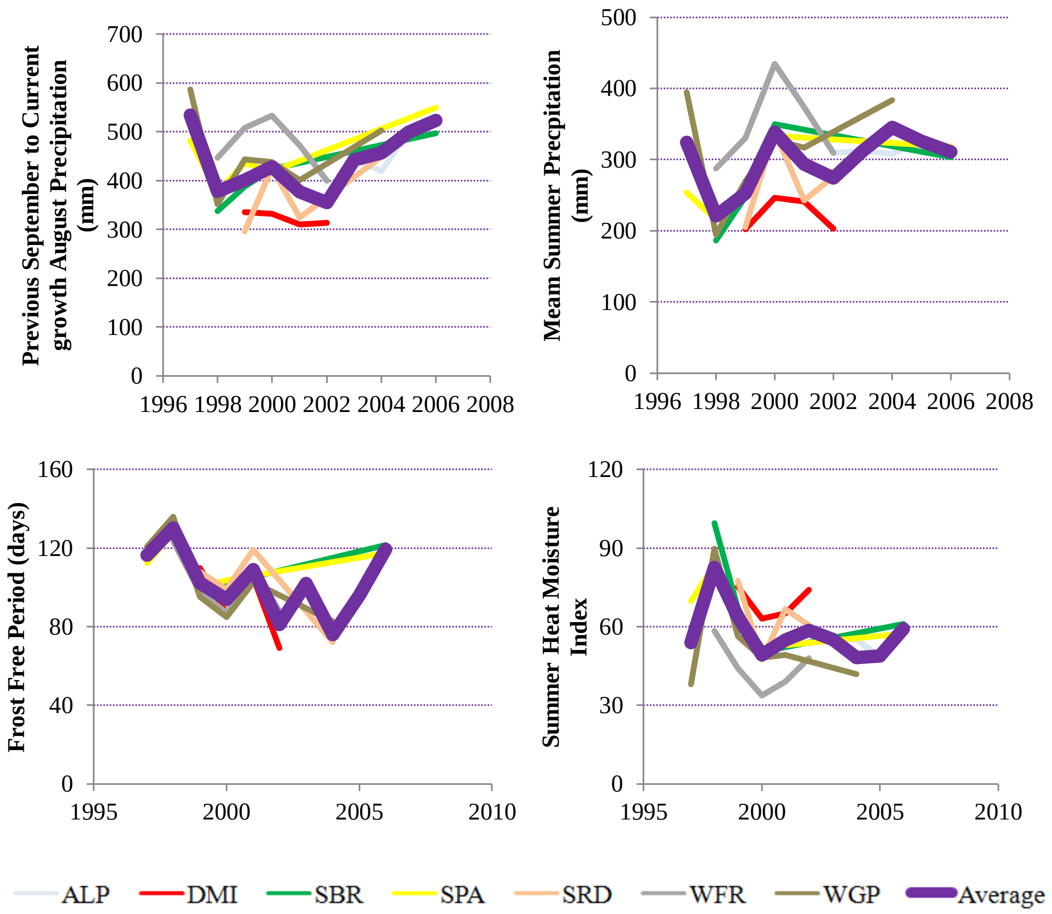




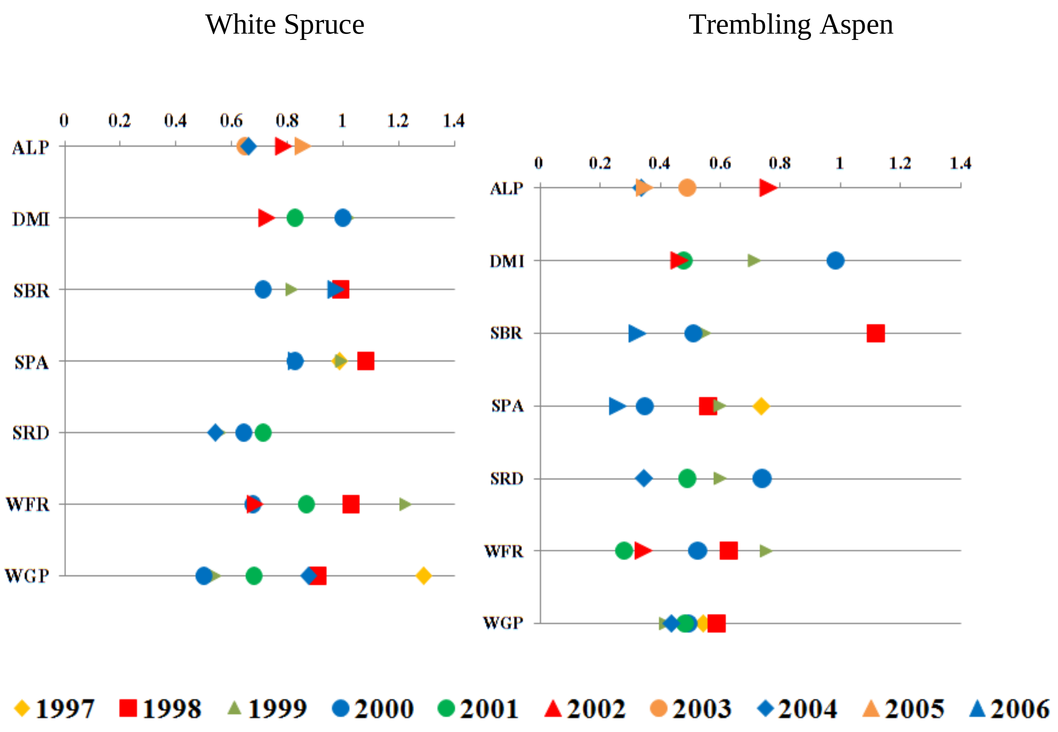

White Spruce Other Trials
Observed Values
Predicted Values
2
1.5
1
0.5
0
0
0.5
1
1.5
2
VCH Siphon
UNH Siphon
VCH Peace R.
UNH Peace R.
VCH GP
UNH GP
VCH Edson M
UNH Edson M
VCH Edson S.
UNH Edson S.
Y:X

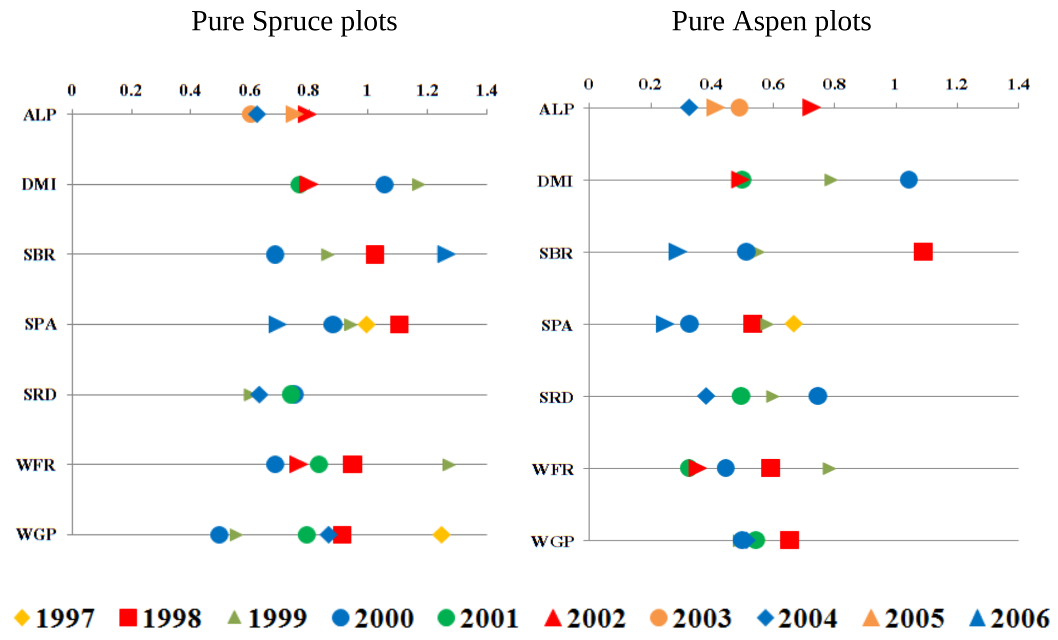
APPENDIX 5.

Climate Information and Relative Volume Growth of the WESBOGY sites

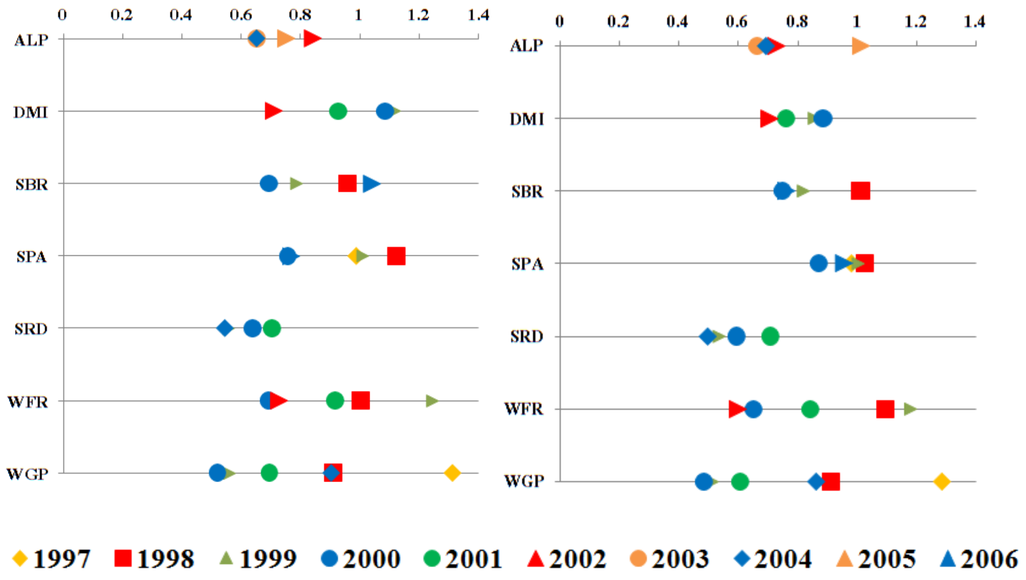


Study level average of Relative Volume Growth:



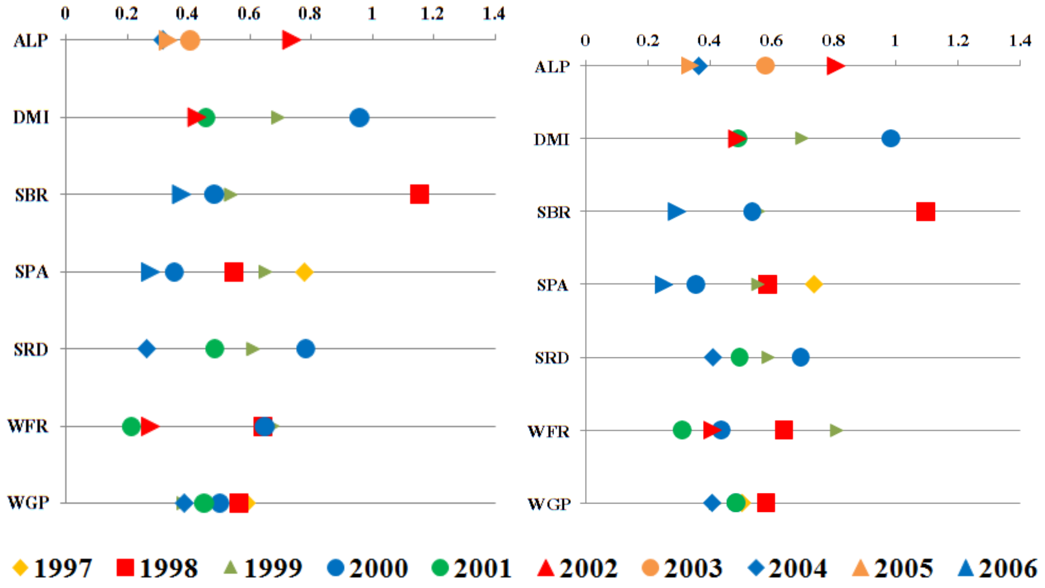


White Spruce Relative Volume Growth:


Low Density Mix plots

High Density Mix plots

Trembling Aspen Relative Volume Growth:


Low Density Mix plots

High Density Mix plots