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CONNECTING INVENTORY INFORMATION SOURCES FOR LANDSCAPE LEVEL ANALYSES

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ABSTRACT. In forest landscape level analyses, forest information is commonly represented by separate polygons, defined by differences in species composition, stand structure, crown closure, and productivity. The simplest approach to projecting yield of stands over the land base is to create an aggregated yield table, weighted by area of each stand type (groups of polygons with similar attributes) as a means of projecting future volume per ha and other attributes. At the other end of complexity, each polygon is projected forward, using a particular management pathway where a record of each tree (and other elements) is maintained. Polygons may also be subdivided and/or recombined based on changes over time, and on features identified on other data sources (e.g., soils maps). As information needs increase, the trend has been toward the more complex approach to landscape level analysis. However, data are commonly limited, in terms of attributes, space, time, and management pathways represented. As a result, most resource managers rely on the very simple projection of forests in time, using an aggregated yield table. Others try to represent this spatial complexity via spatial mapping using polygons defined on aerial photography or other remotely sensed media. Gains have been made in presenting the spatial maps in Geographic Information Systems, and in producing models for a variety of attributes and management pathways, often by producing hybrid models. However, improved linkages between models, ground data, and spatial maps are needed, as are statements of model accuracy at larger spatial and temporal scales. For Canada, the spatial and temporal scales are particularly of interest, since the forested area is very large, and tree species have long life spans. This study discusses and compares commonly used methods to link data sources, using a small land area of about 5,000 ha located in British Columbia, Canada.

Key words: projection of forest land, landscape level analysis, linkages across scales.

1 INTRODUCTION

Forest lands in Canada occupy 417.6 million ha, representing approximately 50% of the land area, and 10% of the World's forests (Canadian Forest Service, 2003). Most of Canada's forest lands are public lands (94%). Information needs have increased, in terms of longer time periods, more variations on management pathways (i.e., timber extraction, stand amelioration, planting, etc.) and a greater number of attributes of interest. However, the Canadian population is small, with about 31.4 million people mostly located along the Southern border with the US. Access for much of Canada's forests is limited to air travel, much of the work in gathering ground data is limited to six months or less in a given year, and terrain is rugged, with great changes in elevation in many parts of Canada, and dispersed water bodies and swamps in other parts of the country. At the same time, the forests are quite variable, with high productivity Pacific Coastal Forests in the extreme west of the country, deciduous forests in the south-centre, and tundra in the North. As a result, information for many forests is limited to remotely sensed data from airborne and satellite platforms. Ground data are sparse, with larger concentrations in the south and where timber extraction takes place.

Forest management is largely a provincial responsibility. However, the Canadian Forest Service is responsible for providing statistics on the entire forested land base of Canada. Two approaches have been used. The first involves collection of provincial and territorial summarized inventory data, and

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summarizing this for country-wide statistics. This has resulted in reporting the area of forests, annual harvests, separation into coniferous versus deciduous areas, and other statistics that are particularly useful in tracking forest land and timber. However, this has not led to reports of other information, such as carbon balance, habitat analysis, or biodiversity. Although changes in the forests can be viewed as a difference in reports, this may not be strictly true as definitions of forested lands may have changed between reports. The second approach is heavily weighted toward the use of remote sensed data, particularly, satellite-based data, as a means of tracking changes over time1. Reporting is expected to be for broad ecological units, rather than by province. This would likely improve the ability to evaluate change in major features (e.g., area of forested land) over time. However, reports by province will likely not be accurate, and therefore, are not planned. Also, there are many challenges in combining ground information, collected at very widely spaced grid points, and remotely sensed data, to provide the information of interest, such as carbon balance.

Within each province, the forest land is divided into land parcels (management units). Licenses to extract timber range from small areas to management units. Companies with licenses for large land areas are generally required to produce management plans, whereas provincial governments produce management plans for smaller land areas licenses (or volume cuts). Each forested area is viewed as a collection of polygons, defined by differences in species composition, structure, and productivity, based on remotely sensed data (aerial photography and other remotely sensed imagery). The simplest approach to projecting each land parcel in time is to create an aggregated yield table, weighted by growth type, resulting in a simple summary of expected future attributes. This simplest approach is still used in some areas of Canada to indicate possible harvest levels, even though spatial data (e.g., forest cover maps, topography maps, soil maps) exist. At the other end of complexity, each polygon is projected forward, using a particular management pathway and a calibrated projection model, and a record of each tree (and other elements) is maintained. In this complex approach, changes in productivity, stand composition, and other attributes can be introduced for each polygon, based on information from other layers (e.g. soil, climate data, etc.). Summaries are then based on these detailed data. Greater “realism” can be introduced and a greater number of attributes can be modeled. This most complex approach is rarely (perhaps never, in Canada) used.

Most commonly in Canada, and in other countries, landscape level analyses (management unit and country-wide level) are based on an approach between these two extremes. Modeling is simplified from the most complex approach through 1) aggregations of polygons with similar growth types and management pathways (e.g., Whitehead *et al.*, 2001; Glauner *et al.*, 2003); and/or 2) simplifying models to require only a few inputs (e.g., using a stand level model or using a simpler process model, e.g., Landsberg and Waring, 1997; Coops *et al*,. 1998), that are available on aerial photography or other remotely sensed media. Frequently, local data on specific model inputs are missing, and are estimated by values reported for other species, forests types, and locations (e.g., Whitehead *et al.*, 2001).

Bettinger (2001) summarized the issues in linking models of vegetation dynamics with landscape planning tools. Some of the considerations that he raised were: 1) what forest inventory data are available, and where are these data located (spatial distribution over the land area); 2) are the data current; 3) what attributes are available in the data; 4) what projection models are available and what type; and 5) how should structure be summarized and at what point in the projection process? Mäkelä *et al.* (2000) expressed concern that landscape level models be examined to ensure that underlying processes are maintained. Johnsen *et al.* (2001) gave a summary on the issues of approaching the more complex end of the modeling spectrum. They noted that empirical models, often based on projecting whole stands (polygons) forward in time, are accurate, since the variables of interest are being projected. However, the use of hybrid models results in greater amplitude, including the ability to introduce changes, natural or human-induced. Stage (2003) noted that the accuracy of model forecasts depends on the accuracy of inventory data, the spatial and temporal variability of the variables that drive the models, and the stochasticity of the model.

For forests in Canada, linkages between spatial maps, data, and forecast models are absolutely essential. In this paper, we use a small land area in British Columbia (BC) to illustrate the issues in making and evaluating these connections.

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[1] See fact sheet at web address:
http://www.pfc.cfs.nrcan.gc.ca:80/news/InfoForestry/climate_change/ifnfi_e.html.

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2 AREA DESCRIPTION

The University of British Columbia (UBC) Malcolm Knapp Research Forest (MFRF) is approximately 5,044 ha in size[2] located in the southwest of British Columbia Canada. The forested area is classified as Coastal Western Hemlock (CWH) (Meidinger and Pojar, 1991) with moderately high productivity (up to 14 m^3/ha/year) similar to many southern BC coastal forests. Most common species are western red cedar (*Thuja plicata* Donn.), Douglas-fir (*Pseudotsuga menziesii* (Beissn.) Franco), and western hemlock (*Tsuga heterophylla* (Raf.). Other coniferous species include: true fir (*Abies amabilis* (Dougl.) Forbes and *Abies grandis* (Dougl.) Lindl.), sitka spruce (*Picea sitchensis* Bong. (Carr.)), shore pine (*Pinus contorta* var. *contorta* Dougl. Sarg), white pine (*Pinus monticola* Dougl.), western larch (*Larix occidentalis* Nutt., L), yellow cedar (*Chamaecyparis nootkatensis* (D.Don) Spach), and yew (*Taxus brevifolia* Nutt.). Deciduous species include: alder (Alnus rubra Bong.), bigleaf or broadleaf maple (*Acer macrophyllum* Pursh), vine maple (*Acer circinatum* Pursh), paper birch (*Betula paperifera* Marsh.), poplar (*Populus tremuloides* Michx. and *Populus trichocarpa* Torr & Gray), bitter cherry (*Prunus emarginata* Dougl.), cascara (*Rhamnus purshiana* DC.), and willow (*Salix* spp.). Unlike many areas in Canada, road access is quite good, especially, north to south. The terrain is rugged, with slopes well over 100% in many places. Because of the terrain, closed canopies, and the tall tree heights (up to 60 m), the effective use of Global Positioning System (GPS) measures is largely restricted to open areas (e.g., rock outcrops) and roads. The aspect is generally to the south towards a river floodplain. Major natural disturbances due to fires, landslides, or other impacts, occur only in very long time scales. Stand dynamics are mostly based on the creation of gaps, rather than the large changes due to fires that occur in much of Canada.

The MKRF is funded via timber sales, research projects, and other sales, such as the renting of camp facilities by user groups, and the use of the forests for movie scenes. Data are, primarily, managed by one person; funding for collection and detailed analysis of data is minimal. The population to the south is one of the largest localized populations in Canada (greater Vancouver area).

3 AVAILABLE FOREST INVENTORY DATA

In 1989, polygons were delineated using 1:15,000 black and white photography. Each polygon includes forest cover information on species composition (for six leading species), site index class (good, medium, or poor), height class (by 10 m), and crown closure class (by 20%). All spatial and attribute data were entered into a database and accessible via a Geographic Information System (GIS). Excluding water bodies, rock outcrops, and non-productive areas, there were 936 forested polygons identified on the 1989 photographs. Fifteen of these polygons had been recently harvested, prior to the collection of the 1989 photographs. Forested polygons ranged in size from 0.02 to 66.8 ha with an average size of 5.1 ha, covering a total of 4786 ha. The spatial and attribute data are periodically updated, based on aerial photography, and ground survey data, as trees are removed through harvest, windthrow, and other activities. As a result, the number of polygons has increased over time. As well as forest cover information, topographic and ecological classification maps are available. Remotely sensed data are also available. However, time series remotely sensed data are difficult to obtain because of extensive cloud cover in the coastal areas of BC (1,927 mm of precipitation in 2002). Also, there are four climate stations in the area, but only one is currently active.

Although the area has a great number of active research projects, these are spatially clustered. Ground data collected in 1995 do exist for trees measured in 82 plot clusters (3 to 5 plots in a cluster, with a centre plot and up to four plots in cardinal directions at 25m from the centre point) evenly spaced over the 5,044 ha area (Figure 1). Four grid positions were not recorded in the data base. Two of these are lakes, a third is a forested area on an extremely steep slope, and the fourth is a clear-felled area (no trees).

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[2] UTM Universal Transverse Mercantor Projection

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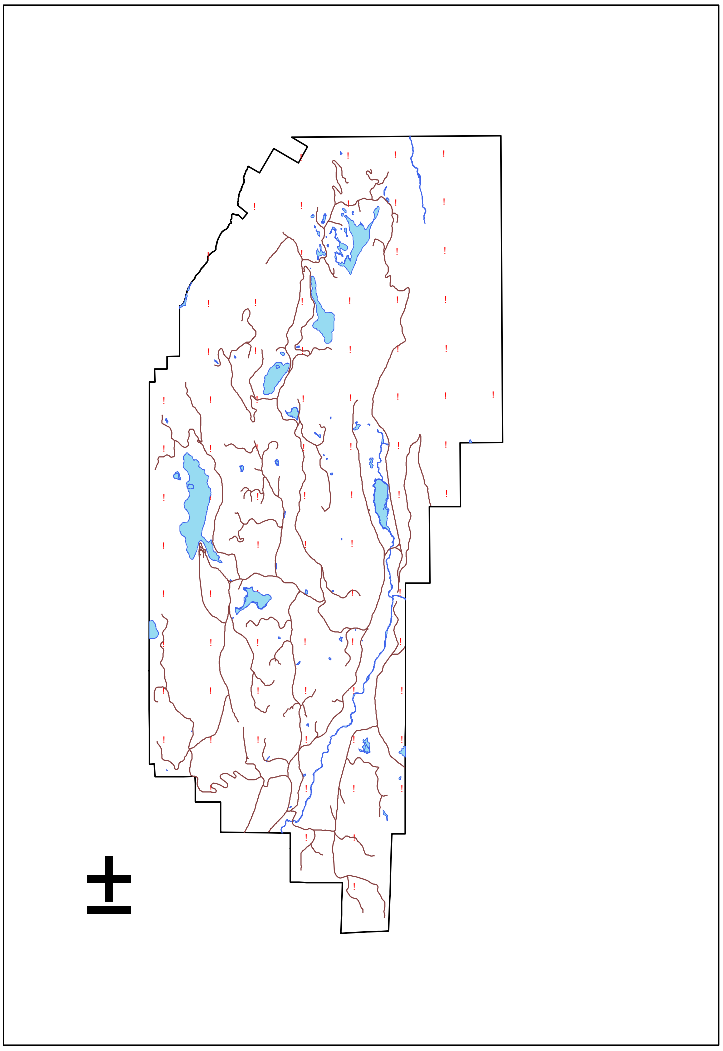

Figure 1. Plot cluster locations over the MKRF. Each dot indicates a cluster of three to five plots.

4 AVAILABLE MODELS

Accessible growth and yield (empirical) models include:

- Variable Density Yield Projection (VDYP), a stand level model, that utilizes aerially measured polygon data, and is calibrated for this area;
- The Tree and Stand Simulator (TASS), a tree-level, spatially dependent model, beginning with stand initiation. TASS, has been calibrated for this area, but is generally only available as a yield "look-up" model called TIPSY;
- A hybrid model developed by Kimmins *et al.* (1999) could also be used. This model uses VYDP as the base empirical model, and processes are modelled. However, specific inputs to the model are lacking for this area;
- Other projection models have been developed for the Pacific Coast in the US, but these have not been calibrated for this area, and some are proprietary; and
- For landscape level analysis, the spatially explicit landscape forecast model called ATLAS (Nelson 1999) was developed at the University of BC and is available for use in this area.

There is no single-tree projection model available and calibrated for this area that will project an existing stand forward in time. For clear-felled stands, TASS (or TIPSY) is available and is calibrated for this location.

5 LINKAGE APPROACHES

Several ways of combining ground and spatial data with models were used. In all cases, catastrophic mortality was not included and is rare in this area. Also, no removal of trees was simulated, similar to the no harvest pathway used by Glauner *et al.* (2003). This restriction to one management path reduced the variability in the projection, thereby simplifying the problem. To make this more "plausible" a shorter time frame of only 30 years was used. These two simplifications would not be realistic for this area, particularly for the longer term. The starting date was 1989, close to the date of the ground data collection. Variables of interest, current and projected, were: average merchantable volume per ha, merchantable volume for all forested polygons combined, average mean annual increment, and average volume per ha (and percentages) by species. Changes in these variables were also of interest. These values are commonly available on forest inventory data. Also, these methods could be used for any ground- measured variable, if a method to project that variable was available.

Results for several approaches were obtained, representing different levels of spatial aggregation, and ways of utilizing the ground and aerial data with the models. Since a single-tree growth projection model was not readily available for this area, imputation and projection of tree-lists was not included in the methods (Temesgen *et al.*, 2003).

5.1 Grid points only. The ground dataset is a representative sample, and, therefore is an unbiased (nearly, as this is a systematic sample) estimate of each attribute for 1995. For the current attributes, the plot clusters were averaged (Grid Points, Ground). Also, 95% confidence intervals based on estimators for simple random sampling were obtained for the average volume per ha. The four missing grid points were treated as follows:

- A grid point was added to the data to represent the point in the cleared area, resulting in 83 clusters in the ground data. Each stand attribute was given a zero value;
- Two of the missing grid points were in lakes not included in the 4786 ha of forested areas, and therefore, excluded from the analysis; and
- The grid point in the forested area with extreme terrain was treated as missing data. It was assumed that this point would not have different attributes from the remaining data; therefore, no change was made to the remaining data to accommodate this missing point.

Since no tree-level model was available to project existing stands, the detailed ground data could not be used directly to obtain projected attributes.

The grid positions were then overlaid onto the forest cover map, and the aerial attributes for the polygon in which the grid point resided were then used with VDYP to obtain current and projected estimates of attributes. For the one grid point in a clear-felled area, TIPSY was used to obtain the future attributes. Averages for attributes were calculated using these model-estimated attributes, current and projected (Grid Points, Aerial). Since the error associated with these estimates is unknown model and measurement (or classification) error, no confidence interval was calculated for the average volume per ha.

The ground and aerial information were then combined, and the relationship between the current volume per ha using the ground data versus the model estimates based on the aerial data was examined. The relationship was then used to adjust the model estimated current and future volumes per ha (Grid Points, Aerial+Ground). The base model for this relationship was:

$$\hat{y}_i = \beta_0 + \beta_1 \times x_i^{\beta_2} \tag{1}$$

where $\hat{y}_i$ is estimated ground volume (m^3/ha); x_i is the aerial volume, estimated using measures on aerial photographs as inputs to a stand level yield model; and β_0, β_1, and β_2 are model parameters. Although the restriction of $\beta_0 = 0$ to obtain a zero estimated ground volume when the aerial volume was zero is intuitively appealing, this might not be supported by the data. Errors in measurement, in the models used to obtain aerial volumes, and/or registration of data sources may contribute to obtaining non-zero ground volumes when aerial volumes are zero.

To obtain the future species volume per ha estimates (and proportions by species) for the Grid Points, Aerial+Ground, two approaches were used:

- The proportions using the ground data were applied to the current and projected volume per ha to obtain species volumes (Grid Points, Aerial+Ground, Ground Percents); and
- The proportions using the aerial information in which the cluster resided were used to obtain the current and projected volume per ha by species (Grid Points, Aerial+Ground, Aerial Percents).

This approach is more commonly associated with monitoring forest land area, where ground sample data located on a widely spaced grid are available for large land areas.

5.2. Aerial (forest cover) data, all polygons. Assuming that the aerial descriptors are correct and sufficient, and that the projection models are correct for this local area, each of the 936 polygons was projected using VDYP, based on the 1989 forest cover information. For the 15 recently cut polygons, TIPSY was used to obtain projected attributes (current attributes were all zero). Information for each attribute on each polygon was obtained at the beginning and end of the projection period, and averages weighted by area were calculated (Polygons, Aerial). Volumes per ha was also displayed as spatial maps. Since there is unknown model error, no confidence intervals were calculated.

This approach is commonly used with remotely sensed data for very large land areas, where a model is linked to the spatial data, without localized information on the specific attributes of interest.

5.3 Aerial and ground data, all polygons. The models are calibrated to this area of BC, but not localized to the MKRF. To localize the model projections, the relationship between the measured ground volumes per ha versus the model-estimated volumes per ha for the 83 grid points was used to adjust the yield estimates from the projections (Polygons, Aerial Adjusted). Species volumes were then obtained using the species proportions in the aerial data. For the current time period, this is the commonly used regression sampling method. For current volume per ha, confidence intervals were calculated using the regression sampling estimator for the standard error, where the mean of the auxiliary variable is known since there was a complete census of model-estimated aerial volumes.

This approach might be more commonly used for a small land area, where localizing the projection model is important, or for large land areas, where relationships are developed between ground and aerial data and applied to the entire land area (for a review of these and other approaches using remotely sensed data see Plummer (2000)). Stage (2003) emphasized the importance of correspondence between model and inventory estimates.

5.4 Aerial data, aggregated polygons. The projection of every polygon using the aerial information was repeated, except that polygons were aggregated into 37 yield strata, representing 6 species groups (Douglas-fir, red cedar, or hemlock dominated; mixed Douglas-fir, red cedar, and hemlock; mixed coniferous/deciduous; and deciduous), two crown closure groups, and three site groups, plus a separate group for the cleared areas. VDYP was used for all strata, except for cleared areas where TIPSY was used. Each forested polygon was then assigned to a yield stratum, and current and projected attributes for the strata were allocated to the polygon (Aggregated, Aerial).

This area had only 936 forested polygons, whereas larger land areas would have many more and likely larger less homogeneous, polygons. Aggregation of polygons into classes is commonly used, to reduce *modeling* time (e.g., Whitehead *et al.* 2001; Glauner *et al.* 2003). The level of aggregation varies with the complexity of the spatial landscape model. Models with more spatial constraints and management pathways to activities often have more aggregation of projection units to reduce the number of tables of current and projected attributes.

6 RESULTS AND DISCUSSION

6.1 Linking ground points to aerial data. Plots clusters were linked to the aerial data via the polygon number that was recorded with the data. However, there were some plot clusters that were in question, and these were linked via the spatial position of the plot cluster overlaid onto the 1989 GIS forest cover layer. In some cases, the correct aerial data was not clear (Figure 2).

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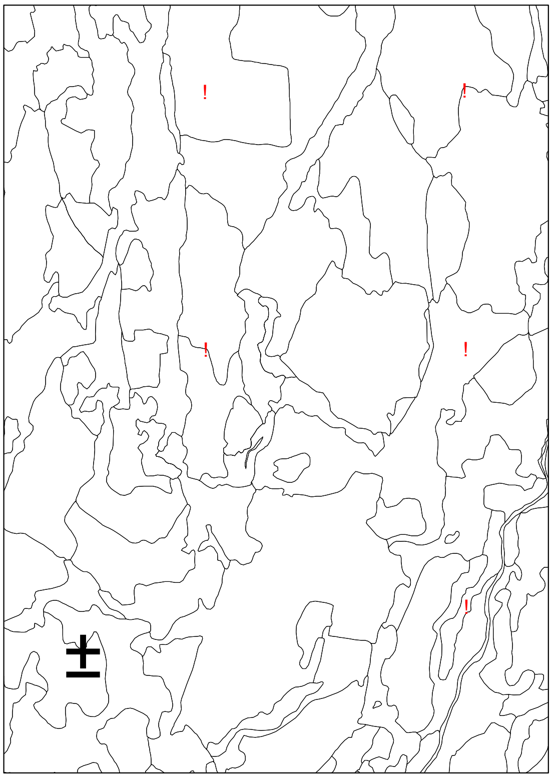

Figure 2. Linking ground points (points) to aerial data from polygons (lines); difficulties occurred where points intersected with a polygon boundary.

In that case, the information in the plot cluster was used to guide the selection of the associated polygon information. This is similar to the spatial imputation approach suggested by Halme and Tomppo (2001) to link ground data to satellite data pixels. This did highlight the problems in linking a grid of ground data to forest cover based on polygons. Ground sampling within polygons would provide a better linkage; however, polygon boundaries change over time. On the other hand, a grid of points is easier to link to a grid of remote sensed data such as that provided by satellite imagery and used by Halme and Tomppo. However, in both circumstances (grid points with satellite data or ground sampling within polygons), errors in spatial positioning will occur. The use of a global positioning system was used in the case of MKRF to locate plots where possible, but this was of limited value since it was not possible to get accurate positions under tall trees with nearly complete crown closure. For these latter plots, navigation from a note GPS location was used to reach plot centre.

6.2 Relationship between ground and model estimated volumes. Using a simple linear model, the relationship between the 83 ground measured volumes and the model estimated volumes using the aerial data (aerial volume) as inputs to the models was obtained.

$$\hat{y}_i = 165.785 + 0.69483 \times \mathrm{x}_{\mathrm{i}} \tag{2}$$

The model showed no lack-of-fit (Figure 3), had a coefficient of determination (R^2) value of 0.56, and had a root mean squared error of 163.10 m^3/ha. Other models were also tested, including restricting the intercept to zero, and allowing the power with aerial volume to vary from 1. However, restricting the intercept to zero volume was not justified, and a power other than 1 did not improve the fit. This did result in all zero model estimated volumes becoming 166 m^3/ha, and values were moved toward the indicated by the ranges of volumes Grid Point, Ground versus Grid Point, Aerial+ Ground (Table 1).

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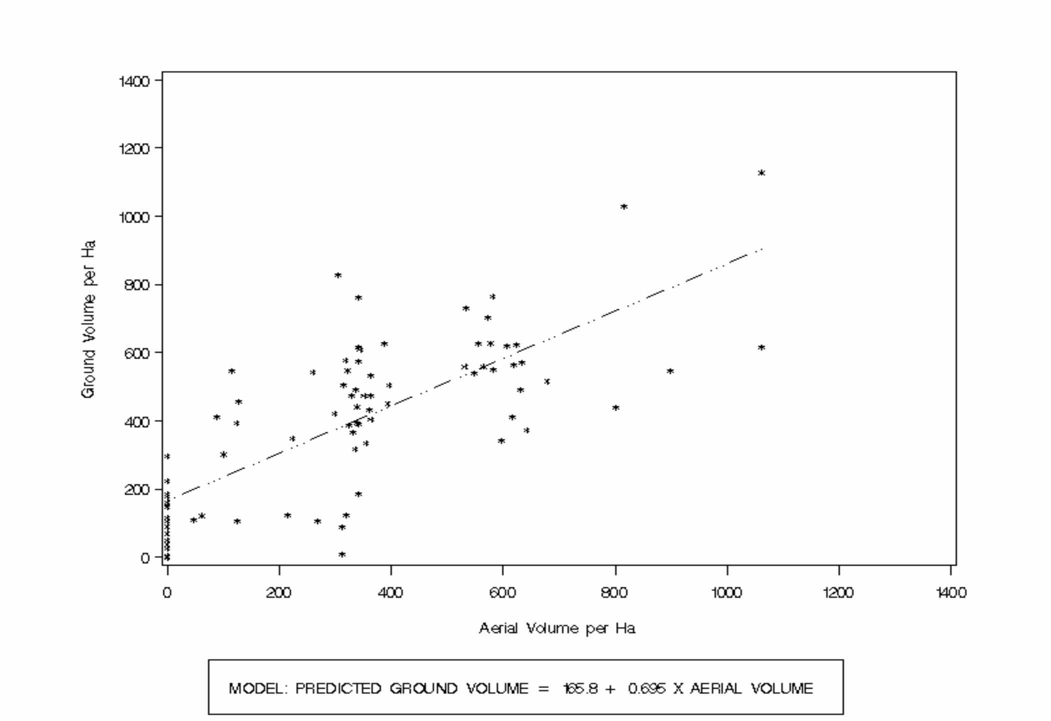


3Figure 3. Scatterplot of current ground measured volume versus model-estimated aerial volume using the 83 grid points.

Table 1. Current (1989) and projected (2019) inventory information based on different methods of combining data sources

Method	Grid Points			Polygons		Aggregated
	Ground	Aerial	Aerial+Ground	Aerial	Aerial+Ground	Aerial
1989 (0 years)						
Volume/ha (m^3/ha)						
Mean	394	329	395	378	428	385
Minimum	0	0	166	0	166	0
Maximum	1128	1062	904	1189	992	1564
Range	1128	1062	738	1189	826	1564
Mean mai (m^3/ha/year)	6.35	4.17	7.75	4.49	7.40	4.44
Total volume (m^3)	1,885,684.00	1,574,594.00	1,890,470.00	1,809,108.00	2,048,408.00	1,842,610.00
Mean age (yrs.)	68	65	79	79	79	79
2019 (30 years)	N/A					
Volume/ha (m^3/ha)						
Mean		539	540	568	560	558
Minimum		0	166	0	166	0
Maximum		1154	967	1354	1107	1654
Range		1154	801	1354	941	1654
Mean mai (m^3/ha/year)		6.20	6.39	5.93	6.12	5.4
Total volume (m^3)		2,579,654.00	2,584,440.00	2,718,448.00	2,680,160.00	2,670,588.00
Mean age (yrs.)		96	109	109	109	109
Change						
Mean volume/ha (m^3/ha)		210.0	145.0	190.0	132.0	173.0
Mean mai (m^3/ha/year)		2.0	-1.4	1.4	-1.3	1.0
Total volume		1,005,060.00	693,970.00	909,340.00	631,752.00	827,978.00
Mean age (yrs.)		31.0	30.0	30.0	30.0	30.0

Another alternative is to localize model inputs instead of model outputs using ground data. Consistencies among inputs would need to be maintained; simultaneous *modeling* approaches might be used to provide these logical consistencies.

Imputation approaches are alternatives to the *modeling* approach. This has been applied to similar data with some success by Temesgen *et al.* (2003) for other areas in BC. Katila and Tomppo (2002) extended the imputation approaches to imputation within strata and found improvements over general imputation. Unlike *modeling* approaches, imputation approaches would retain the variability shown in the ground information. Also, imputation might help remove some of the measurement error associated with linking ground data to aerial data, since matching can be done via similar attributes, coupled with spatial proximity.

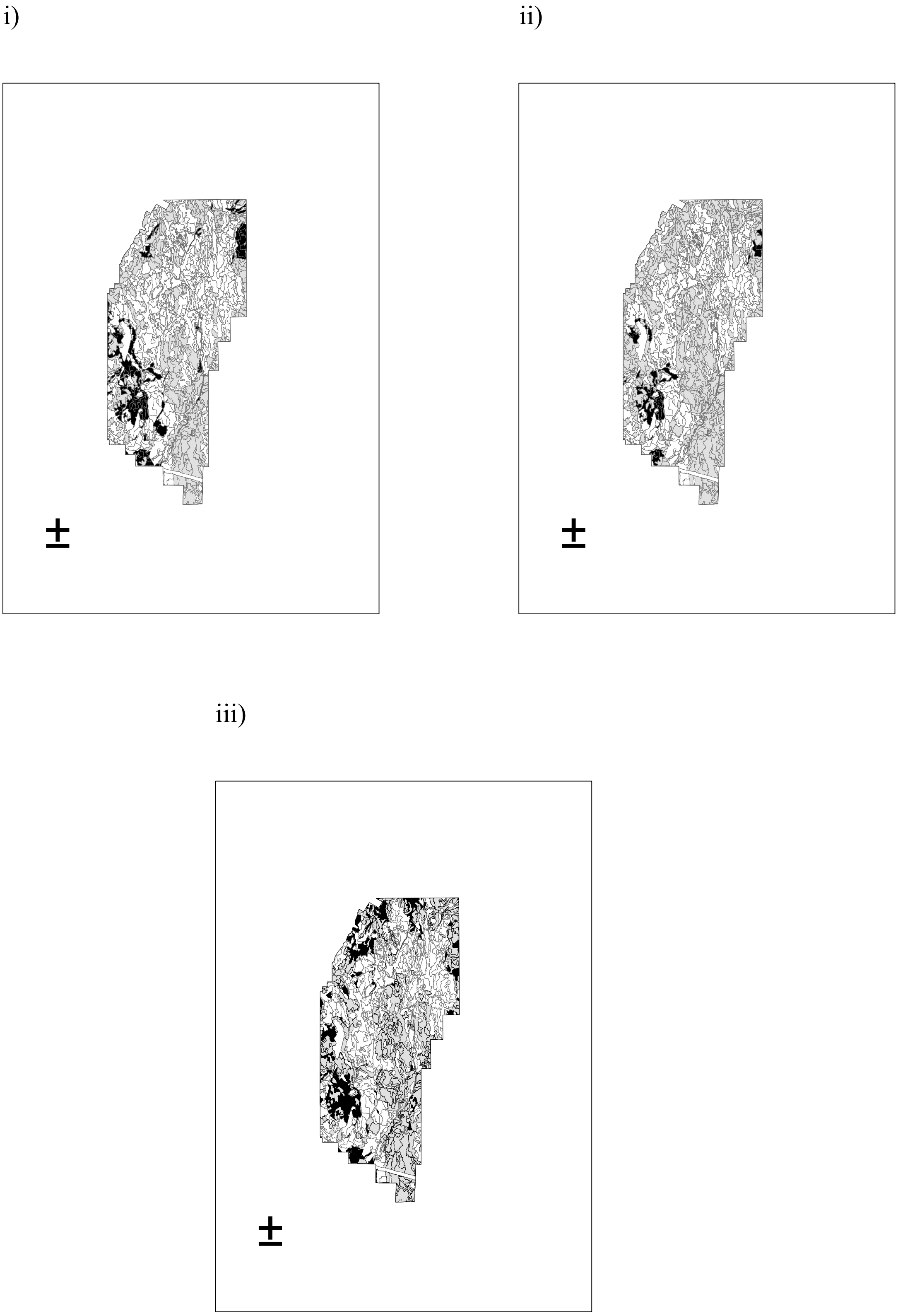
6.3 Current and projected attributes using the different methods. The estimated current (1989) average volume per ha values ranged from 329 m^3/ha using Grid Points, Aerial (Air-Grid), to 428 m^3/ha for Polygons, Aerial+Ground with a corresponding range of 1,574,594 to 2,048,408 m^3 using the different methods (Table 1). The average current volume per ha for the Grid Points, Ground representative sample was 394 m^3/ha, with a 95% confidence interval of 341 to 448 m^3/ha. Zero aerial volumes were adjusted to 166 m^3/ha using the relationship between ground and aerial volumes developed using the grid points, resulting in an average volume per ha for Polygons, Aerial+Ground of 428 m^3/ha, with a 95% confidence interval of 393 to 463 m^3/ha. The range of volume per ha values for the Polygons, Aerial+Ground was the most limited of the three methods that used all polygons (Polygons, Aerial; Polygons, Aerial+Ground; and Aggregated, Aerial; Table 1 and Figure 4). The largest maximum volume per ha was obtained with the Aggregated, Aerial approach. The attributes for each stratum were obtained by examining the spread of aerial attributes for the stratum. However, compromises in species combinations, site indices, and crown compositions were necessarily made. These compromises appeared to result in more extreme attributes, but these were more spatially clustered over the area (Figure 4). The average mean annual increment (m.a.i.) was highest for the Grid Points, Aerial+ Ground and Polygons, Aerial+Ground methods (Table 1, m.a.i. over 7 m^3/ha/year), since all zero aerial volumes were adjusted to 166 m^3/ha and these were associated with younger ages. This was not compensated by the lower adjusted volumes for older (higher aerial volume) polygons. As a result, average m.a.i. was higher.

Projected (2019) average volume per ha values were more similar across the methods; however, the range of volume per ha values was still smaller for the ground adjusted aerial volumes (Table 1 and Figure 5). Average m.a.i values were also similar, since there were few zero aerial volumes; therefore, few were adjusted to the 166m^3/ha intercept. Likely, further projections would result in the ground adjusted aerial volume per ha values dropping between unadjusted model-estimated aerial volumes, given the nature of the model used for the relationship between ground and aerial volumes.

Although the values for each period are different using the different methods, we might expect that the change data would be similar, indicating that there is less sensitivity to methods if only change data were of interest. However, the changes in average volume per ha were quite different, resulting in changes in volume for all forested polygons from about 630 thousand m^3 for Polygons, Aerial+Ground, to just over 1 million m^3 for Grid Points, Aerial (Table 1).

6.4 Species proportions. Rare or scarce species were only recorded for ground measures, and were only 0.5 percent of the volume per ha (Table 2). For hemlock, one of the three common species, the percent was about 40% for all methods. However, for the other two main species, Douglas-fir and red cedar, the percents were variable. In particular, the assumptions used to set attribute data for the aggregated polygons seemed to result in more Douglas-fir and less red cedar than the other methods. The most prevalent deciduous species, alder, also seemed to be overestimated for the Aggregated, Aerial method. Changes in species over time could not be modelled with the models available for this area.

Overall, scarce species are very difficult to include in inventories without detailed ground data. Also, a single tree model with individual tree mortality is needed to model changes in species over time. For aggregations of polygons, assumptions of species mixtures for these aggregates can greatly impact the species proportions. Simply taking the averages of available polygon information for a particular stratum will not necessarily result in realistic combinations of species (i.e., may result in six species that are not normally combined). This would also be true of k-nearest neighbour imputation approaches, where unrealistic species combinations may occur (Temesgen *et al.* 2003).



i)

ii)

iii)

Figure 4. Current (1989) volume per ha as low (white, up to 400 m^3/ha), medium (grey, up to 800 m^3/ha), or high (black, greater than 800 m^3/ha) classes for i) aerial data and model only; ii) aerial data and model, localized using the ground data; and iii) iii) aerial data and model, based on aggregated stands.

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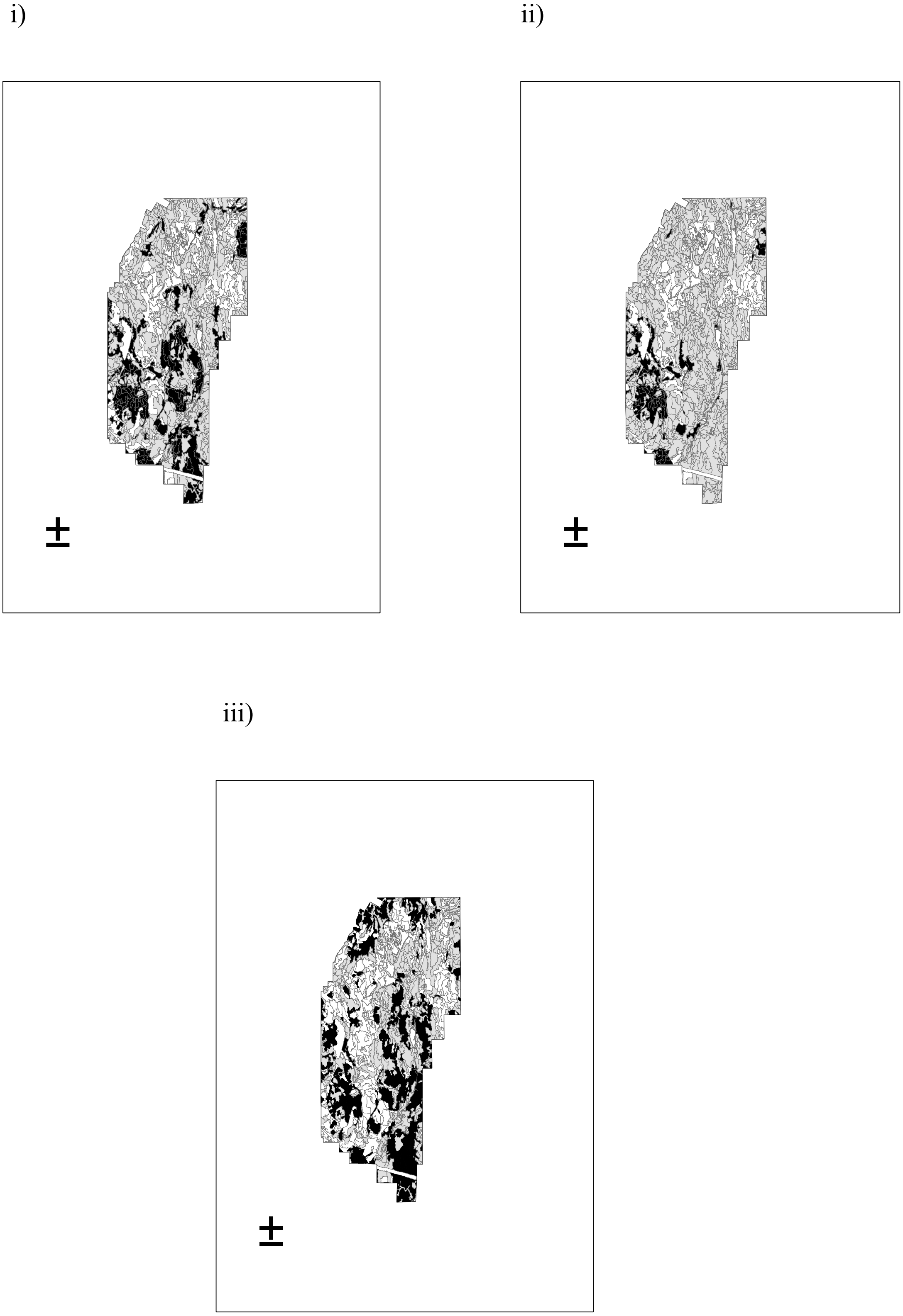

Figure 5. Projected (2019) volume per ha as low (white, up to 400 m^3/ha), medium (grey, up to 800 m^3/ha), or high (black, greater than 800 m^3/ha) classes for i) aerial data and model only; ii) aerial data and model, localized using the ground data; and iii) aerial data and model, based on aggregated stands.

Table 2. Current species volume per ha and percent based on different methods of combining data sources.

Method 1989 (0 years)	Grid Points								Polygons				Aggregated	
	Ground (G)		Aerial (A)		A+G Ground %		A+G Aerial %		Aerial		A+G		Aerial	
	m^3/ha	%	m^3/ha	%	m^3/ha	%	m^3/ha	%	m^3/ha	%	m^3/ha	%	m^3/ha	%
Coniferous														
Douglas fir	90.6	23.0	101.5	30.9	121.9	30.9	90.8	23.0	115.0	30.4	130.2	30.4	144.0	37.4
True fir	1.3	0.3	2.8	0.9	3.4	0.9	1.3	0.3	3.3	0.9	3.7	0.9	0.0	0.0
Redcedar	123.0	31.2	82.0	24.9	98.4	24.9	123.3	31.2	84.2	22.3	95.3	22.3	61.9	16.1
Hemlock	162.0	41.1	127.2	38.7	152.7	38.7	162.4	41.1	160.9	42.6	182.2	42.6	150.3	39.0
Larch	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pine	2.1	0.5	0.8	0.2	1.0	0.2	2.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Spruce	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow Cedar	0.0	0.0	2.4	0.7	2.9	0.7	0.0	0.0	4.3	1.1	4.9	1.1	0.0	0.0
Total	379.0	96.2	316.7	96.3	380.2	96.3	380.0	96.2	367.7	97.3	416.3	97.3	356.2	92.5
Deciduous, common														
Alder	7.7	2.0	11.5	3.5	13.8	3.5	7.7	2.0	8.5	2.2	9.6	2.2	27.9	7.2
Birch	0.9	0.2	0.0	0.0	0.0	0.0	0.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Poplar	0.8	0.2	0.2	0.1	0.2	0.1	0.8	0.2	0.8	0.2	0.9	0.2	0.6	0.2
Broadleaved Maple	3.8	1.0	0.6	0.2	0.7	0.2	3.8	1.0	0.6	0.2	0.7	0.2	0.7	0.2
Total	13.2	3.4	12.3	3.7	14.8	3.7	13.2	3.4	9.9	2.6	11.2	2.6	29.2	7.6
Rare														
Yew	0.2	0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bitter cherry	0.3	0.1	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Cascara	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vine maple	1.3	0.3	0.0	0.0	0.0	0.0	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Willow	0.3	0.1	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Total	2.1	0.5	0.0	0.0	0.0	0.0	2.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Deciduous plus rare	15.3	3.9	12.3	3.7	14.8	3.7	15.3	3.9	9.9	2.6	11.2	2.6	29.2	7.6

6.5 Overall. Aerial data often represent a complete census of information for the entire land area. However, often more detail is needed than can be obtained using only aerial data. Also, for projecting attributes over time, a localized model is more often preferred to a calibrated model. Ground data can be used to provide detail and to localize projection models. However, as shown in this example, results can be quite different, depending upon the use of these data, and the spatial arrangement of the aerial versus the ground data. The use of the regression estimator can result in a reduction of variability, which will indicate reduced spatial heterogeneity also. Other approaches using imputation methods may be more desirable, but are not necessary unbiased. Imputation methods provide more spatial heterogeneity, and result in estimates for many variables, simultaneously (multivariate).

These approaches could be used for any ground-measured attribute, if a projection model is available to forecast future values. Also, other remote sensing data could be used in a similar fashion, with differing issues of spatially linking the data.

For small land areas and short periods of time, results for differing methods will likely be similar. However, calibrating the current time period using existing ground information does increase plausibility in the numeric results, and more detail can be included, as shown in this example for rare species. Imputation methods would give better results than regression approaches, if spatial variability is being modelled.

For very large land areas, little ground data will be available. The accuracy of the models is then extremely important, if outcomes are to be used in planning. In this small example, the available models were accurate for the short term projection (Polygons, Aerial), but do not provide much detail, in that they were stand level models.

7 SUMMARY REMARKS

Linkage of a variety of data sources is essential to obtaining information for small to very large landscapes. The use of ground data is very important for localizing models and providing some assurances on model accuracies. However, linking these ground data provides some challenges in matching the ground data to appropriate aerial data, because of spatial arrangement differences in aerial versus ground data, and because of difficulties in getting accurate locations on each data source. In Canada, ground data are extremely scarce and spatially clustered around high population areas near the border with the US, and where timber extraction is actively taking place. Therefore, for Canada wide statistics, and for large management unit inventories, accurate models are essential to provide reliable information.

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9 REFERENCES

Bettinger, P. (2001) Challenges and opportunities for linking the modeling of forest vegetation dynamics with landscape planning models. *Landscape and Urban Planning* 56, 107-124.

Coops, N.C., Waring, R.H., and Landsberg, J.J. (1998) Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. *Forest Ecology and Management* 104, 113-127.

Glauner, R., Ditzer, T., and Huth, A. (2003) Growth and yield of tropical moist forest for forest planning: an inquiry through modeling. *Canadian Journal of Forest Research* 33, 521-535.

Halme, M and Tomppo, E. (2001) Improving the accuracy of multisource forest inventory estimates by reducing plot location error -- a multicriteria approach. *Remote Sensing of Environment*. 78(3), 321-327.

Johnsen, K., Samuelson, L., Teskey, R., McNulty, S., and Fox, T. (2001) Process models as tools in forestry research and management. *Forest Science* 47(1), 2-8.

Katila, M. and Tomppo, E. 2002. Stratification by ancillary data in multisource forest inventories employing k-nearest-neighbour estimation. *Canadian Journal of Forest Research* 32 (9), 1548-1561.

Kimmins, J.P., Mailly, D., and Seely, B. (1999) *Modeling* forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. *Ecological Modeling* 122, 195-224.

Landsberg, J.J. and Waring, R.H. (1997) A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* 95, 209-228.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I., Oliver, C.D., Puttonen, P. (2000) Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiology* 20, 289-298.

Meidinger, D. and Pojar, J. (1991) *Ecosystems of British Columbia*. British Columbia Ministry of Forests, Research Branch, Victoria, BC, 330pp.

Nelson, J.D. (1999) *Operations Manual - ATLAS/FPS*. Faculty of Forestry, University of British Columbia, Vancouver, BC, 67pp.

Plummer, S.E. (2000) Perspectives on combining ecological process models and remotely sensed data. *Ecological Modeling* 129, 169-186.

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

Temesgen, H., V.M. LeMay, K.L. Froese, and P.L. Marshall. (2003) Imputing tree-lists from aerial attributes for complex stands of south-eastern British Columbia. *Forest Ecology and Management* 177, 277-285.

Whitehead, D., Leathwick, J.R., and Walcroft, A.S. (2001) Modeling annual carbon uptake for the indigenous forests of New Zealand. *Forest Science* 47(1), 9-20.