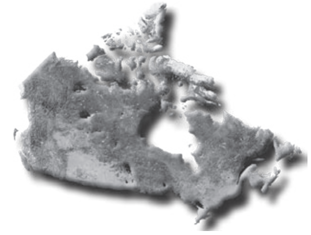

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Mountain Pine Beetle
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Abstract

Under the federal Mountain Pine Beetle Program, research is being implemented to study the economic and ecological characteristics of mountain pine beetle-damaged stands in British Columbia and Alberta. Stand development projections following beetle attack will depend upon the ability to accurately project natural regeneration following attack. In this study, stand structure measured on affected stands shortly after attack was used to estimate the abundance and composition of natural regeneration a number of years following attack. Based on plot data previously gathered by the Canadian Forestry Service and additional data gathered under separate BC Forest Science Program funding, the average amount of regeneration per hectare was quite high, and included predominantly pine and deciduous species, with few other conifers. Only three of the 326 plots had no regeneration. Fourteen overstorey variables were selected for estimating regeneration by species and size classes using multivariate nearest-neighbour imputation: elevation; stems and basal area per hectare for all live trees by three species groups; crown competition factor and quadratic mean diameter (QMD) for all live trees; stems per hectare, basal area per hectare, and QMD for pine snags; years since disturbance; and site series. There was wide variability in estimated versus observed regeneration at the plot level. However, the average estimated regeneration by species and size class was very similar to the average measured regeneration, except within the smallest size class. A prototype to incorporate this estimation procedure into Prognosis^{BC} was developed to project stands following beetle attack, using overstorey measures shortly after attack.

Keywords: natural regeneration; mountain pine beetle disturbance; stand dynamics modeling; multivariate imputation; Prognosis^{BC}

Résumé

Dans le cadre du Programme sur le dendroctone du pin ponderosa du gouvernement fédéral, des recherches sont entreprises pour étudier les caractéristiques économiques et écologiques des peuplements ravagés par le dendroctone du pin ponderosa en Colombie-Britannique et en Alberta. Les projections de développement des peuplements suite à l'attaque du dendroctone dépendront de la capacité de prévoir avec exactitude la régénération naturelle après l'infestation. Dans la présente étude, la structure du peuplement mesurée sur les peuplements touchés peu de temps après l'attaque a été utilisée pour estimer l'abondance et la composition de la régénération naturelle plusieurs années après l'attaque. Selon les données des parcelles d'essai recueillies auparavant par le Service canadien des forêts et d'autres données obtenues dans le cadre du financement distinct du programme des sciences forestières de la C.-B., la quantité moyenne de régénération moyenne par hectare était plutôt élevée et comprenait principalement du pin et des espèces à feuilles caduques, ainsi que quelques autres conifères. Seulement trois des 326 parcelles d'essai ne comportaient aucune régénération. Quatorze variables d'étage dominant ont été choisies pour estimer la régénération selon les espèces et les catégories de taille au moyen de l'imputation multivariée des plus proches voisins: altitude; faux-troncs et surface terrière par hectare pour tous les arbres verts selon trois groupes spécifiques; facteur de concurrence des cimes et diamètre de la tige de surface terrière moyenne pour tous les arbres verts; faux-troncs par hectare, surface terrière par hectare, et diamètre de la tige de surface terrière moyenne pour les chicots de pin; nombre d'années depuis la perturbation; et séries de sites. Il y avait une grande variabilité dans la régénération estimée par rapport à la régénération observée dans les parcelles. Cependant, la régénération estimée moyenne par espèce et catégorie de grosseur était très semblable à la régénération mesurée moyenne. Un prototype visant à intégrer cette procédure d'estimation dans Prognosis^{BC} a été mis au point pour faire des projections de peuplements à la suite d'une attaque du dendroctone, à l'aide de mesures de l'étage dominant peu de temps après une attaque.

Mots-clés : régénération naturelle; perturbation du dendroctone du pin ponderosa; modélisation de la dynamique des peuplements; imputation à plusieurs variables; Prognosis^{BC}

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1 Introduction

The current infestation of lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) trees by mountain pine beetle (*Dendroctonus ponderosae*) (MPB) has been estimated to have affected over 7 million hectares in British Columbia (BC). Recent favourable weather conditions and abundance of mature pine stands have provided ideal conditions for quick and extensive spread of the beetle. Provincial and federal programs have been initiated to address the epidemic. Despite increases in cutting over the next few years, some MPB-affected areas may not be harvested and planted in time to salvage dead standing timber. Future management of MPB-affected forests, particularly large areas of standing dead timber, will depend greatly on our ability to project stand development over long time horizons. The accuracy of these stand development projections will depend on our ability to predict natural regeneration following MPB disturbances. These projections will provide the information needed to evaluate long-term effects of MPB disturbances on stand structure, habitat availability, fuel management and timber production.

To project stands following MPB attack, trees could be measured shortly after attack and then projected forward in time using a growth simulator such as Prognosis^{BC}. Regeneration would then occur depending upon light, water, and nutrient resources, and available seed source. One logical way of adding regeneration is to incrementally add it at each projection cycle. An existing model, SORTIE-ND (e.g., Kobe and Coates 1997; Wright et al. 1998), was tested in the first year of this project as a possible means of obtaining dynamic estimates of regeneration to add to Prognosis^{BC}. Results of this initial testing can be found in LeMay et.al., 2006, Section 4). However, this method requires detailed information on recruitment and survival. Another approach is to introduce regeneration and saplings at a fixed point in the future, when all responses to the disturbance have occurred. Since a number of species and sizes can be present in this list of regenerated trees, including saplings, the challenge becomes estimating these species and sizes simultaneously. A multivariate estimation approach can be used to obtain logical consistency across species and size classes. The focus of this research is the use of this second approach to estimate regeneration including saplings following MPB attack.

1.1 Objectives and Outcomes

The main objective of this research project was to use existing data to quantify and model the abundance and composition of natural regeneration (including saplings) in MPB-affected stands. Specific objectives were:

1. to assess natural regeneration development in stands that have sustained mortality during current and/or previous MPB outbreaks;
2. to develop a natural regeneration database for use in connection with the Prognosis^{BC} growth and yield simulator;
3. to use imputation techniques to extend the existing natural regeneration model to MPB-affected stands in the southern and central interior of the province; and
4. to develop and enhance the software necessary to allow reasonable projections of MPB-affected stands.

Data collected by the Canadian Forest Service (CFS data) along with data collected by the University of British Columbia (UBC) research team under separate funding (FSP data collected in the summer 2006) from three Biogeoclimatic Ecosystem Classification (BEC) zones in central BC were used in this project. The CFS data consisted of overstorey and understory trees in plots measured shortly after attack and again 14 years later. The FSP data were collected in stands that had been attacked by MPB a number of years ago (approximately 25 years ago for most of the plots). For these stands, overstorey conditions shortly after MPB attack were reconstructed based on the current condition of standing and fallen dead tress, and a reverse diameter growth model. Expected stand conditions and dynamics shortly after attack served to guide the reconstruction process. The FSP and CFS data were pooled to provide an overstorey tree-list shortly after MPB attack, coupled with regeneration (understory trees) a number of years after the attack.

Other datasets provided through the Mountain Pine Beetle Initiative included measurements recorded at a single point in time following MPB attack. However, there was insufficient detail to reconstruct the overstorey, as was done with the FSP data. Consequently, these other datasets were not used in this project.

The specific outcomes of this research project were:

1. A combined FSP plus CFS dataset was constructed, which coupled information on overstorey trees shortly after attack with measures of regeneration a number of years after attack. The existing regeneration database is housed by ESSA Technologies, Ltd., the firm that is under contract to maintain and modify Prognosis^{BC}. The format of this database was modified to include these new data for MPB-attacked stands. The combined data were transferred to ESSA for storage and use. As noted earlier, no other datasets were included in this database, as the information needed to reconstruct the overstorey shortly after the MPB attack was not available.
2. The amount and type of regeneration following MPB attack was assessed initially using the repeated measures CFS data only, and then again using the combined CFS plus FSP dataset, once the FSP data became available.
3. The overstorey measures were then used to estimate regeneration following attack using multivariate nearest neighbour imputation methods. The overstorey measures to be used in the imputation of regeneration were tested using the CFS data alone. Selected variables were then used to evaluate the results of regeneration imputation using the combined CFS plus FSP dataset once the FSP data become available.
4. The data and multivariate imputation model were then incorporated into the Prognosis^{BC} model for testing by ESSA Technologies, Ltd.

1.2 Background

1.2.1 The Extent of Mountain Pine Beetle Attack in BC

Mountain pine beetle has long been recognized as a destructive insect of mature pine forests in western North America (Wood 1963). The species is native to more than 30 million hectares of habitat of which lodgepole pine is a significant component (Wood and Unger 1996). Pine forests cover some 14 million hectares of forest land in BC (BC Ministry of Forests 1995). Of the five species of pine occurring in the province, lodgepole pine is by far the most abundant by area (Taylor and Carroll 2004). Lodgepole pine stands are almost entirely of fire origin. Following crown fires where the majority of trees are killed, virtually even-aged pine stands are usually re-established after a few years (Taylor and Carroll 2004). The frequency of such stand-replacement fires varies widely; based on an analysis of inventory data, Smith (1981) suggested that the average fire cycle in lodgepole pine forests in BC was about 60 years.

Mountain pine beetle was first recognized as a problem in the early 1900s when it came into direct competition with the forest industry and recreational land owners (Wood and Unger 1996). In BC, reports of MPB outbreaks and tree mortality have been documented since 1910. These reports were compiled and summarized by Wood and Unger (1996), with recent updates by Taylor and Carroll (2004) and Ebata (2004). Between 1960 and 1996, annual losses due to MPB infestation averaged 7.8 million trees, with a peak in 1983 when 80.4 million trees were killed (Wood and Unger 1996). Table 1.1 provides a summary of the number of trees killed by MPB in BC up to 1995.

Table 1.1 Number of trees killed by MPB in BC up to 1995 *(adapted from Wood and Unger 1996)*.

Period	Number of trees killed
Pre-1950	251,970,000
1951-1960	3,950,209
1961-1970	718,232
1971-1980	24,362,910
1981-1990	228,318,764
1991-1995	19,440,256

Historically in BC, MPB infested an average of 50,000 ha annually in the endemic stage and more than 450,000 ha per year during epidemics (Wood and Unger 1996). In recent years, areas infested by the MPB have increased considerably, thereby making the issue a major concern in the forestry sector (Allen 2004; Gibson 2004; Stockdale et al. 2004). BC Ministry of Forests (2001) reported that the current epidemic of MPB was affecting more than 600,000 ha per year. This trend continued to rise such that in 2003, approximately 4 million hectares in the province were infested by MPB (Ebata 2004). In response to the threat posed by the recent epidemic, a number of studies are being conducted to provide a better understanding of the problem. Among other things, these studies are designed to provide information needed to develop strategies for using the wood from attacked trees, estimating impacts, preventing future infestations, and promoting stand recovery.

1.2.2 The Ecological Characteristics of Mountain Pine Beetle

Mountain pine beetles attack and kill mostly large diameter lodgepole pine trees (Cole and Amman 1969; Amman 1977). The attacks are initiated by the female, which bores into the bark of a tree. Upon successful penetration, the female beetle burrows a characteristic gallery between the bark and the wood, where she lays her eggs. Her burrowing introduces into the conducting sapwood inoculums from various fungi, which she carries in a mycangial pouch (Waring and Pitman 1985). The fungi spread across the sapwood and eventually halt water transport through the stem. The female beetle also releases trans-verbenol through a chemically mediated synergistic reaction with host chemicals (Bentz et al. 1996). Trans-verbenol is an aggregative pheromone that attracts MPB of both sexes (Pitman 1971; Hughes 1973). Through this method of chemical communication, massive aggregation of MPB occurs on the affected tree. Because a single host tree offers limited food and breeding resources, MPB populations have evolved a mechanism for termination of colonization on a tree at optimal beetle densities, with a concomitant switch of attacks to nearby trees (Bentz et al. 1996). Attack densities are normally higher on trees with rough bark, as female beetles prefer to initiate galleries in bark crevices (Safranyik and Vithayasai 1971). Similarly, trees with thick bark tend to produce a larger brood than thin-bark trees due to the protection they provide from natural enemies of MPB and temperature extremes (Reid 1963).

Although MPB are known to be very destructive when present in epidemic proportions, they can also play very important ecological roles in pine forests. Endemic populations of MPB could function alternately as cybernetic regulators to channel the flow of energy, nutrients and water to better adapted species (Mattson and Addy 1975). They also act as biological thinning agents, attacking large older trees, creating openings for regeneration, and contributing fuel for eventual stand replacing fires (Anhold et al. 1996). Waring and Pitman (1985) also reported that any reduction in the canopy (following MPB attack) will permit more solar radiation and precipitation to penetrate to the ground, stimulating decomposition, mineralization, and proliferation of ground flora. This was supported by Kovacic et al. (1985) who observed that a peak in understory biomass was reached by 5 years following MPB infestation while levels of wildlife forage remained elevated above pre-infestation levels for 10 – 15 years.

Schmidt et al. (1980) examined the vertical distribution of MPB at three levels above ground in both thinned and unthinned stands of lodgepole pine in Montana and Wyoming, USA. The results of their study showed that the MPB population was highest at the mid-bole area and lowest at the mid-crown. Similar results were given by Avis (1971) who observed that most MPB fly within 2.4 m to 4.9 m above ground, and that attack densities decrease with increasing height of the bole. One reason for the abundance of MPB at the mid-bole layer could be that most of the beetles adjusted their flight height to select the stratum with the fewest physical barriers within a stand environment (Schönherr 1976). Schmidt et al. (1980) reported that unthinned stands appeared to have slightly higher frequencies of MPB attack than thinned stands, although the differences were not significant.

For an MPB outbreak to develop, two requirements must be satisfied (Safranyik 1978). The first requirement is a period of favourable weather sustained over several years, including summer heat accumulations and higher winter minimum temperatures. In areas where summer heat accumulation is limited or where winter minimum temperatures are below a critical threshold, MPB infestations cannot establish nor persist (Carroll and Safranyik 2004). The second requirement is abundance of susceptible host trees. These are mainly large-diameter pine trees whose phloem tissues are thicker, thereby providing an optimal resource for the development of MPB larvae (Shore and Safranyik 1992). Wilson (2004) observed that the current outbreak of MPB in BC can be attributed to two principal reasons, namely:

1. effective fire control measures which have helped to retain a large stock of mature lodgepole pine trees; and
2. reduced frequency in cold temperature events required to knock back MPB populations to endemic or incipient levels.

1.2.3 Mountain Pine Beetle Attack and Stand Dynamics

Forest stand dynamics are the composite of mortality, regeneration and growth processes (Hawkes et al. 2004). Disturbances such as MPB attack or forest fires can change the structure of forests. Since MPB more commonly attack large diameter pine trees, the diameter distribution, stems per ha and species composition are altered. A number of studies have been conducted to examine effects of stand management on MPB attacks, and, conversely, the effects of MPB attacks on stand structure and dynamics.

Amman et al. (1988) tested the effectiveness of partial cutting as a possible means of reducing losses to MPB in the Shoshone National Forest, Wyoming, USA. The treatments were: 1) removal of all trees ≥ 17.8 cm (7 inches) DBH (diameter at breast height); 2) removal of all trees ≥ 25.4 cm (10 inches) DBH; 3) removal of all trees ≥ 30.5 cm (12 inches) DBH; 4) spacing of trees to retain about 50 of the best trees; or 5) no cutting (i.e., control). Their results indicated that tree losses to MPB were significantly greater in the control plots than in the partially cut plots. However, tree mortality did not differ significantly among the partial cutting treatments, although the general trend was for greater losses where cutting was less. Regeneration 5 years after thinning ranged between 2,866 and 8,796 seedlings per hectare. While pine species were generally more abundant in the more open stands, the more shade-tolerant conifers (interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), subalpine fir (*Abies lasiocarpa* (Hook) Nutt.) and spruce (*Picea* spp. (A. Dietr.)) were more abundant in control plots and in plots where only large trees ≥ 30.5 cm DBH were removed.

Another study to investigate the effects of MPB attacks on stand dynamics was carried out by Heath and Alfaro (1990). They examined the growth response of residual trees in a Douglas-fir/lodgepole pine stand after thinning of lodgepole pine by MPB in the Cariboo Forest Region of BC. They observed that the beetles killed mainly the large diameter lodgepole pine trees in the stand, and therefore described this as a type of thinning from above. Their study showed that even though 76% of the lodgepole pine trees were killed during the MPB outbreak in the study area, all the Douglas-fir and a large proportion of the remaining lodgepole pine trees responded to the MPB-induced thinning with a diameter growth increase which persisted 14 years after the infestation. Annual diameter growth rates of Douglas-fir in the post-outbreak period averaged 2% per year without the beetle-induced thinning and 2.9% following thinning. For the surviving lodgepole pine trees, the annual diameter growth rates doubled from 0.4% per year without thinning, to 0.8% per year following thinning. Their results agreed with those of Cole and Amman (1980) who detected growth acceleration in lodgepole pine after each of several beetle infestations.

Hawkes et al. (2004) conducted a three-year study to examine the impact of MPB on stand dynamics in BC. Pine stands in the Chilcotin Plateau, Kamloops and Nelson Forest Regions, Entiako Protected Area, Manning Provincial Park, Kootenay National Park, and Bull Mountain were sampled. Selected stands were dominated by lodgepole pine, mixed with interior Douglas-fir, spruce, and other species. Data were gathered from direct field measurement and PSP (permanent sample plot) records. Increment cores were also collected in the plots and ring-width measurement was done in order to construct chronologies. Their results indicated that post-outbreak standing live tree volume and density were reduced by 22% and 36% respectively, although there was significant variation due to differences in stand structure. They also observed that the effects of MPB on forest stand dynamics were similar to that of defoliating insects. Defoliating insects are known to improve the growing environment of surviving trees following an epidemic attack (Mattson and Addy 1975; Wickman 1978) since more resources become available to fewer trees. For example, mortality of lodgepole pine after an MPB epidemic permits the accelerated growth of small Douglas-fir and spruce trees or seedlings (Hawkes, et al. 2004). This pattern of succession indicates a shift towards shade-tolerant species over a long period of time. A similar pattern was reported by Veblen (1998) following wind-thrown lodgepole pine-dominated stands in Colorado, USA. The accelerated growth observed in stands following MPB attack contrasts with disturbance by high intensity fires where very few trees survive, leading to complete or nearly complete stand renewal.

Several methods have been used to combat MPB outbreak. Common management strategies are:

1. salvaging beetle-killed trees;
2. manipulating the stand structure to increase tree vigour and increase the ability of trees to repel attacking beetles with copious resin flow (Reid et al. 1967); or
3. using partial cutting to create a mosaic of different age and size classes, breaking up the continuity of large diameter pine trees and reducing the possibility of an MPB epidemic (Cole and Amman 1980; Samman and Logan 2000).

Other methods have been attempted as well. For example, chemicals such as ethylene dibromide in diesel oil (EDB) can be sprayed on infested tree trunks to kill beetles beneath the bark (Amman and Baker 1972). However, use of these chemicals for large outbreaks over a large land area is very expensive and often ineffective.

1.2.4 Regeneration after Mountain Pine Beetle Attack

Germination and growth of lodgepole pine is promoted via fire disturbance (Lotan et al. 1985; Stone and Wolfe 1996). Regeneration of lodgepole pine following MPB attack is possible, since seeds remain viable for a long period of time.

Following a MPB outbreak, needles of affected trees change in colour from green to red and yellow, and then trees begin to lose their branches, starting with smaller branches, as they dry out and become fragile (Hawkes et al. 2002). Eventually, each dead tree falls to the ground and decomposition sets in. Dead pine trees usually remain standing for some time, unless there are heavy storms resulting in windthrow. In thinned stands, Mitchell and Preisler (1998) noted that it took up to 3 years after MPB attack before dead pine trees began to fall, 50% of dead trees had fallen after 8 years, and 90% trees had fallen after 12 years. In unthinned stands, the process was slightly slower, with some dead trees falling after 5 years, 50% of dead trees falling within 9 years, and 90% falling within 14 years (Mitchell and Preisler, 1998). In general, the time to fall-down depended on local environmental factors.

A number of studies have examined understory vegetation following MPB attack. Kovacic et al. (1985) studied understory biomass in ponderosa pine after MPB attack. They reported that mortality of trees following MPB attack was similar to thinning impacts, and that all understory biomass peaked at 5 years after MPB attack. Heath and Alfaro (1990) summarized stand conditions before and after MPB attack for a mixed stand of lodgepole pine and interior Douglas-fir in the Cariboo Forest Region of BC. Before the MPB outbreak, the stand overstorey had about 560 stems per ha consisting of 80% lodgepole pine, 19% interior Douglas-fir and 1% white spruce. The understory vegetation of 3190 small trees per ha was comprised of 90% interior Douglas-fir, 5% lodgepole pine and 5% white spruce. Seventy-six percent of the pine trees were killed by MPB. Fourteen years after the first measurement, the percentage of interior Douglas-fir and white spruce in the overstorey increased. However, the understory vegetation of 2698 trees per ha was similar in composition to that prior to the MPB attack, with 91% interior Douglas-fir, 7% lodgepole pine and 2% white spruce. They concluded that MPB attack affects the composition of tree species in the overstorey more than in the understory.

In a study by Stone and Wolfe (1996), the amount of understory biomass was shown to depend upon the mortality rate of lodgepole pine in the overstorey. Murphy et al. (1999) examined the response of advanced lodgepole pine regeneration to overstorey removal in eastern Idaho after salvage logging 15 years after MPB attack. The lodgepole pine regeneration showed a significant increase in growth rates 3 years after salvage logging.

In their study of regeneration following MPB outbreak in the Chilcotin Plateau, BC, Hawkes et al. (2004) observed that lodgepole pine had the highest rate of regeneration followed by other species such as Douglas-fir, spruce and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) in the year immediately following an epidemic. Four years later, sub-alpine fir had disappeared while trembling aspen (*Populus tremuloides* Michx.) and willow (*Salix* spp. L.) had regenerated. Stockdale et al. (2004) obtained results similar to those reported by Hawkes et al. (2004).

Zumrawi et al. (2005a) used the Prognosis^{BC} regeneration sub-model to predict regeneration in MPB-affected stands. The sub-model was developed and calibrated for predicting natural regeneration following partial harvesting. For long term impacts, the regeneration sub-model has some potential; however, for short period impacts, the model is not suitable. The reasons given for this include: 1) the dead trees were still standing, causing shading, unlike partially harvested stands; 2) it was not certain as to when the dead trees would fall down; and 3) fallen trees remain on the ground thereby covering part of the seedbed and restricting germination.

1.2.5 Estimation of Regeneration Using Prognosis^{BC}

Prognosis^{BC} is a growth and yield distance-independent tree growth model adapted from the northern Idaho version of the Forest Vegetation Simulator (FVS; Stage 1973; Wykoff *et al*. 1982; Dixon 2002). Prognosis^{BC} is designed to forecast future stand conditions in mixed-species and/or multi-aged (complex) stands found in southeast and central BC. It retains much of the architecture of the original FVS model; however, many of the internal equations have been reformulated and the remainder have been recalibrated. The habitat types required in the original model have been replaced by appropriate units within BC's Biogeoclimatic Ecosystem Classification (BEC) system and inputs and outputs have been converted to metric units (Snowdon 1997; Zumrawi *et al*. 2002). Several different versions of Prognosis^{BC} applicable to various BEC zones or subzones have been developed.

The model requires a tree-list of species, diameter outside bark at breast height (DBH; 1.3 m above ground), and stems per ha which is projected forward. Disturbances are also simulated by the model. Following disturbance, the model removes overstorey trees (i.e., dead or cut trees), and retains the altered tree-list. Regeneration will occur in response to stand structural changes, and this regeneration must be estimated and added to the tree-list at a future point in time. Therefore, a regeneration module is an essential component of Prognosis^{BC} and other growth models.

Multivariate nearest neighbour methods have recently been used to simultaneously predict regeneration for a number of species and sizes for use in Prognosis^{BC} following partial cutting. For example, Hassani et al. (2004) predicted regeneration for Interior Douglas-fir dry cool subvariants (IDFdk1, dk2, and dk3) in partially cut complex stands of the Kamloops and Cariboo Forest Regions using this approach with reasonably accurate results (low biases and root mean squared errors (RMSE)).

2 Materials and Methods

2.1 Data

Data collected by the Canadian Forest Service (CFS data) along with data collected by the research team under separate funding (FSP data) from three BEC zones in the central interior of BC were used in this study. The CFS data involved repeated measures, since measurements were taken shortly after MPB attack and 14 years after the attack.

2.1.1 CFS Data

The CFS data used in these analyses were obtained from stands that had been attacked by MPB at least 2 years before the initial measurements. The selected stands from Cariboo, Nelson and Kamloops regions were measured in 1987 and 1988 as part of a Natural Resources Canada project (Shore and Safranyik 1996). In 2001, these stands were remeasured, but the number of sampled stands was reduced because of logging or wildfire (Table 2.1).

Table 2.1 Number of MPB-affected stands sampled by region in 1987 and 2001 (CFS data).

Year	No. of Stands	Cariboo	Nelson	Kamloops
1987	41	30	6	5
2001	20	15	1	4

The selected stands represent three Biogeoclimatic Ecosystem Classification (BEC) zones: Interior Douglas-fir zone (IDF), Sub-Boreal Pine-Spruce zone (SBPS) and Montane Spruce zone (MS). Five stands were not classified by BEC zone, and there were few stands in the MS zone. A number of plots were established in each of the selected stands, resulting in a total of 175 plots with overstorey measures in both 1987 and 2001 (Table 2.2).

Table 2.2. Number of MPB-affected stands and plots sampled by BEC zone for 1987 and 2001 (CFS data).

Year	IDF		SBPS		MS		All Zones	
	No. of Stands	No. of plots	No. of Stands	No. of plots	No. of Stands	No. of plots	No. of Stands	No. of plots
1987	13	129	20	220	3	31	36	380
2001	9	80	9	75	2	20	20	175

NOTE: 5 stands were not classified by BEC zone

For each plot and for both times, the DBH, species and cause of death were recorded for each tree, and the number of regenerated trees was recorded by size class and species. In Prognosis^{BC} two size groups of trees are defined: small trees (2.0 cm < DBH ≤ 7.5 cm) and large trees (> 7.5 cm DBH). Regeneration is considered to be trees ≤ 2.0 cm DBH (Ferguson et al. 1986; Ferguson and Carlson 1993). For the purposes of this study, regeneration was considered to be all trees ≤ 7.5 cm DBH and overstorey trees were considered to be those trees > 7.5 cm DBH, since the data could not be distinguished into the categories of regeneration and small trees used by Prognosis^{BC}. The regeneration class was divided into saplings 0.1 to 7.5 cm DBH, and seedlings of 0 to 1.5 m height.

A variable-radius plot with either a basal area factor (BAF) of 2.3 m^2/ha (10ft^2/ac) or 4.59 m^2/ha (20ft^2/ac) was used for overstorey trees. The same plot centre was used for regeneration. Seedlings were recorded by height class using a fixed-area plot of 3.1 m radius; height classes employed varied slightly between 1987 and 2001 (Table 2.3). In 2001, saplings were recorded by diameter class using either a 5.64 m or 7.98 m plot radius. In 1987, the largest height class could be considered to be saplings, but there may be some missing trees > 2.0 m height, but ≤ 7.5 cm DBH. However, information on the 1987 regeneration was not used in analysis. Rather, the 1987 overstorey (or the 2001 overstorey) was used to estimate the 2001 regeneration.

2.1.2 FSP Data

The FSP data were collected during the summer months of 2006. The time since MPB attack for the majority of stands sampled was estimated as 25 years; however, some stands were sampled which had been attacked 8 years ago. Selected stands were located in the vicinity of Williams Lake, BC, in the IDF, SBPS, MS, and SBS (Sub-boreal Spruce). A total of 175 plots from 55 stands were sampled, and overstorey and understory trees were measured (Table 2.4).

Table 2.3. Size classes and plot sizes for regeneration in 1987 and 2001 (CFS data).

1987 Height Classes(m)	2001 Height Classes(m)	Plot Radius (m)
0 - 0.1	0 - 0.1	3.1
0.1 - 0.5	0.1 - 0.5	3.1
0.5 - 1.0	0.5 - 1.0	3.1
1.0 - 1.5	1.0 - 1.5	3.1
1.5 - 2.0		3.1
	Saplings: DBH Classes(cm)	
	0 – 3.9	5.64 or 7.98
	3.9 – 7.5	5.64 or 7.98

Table 2.4. Number of MPB-affected stands sampled in 2006 by BEC zone (FSP data).

BEC Zone	No. of Stands	No. of Plots
IDF	16	58
SBPS	32	100
SBS	5	13
MS	2	4
All Zones	55	175

Each plot consisted of seven sub plots: one for large trees (11.28 m radius), another for small trees (5.64 m radius), and five for regeneration (2.07 m radius). In the large tree plot (overstorey trees), all trees ≥ 7.5 cm DBH were measured. Each dead standing or downed tree was classified into a decay class (Appendix I). Height to live crown (m) was measured for all live trees. Species, DBH (cm), and height (m) of each standing tree, live or dead, were recorded. For downed trees in decay class 7 or greater, species, DBH, and height were recorded. For trees with broken tops, the height to the broken top (m) was measured, and the total height of the tree was estimated. Crown width was measured along two axes at right angles for two trees selected randomly for each species. In the small tree plot, all trees from 2 cm to < 7.5cm DBH were included and species, DBH, status (live or dead), visual estimate of live crown ratio (live only), and height was recorded for each tree. In the regeneration subplots, the number of live seedlings less than 2 cm DBH and over 15 cm in height were recorded by species into four height classes: 1) >0.15 to ≤ 0.5 m; 2) >0.5 to ≤1m; 3) >1.0 to ≤1.5 m; and 4) >1.5 m in height and < 7.5 cm DBH.[1]

[1] For convenience, class limits are sometimes shown as 1=0 – 0.5; 2=0.5 to 1; 3=1 to 1.5; 4= >1.5, or as 0 to 7.5 cm DBH.

The overstorey shortly after time of attack was reconstructed using the measures of live and dead trees in the large tree plot. Each live tree was grown back in time by subtracting estimated 10-year diameter growth (DG), using functions previously fitted by Zumrawi (2005b, and pers.comm.). For plots that were 25 years post-MPB attack, this process was repeated for three intervals, with the third period prorated at half of the estimated growth rate. Since measures of competition are used in the DG functions, these were summarized for each 10-year interval and used in estimating the DG. For plots that were 8 years post-MPB attack, the 10-year DG was prorated for 8 years. Once DBH shortly after the attack was estimated for each live tree, heights were estimated from DBH using existing regression equations (provided by Zumrawi). These heights were localized for each tree by multiplying them by the ratio of measured height to estimated height for the 2006 measures. For dead trees, the decay class was used to decide whether the tree was live or dead shortly after attack, as described in Appendix II, Table AII.1. For all trees that were alive at some point after MBP attack, the crown ratio was estimated using crown ratio functions developed for this area (see Appendix II). Ten-year DG was then estimated using the estimated crown ratio, and the same process as for trees that were alive at the time of sampling was followed. An estimated tree-list of all live and dead trees ≥=7.5 cm DBH was, therefore, obtained for each plot shortly after attack, and coupled with the regeneration (<7.5 cm DBH) measured in 2006, 8 or 25 years following MPB attack.

2.1.3 Combined Data

The two datasets were then pooled to provide an overstorey tree-list shortly after attack, coupled with regeneration a number of years after attack. This resulted in 138 plots for the IDF zone, and 188 plots for the combined SBPS and SBS zones (Table 2.5). The overstorey and understory tree measures were summarized to obtain stems per ha, basal area per ha by species group, live versus dead, and other variables used in the assessments of levels of regeneration and in the multivariate nearest neighbour imputation assessments.

Table 2.5. Number of plots by BEC zone and data source (combined data).

BEC zone	CFS data	FSD data	Total
IDF	80	58	138
SBPS(SBPS&SBS)	75	113	188
Total	155	171	326

2.2 Assessing the Amounts of Regeneration Following Mountain Pine Beetle Attack

Because the plots included in the CFS data were measured twice, the overstorey and understory tree measures could be determined twice (shortly after attack in 1987 and 14 years later in 2001). These data were used to examine the changes in overstorey and understory trees over this time period, and were reported in LeMay et al. (2006). Many of these results are included in this report as well.

The larger combined dataset was used to examine the amount of regeneration a number of years after the MPB attack (8, 14 or 25 years), in relation to the overstorey shortly after the time of attack.

2.3 Multivariate Nearest Neighbour Imputation

In multivariate nearest neighbour imputation, data are divided into reference data (where all attributes are available including the variables of interest (Y) and auxiliary variables (X) and target data (where only the X variables are available). A search of the reference data is used to find neighbours with X attributes similar to that of the target observation. The Y variables for the neighbours are then imputed to the target observation. A single neighbour or an average of several neighbours can be used, along with different measures of similarity (LeMay and Temesgen 2005). Unlike regression analysis, all Y variables are imputed at once (multivariate analysis), and the variance of the reference data is retained if a single neighbour is used.

For imputing regeneration, the auxiliary (X) variables measured for the target stand were overstorey variables measured at Time 1, following disturbance. The variables of interest (Y) were regeneration levels at Time 2. For partially cut stands, the overstorey following cutting at Time 1 is expected to be the same (or nearly) as the overstorey at Time 2. However, the use of multivariate imputation of regeneration following MPB attack is more difficult, since dead stems remain standing, causing a shaded environment for new seedlings (Mitchell and Preisler 1998; Zumwari et al. 2005a). After some time, these snags fall down, reducing the amount of available substrate. The overstorey measured shortly after MPB attack differs from the overstorey later on as dead trees fall, and regeneration may continue to occur for a long period of time after the MPB attack. Also, in partially cut complex stands, a variety of diameter distributions are left following cutting. In MPB affected stands, lodgepole pine trees killed by MPB are more commonly large diameter trees, resulting in the mostly smaller diameter trees as survivors (Hawkes et al. 2004).

In the initial MSN analyses, the CFS data were used to test a number of alternative summarized overstorey variables at Time 1, shortly after attack, and regeneration variables at Time 2, once regeneration has occurred. Details on the variables tested and the results of testing are presented in LeMay et al. (2006), and are summarized in this report. For all MSN analyses, the MSN imputation program developed by Moeur and Stage (1995), and extended by Crookston et al. (2002) was used. Version 2.12 of the MSN software was used to select a single nearest neighbour from the reference dataset based on the following measure of distance (similarity) by Moeur and Stage (1995):

$$d^2_{ij} = (X_i - X_j)W(X_i - X_j)' \qquad [1]$$

where: d^2_{ij} is the squared distance between the target plot i and the reference plot j; X_i is the vector of normalized X-variables for the target data; X_j is the vector of normalized X-variables for the reference data; and W is a weight matrix based on

canonical analysis between X and Y variables. The equation for W (Moeur and Stage, 1995) is:

$$W = \Gamma\Lambda^2\Gamma' \qquad [2]$$

where: Γ is the matrix of standardized canonical coefficients for the X variables; and Λ^2 is the diagonal matrix of squared canonical correlations between X and Y variables. This distance measure is essentially the squared Euclidean distance, weighted by the canonical correlation between the X and Y variables. The canonical correlation analysis indicates which X variables (the overstorey variables) are most correlated to the Y variables (the regeneration variables). The result of the MSN analyses is a list of the matches for each target plot, based on distances weighted by these multivariate correlations.

The MSN analyses were repeated using the combined data and selected overstorey and regeneration variables based on the initial MSN analyses. The selected overstorey variables were: elevation; live stems per ha and basal area per ha by three species classes (conifer except pine, pine, deciduous); crown competition factor (CCF); quadratic mean diameter (QMD); and stems per ha, basal area per ha, and QMD for standing dead pine (snags). Since the numbers of years following MPB attack varied in the combined datasets, the years since disturbance (YSD) was included as an X variable in the imputation tests. Site series was also included. For the CFS dataset, the site series was not specifically assessed for each plot, consequently modal sites (site series 01) were assumed. The selected regeneration variables were regenerated stems per ha by three species groups (conifer except pine, pine, deciduous), in four size classes (0 to 0.5 m height; 0.5 to 1 m height; 1 to 1.5 m height; and 0 to 7.5 cm DBH) for a total of 12 variables. As with the initial analyses, once a plot was selected as a match to the target plot using MSN, the complete regeneration tree-list was assigned to the target plot, rather than the summarized information used to select the match.

2.4 Measures of Accuracy

To evaluate the results of regeneration imputation, the combined plot data for each BEC zone were randomly divided into four approximately equal sets of data prior to MSN analysis (Snee 1977). One of these four sets (25% of plots) was the target data, considered to have only overstorey variables, and the remaining 75% of plots were used as reference data, with both overstorey and regeneration variables (Table 2.6).

Table 2.6. Number of target plots in each test data set by BEC zone.

BEC Zone	Dataset 1	Dataset 2	Dataset 3	Dataset 4	Total Number of Plots
IDF	39	32	34	33	138
SBPS & SBS	56	45	44	43	188

The actual regeneration for each target plot was then compared to that imputed for that target plot. This analysis was repeated four times, using a different set from the four sets as the target data. The differences between observed and predicted (estimated) regeneration for all target data was then summarized into bias (average difference) and root mean squared error (RMSE) statistics for each regeneration variable.

$$Bias = \sum_{i=1}^{n}\left[\frac{(y_i - \hat{y}_i)}{n}\right] \qquad [3]$$

$$RMSE = \sqrt{\sum_{i=1}^{n}\left[\frac{(y_i - \hat{y}_i)^2}{n}\right]} \qquad [4]$$

where y_i is observed regeneration per ha; $\hat{y}_i$ is predicted regeneration per ha by MSN analysis; and *n* is the number of target plots for which regeneration was estimated.

2.5 Projecting Stands Following MPB Attack Using Imputed Regeneration and Prognosis^{BC}

Multivariate imputation for estimating regeneration given overstorey characteristics has previously been added to Prognosis^{BC} for partially cut stands. Modifications to the database format and the linkage to this database were made in order to use this approach to estimate regeneration following MPB attack.

3 Results and Discussion

3.1 Amount of Regeneration Following Mountain Pine Beetle Attack

3.1.1 Trends Over Time

Graphs of stand-level regeneration variables (seedlings versus saplings for all species, pine only, and other) versus stand-level overstorey variables (stems per ha and basal area per ha for all trees, live only, and dead only) for the CFS data by BEC zone (IDF and SBPS only) indicated that the numbers of standing trees decreased from Time 1 to Time 2 for all stands (Appendix III; see data summary in Appendix IV, Table IV.1 also). Stems per ha also decreased for live trees, except in stands 125 and 129 of the SBPS zone (see Figure AIII.7 of Appendix III). The number of seedlings, all species combined, increased for some stands, but decreased in other stands (Figures AIII.1 and AIII.7). The number of saplings, all species combined, declined over time (Figures AIII.2 and AIII.8). Also pine saplings decreased (Figures AIII.4 and AIII.10); however, seedlings did not show a consistent trend (Figures AIII.3 and AIII.9). For other species, seedlings and saplings increased or were the same over time (Figures AIII.5 and AIII.11; Figures AIII.6 and AIII.12).

The number of saplings, all species combined, increased with a decrease in overstorey trees for both IDF and SBPS (Figures AIII.2a and AIII.8a), particularly with a decrease in stems and basal area per ha of standing dead trees (Figures AIII.2 and AIII.8e and f). Pine saplings generally followed a similar trend. Saplings for other species either decreased or remained the same as the stems and basal area per ha of dead trees decreased over time. Seedlings did not show a consistent increase or decrease in response to changes to the overstorey stems and basal area per ha (e.g., Figure AIII.1).

Since sapling survival and growth is dependent upon growing space and light, saplings responded to overstorey mortality and subsequent falling of snags. Seedling establishment was restricted by fallen snags, because of reduced substrate availability. However, this is somewhat arbitrary since there is a continuum in size between trees classified as seedlings versus saplings.

3.1.2 Amount of Regeneration

Using the combined dataset, simple statistics concerning the amount of regeneration by size class and species group indicated that the average amount of regeneration per ha was quite high, and were predominantly pine and deciduous species, with a few other conifers mixed in (Table 3.4, shown in Section 3.2.2). Out of the 138 plots in IDF, only two plots had no regeneration, and both were plots measured 16 years after disturbance. Only one plot in the SBPS/SBS had no regeneration (25 years since disturbance). However, regeneration is highly variable in space and there may have been regeneration in the stands, even though these few plots showed no regeneration. In terms of pine regeneration, 42% of the plots in IDF, and 37% of plots in SBPS/SBS had no pine regeneration, with the majority of these being plots 16 years after disturbance. In terms of none-pine conifer regeneration, 45% of the plots in IDF, and 64% of plots in SBPS/SBS had no other conifers. Deciduous species did not regenerate in 19% of the IDF and 40% of the SBPS/SBS plots.

Simple correlations between each regeneration variable a number of years attack (8, 16, or 25 years) and each overstorey variable shortly after attack indicated moderate positive correlations between regeneration of non-pine coniferous trees and the stems per ha and basal area per ha of the non-pine conifers (Table 3.1). For both IDF and SBPS/SBS zones, there was a low negative correlation between non-pine regeneration and pine overstorey stems per ha. Pine regeneration was positively related to elevation and negatively related to stems and basal area per ha of non-pine conifers. Deciduous regeneration was negatively correlated with non-pine overstorey in IDF. Non-pine conifers were positively correlated with competition as measured by CCF, whereas pine and deciduous trees were negatively related. Correlations with other individual overstorey variables, including the stems per ha, QMD, and basal area per ha of pine snags were generally very low.

Table 3.1. Simple correlations between regeneration a number of years MPB attack and overstorey shortly after attack.

BEC Zone	Species Group	Elev[1]	NT_C	NT_P	BA_C	BA_P	QMD	CCF
IDF	C[2]	-0.3485	0.4498	-0.2373	0.6045	-0.2105	0.3293	0.2090
	P	0.1400	-0.2078	-0.2085	-0.2279	-0.2030	-0.0060	-0.3250
	D	-0.0392	-0.2429	0.1210	-0.2522	0.0023	-0.2754	-0.1764
	ALL	-0.0539	-0.2131	-0.0615	-0.1916	-0.1600	-0.1684	-0.2772
SBPS & SBS	C	0.1026	0.3242	-0.1416	0.2732	0.0385	0.1690	0.1137
	P	0.2282	-0.1628	-0.1771	-0.1513	-0.2036	0.0676	-0.2561
	D	-0.1604	-0.0720	-0.2007	-0.0568	-0.1453	0.0946	-0.1894
	ALL	0.0357	-0.1228	-0.3008	-0.1096	-0.2593	0.1452	-0.3094

1: Elev=elevation(m); NT_C=Stems per ha, conifers not pine; NT_P=Stems per ha, pine; BA_C=basal area per ha, not pine; BA_P=basal area per ha, not pine; QMD=Quadratic mean diameter, cm; CCF=crown competition factor
2: C=conifers (except pine); P=pine; D=deciduous

3.2 Multivariate Imputation Results

3.2.1 Preliminary Analysis to Select Overstorey Variables

Using the repeated measures CFS data only, a number of combinations of overstorey variables were tested for imputing regeneration using MSN analysis. The basic set of overstorey variables were: elevation, live stems per ha, basal area per ha (BA), crown competition factor, and quadratic mean diameter (QMD). Incremental to these base variables, other variables were added, and/or some of these variables were subdivided into species groups, as shown in Table 3.2. These were used to examine the accuracy in estimating regeneration into three species groups by four size classes (12 variables). Two different groupings of species were used for the overstorey and regeneration, as shown in Table 3.3.

Table 3.2. Overstorey variable sets used in preliminary analyses. (Bold indicates variables incremental or changed from the list above)

Overstorey (X) Variables
Elevation; live stems per ha, basal area per ha (BA), crown competition factor (CCF), and quadratic mean diameter (QMD)
Elevation; live stems per ha, basal area per ha, CCF, QMD; **stems per ha, BA, and QMD of snags**
Elevation; live stems per ha and basal area per ha **by three species classes**), CCF, QMD
Elevation; live stems per ha and basal area per ha by three species classes, CCF, QMD; **stems per ha, BA, and QMD of snags**
Elevation; live stems per ha and basal area per ha by three species classes, CCF, QMD; stems per ha, BA, QMD, and **fall down rate of snags**

Table 3.3. Species list for two different species groupings used in preliminary MSN analysis.

Criterion	Groups	Species [1]
Shade tolerance	Shade tolerant	grand fir (*Abies grandis* (Dougl.) Lindl.), subalpine fir, western redcedar (*Thuja plicata* Donn), hemlock (*Tsuga heterophylla* (Raf.) Sarg.), spruce
	Semi-shade tolerant	interior Douglas-fir, western white pine
	Shade intolerant	yellow (Ponderosa) pine (*Pinus ponderosae* (Laws.), amabilis fir (*Abies amabilis* (Dougl.) Forbes), subalpine larch (*Larix lyallii* Parl.), western larch (*Larix occidentalis* Nutt.), Douglas maple (*Acer glabrum* Torr. var. *douglasii* (Hook.) Dipp.), alder (*Alnus* spp. B. Ehrh.), willow, trembling aspen
Species	Conifer except pine	interior Douglas-fir, western larch, spruce, hemlock, grand fir, subalpine fir, amabilis fir, western redcedar, spruce, subalpine larch
	Pine	lodgepole pine, western white pine, yellow pine
	Deciduous	trembling aspen, willow, Douglas maple, alder

1: not all species occur in the zones covered by this study.

Detailed results comparing these different overstorey variables and separation by tolerance versus species group are presented in LeMay et al. (2006), Section 3.3. In summary, the average observed versus predicted regeneration by size class and species group indicated that:

1. the addition of overstorey variables by species group did not appear to result in substantial improvements in average estimated regenerated stems per ha by size class; and
2. there were no obvious improvements in adding the information on snags, nor in adding the snags plus fall-down rate.

The expectation was that the separation into species group, particularly by pine, non-pine conifer and deciduous would improve imputation results, but there was little evidence of this in the preliminary analysis. However, this may improve the estimates of species composition of the regenerated trees, on average. Also, including the pine snag information did not result in noted improvements. The CFS dataset was limited to a few stands, which may have limited the ranges of overstorey variables.

Based on this preliminary analysis, and expectations of overstorey variables that may affect regeneration levels, the basic variables were used in the MSN analysis using the combined data, and stems per ha and basal area were divided by pine, non-pine conifer, and deciduous for the overstorey. These same species groupings were used to separate regeneration by species and size. In addition, site series was added to the data, as this was considered an important variable for regeneration. All CFS plots were considered to be measured on modal sites (series 01), based on the documentation for these data. The pine snag stems per ha, basal area per ha and QMD were also retained for the overstorey. The snag fall down rate was not included, since this would not normally be available at the time of attack.

3.2.2 Regeneration Imputation Using the Combined Data and Selected Overstorey Variables

MSN was used to impute the regeneration for each of the target plots in the four datasets created by splitting the combined data for the IDF and SBPS/SBS zones. The 14 selected overstorey variables for imputing regeneration used in MSN were: elevation; stems per ha and basal area per ha for all live trees by three species groups (conifer except pine, pine, and deciduous); CCF and QMD for all live trees; stems per ha, basal area per ha, and QMD for pine snags; years since disturbance; and site series. In the MSN analysis, these variables were correlated to 12 regeneration variables (regeneration stems per ha by three species group crossed with four size classes) using a canonical correlation analysis. Three canonical axes were included for all IDF test datasets and four were included for all SBPS/SBS test datasets out of 12 possible axes, based on a likelihood ratio test of significant axes using α=0.05.

For the IDF zone, the three canonical axes indicated that the overstorey variables accounted for 10% to 20% of the variance in the regeneration variables, depending upon the test dataset. Site series was dropped from the IDF analyses, as there were only two site series represented in the dataset. Based on correlations of more than 0.4 (absolute value) between the three canonical variates and the overstorey and regeneration variables, the stems per ha and basal area per ha for conifers (non-pine), along with the QMD for live trees and CCF for live trees correlated with the conifer (non-pine) and deciduous regeneration (for most size classes). Years since disturbance (YSD), and basal area per ha and stems per ha for pine were correlated with pine regeneration and, for one test dataset only, with deciduous regeneration.

For the SBPS/SBS zones, the variance in regeneration explained by the overstorey variables using the four canonical variates was 18% to 27%. There were several site series represented in the SBPS and this was an important variable in the analysis. Based on correlations of more than 0.4 (absolute value) between the four canonical variates and the overstorey and regeneration variables, site series, CCF, and stems per ha and basal area per ha for conifers (non-pine), correlated with the conifer (non-pine) and deciduous regeneration (for most size classes). Years since disturbance, CCF, and basal area per ha and stems per ha for pine correlated with pine regeneration (all sizes). Elevation was correlated with deciduous regeneration (all sizes) for only one of the test datasets. The number of pine snags correlated with the amount of large-sized pine regeneration for two of the test datasets.

The canonical correlation results were used to weight the distances between the target and reference overstorey variables, and the reference plot with the smallest MSN distance was selected as the match for that plot. The regeneration from the matched plot was then used as the predicted regeneration for that target plot and was compared to the actual regeneration recorded for the plot. On average, the predicted regeneration per ha by BEC zone and size class was similar to the observed regeneration by size class and species, except for the smallest size class in IDF, where the estimated stems per ha was higher than the observed stems per ha (Table 3.4). When further subdivided by species group, this overestimation in the smallest size class for IDF was shown for all three species groups.

The bias in regeneration amount for all plots was -43 stems per ha for the IDF zone and -59 stems per ha for the SBPS/SBS zones (Table 3.5). These are relative to averages of 6842 stems per ha (-0.6% bias) and 4343 stems per ha (-1.3% bias), respectively, for the two zone groupings. The bias was smaller for the middle size classes. The RMSE was lowest for height class 3 (1.0 to 1.5 m) for both zones, but were quite high overall indicating high variability between measured and observed regeneration by plot. Bias and RMSE values were lower than those obtained using the CFS data alone (as reported in LeMay et al. 2006, Section 3.3), indicating the expected improvements because of a larger reference dataset.

Table 3.4 Average observed regeneration (stems per ha) versus average predicted regeneration based on MSN using Time 1 overstorey by BEC zone, size class, and species group.

BEC Zone	**Species Group**	**Observed regeneration**					**Predicted regeneration**				
		1[1]	2	3	4	All	1	2	3	4	All
IDF	C[2]	437	162	60	153	812	812	177	43	160	682
	P	863	500	306	456	2125	2125	578	313	531	2408
	D	2150	794	368	595	3907	3907	711	363	616	3924
	ALL	3450	1456	734	1204	6844	6844	1465	720	1308	7014
SBPS & SBS	C	91	42	24	83	240	162	39	26	76	303
	P	763	438	214	723	2138	911	540	259	704	2414
	D	638	372	225	730	1965	608	394	200	660	1862
	ALL	1492	852	463	1536	4343	1681	973	486	1439	4679

1: Size classes: 1=0 to 0.5 m in height; 2=0.5 to 1 m in height; 3=1 to 1.5 m in height; 4=0 to 7.5 cm in DBH;
2: C=conifers (except pine); P=pine; D=deciduous

Table 3.5. Bias and RMSE (regeneration stems per ha) values using MSN by BEC zone and size class.

BEC Zone	**Bias**				**RMSE**				**Overall**	
	1[1]	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**Bias**	**RMSE**
IDF	-72	-8	15	-105	7437	1944	911	1615	-43	2977
SBPS & SBS	-190	-121	-23	97	3532	1761	884	2134	-59	2078

1: Size classes: 1=0 to 0.5 m in height; 2=0.5 to 1 m in height; 3=1 to 1.5 m in height; 4=0 to 7.5 cm in DBH

Graphs of predicted versus observed regeneration further confirmed the high variability between measured and estimated regeneration. In terms of regeneration by size class regardless of species group (Figures 3.1 and 3.2), estimates of regeneration were similar to measured estimates on average, as indicated by the balance of points around the 45 degree line on these graphs, with low bias as previously noted. However, estimates for particular plots could differ by as much as 4,000 stems per ha from measured values. Trends by species and size were generally similar (Appendix V) to those by size class alone.

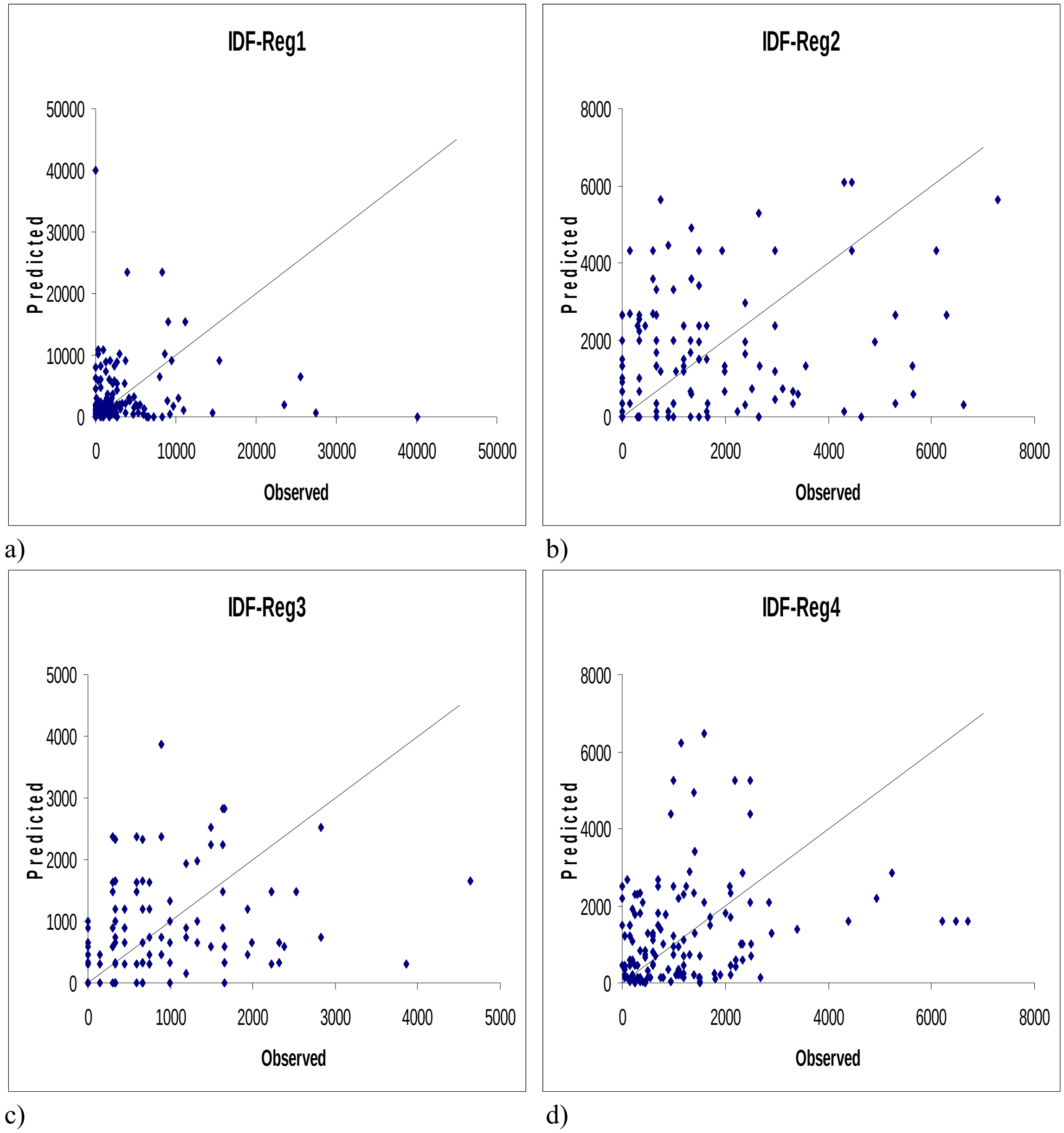

Figure 3.1. Observed vs. predicted regeneration by size class (a) 0-0.5 m, b) 0.5-1.0 m, c) 1.0-1.5 m in height, d) 0-7.5 cm in DBH) in IDF using MSN and the overstorey and regeneration measures in the combined data.

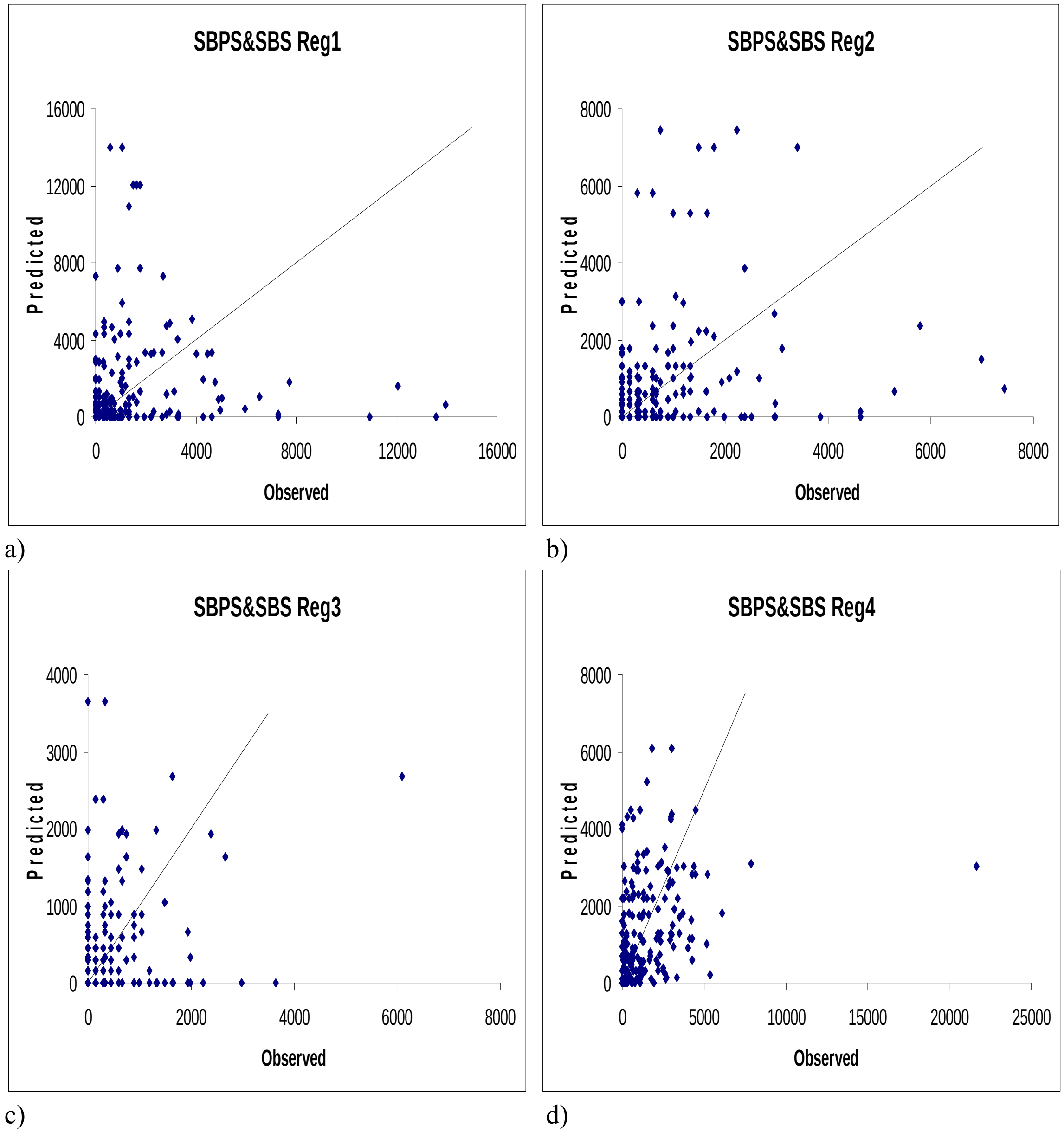

Figure 3.2. Observed vs. predicted regeneration by size class (a) 0-0.5 m, b) 0.5-1.0 m, c) 1.0-1.5 m in height, d) 0-7.5 cm in DBH) in SBPS and SBS using MSN and the overstorey and regeneration measures in the combined data.

Multivariate nearest neighbour imputation has the advantage of estimating all species and sizes of regeneration in one step, by selecting an observation from a reference dataset to be used for a target observation without the regeneration variables. This results in consistency across variables. Results improve with larger reference datasets, and with better correlation between the auxiliary variables and the variables of interest (LeMay and Temesgen 2005). In this study, results improved when using the combined dataset with the wider range of overstorey conditions compared to using the CFS data alone. However, simple correlations between individual overstorey variables and understory variables were generally low, and the overstorey variables explained only 10% to 25% of the variance in regeneration variables depending upon the zone and the test dataset and based on canonical correlation analyses. Other variables such as seed source availability and substrate availability would help to explain and estimate the amount of regeneration following MPB attack. These were not measured on the repeated measures CFS data, and could not be reconstructed using the single time measured FSP data. However, on average, the estimated regeneration vector by species and size was very similar to that observed.

3.3 Modifications to Database and to Prognosis^{BC} to Impute Regeneration Following Mountain Pine Beetle Attack

Modifications to the database format used for partially cut stands were made to incorporate the MPB overstorey tree-list at Time 1 and the regeneration tree-list at Time 2 for every plot in the combined datasets. The fields that were added to the database included: tree status, decay class, height to break, estimated height, pathological remarks, and a field to identify reconstructed versus measured data (Appendix VI). Additional species and other codes were added to the database tables to accommodate the zones sampled, and a data source table for metadata was also added. Under this project, the database increased to 1,234 stands, with several plots in each stand, including plots following partial harvesting and these new plots following MPB attack. The database is freely available, but additions to the database are carefully managed to ensure accuracy, quality, and continued usability of the Prognosis^{BC} growth and yield modelling system.

In a previous research project for imputing regeneration following partial harvest, a run-time linkage was developed between the Prognosis^{BC} system and the regeneration database using the Most Similar Neighbor (MSN) procedure (Moeur and Stage 1995; Crookston et al. 2002). The MSN method finds the best match between site and stand structure in a simulated stand with unknown post attack regeneration, to site and stand structure conditions drawn from the regeneration database stands with known levels of regeneration.

Under this project, analyses of the conditions found in stands attacked by MPB have led to the revision of the site and stand indicators being used for stand matching. These revised indicators (X variables) are shown in a table in Appendix VI, and have been implemented as a stand-alone executable program that links the Prognosis^{BC} with the MSN software. The major change in the MSN model terms has been the removal of disturbance-specific classes and inclusion of snag measures. The Y-variables, predicted regeneration in the best-match stand, are unchanged.

To project each plot in a stand following MPB attack, the plot tree-list (all tree sizes) measured shortly after attack would be input to Prognosis^{BC}. This list would be projected forward (projected tree-list) using growth and mortality functions. At a fixed point in the future, the overstorey trees (DBH $\geq$ 7.5 cm) and other plot characteristics would be summarized into the variables needed for the MSN imputation of regeneration.

Additions were made to the Prognosis^{BC} software to calculate the needed variables, and to pass these to MSN. Based on the summarized overstorey variables from the projected tree-list and the regeneration summarized into 12 variables (species by size class), one plot would be chosen from the reference dataset. The regeneration as a tree-list from this matched plot would then be added to the projected tree-list. Projection of the combined tree-list would then continue.

4 Conclusions

Based on the data used in this study, the amount of regeneration following MPB attack is quite variable. Only three of the plots showed no regeneration. However, regeneration varied greatly over space, and other plots in these stands had regeneration. The majority of plots had pine regeneration, mixed with deciduous trees, and some non-pine regeneration. Relationships between the overstorey structure and regeneration were complex, but the selected variables and canonical correlation analysis resulted in 10% to 20% of the variance in the regeneration variables accounted for in the IDF zone and 18% to 27% in the SBPS/SBS zones, depending upon the test dataset.

Multivariate nearest neighbour analysis to estimate regeneration a number of years following MPB attack for overstorey structure shortly after attack results in logically consistent estimates of regeneration by species and sizes, since a plot in the reference set is selected to represent the regeneration in the target plot. Using this imputation method, the average estimated regeneration vector by species and size classes was similar to the average observed vector, except for the smallest size class in IDF, where the estimated stems per ha was higher than the observed stems per ha. However, the variation in these estimates versus the observed vectors was large, representing the large variability in seed source availability, seedling success, and site characteristics. Other dynamic approaches to estimating regeneration following MPB attack may help to better explain the variation in regeneration among stands.

The multivariate approach used in this study will provide estimates that can be used to forecast stand dynamics using Prognosis^{BC} and provide some insights to management of stands following MPB attack. A prototype linking multivariate imputation to Prognosis^{BC} for stands attacked by MPB was developed.

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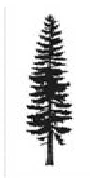
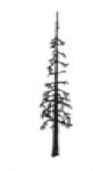
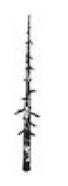
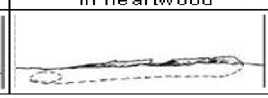
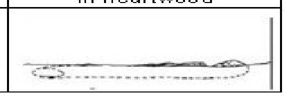
7 Appendices

7.1 Appendix I. Decay Classes for FSP Data

Decay class						
Decay class	Live-- not used		Dead Standing			
			Hard			Spongy
			1	2	3	4
Description	Live/healthy: no decay; tree has valuable habitat characteristics such as large, clustered or gnarled branches, or horizontal, thickly moss-covered brances.	Live / unhealthy; internal decay or growth deformities (including insect damage, broken tops); dying tree	Dead; needles or twigs may be present; roots sound	Dead; no needles / twigs; 50% of branches lost; loose bark; top usually broken; roots stable	Dead; most braches.bark absent; some internal decay; roots of larger trees stable	Dead; no braches or bark; sapwood/ heartwood sloughing from upper bole; decay more advanced; lateral roots of larger trees softening; smaller ones unstable
						

Decay Class
1 to 4 (standing) -- still standing so in the stand structure at both times. If time since disturbance is more than 14 years, a dead tree at time of attack would have fallen down (likely). Therefore, if more than 14 years, will assume that the dead standing tree was alive at the time of attack. If time since disturbance is less than 14 years, then this will depend upon the decay class. If the tree is DC =1 (as per the new combined code), we will assume the tree was alive at the time of attack. If the DC=2, 3 or 4, we will assume that the tree was dead at the time of attack.
5 to 6 (down)– likely was standing at time of attack, if attack is more than 14 years, include in calcs for stand structure at time of attack as a LIVE stem at time 1. If attack is less than 14 years, assume these were down at time of attack and DO NOT include them in stand structure at time of attack.
7 to 9 – do not include these as they were likely down at time of attack as well as now.

Decay Class	5	6	7	8	9
Wood texture	intact, hard	intact, hard to partly decaying	hard, large pieces, partly decaying	small, blocky pieces	many small pieces, soft portions
Protion on ground	elevated on support points	elevated but sagging slightly	sagging near ground, or broken	all of log on ground, sinking	all of log on ground, partly sunken
Twigs<3cm (if originally present)	twigs present	no twigs	no twigs	no twigs	no twigs
Bark	bark intact	intact or partly missing	trace bark	no bark	no bark
Shape	round	round	round	round to oval	oval
Invading Roots	none	none	in sapwood	in heartwood	in heartwood
					

Decay classes 1 to 4 are based on wildlife tree classification classes 3 to 6 for coniferous trees, as found in:: *Vegetation Resource Inventory Ground Sampling Procedures*. 2002. B.C. Ministry of Sustainable Resource Management, Terrestrial Information Branch for the Resource Inventory. Committee.(http://www.env.gov.bc.ca/wld/documents/identified/App06-Interim.pdf , accessed March, 2007. Decay classes 5 to 9 are coarse woody debris classes 1 to 5 as found in: *Vegetation Resource Inventory Ground Sampling Procedures*. 2002. B.C. Ministry of Sustainable Resource Management, Terrestrial Information Branch for the Resource Inventory Committee. (http://ilmbwww.gov.bc.ca/risc/pubs/teecolo/fmdte/cwdcom.htm, accessed March, 2007.

7.2 Appendix II. Reconstruction of Trees at Time of Attack for FSP Data

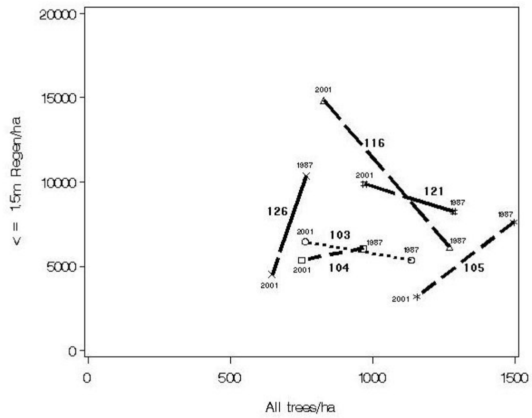
Table A.II.1. Tree condition in each period, based on decay class and time since MPB attack.

Decay Class in 2006	8 years since disturbance: status shortly after attack	25 years since disturbance: status 15 year after attack	25 years since disturbance: status shortly after attack
Live tree	Live	Live	Live
Snag (decay class 1)	Live	Live	Live
Snag (decay class 2)	Snag	Live	Live
Snag (decay class 3 & 4)	Live(others) Snag(Pine)	Live(others) Snag(Pine)	Snag
Down tree (decay class 5)	Live	Live	Live
Down tree (decay class 6)	Snag	Snag	Snag
Down tree (decay class 7)	Snag	Snag	Snag
Down tree (decay class 8)	Down tree	Down tree	Down tree

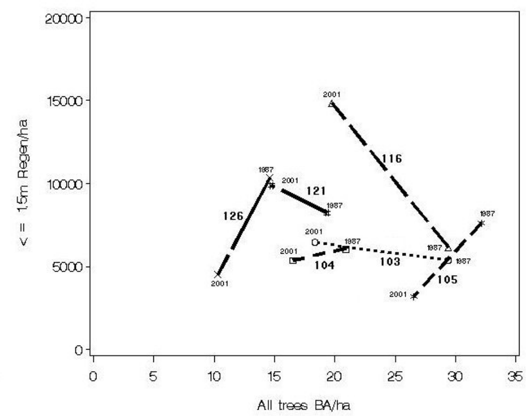
Table A.II.2 Functions used in overstorey reconstruction.

Variables	Function
10-year DBH growth	For: IDF(IDFdk3 & IDFdk4) (provided by A-A, Zumrawi): DG(FD) = exp(0.5596-0.198*ccf/100-0.00034*DBH06**2-0.1045*bal /(log(DBH06+1))+1.3635*cr) DG(PL,AT&EP)=exp(-0.2238+0.3479-0.3124*ccf/100+0.00038*DBH06**2-0.0433*bal /(log(DBH06+1))+1.5667*cr) For: SBS&SBPS(SBPSxc, SBPSmk, SBPSdc, SBSdw1 & SBSdw2) (Zumrawi et al. 2005b) (Zumrawi et al., 2005b): DG(BL)=exp(0-0.0152*ccf+0*bal+3.1925*cr+0*sasps+0.0737*DBH06-0.00182*DBH06**22); DG(FD)=exp(0.00793-0.00654*ccf-0.00312*bal+0.926*cr+0.00327*sasps+0.056*DBH06 -0.00044*DBH06**2); DG(PL)=exp(-1.2424-0*ccf-0.0202*bal+1.6043*cr+0.00955*sasps+0.0630*DBH06 -0.00112*DBH06**2); DG(SX)=exp(-1.4917-0.00079*ccf+0*bal+2.4255*cr+0*sasps+0.0113*DBH06 -0.000226*DBH06**2) DG(AT&EP)=exp(-0.2238+0.3479-0.3124*ccf/100+0.00038*DBH06**2 -0.0433*bal/(log(DBH06+1))+1.5667*cr) (IDF) DG(CW)=exp(-1.2424-0*ccf-0.0202*bal+1.6043*cr+0.00955*sasps+0.0630*DBH06-0.00112*DBH06**2) (pine in SBS)
Height	Pred. HT=1.3+EXP(C_0+C_1*(1/(DBH+1) (Stage, 1973; fitted using project data) HT(past)= Pred. HT(past) * (Measured Ht.(present) / Pred. Ht (present))
Crown ratio	CR=1/(1+exp(b0+b1*DBH06+b2*DBHsq+b3*height+b4*hdr+b5*lnccf+b6*bal+b7*el_100 +b8*elevsq+b9*sl_100+b10*sin_slp+b11*cos_slp+b12*bar)) (fitted using project data)

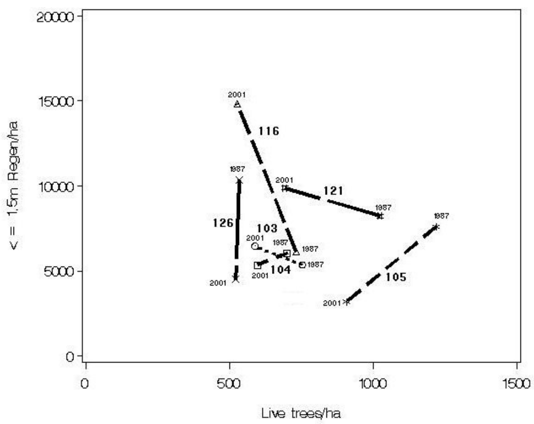
7.3 Appendix III. Regeneration Versus Overstorey Variables Over Time



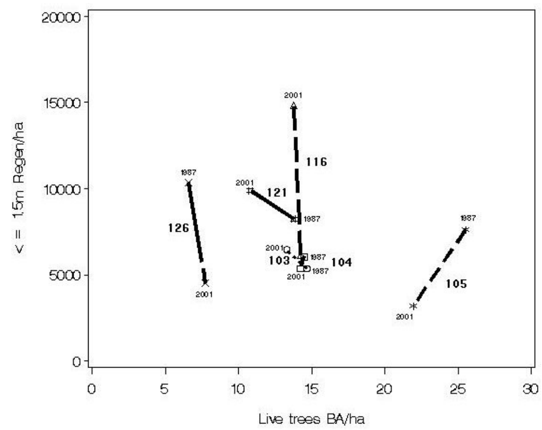
a)



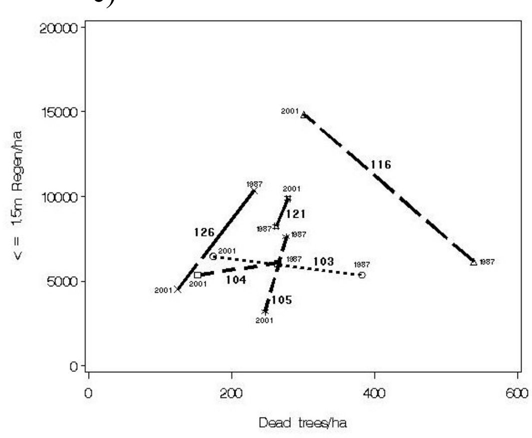
b)



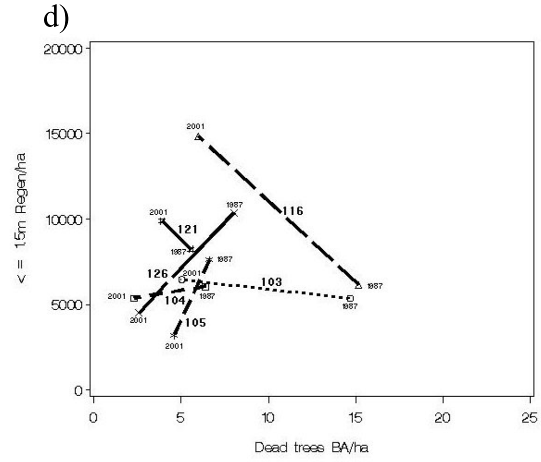
c)



d)



e)



f)

Figure AIII.1. All seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.

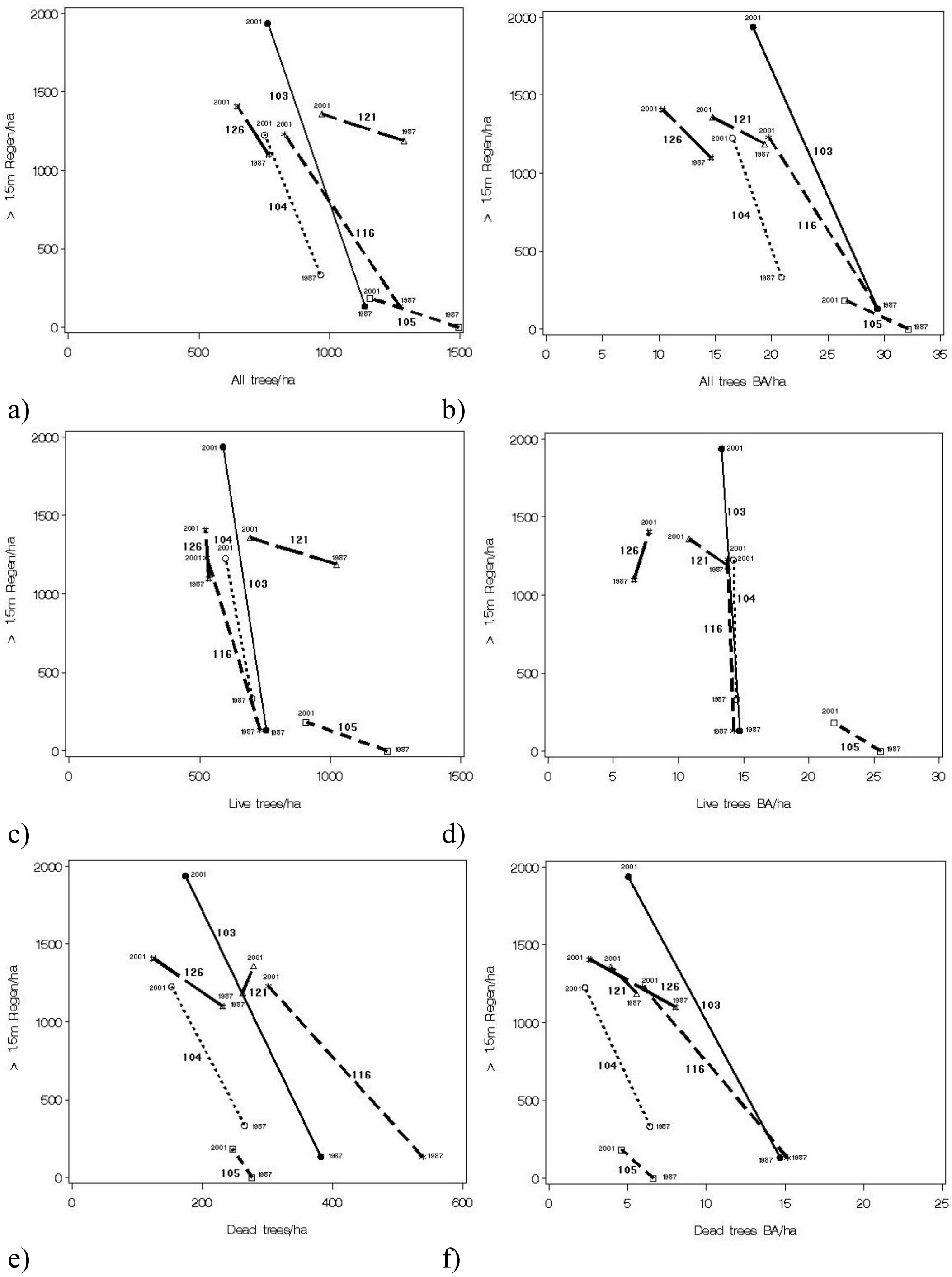


Figure AIII.2. All saplings (1.5m<height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.

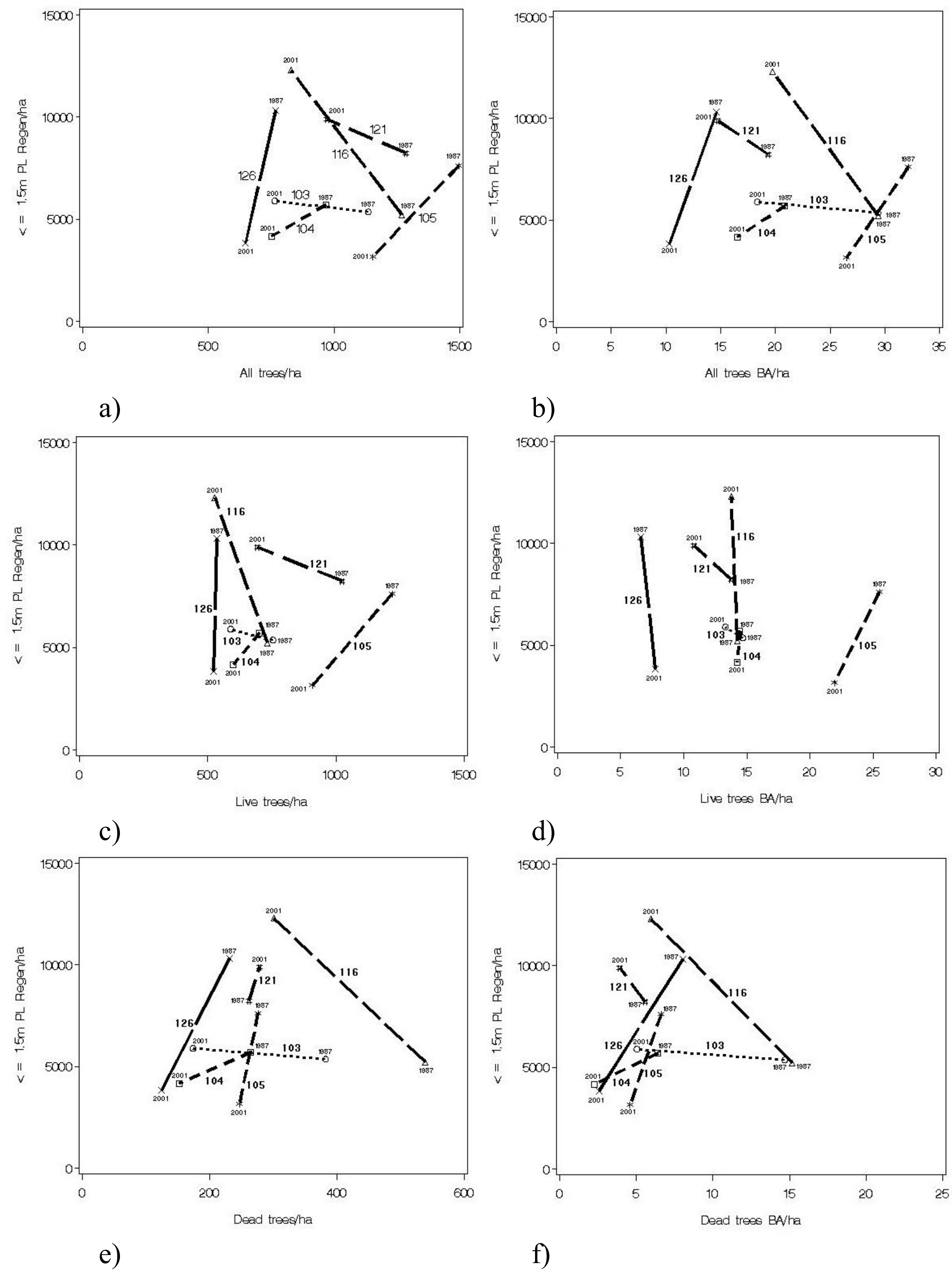


Figure AIII.3. Lodgepole pine seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.

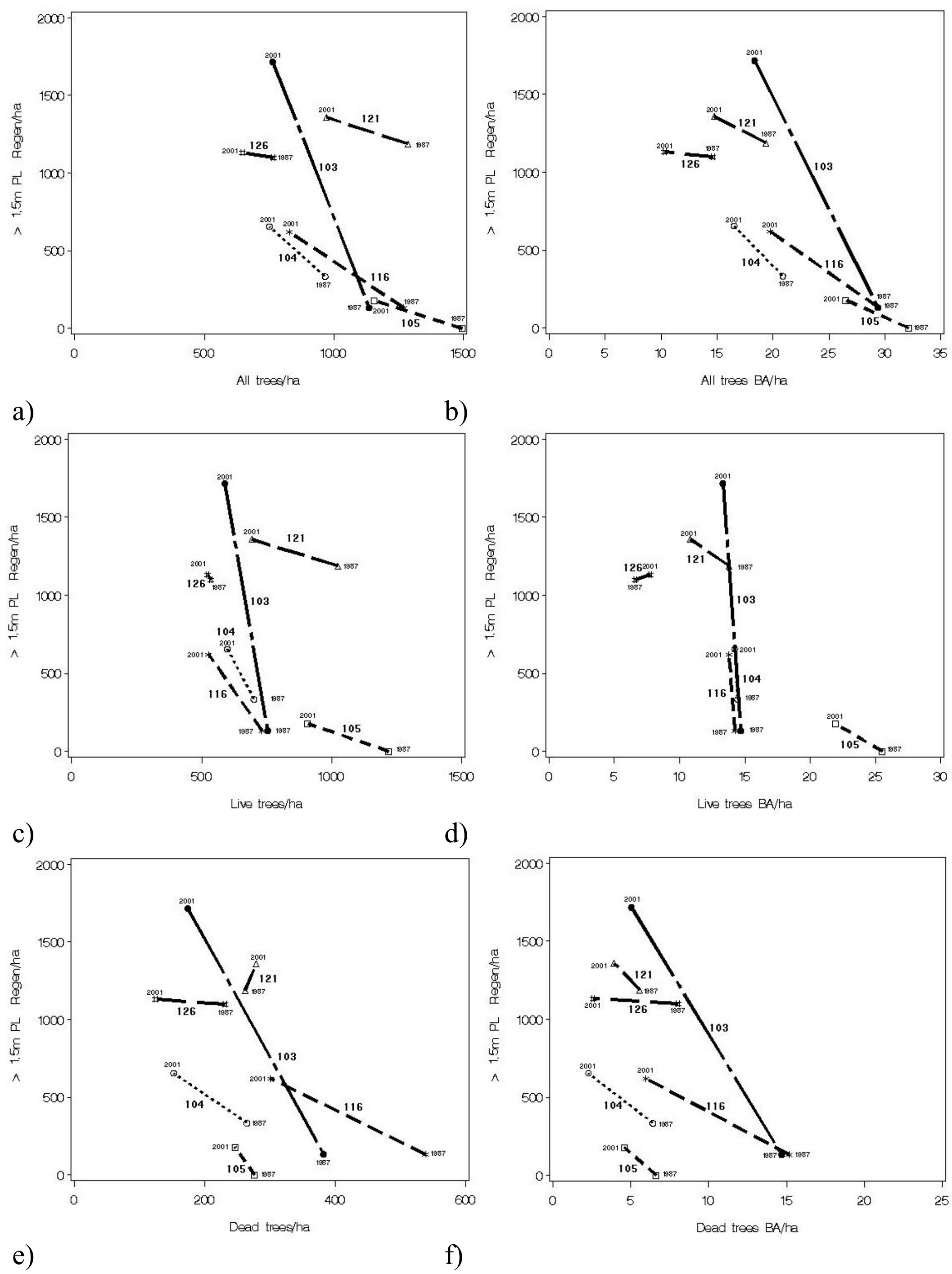


Figure AIII.4. Lodgepole pine saplings (1.5m<height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.

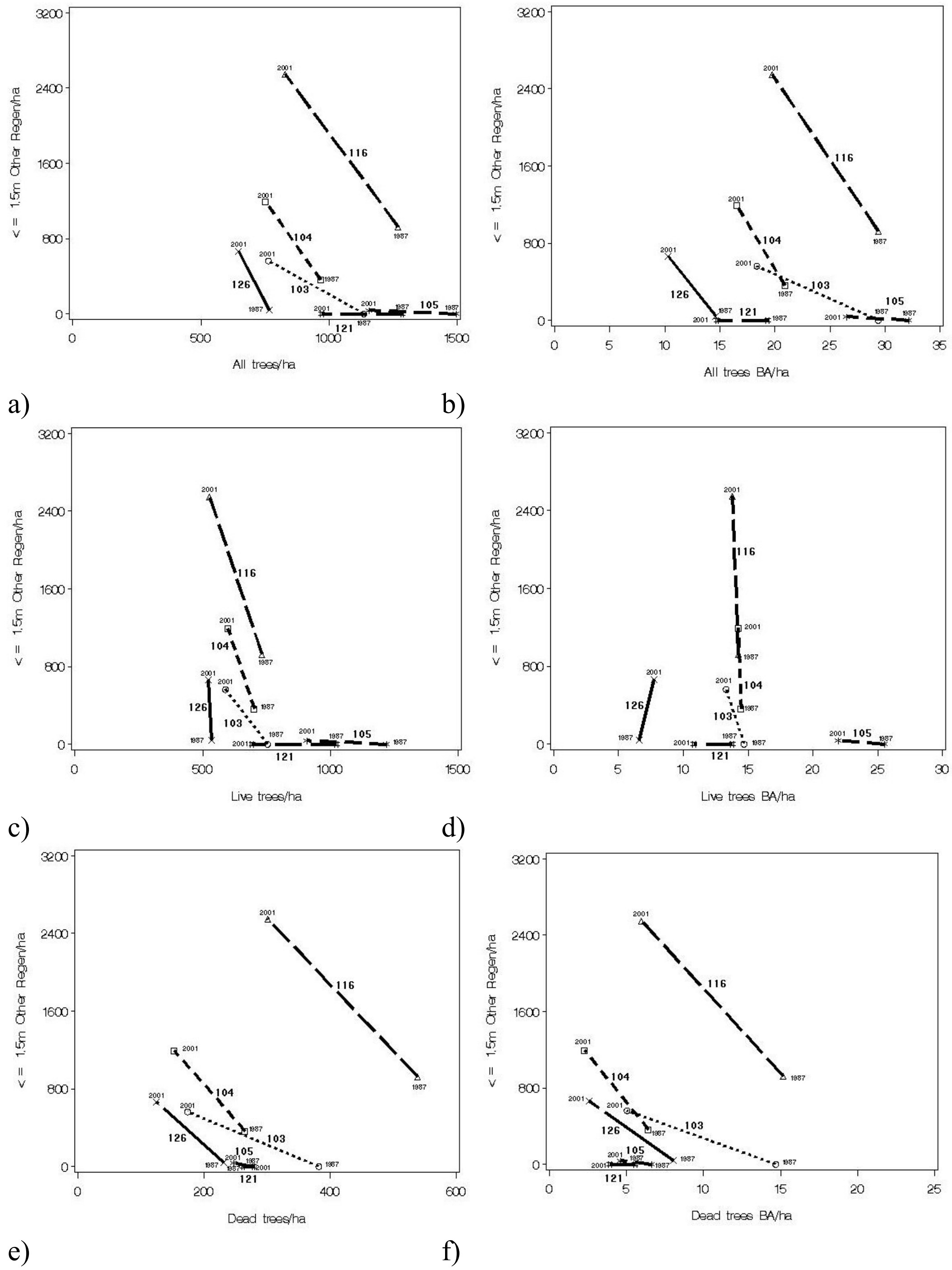


Figure AIII.5. Other seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.

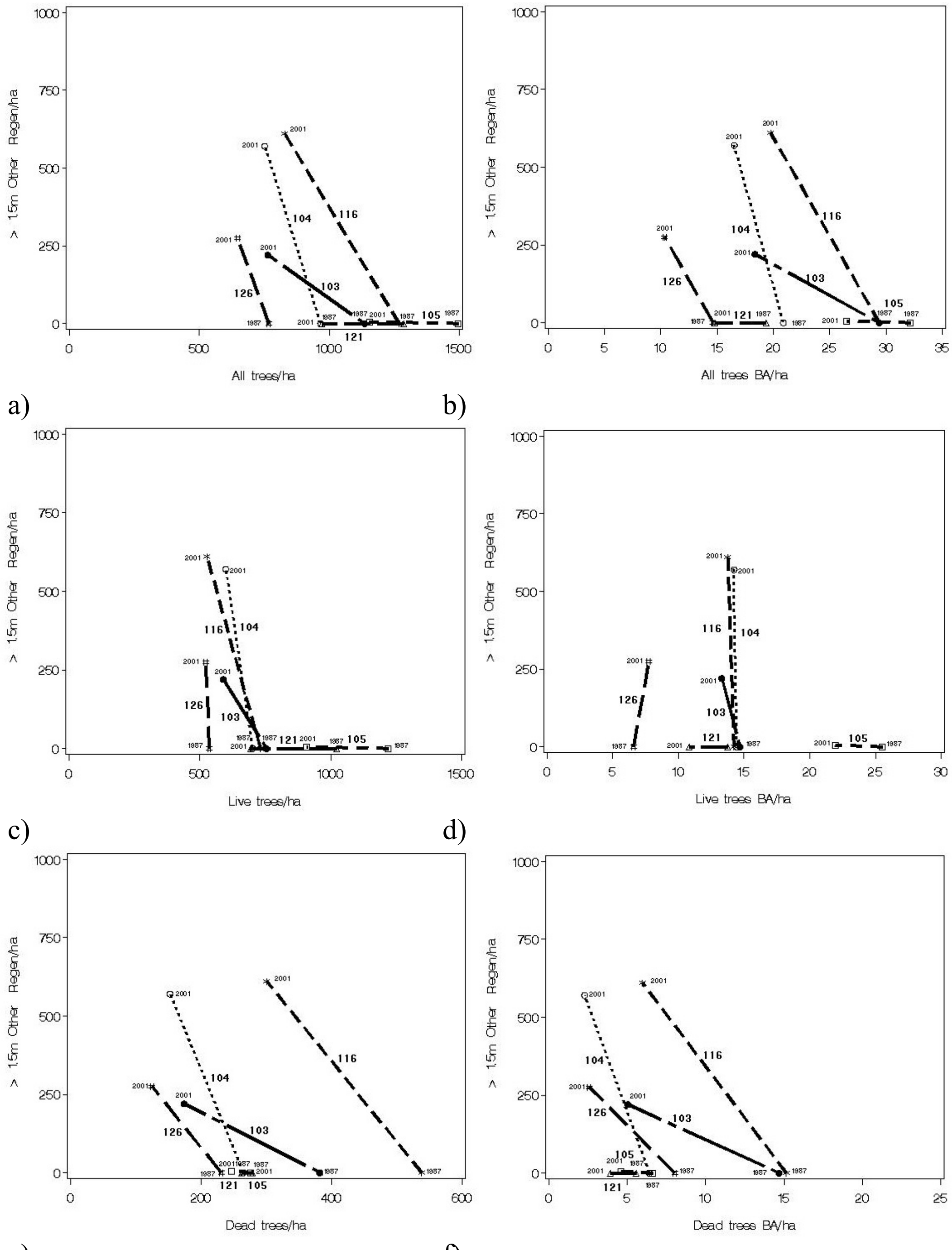
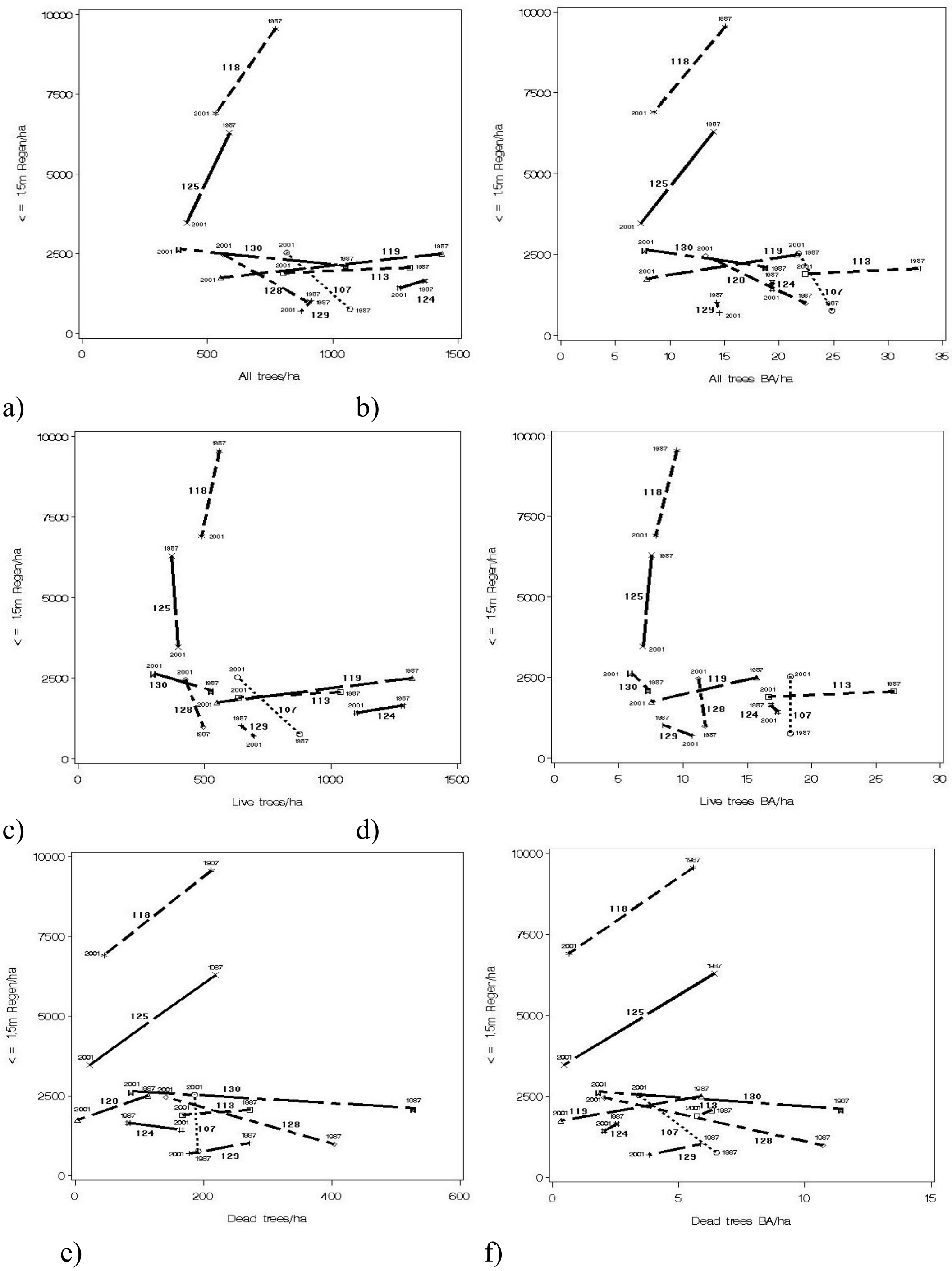


Figure AIII.6. Other saplings (1.5m<height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the IDF zone for 1987 and 2001.



a) b)

c) d)

e) f)

Figure AIII.7 All seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

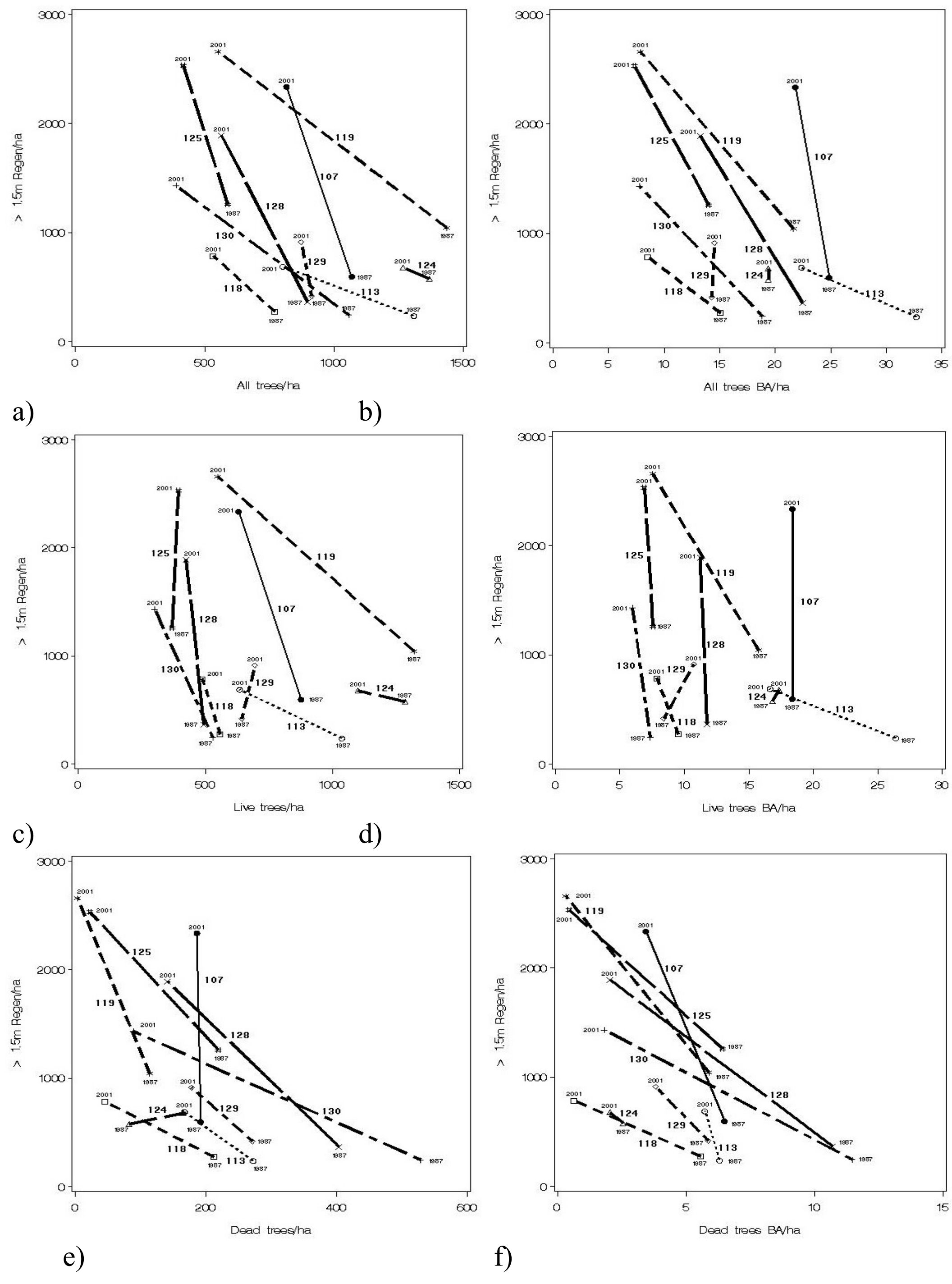


Figure AIII.8. All saplings (1.5m<height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

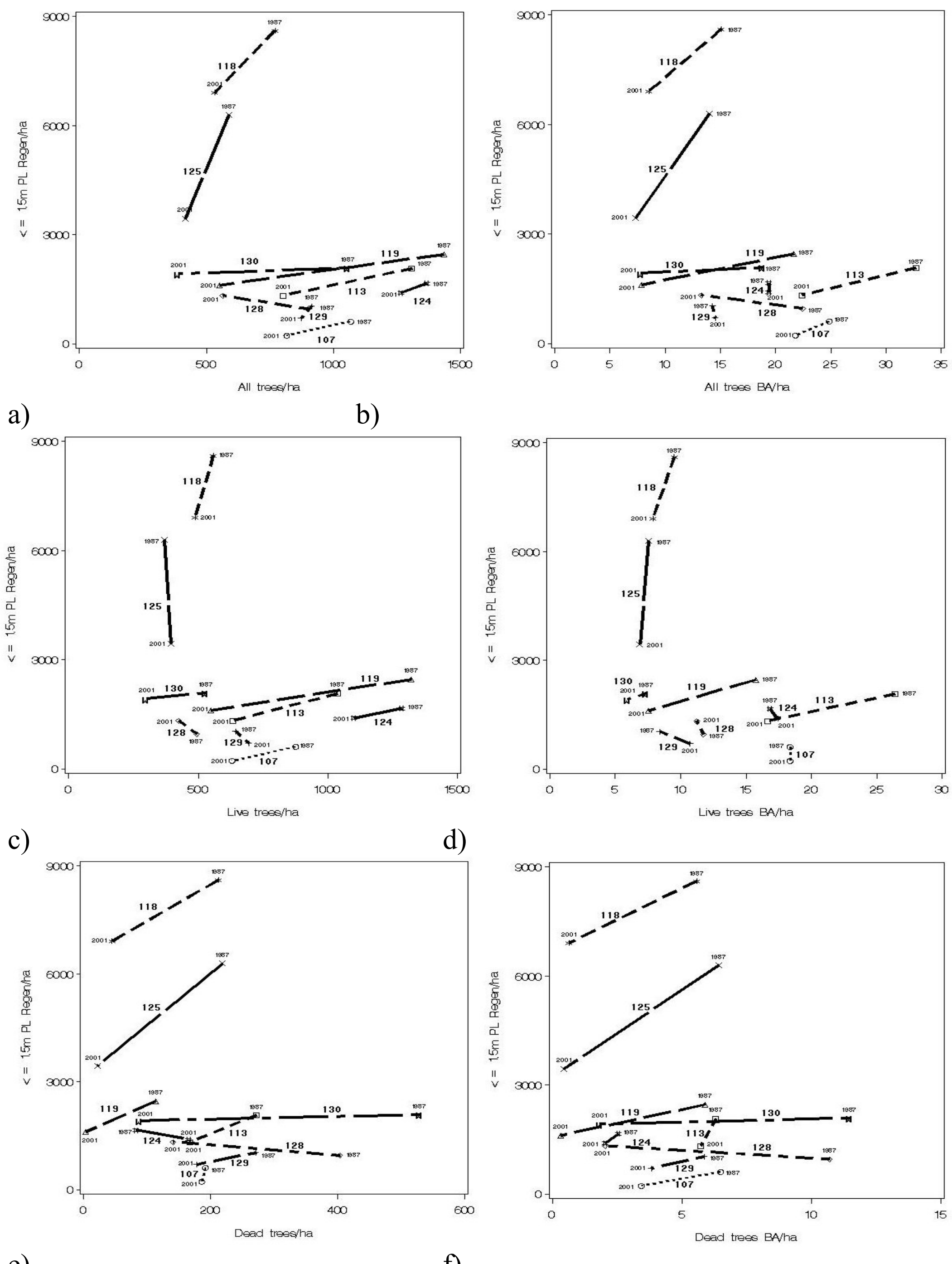


Figure AIII.9. Lodgepole pine seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

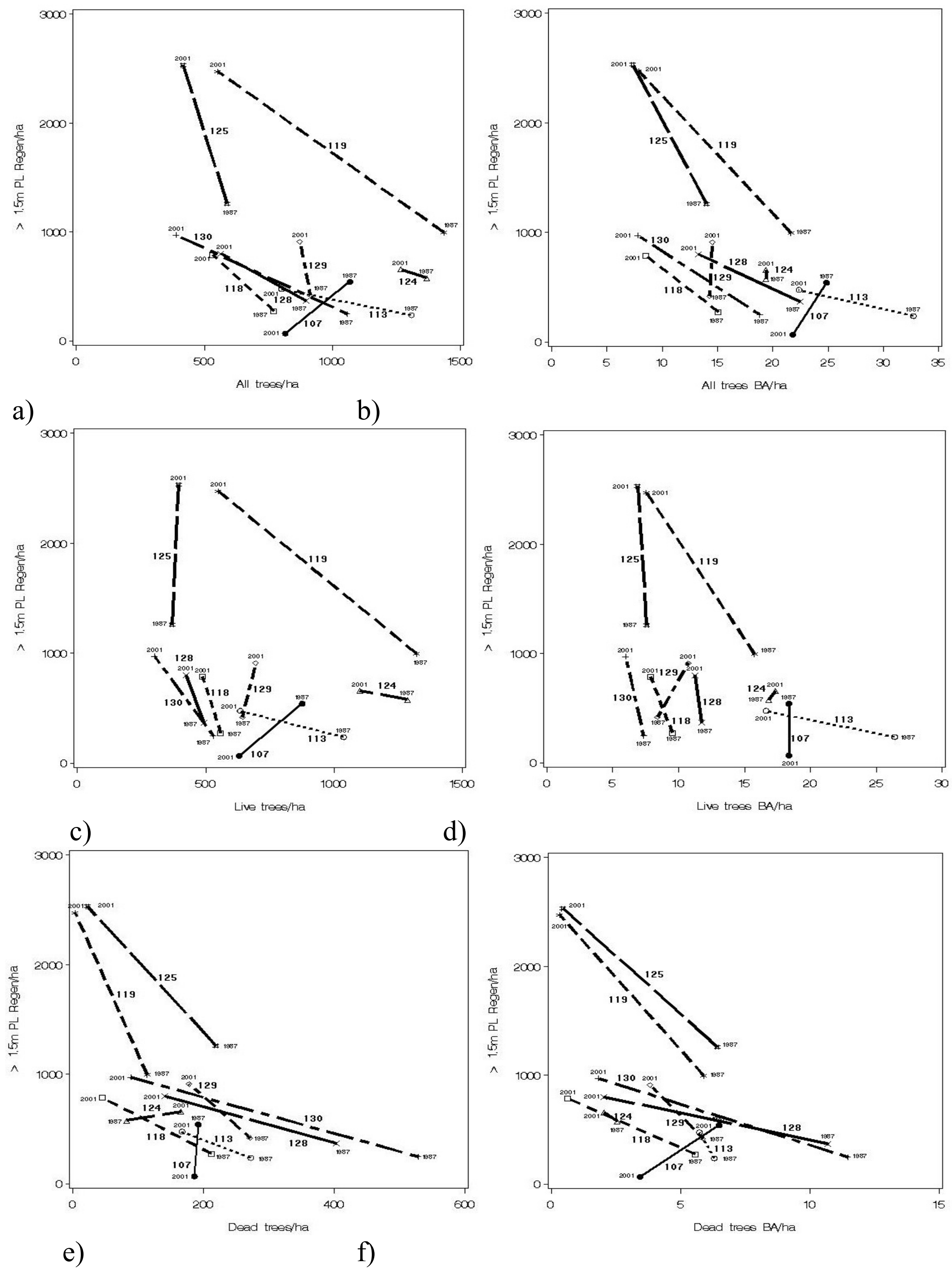


Figure AIII.10. Lodgepole pine saplings (1.5m<height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

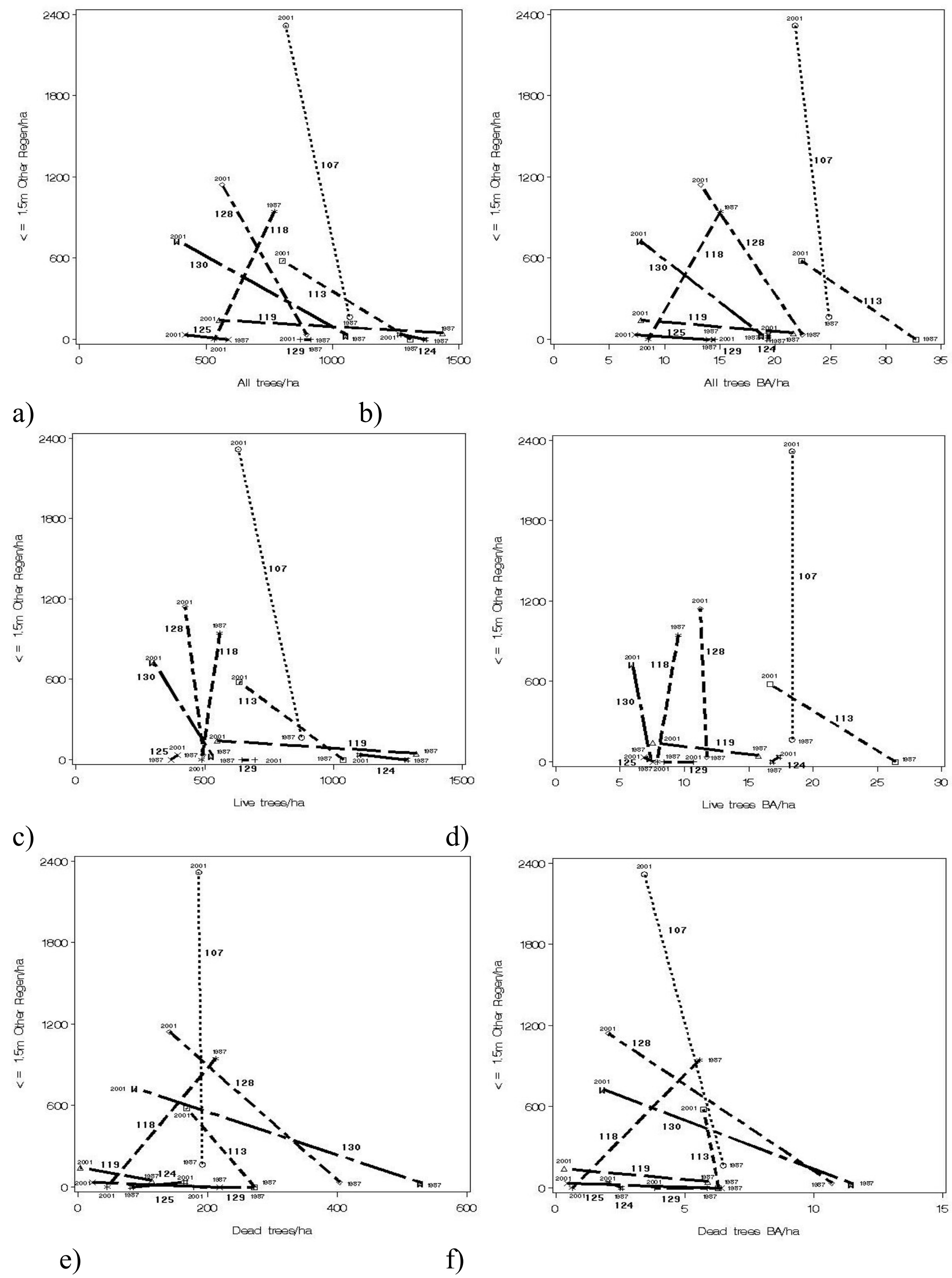


Figure AIII.11. Other seedlings (height≤1.5m) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

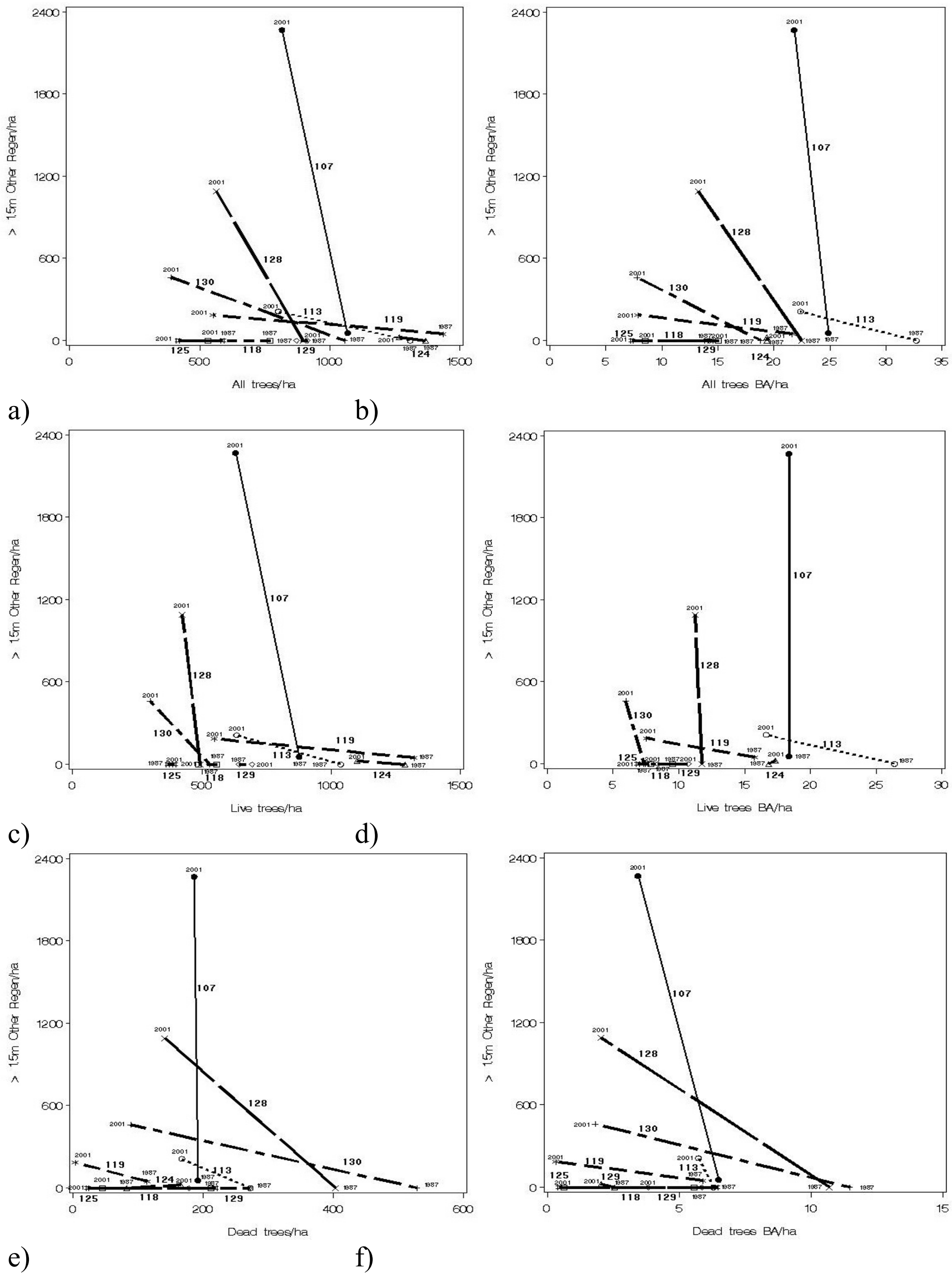


Figure AIII.12. Other saplings (1.5m〈height≤2m and DBH≤7.5cm) versus a) all trees/ha (DBH >7.5cm), b) basal area (BA) per ha of all trees c) live trees/ha, d) BA per ha of live trees, e) dead trees/ha, and f) BA per of dead trees in the SBPS zone for 1987 and 2001.

7.4 Appendix IV. Data Summaries by Data Source and BEC Zone

Table A.IV.1. Stand-level overstorey and regeneration characteristics for IDF between 1987 and 2001 (CFS Data).

BEC	stand	year	tph[1]	tph_L	tph_D	ba[2]	ba_L	ba_D	sph01[3]	sph_p01	sph_o01	sph02[4]	sph_p02	sph_o02	sph[5]	sph_p	sph_o
IDF	103	1987	1137	755	382	29	15	15	5366	5366	0	132	132	0	5498	5498	0
		2001	764	590	174	18	13	5	6459	5896	563	1936	1716	220	8395	7612	783
	104	1987	967	702	265	21	14	6	6061	5697	364	333	333	0	6395	6030	364
		2001	752	599	153	17	14	2	5366	4173	1192	1226	655	570	6592	4829	1763
	105	1987	1496	1220	276	32	26	7	7618	7618	0	0	0	0	7618	7618	0
		2001	1155	909	247	27	22	5	3202	3165	37	183	178	6	3385	3343	42
	116	1987	1270	732	538	29	14	15	6161	5233	927	132	132	0	6293	5366	927
		2001	828	527	301	20	14	6	14839	12289	2550	1231	620	610	16070	12909	3161
	121	1987	1286	1024	262	19	14	6	8233	8233	0	1189	1189	0	9422	9422	0
		2001	972	694	279	15	11	4	9890	9890	0	1358	1358	0	11248	11248	0
	126	1987	767	536	231	15	7	8	10351	10309	41	1099	1099	0	11450	11408	41
		2001	648	523	125	10	8	3	4513	3851	662	1407	1132	275	5920	4982	938
	301	1987	1037	700	337	41	21	19									
		2001	905	236	669	38	11	27	773	221	552	392	58	333	1165	279	885
	302	1987	1081	622	460	28	15	14									
		2001	907	544	363	21	13	7	1093	994	99	525	520	5	1618	1514	104
	304	1987	1060	575	485	38	22	16									
		2001	677	418	260	28	20	8	3180	66	3114	735	40	695	3915	106	3809

1: stems per ha for all standing trees (tph), live trees only (_L), and dead standing trees only (_D)
2: basal area per ha of all standing trees (ba), live trees only (_L), and dead standing trees only (_D)
3: stems per ha (sph01) for small all saplings (≤1.5m in height), pine saplings only (sph_p01), and non-pine (other) saplings (sph_o01)
4: stems per ha (sph02) of all larger saplings (1.5m<height≤2.0m, DBH≤7.5cm), pine larger saplings only (sph_p02), and non-pine larger saplings (sph_o02)
5: regenerated stems per ha, all species (sph), pine only (sph_p), and non-pine (sph_o)

Table A.IV.2. Stand-level overstorey and regeneration characteristics for SBPS between 1987 and 2001 (CFS Data).

BEC	stand	year	tph[1]	tph_L	tph_D	ba2	ba_L	ba_D	sph01[3]	sph_p01	sph_o01	sph024	sph_p02	sph_o02	sph5	sph_p	sph_o
SBPS	107	1987	1069	877	192	25	18	7	773	607	166	596	541	55	1369	1149	221
		2001	817	631	186	22	18	3	2539	221	2319	2335	67	2268	4874	288	4587
	113	1987	1310	1038	273	33	26	6	2070	2070	0	236	236	0	2306	2306	0
		2001	803	636	167	22	17	6	1905	1325	580	688	475	213	2592	1800	792
	118	1987	771	558	212	15	10	6	9558	8612	946	274	274	0	9832	8886	946
		2001	533	488	45	9	8	1	6908	6908	0	786	786	0	7695	7695	0
	119	1987	1436	1322	114	22	16	6	2508	2461	47	1042	995	47	3550	3456	95
		2001	553	549	4	8	8	0	1751	1609	142	2659	2473	186	4410	4082	328
	124	1987	1369	1286	83	19	17	3	1656	1656	0	577	577	0	2233	2233	0
		2001	1267	1101	166	19	17	2	1435	1399	37	678	656	22	2113	2054	59
	125	1987	588	369	219	14	8	6	6293	6293	0	1260	1260	0	7553	7553	0
		2001	417	395	23	7	7	0	3478	3445	33	2532	2532	0	6010	5976	33
	128	1987	898	494	404	22	12	11	994	957	37	368	368	0	1361	1325	37
		2001	565	424	141	13	11	2	2466	1325	1141	1890	801	1090	4356	2125	2231
	129	1987	915	643	272	14	8	6	1030	1030	0	418	418	0	1449	1449	0
		2001	873	695	178	15	11	4	699	699	0	912	912	0	1611	1611	0
	130	1987	1058	530	528	19	7	11	2120	2087	33	246	246	0	2366	2333	33
		2001	390	301	89	8	6	2	2650	1921	729	1431	971	460	4081	2892	1189

1: stems per ha for all standing trees (tph), live trees only (_L), and dead standing trees only (_D)
2: basal area per ha of all standing trees (ba), live trees only (_L), and dead standing trees only (_D)
3: stems per ha (sph01) for small all saplings (≤1.5m in height), pine saplings only (sph_p01), and non-pine (other) saplings (sph_o01)
4: stems per ha (sph02) of all larger saplings (1.5m<height≤2.0m, DBH≤7.5cm), pine larger saplings only (sph_p02), and non-pine larger saplings (sph_o02)

Table A.IV.3. Stand-level overstorey (post MPB attack, reconstructed) and regeneration characteristics (measured 2006) for IDF, SBPS, and SBS (FSP Data).

BEC	stand	tph[1]	tph_L	tph_D	ba[2]	ba_L	ba_D	sph01[3]	sph_p01	sph_o01	sph02[4]	sph_p02	sph_o02	sph[5]	sph_p	sph_o
	1	919	619	300	35.1	19.6	15.8	2266	0	2266	274	0	274	2540	0	2540
	7	767	542	225	45.1	34.3	10.8	7775	0	7775	1245	50	1196	9021	50	8671
	11	671	446	225	13.5	5.2	8.2	6711	2724	3987	1980	1806	174	8691	4530	4161
	12	951	776	175	28.4	17.9	10.5	3021	50	2971	1162	0	1162	4183	50	4134
	23	976	650	325	22.4	13.7	8.7	5547	2971	2575	1573	679	893	7119	3651	3469
	25	625	375	250	15.0	5.4	9.6	7429	2476	4952	1144	897	248	8573	3373	5200
	28	1032	751	284	21.1	11.4	9.8	4952	2773	2179	1441	747	694	6394	3520	2873
IDF	31	442	217	225	16.1	4.2	11.9	6834	5299	1535	5877	4149	1728	12712	9448	3264
	33	1132	807	325	18.8	14.0	4.7	3566	2823	743	509	261	248	4074	3084	991
	37	1207	1207	0	24.3	24.3	0	5646	3603	2043	769	669	99	6414	4272	2142
	46	994	738	256	18.8	10.5	8.3	5163	2860	2303	2697	935	1762	7860	3795	4065
	47	1268	1268	0	26.1	26.1	0	5695	1931	3764	1058	282	776	6754	2213	4540
	49	575	575	0	16.3	16.3	0	18014	17866	149	720	658	62	18735	18524	211
	51	482	419	63	16.3	14.2	2.1	3640	1263	2377	2003	737	1266	5643	2000	3643
	54	519	394	125	10.1	6.4	3.7	4717	3539	1189	1668	1631	37	6386	5160	1226
	55	867	634	233	20.8	11.6	9.2	3467	2377	1090	564	33	531	4031	2411	1620
	3	388	113	275	17.9	4.0	14.0	7429	6834	594	2368	2294	74	9797	9128	669
	5	375	188	188	15.6	3.4	12.3	1040	817	223	3000	2800	200	4040	3617	423
	6	475	288	188	18.8	9.7	9.1	5423	4903	520	3343	3343	0	8766	8246	520
	16	482	256	225	18.3	9.3	9	5349	5014	334	2164	2127	37	7513	7141	371
	17	1268	742	525	23.1	15.4	7.7	5002	4952	50	1364	1364	0	6365	6316	50
SBPS	18	892	751	142	23.8	17.4	6.4	1238	743	495	863	481	382	2101	1224	877
	19	1076	851	225	25.5	20.5	4.9	1189	409	780	1220	112	1108	2409	521	1888
	24	684	450	233	27.3	18.4	8.9	990	842	149	2482	1999	483	3473	2841	632
	30	1413	951	463	38.0	28	10.1	1783	1189	594	797	500	297	2580	1689	891
	36	1576	1576	0	45.2	45.2	0	2476	0	2476	1327	0	1327	3803	0	3803
	48	1876	1876	0	32.7	32.7	0	446	149	297	883	850	33	1329	999	331

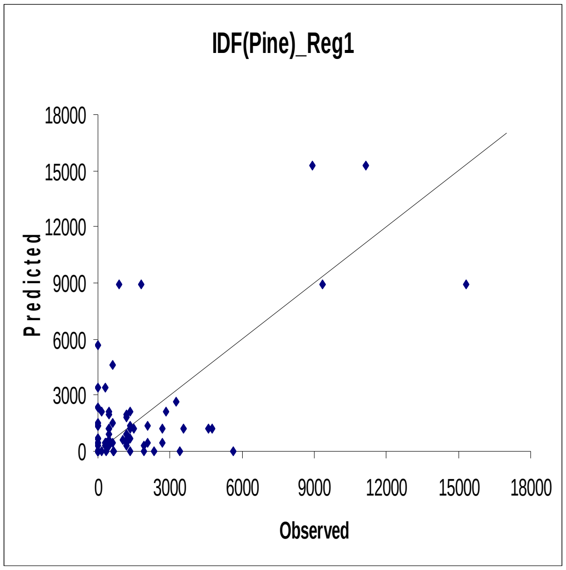
1: stems per ha for all standing trees (tph), live trees only (_L), and dead standing trees only (_D)
2: basal area per ha of all standing trees (ba), live trees only (_L), and dead standing trees only (_D)
3: stems per ha (sph01) for small all saplings (≤1.5m in height), pine saplings only (sph_p01), and non-pine (other) saplings (sph_o01)
4: stems per ha (sph02) of all larger saplings (1.5m<height≤2.0m, DBH≤7.5cm), pine larger saplings only (sph_p02), and non-pine larger saplings (sph_o02)
5: regenerated stems per ha, all species (sph), pine only (sph_p), and non-pine (sph_o)

Table A.IV.3 (con't). Stand-level overstorey (post MPB attack, reconstructed) and regeneration characteristics (measured 2006) for IDF, SBPS, and SBS (FSP Data).

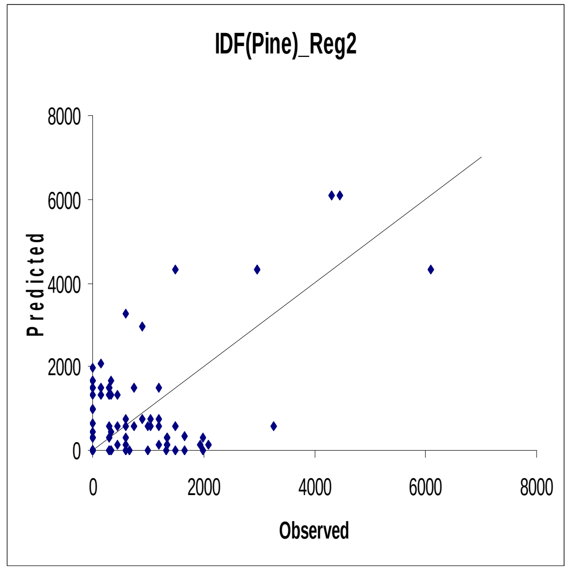
BEC	stand	tph[1]	tph_L	tph_D	ba[2]	ba_L	ba_D	sph01[3]	sph_p01	sph_o01	sph02[4]	sph_p02	sph_o02	sph[5]	sph_p	sph_o
SBPS	2	842	509	334	16.3	8.4	7.9	16492	11242	5250	3067	365	2702	19558	11607	7951
	4	350	350	175	16.5	6.1	10.4	9905	5101	4804	1430	617	814	11335	5718	5618
	9	559	559	192	14.9	8.3	6.6	3566	1288	2278	2487	316	2171	6053	1604	4449
	10	1995	1995	0	29.3	29.3	0.0	446	111	334	324	0	324	769	111	658
	13	1217	742	475	22.0	12.5	9.5	2922	2625	297	67	33	33	2989	2658	331
	14	588	213	375	15.6	6.1	9.4	6834	6537	297	1974	1924	50	8808	8461	347
	15	517	208	309	17.1	6.4	10.7	2922	2377	545	3126	2861	265	6048	5239	810
	20	1421	1236	185	28.6	25.5	3.1	1931	1753	178	298	298	0	2230	2052	178
	22	869	751	119	17.6	14.0	3.6	3603	2191	1411	1282	760	522	4885	2952	1933
	27	851	688	163	21.9	17.3	4.6	4903	4234	669	769	421	347	5672	4656	1016
	32	1951	1951	0	30.5	30.5	0.0	990	495	495	1468	1468	0	2458	1963	495
	35	1243	759	484	27.5	14.5	13.0	5051	3368	1684	1031	981	50	6082	4349	1733
	39	1559	1559	0	20.3	20.3	0.0	3071	2872	198	1965	1849	116	5035	4721	314
	40	1726	1726	0	32.6	32.6	0.0	1634	1411	223	100	50	50	1734	1461	273
	41	882	782	100	12.3	9.9	2.4	1151	1114	37	1733	1733	0	2884	2847	37
	42	842	759	83	9.5	7.8	1.7	792	792	0	883	883	0	1676	1676	0
	43	1295	1295	0	14.5	14.5	0.0	1300	1300	0	3123	3097	25	4423	4398	25
	44	584	142	442	14.1	2.7	11.4	2724	2724	0	1378	1378	0	4101	4101	0
	45	363	275	88	7.2	3.1	4.1	149	149	0	700	700	0	849	849	0
	52	1885	1885	0	18.2	18.2	0.0	545	50	495	1467	1467	0	2011	1516	495
	53	1182	938	244	25.6	18.0	7.7	1597	1597	0	125	125	0	1722	1722	0
SBS	8	288	288	0	18.3	18.3	0.0	8097	223	7874	12709	174	12535	20806	397	20409
	26	1734	1351	384	65.2	52.3	13.0	1288	0	1288	1029	0	1029	2317	0	2317
	34	2368	2368	0	43.6	43.6	0.0	1733	446	1288	431	0	431	2164	446	1718
	38	1614	1489	125	34.1	32.4	1.7	1040	0	1040	649	0	649	1689	0	1689
	50	1192	1192	0	46.0	46.0	0.0	297	0	297	816	0	816	1113	0	1113

1: stems per ha for all standing trees (tph), live trees only (_L), and dead standing trees only (_D)
2: basal area per ha of all standing trees (ba), live trees only (_L), and dead standing trees only (_D)
3: stems per ha (sph01) for small all saplings (≤1.5m in height), pine saplings only (sph_p01), and non-pine (other) saplings (sph_o01)
4: stems per ha (sph02) of all larger saplings (1.5m<height≤2.0m, DBH≤7.5cm), pine larger saplings only (sph_p02), and non-pine larger saplings (sph_o02)
5: regenerated stems per ha, all species (sph), pine only (sph_p), and non-pine (sph_o)

7.5 Appendix V. Graphs of Estimated Versus Measured Regeneration by Plot



a)



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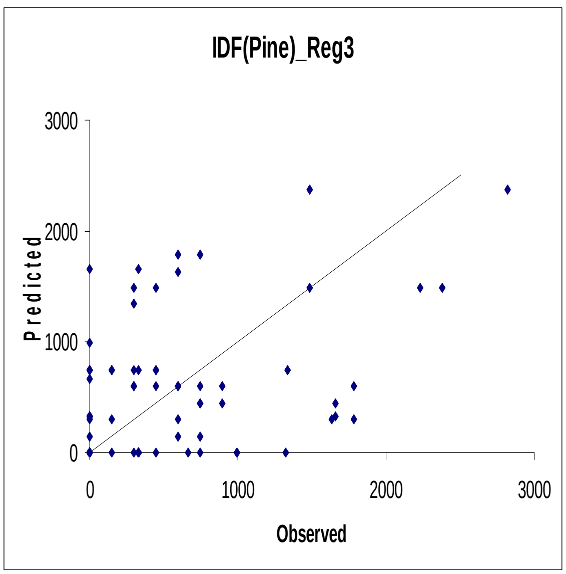
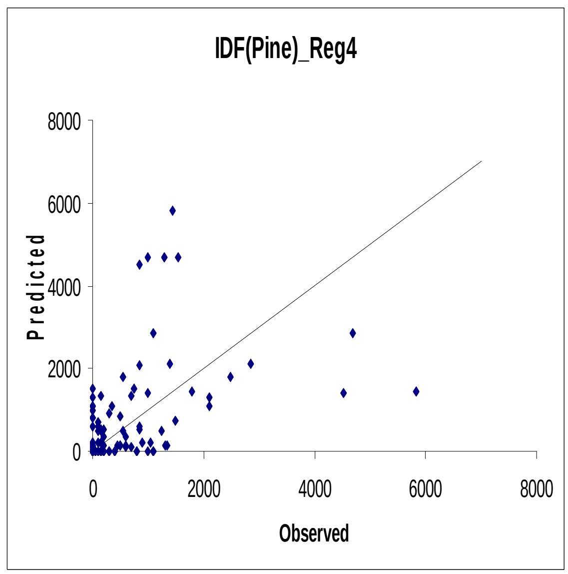
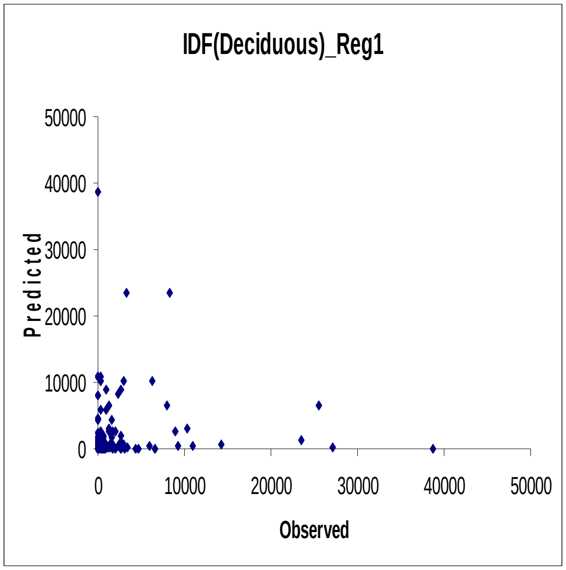


c)



d)

Figure A.V.1. Observed vs. predicted regeneration by species class (Pine) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in IDF using MSN and the overstorey and regeneration measures in the combined data.



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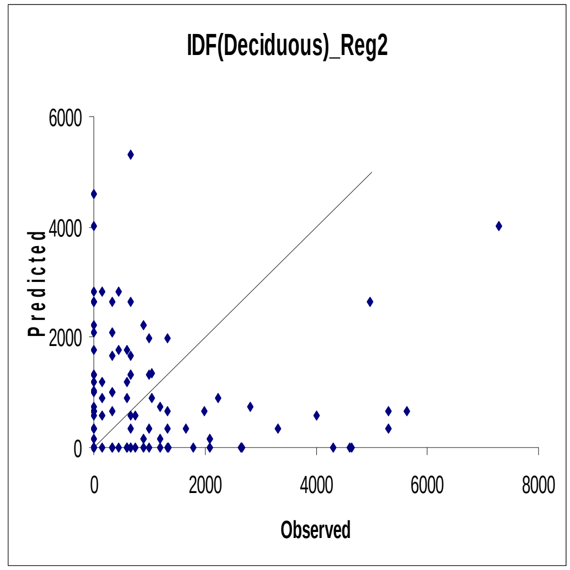
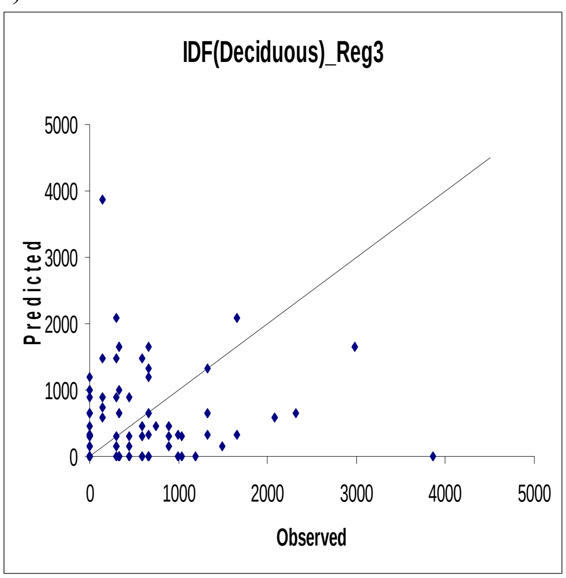
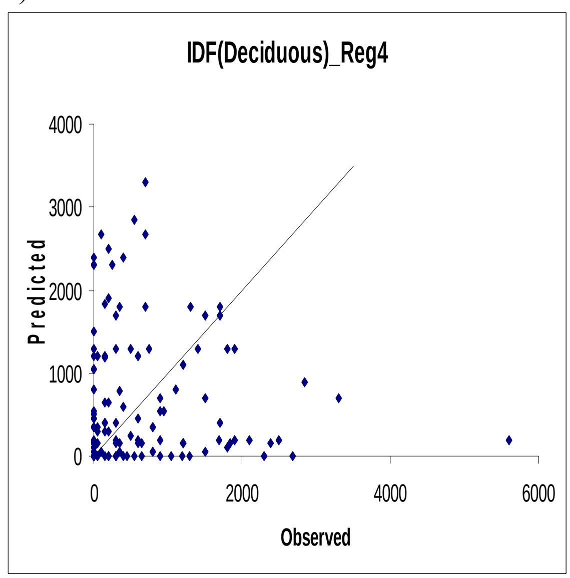


b)

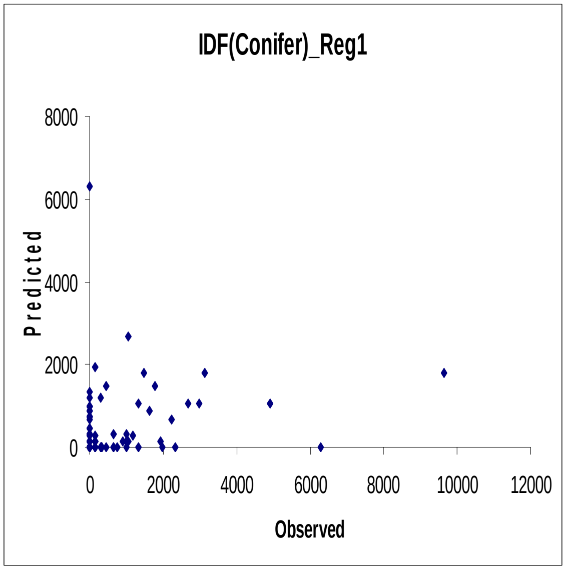


c)

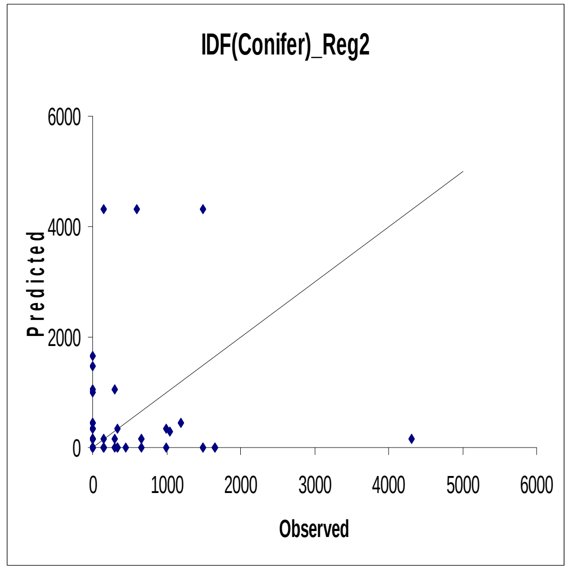


d)

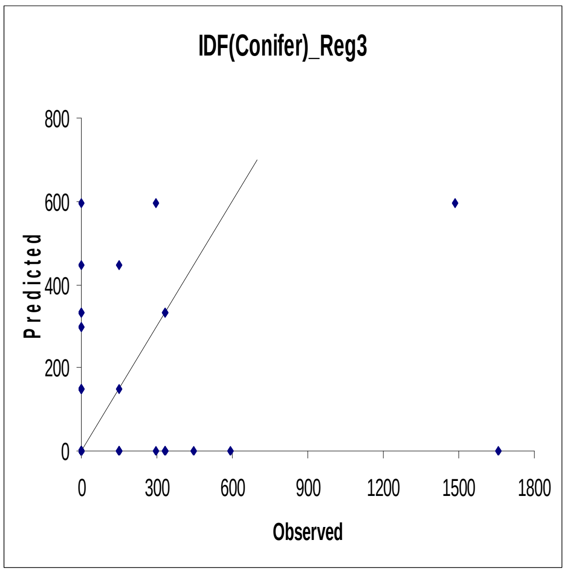
Figure A.V.2. Observed vs. predicted regeneration by species class (Deciduous) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in IDF using MSN and the overstorey and regeneration measures in the combined data.



a)



b)



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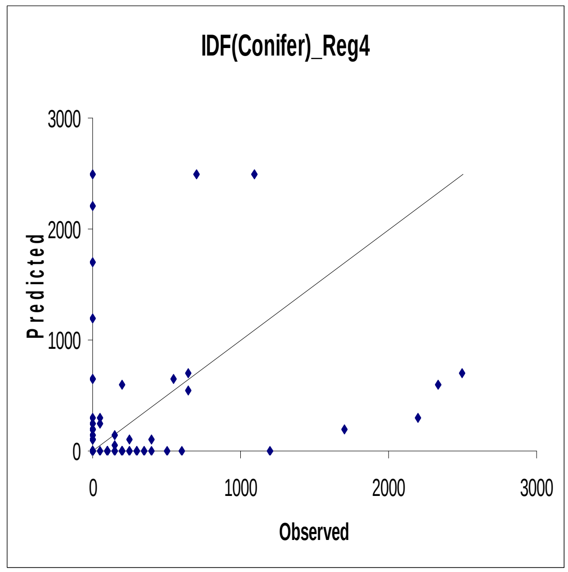
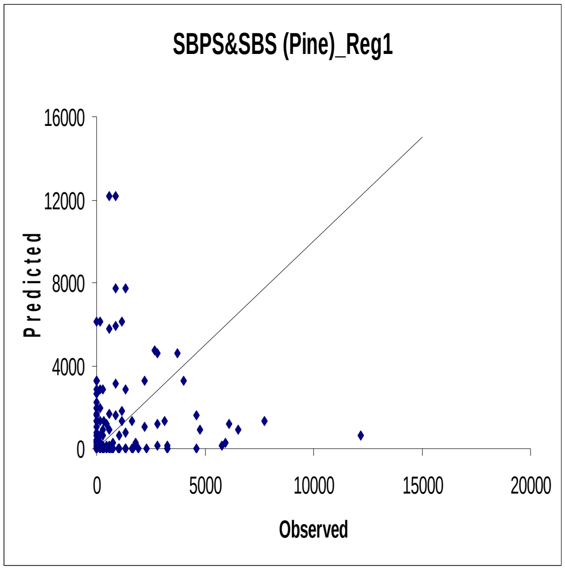


d)

Figure A.V.3. Observed vs. predicted regeneration by species class (Conifers except pine) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in IDF using MSN and the overstorey and regeneration measures in the combined data.



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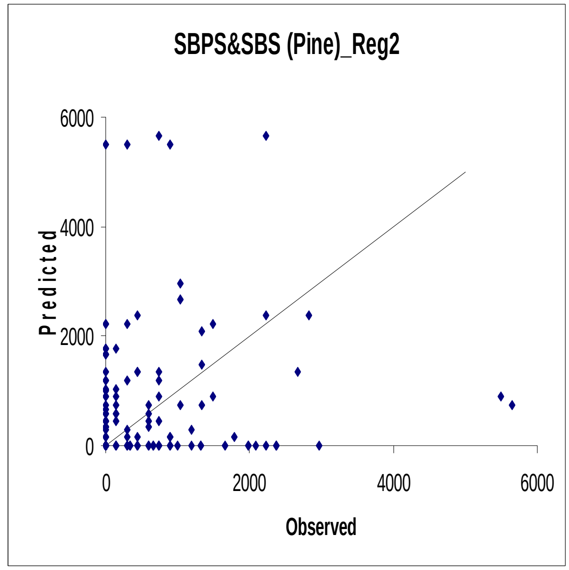

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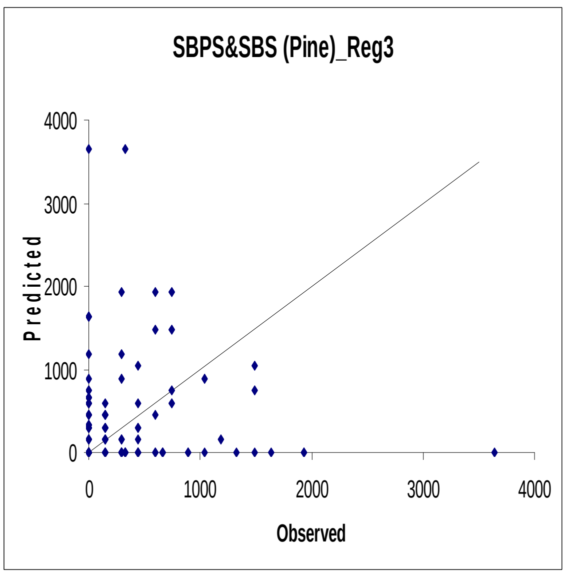

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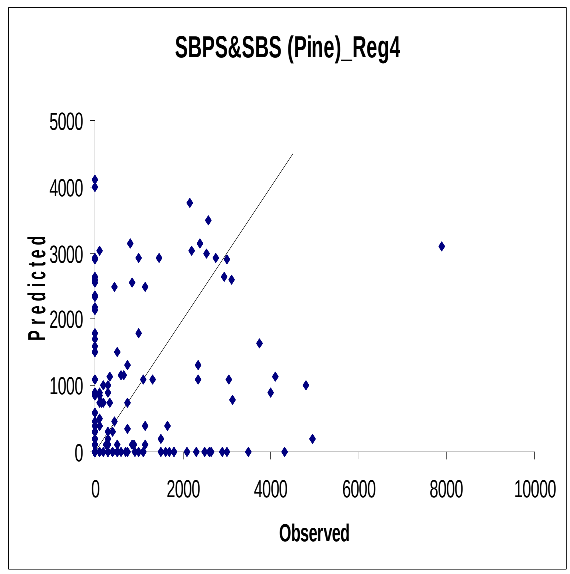
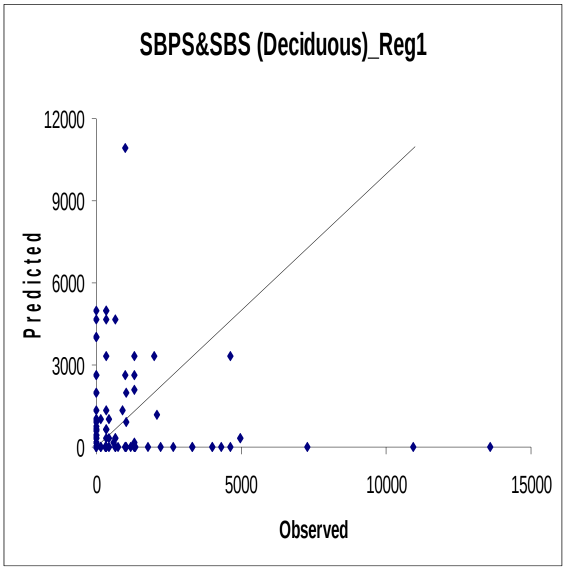


d)

Figure A.V.4. Observed vs. predicted regeneration by species class (Pine) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in SBPS and SBS using MSN and the overstorey and regeneration measures in the combined data.



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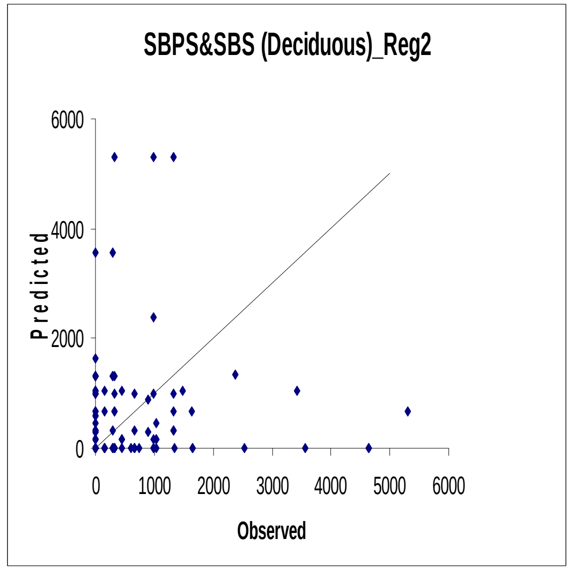
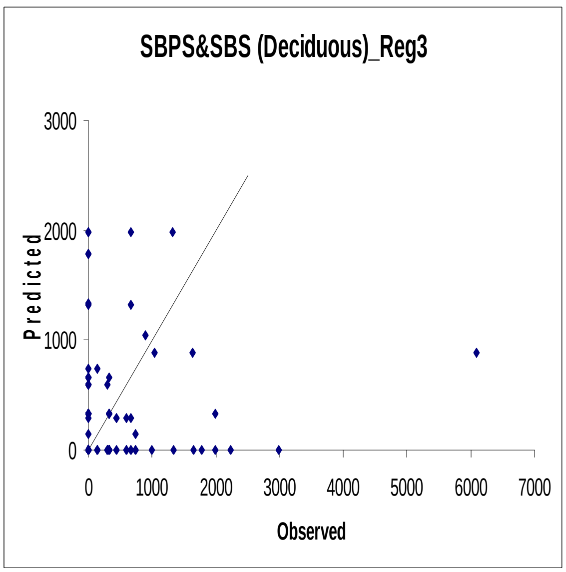
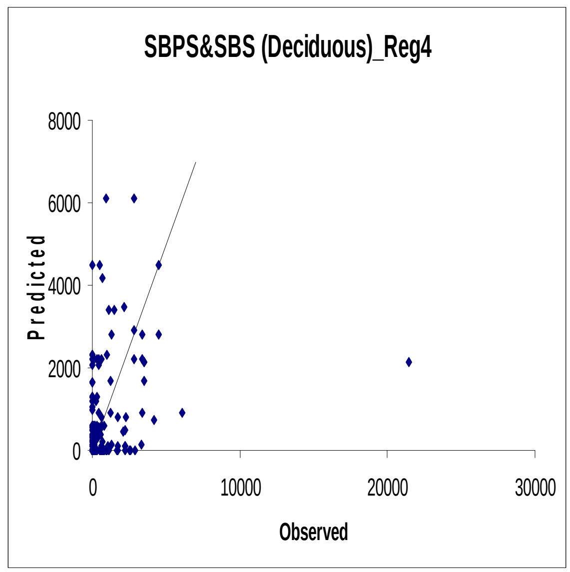


b)



c)



d)

Figure A.V.5. Observed vs. predicted regeneration by species class (Deciduous) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in SBPS and SBS using MSN and the overstorey and regeneration measures in the combined data.

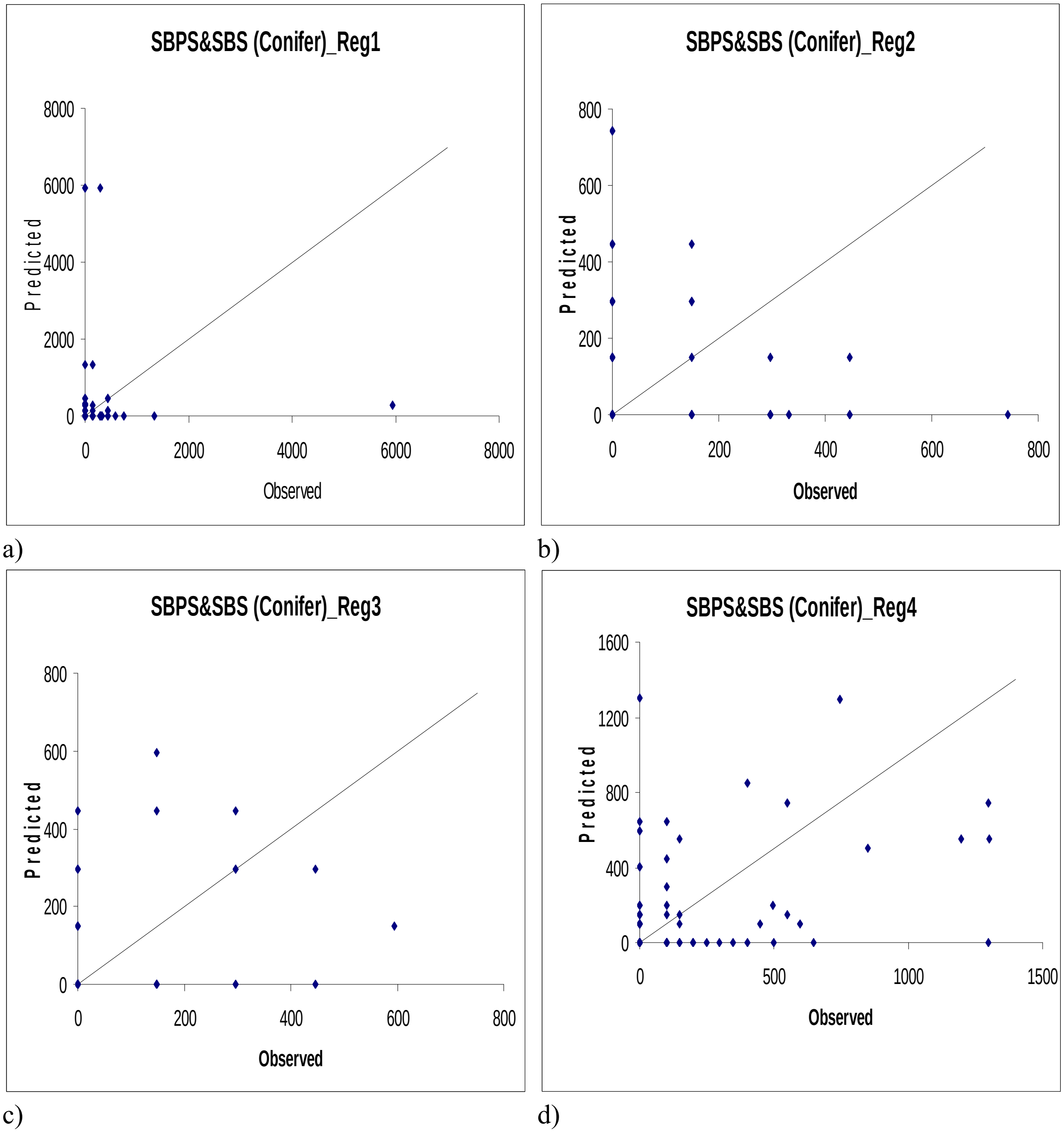


Figure A.V.6. Observed vs. predicted regeneration by species class (Conifers except pine) and size class (a) 0-0.5m, b) 0.5-1.0m, c) 1.0-1.5m in height, d) 0-7.5cm in DBH) in SBPS and SBS using MSN and the overstorey and regeneration measures in the combined data.

7.6 Appendix VI. Summary of Changes to the Regeneration Database

The regeneration database was originally conceived and developed in previous projects to estimate regeneration under partially cut stands. Under this project, the database has grown from 1,038 to 1,234 stands, with several plots measured in each stand. Actual tree data records have also grown accordingly (Table VI.1).

Table A.VI.1. Number of records in regeneration database.

Table Name	Records		
	Previous	Current	Added
LargeTrees	14,119	23,797	9,678
SmallTrees	12,004	16,145	4,141
Regeneration	36,794	44,483	7,689

The database is freely available, but additions to the database are carefully managed to insure accuracy, quality and continued usability for the Prognosis^{BC} growth and yield modelling system. The current totals shown in Table VI.1 include plot data provided by the Canadian Forest Service with measured overstorey in 1987 and regeneration in 2001.

Besides the substantial increase in the number of records noted above, there have been changes to the database structure. Some changes – required index fields and default values – are invisible but will strengthen future database additions. Eleven new tables have been added to support the inventory of snags, pathology and substrate. These new tables are summarized in Table VI.2, along with some of the more important data fields in each table.

In addition to new tables, new fields have been added to eight existing tables (Table VI.3). These additions reflect linkages for metadata and records for new data classes.

Table A.VI.2. Data tables added to regeneration database.

New Table Name	Comment	Fields
DataSource	Metadata for LargeTrees, SmallTrees and Regeneration records	DataSourceID, ProjectName, FirstName, LastName, StudyYear, Affiliation, PhoneNumber, Email, Comment, Summary
Datum	Georeference datum	
DecayClass	Snag decay classes	
HeightMethod	Height estimation method	
PathologyRemark	Pathology comments	
RegenSubstrate	Class and amount of substrate around regeneration	DBPlotID, SubPlotID, SubstrateTypeID, SubstrateID, Percentage
SnagCause	Disturbance that created snag	
Substrate	Substrate types	'conifer litter', 'lichen', *etc.*
SubstrateType	Substrate measurement method	
TreeStatus	Live or dead status	'down', 'snag' or 'live'
YearSinceDisturbanceMethod	Disturbance estimation method	

Table A.VI.3. Fields added to exiting tables in regeneration database.

Modified Table Name	New Records Added
BEC	6 BEC zones/subzones
HeightClass	2 height classes
LargeTrees	HeightDeterminationID, BrokenTopHeight, CrownWidth1, CrownWidth2, CrownRatio, TreeStatusID, SnagCauseID, DecayClassID, PathologyRemarkID, and DataSourceID
PlotInfo	GPSX,GPSY, DatumID, ForestCoverID, MapSheetID, YrSinceDisturbanceID, Stand, Plot and DataSourceID
Regeneration	DataSourceID
SmallTrees	TreeStatusID, CrownRatio and DataSourceID
Species	1 species
Disturbance	mountain pine beetle, low fire, ice storm, root disease and unknown

Under this project, analyses of the conditions found in stands attacked by mountain pine beetle have led to the revision of the site and for stand indicators to be used for stand matching. These revised indicators (X variables) are shown in Table VI.4, and have been implemented as a stand-alone executable program that links the Prognosis[BC] with the MSN software.

Table A.VI.4. Variables used to imput regeneration for partially cut stands (current) versus stands following MPB attack (current).

<table>
<tr><th rowspan="2">X variable</th><th colspan="2">MSN Model Terms</th></tr>
<tr><th>Previous</th><th>Current</th></tr>
<tr><td>BEC + Site Series</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Site Series</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Slope Position Class</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Site Preparation Class</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Disturbance Class</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Years Since Disturbance</td><td style="background:#aaa"></td><td style="background:#aaa"></td></tr>
<tr><td>Aspect (class)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Slope (%)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Elevation (m)</td><td style="background:#aaa"></td><td style="background:#aaa"></td></tr>
<tr><td>QMD (cm)</td><td style="background:#aaa"></td><td style="background:#aaa"></td></tr>
<tr><td>CCF</td><td style="background:#aaa"></td><td style="background:#aaa"></td></tr>
<tr><td>Shade Tolerant (/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Semi -Tolerant (/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Shade Intolerant (/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Shade Tolerant (m^2/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Semi -Tolerant (m^2/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Shade Intolerant (m^2/ha)</td><td style="background:#aaa"></td><td></td></tr>
<tr><td>Non-pine conifer (/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Pine conifer (/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Deciduous (/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Non-pine conifer (m^2/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Pine conifer (m^2/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Deciduous (m^2/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Pine snags QMD (cm)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Pine snags (/ha)</td><td></td><td style="background:#aaa"></td></tr>
<tr><td>Pine snags (m^2/ha)</td><td></td><td style="background:#aaa"></td></tr>
</table>

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