Growth and Yield Modelling Systems for BC

A Review

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Executive Summary

Forest Growth and Yield (GY) models are used in British Columbia (BC) for timber supply analysis, projecting forest inventories and for silviculture planning. The provincially supported GY models are TASS, TIPSY and VDYP. These models predict the growth of managed and unmanaged single species, even-aged stands for most of BC and for mixtures of spruce and pine.

This project assesses the current GY models used in BC and models with potential for use in BC. Models were evaluated on how well they currently address GY needs in BC and their potential to be adapted to address GY needs in BC.

For timber supply analysis, VDYP is used for unmanaged stands and TIPSY, a stand level derivative of TASS, is used for managed stands. VDYP is calibrated for most unmanaged conditions in the province and is working well for short to medium term projections. VDYP does not model species dynamics so its use for longer term projections is limited. TIPSY is calibrated for single-species managed stands for Douglas-fir, western hemlock, western redcedar, sitka spruce and red alder on the coast and Douglas-fir, western hemlock, lodgepole pine, white spruce and trembling aspen in the interior.

For projecting forest inventories, VDYP is the main model used and links well to the inventory. Stands younger than 30 years are assumed to be managed and VDYP has limited functionality for young stands. TIPSY does not link well to the inventory but recent work has focused on taking information from managed stands to create a TIPSY input file and generate yield curves for each stand. This has potential for inventory projection of managed stands but is limited to the conditions for which TIPSY is designed.

For silviculture planning, the main models used are TIPSY, TASS II and TASS III. TASS II, while not publicly available, is accessed for this purpose via requests to Forest Analysis and Inventory Branch (FAIB) for custom runs. TIPSY provides access to TASS-generated, managed-stand yield tables. It supports a variety of spatial distributions and silviculture treatments including initial spacing, fertilization, genetic gain, pre-commercial and commercial thinning and variable retention harvesting. TIPSY projections include attributes important in predicting fire behaviour and suppression including mean crown length, base of the live crown and crown bulk density. TIPSY does not model mixed-species dynamics. TASS III is publicly available and provides predictions for interior spruce, lodgepole pine and mixtures of the two species and is an example of the potential of TASS for operational use.

In summary, the current GY models are working well for timber supply analysis for unmanaged and managed stands for pure species conditions. VDYP is working well for inventory projection and TIPSY shows promise. TIPSY and TASS III (spruce/pine) are directly available to users for silviculture planning; custom TASS runs are available on request. The current models have limited ability to model species dynamics (with the exception of spruce/pine in TASS III) and major disturbances. TIPSY benefits from TASS research and development. TASS is capable of modelling complex processes including species mixtures and disturbances. The current limitations of TASS are more a function of available resources and data rather than model architecture.

There are needs not currently met with the BC GY models. The main GY gaps identified by users were i) yield curves for complex stands including stands with mixtures of species, ages, vertical layers and horizontal arrangements; ii) improved modelling of growth response to silvicultural treatments including genetic gain, fertilization and patch harvesting; and iii) growth following disturbance agents including fire, insects and disease. These yield curves and growth estimates are needed for silviculture planning and are used in wood supply. Users identified the need to predict stand development under climate change. This is particularly important information when choosing which species to plant and/or promote following disturbances. Users also identified a lack of training and documentation as barriers to model use.

Given data and resources, TASS and TIPSY should be capable of addressing these needs. TASS development is limited by staff time, resources and data. Recent published research on climate change and response to fertilization has not yet been incorporated into TASS or TIPSY due to capacity limitations, although some development is underway. In addition to GY model development, the current program

needs to support tree and stand dynamics studies, maintain and establish research trials and permanent sample plots to provide data for future model development.

People involved in TASS development and its use are very positive about TASS and its potential to meet BC's GY needs. Unfortunately, this is a small group. People outside the TASS community who were interviewed were very frustrated with the limitations of TASS and TIPSY, the slow pace of development and the lack of documentation and training. As a result, there is interest in looking at other models and calibrating them for BC conditions to address specific short to medium term needs.

The following recommendations are made, based on the model review and interviews.

Step 1 – Document Provincial models
TASS, TIPSY and VDYP require more documentation. Lack of documentation is a significant barrier to model acceptance and use. Documentation should include a description of the model architecture and intended application, an assessment of model performance and reliability, model availability, supporting literature and current research efforts.

Step 2 – Prioritize needs
The GY needs should be summarized in terms of scope, impact (on policy and wood supply), resources required and time frame. GY needs include model development, documentation, training of more model developers and model users and more data from long term remeasured field plots.

Step 3 – Identify resources
The available resources need to be identified. Resources include the current and potential models as well as published research such as the impact of fertilization on growth. The data available to calibrate models should be summarized as it will limit model development. Human and financial resources should be summarized including potential funding sources and collaborators.

Step 4 – Assess Models
The reliability of TASS, TIPSY, VDYP, Prognosis^{BC}, MGM and SORTIE should be evaluated against the needs and conditions of interest in Step 2. The evaluation should include quantitative measures (bias, precision) as well as subjective criteria such as model logic. Each model should be evaluated against validation datasets representing the conditions of interest, using the evaluation criteria.

The FAIB should host a meeting of people involved in GY research including those involved with TASS, TIPSY, VDYP, Prognosis^{BC}, SORTIE and possibly MGM. The models should be summarized as well as the research efforts. Ideally this would be an annual meeting, possibly as a formal working group.

S**tep 5 – Develop a plan**
Given the needs, model assessments and the available resources (including current models, potential models, research, and calibration data), a GY plan should be developed. For each need, the plan should summarize the model options, the data required and availability, the resources required and the timing. The plan should include a realistic time frame and be updated regularly.

FAIB should develop a plan to encourage model development, targeted at specific needs. This plan should include data sharing, financial and in-kind support of external projects as well as internal model development.

BC is committed to sustainable management of its forests, requiring GY models covering the range of forest conditions and management activities in BC. Staff and resources are needed to maintain current models. Additional resources are required to address gaps. Without additional resources, the gap between GY model capabilities and user needs will continue to increase.

Acknowledgements

This project was coordinated by the Forest Analysis and Inventory Branch.

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1 Scope and Objectives

The objective of this project was to review growth and yield modelling systems for British Columbia (BC). Tree and stand-level growth and yield (GY) models currently used in BC were assessed as well as models with potential for use in BC. Models were evaluated on how well they currently address GY needs in BC and their potential to be adapted to address GY needs in BC.

For the purposes of this report, a GY model is defined as a model capable of simulating the development of a forest (an aggregation of trees) over time. Two key uses of GY models are i) to predict future yields and ii) to explore silvicultural options (Vanclay 1990). Pretzsch's (2010) chapter on forest growth models includes models ranging from yield tables to gap models to matter balance models. This report focuses on GY models in terms of forest management - models that include the capability to estimate current and future stand-level timber volumes. A GY model may include the prediction of products and other values but the prediction of economic return is not considered here.

2 Methods

First, modelling needs in BC were identified by consulting with modellers and model users. The list of model needs is not definitive but guided the evaluation of current and potential models. Next, current BC models were evaluated on how well they are addressing the identified needs. Next, other GY models with potential to address BC needs were identified and assessed. Finally, recommendations were developed for moving forward. These steps are described in more detail below.

Step 1 - Model needs

The current and anticipated model needs in BC were identified by interviewing government staff, private sector clients, academics and consultants. The assessment identified some major needs which guided the search for potential models and their evaluation. The assessment did not include all users and may not have identified all potential uses of GY models.

The discussion of model needs went beyond GY model capabilities and included barriers to use. Some users identified lack of model documentation, training on use, compatibility of models with available inputs and required outputs as barriers to use.

Step 2 - Current Models

The models currently supported by the provincial government are TASS, TIPSY and VDYP. These were reviewed and their capabilities assessed with respect to the conditions they cover, the data requirements and their intended use.

Step 3 - Potential Models

Models not currently supported by the provincial government but with potential to address GY needs in BC were identified and assessed. In particular, models were evaluated for their potential to address needs in BC in the short (< 5 years) and medium (5 - 10 years) terms.

Step 4 – Recommendations

Given the model needs, the currently supported models and the potential external models, recommendations are given to develop a plan to move forward.

3 Model needs

Model evaluation is the process of determining if a model is suitable for its intended use and specifically if it is preferable to alternative forecasting methods that could be used (Shifley et al. 2017). This not only includes evaluating predictions but also whether a model is compatible with existing systems (e.g., the inventory) and capabilities of the user community. Understanding the current and future needs in BC is the first step in reviewing current and potential models for BC.

3.1 Main needs

The BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRO&RD) develops and maintains a suite of stand-level models and tools (described in section 4) to predict the GY of the province's forests. Predictions from these models play a key role in supporting sustainable forest management decisions by government and its forest licensees in many areas, including:

- Forest inventory update
- Forest and timber-supply analysis
- Silviculture planning

There is overlap between these needs. The most detailed models are used in silviculture planning to compare, among other things, forest growth, yield, costs and values associated with different silvicultural options. These same models may be used to develop yield curves for timber supply analysis. The yield curves used in timber supply analysis may also be used for forest inventory projection. Inventories generally have less detail and simpler models may be more compatible with inventory projection. Generally, silviculture planning requires the most detailed models while inventory projection requires least. Timber supply analysis requirements are intermediate between the two.

The MFLNRO&RD has a long history of GY model development and refinement. VDYP is routinely used to update the provincial forest inventories. VDYP and TIPSY are routinely used to develop yield curves for timber supply analysis. TASS and TIPSY are used to compare silvicultural options including initial density and spatial arrangements, genetic improvement and fertilization. VDYP, TASS III and TIPSY are publicly available. These models are supported by the MFLNRO&RD and continue to be developed and updated.

Users identified emerging needs including:

- Prediction of the development of complex stands. Complex stands include deciduous/coniferous mixtures, multi-species stands, uneven aged and multi-layer stands and stands with complex spatial arrangements.
- Prediction of timber products and non-timber products including species diversity and habitat analyses.
- Prediction of dead trees and coarse woody debris needed for habitat and fire risk analyses as well as carbon accounting.
- GY under different climate scenarios, including the impact of future climate on species choice and on disturbance patterns.
- GY response to disturbances including fire, insects and diseases.

3.2 Specific needs

GY models are required for all forest conditions for all of the province. BC is Canada's most biologically diverse province or territory — encompassing 14 ecological zones and a wide range of ecosystems, from coastal rain forests, to dry interior grasslands, to alpine tundra and northern boreal forest[1]. The diversity of the forests make it challenging to provide GY models for all forest conditions. Provincial GY models are available that have potential to predict the growth of most of the forest conditions in BC.

An increasing proportion of BC forests are complex and a larger proportion of the wood supply is coming from these complex forests. The use of herbicides is declining and the hardwood component is likely to increase. Tools are needed to project these complex forests and evaluate silvicultural alternatives. Complex stands are difficult to inventory using traditional aerial photo interpretation. The Vegetation Resources Inventory (VRI) stand description may not provide sufficient information to initialize GY models that are capable of projecting complex stands.

Some specific conditions of interest are given below.

- Species mixtures including planting one species and expecting ingress of another species.

[1] https://www.for.gov.bc.ca/hfd/pubs/Docs/Bro/Bro06.pdf

- The impact of damage agents such as Swiss needle cast on the coast.
- Non-timber values including habitat and fire risk.
- Changing future conditions including climate change and changing disturbance patterns. The impacts of a changing climate on mortality and survival are already being seen in the southern interior.
- Genetic gain. Estimates of genetic worth and the algorithm for incorporating genetic worth need validation. Realized gain (RG) trials have been established for Douglas-fir (coastal and interior), coastal western hemlock, lodgepole pine, interior spruce and larch. The only publicly available RG results are for coastal Douglas-fir[2].
- Wood supply shortages are anticipated in the medium term. There are questions about whether commercial thinning, fertilization and spacing treatments can be used to address mid-term shortages. The thinning and fertilization responses in the models need validation.
- Conifer/hardwood mixtures including spruce-aspen mixes, and birch stands (northeast) and stand dynamics in the Interior Douglas Fir (IDF) Biogeoclimatic Ecosystem Classification (BEC) zone.
- Stands with partial disturbances including those affected by bark beetles, root diseases and defoliators.
- Regeneration following wildfire or other disturbances
- Volume net downs. The decay, waste and breakage data are routinely compiled to different geographic groupings to get enough data. The default operational adjustment factors are the same for all species for all of BC. Guidelines on net downs and their use are required.
- Years to breast height. The years to breast height can have a significant effect on predictions for young stands. There is interest in being able to use local estimates.

3.3 Model Support

The development of GY models should include documentation, communication and training. Users of BC models were interviewed as part of this project. They expressed uncertainty about the reliability of model predictions. Users are interested in the extent of the calibration data, the basic algorithms and the results of model testing in order to know when to use the models with confidence and when to use more caution. Of the people interviewed, those very familiar with TASS were very positive about its capabilities. Those less familiar with TASS expressed less confidence. FAIB staff noted a decline in growth and yield expertise and understanding among the general forest professional population, leading to increased demands on FAIB staff.

Some of the people surveyed suggested all MFLNRO&RD staff should have some level of training and competency with GY models. Some level of biometrics training should be required of FAIB staff. Specifically, staff need training in the development and use of TIPSY and VDYP. FAIB should have a biometrician who provides advice.

External users, particularly industry, are interested in documentation and training for GY models, especially TIPSY. The documentation should include the model assumptions and sensitivity of the model to different inputs. Inputs include SI, years to breast height and trees/ha. These inputs are often obtained from other sources including the inventory, field surveys and the provincial site productivity layer. If the inputs contain error, what are the implications for the predictions?

Users identified barriers to use of currently supported GY models.

- There is a lack of documentation on model development and testing (including assumptions, calibration data, species substitutions, extrapolations, model precision and accuracy). Users would like more easily accessible documentation on the GY models.
- Users would like more training on model use.

[2] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/forest-genetics/research-projects/realized-genetic-gain-trials#:~:text=Realized%20genetic%20gain%20trials%20have,on%20a%20per%2Dhectare%20basis.

- Access to TASS is limited to TASS III (spruce/pine). TASS II is not publicly available and the number of users is very limited
- Projection of existing managed stands has onerous requirements for model initiation (TASS requires a tree list, TIPSY cannot be run in batch mode for existing stands).
- There is a lack of integration of silviculture surveys with the inventory and model requirements. There is a need to develop surveys and regeneration standards that can be linked to a GY curve

3.4 Model Integration

There is a general feeling of disconnect between the models/model developers and the people who are doing silviculture planning and setting stocking standards.

The new VRI is LiDAR-based for most attributes and these are pixel-based. There is a joint project underway between the Stand Development Modelling Group and remote sensing experts to work on compatibility between GY models and the new VRI.

3.5 Model Development

There is a need to develop standards for GY model development. The standards should include documentation and testing requirements and should apply to MFLNRO&RD models as well as external models.

These standards should specify how accuracy and precision are reported, preferably using independent validation data. Accuracy and precision targets should be given, including spatial and temporal scales. The standards should also specify what a client needs to provide in order to have a GY model approved for use, for example, in timber supply analysis.

Both raw and compiled data should be made available. This will promote model development, improve data screening and checks on compilation and ensure data remains accessible. To promote model development, modellers should retain ownership of models, regardless of whether they use public data.

The MFLNRO&RD is responsible for data management and should have resources to ensure the data are clean and available. Plot remeasurement is an opportunity to check data issues. Crews should be provided with tally sheets from past measurements.

A number of barriers to model development were identified:

- There is not enough capacity for core business due to limited base funding, hindering GY model development.
- Support of academic involvement in GY development is limited.
- The Permanent Sample Plot (PSP) program has been reduced which may limit future GY development. Remeasurement of PSPs with disturbances such as MPB and fire can be particularly useful.
- Data for calibrating models is limited. Field sampling prioritizes establishment and remeasurement of PSPs, long term experiment and stand development monitoring. Ground sampling methods should be aligned across programs where objectives are complementary.

3.6 Current efforts

The following initiatives are underway (from the Forest Inventory Section Highlights: December 2019[3]).

- One of the initiatives is this report which reviews GY models applicable for use within BC's forests and their strengths and weaknesses in relation to the current and future conditions expected in BC.
- Work is underway to improve VDYP projections in Mountain Pine Beetle and wildfire damaged stands. The application of the model in these areas is particularly challenging.

[3] https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/newsletter/forest_inventory_newsletter_december_2019.pdf

- The stand development modelling team is actively engaged in supporting MFLNRO&RD response to current initiatives associated with commercial thinning and other silvicultural treatments to mitigate mid-term timber supply shortages.
- Work continues with recalibration for lodgepole pine and white spruce in TASS II, Fd/Hw mixed species functionality in TASS III and the development of TASS III and TIPSY decision-support tools: PLOTSY V2, TIPSY-CBM-CFS3 linkage, FAN$IER economics features.

4 Current Models

The GY models supported in BC are TASS, TIPSY and VDYP. Although TIPSY is derived from TASS, it has different users, requirements and capabilities. TIPSY is discussed separately from TASS.

A number of models are used by or embedded within the GY models. These submodels are mentioned briefly as they affect the accuracy and prediction of GY models and could be used by other GY models. These submodels include site index models, taper/volume/biomass equations and net downs.

The GY models and supporting models are described in more detail in the appendix. They are summarized here in terms of how they currently address GY needs as well as their potential to address GY needs.

4.1 TASS

The Tree And Stand Simulator (TASS) is the GY model used in BC for managed forests. It is a crown-driven individual tree, spatial model. TASS is based on detailed stem and crown analysis and growth trends observed in fully stocked research plots growing in a relatively pest-free environment. The yields are very close to the potential of a specific site, species and management regime. Managed stand data come from experiments established from about 1960 and later. Data from older permanent samples plots (150+ years old) are used to calibrate the system for projections to older ages.

TASS is designed to initiate a run from bare ground (Figure 1) with species, site index, planting density, ingress and spatial arrangement. It can also be initiated with a tree list that includes, for each tree, species, origin (planted vs. ingress), Dbh, height, height vigour, age, site index and spatial coordinates. The tree list option is not used as frequently and has had less testing. Management options include planting espacement and genetic worth, natural regeneration, cutting snags, fertilizing and cutting (or retention) of select trees. TASS does not predict ingress beyond the establishment period.

The internal structure of TASS is flexible and should be able to accommodate many of the anticipated changes in tree growth and mortality under different climate change scenarios. The fundamental biological relationships underlying tree growth and stand development are expected to remain stable. Stearns-Smith and Associates[4] recommended using genetics provenance trials to examine the relationships between tree growth and climate change. An example is given in O'Neill and Nigh (2011). These can then be incorporated into TASS.

There are a number of releases of TASS, each with different capabilities.

TASS II – predicts the potential GY of even-aged, single-species managed stands for Douglas-fir, western hemlock, western redcedar, sitka spruce and red alder on the coast and Douglas-fir, western hemlock, lodgepole pine, white spruce and trembling aspen in the interior. It has limited ability to simulate multi-species mixtures.

TASS III – includes a light model that simulates relative light levels within the canopy. Height growth and other functions are responsive to relative light levels. This allows more realistic modeling of inter-tree above-ground competition, particularly for species mixtures. TASS III is available to the public and is restricted to lodgepole

[4] Stearns-Smith & Associates. Incorporating climate change into TASS predictions: a problem analysis. Draft prepared for BC Ministry of Forests, Mines and Lands. March 2011

pine, white spruce and mixtures of the two species. The next species mixture to be calibrated will be coastal Douglas-fir and hemlock.

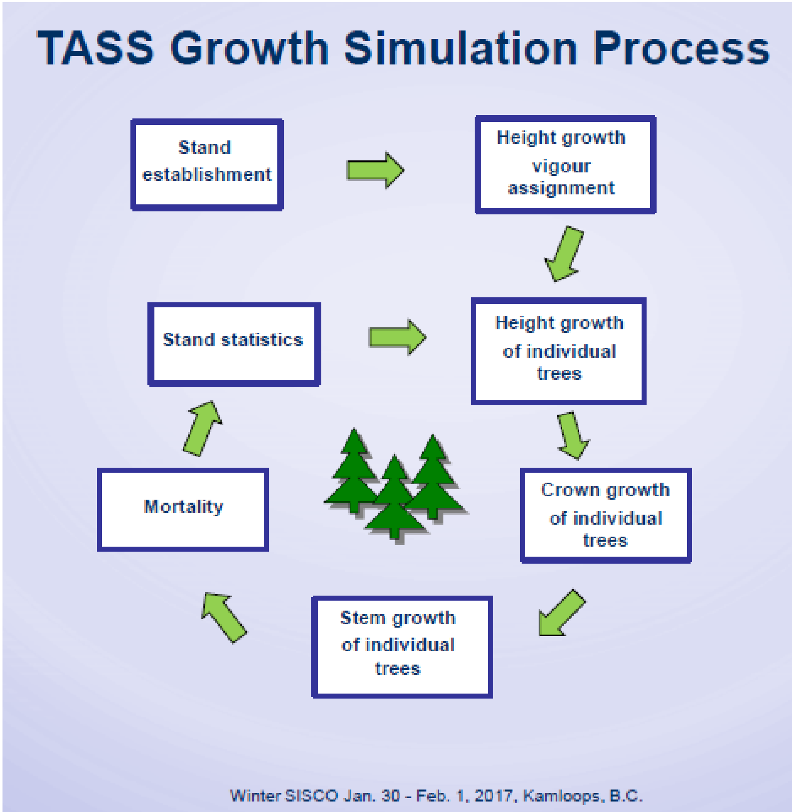

Figure 1. The TASS model starts at stand establishment.

TASS has been linked to a tree-list generated from a LiDAR-based inventory (Suarez 2010, cited in Rosette et al. 2012, see section 12.3.1).

The advantages of TASS include the following:

- Long history of research and development in BC
- Active research within the MFLNRO&RD
- Model architecture capable of supporting a wide range of effects including defoliation and clumped spatial arrangements.
- Includes management treatments such as planting, thinning, pruning, fertilization and genetic gain.
- Includes wood quality and product estimates.
- TASS III models species mixtures.
- TASS III is user-friendly and publicly available.

The disadvantages of TASS include the following:

- Little documentation on model architecture, development and calibration data.
- With the exception of TASS III (white spruce and lodgepole pine), only a few people have access to and are trained to use TASS. This limits its use.
- TASS is not calibrated for all species or species mixtures that occur in BC.
- The default Operational Adjustment Factors (OAFs) are coarse and are independent of species and region. Custom OAFs are not available in TASS III.

4.2 TIPSY

The Table Interpolation Program for Stand Yield (TIPSY) uses a database of managed stand yield tables generated by TASS to predict growth and yield of managed stands. It has different users, requirements, capabilities and uses than TASS. TIPSY generates managed stand yield tables for pure species, even age conditions. Mixed species yield tables are computed as the weighted average of pure-species yield tables. TIPSY is used primarily for developing managed stand yield tables for timber supply analysis and for comparing silvicultural options. In timber supply analysis, stands less than 30 years old are considered to be managed.

TIPSY is available for the same species as TASS (5 coastal, 5 interior).

Like TASS, TIPSY is designed to be started from bare ground. It has an existing stand option that takes an existing stand description – current density, site index and age (or height), and past management. TIPSY then projects the stand backwards in time to estimate the initial density and stand conditions. TIPSY then grows the stand from estimated initial conditions, including any treatments. The backward projection is a complicated process as it must “undo” the effects of past actions including thinning.

Batch TIPSY generates yield curves for multiple stands. It does not include the existing stand option.

Recently, work has been undertaken to take information from managed openings (harvested areas – see section 12.3.2) to create a TIPSY input file. This file can be used as input to a modified version of Batch TIPSY to produce yield tables for each opening. This modified version of TIPSY has reduced functionality (e.g., it does not yet include the carbon feature) and runs faster. Efforts are underway to standardize the use of Batch TIPSY in timber supply analysis. This TIPSY input file is also designed to be compatible with TASS.

TIPSY is working well for predicting relatively pure stands and spruce/pine mixtures including density regulation (spacing and thinning), genetic improvement and fertilization. There is limited information on how well the model is working but more is being done using Young Stands Monitoring (YSM) plots.

The advantages of TIPSY include most of the advantages of TASS:

- TIPSY builds on the long history of research and development of TASS
- There is active research on TIPSY within the MFLNRO&RD
- TIPSY is user-friendly and publicly available.
- TIPSY can be initiated from bare ground or an existing stand
- TIPSY includes a batch processing option, useful for processing many stands.

The disadvantages of TIPSY include the following:

- There are no interactions between species in mixed species stands.
- TIPSY is not calibrated for all species or species mixtures and geographic areas of BC.
- Batch processing is not available with the “existing stand” option.
- Documentation of calibration data, model architecture and testing is limited.

4.3 VDYP

The main component of the Variable Density Yield Prediction (VDYP) program is VDYPGrow, a stand level model that projects growth starting with an inventory polygon description including species composition, age, stand height, basal area, trees/ha and BEC. Additional subcomponents are described in the Appendix.

VDYP can handle multiple layers. The primary layer is grown with a full suite of attributes by species group and utilization level. Attributes include basal area, trees/ha, lorey height and five volumes (whole stem volume, close utilization volume, close utilization volume net of decay, close utilization volume net of decay and waste, and close utilization net of decay, waste and breakage). Select attributes for the remaining layers are updated. Veteran overstory layers are not grown (age is incremented). There are no interactions between layers.

VDYP is used for inventory update and is working well, even for stands affected by Mountain Pine Beetle (MPB) provided adjustments are made to the inventory[5]. It projects the growth of unmanaged, natural-origin stands of pure or mixed-species and is used in timber supply analyses for these conditions. VDYP assumes species composition is constant. It does not predict stand breakup and replacement nor does it include significant insect or disease events. It does not include any management options.

The advantages of VDYP include the following:

- VDYP has a long history of development in BC.
- VDYP is in active use in BC for inventory update and timber supply analysis.
- VDYP works for all of BC (although calibration data may be limited or lacking for some conditions).
- VDYP is relatively easy to use.

The disadvantages of VDYP include the following:

- The use of VDYP is restricted to unmanaged, undisturbed conditions.
- Species composition is constant so VDYP should not be used for long term projections of mixed species stands.
- VDYP does not predict stand break up at older ages.
- VDYP has a limited ability to account for layers and MPB.

4.4 Supporting models

The GY models incorporate submodels that are developed and maintained independently. In some cases, the data used to calibrate GY models is compiled using these submodels.

4.4.1 Site Index

Johnsen et al. (2001) concluded that soil and nutritional limitations are the most difficult model components to make transportable among site and species. Most GY models require relatively simple, standard indices of nutritional limitations.

Site index (SI) is still the most common measure of the stand's productive potential for a particular tree species. SI in BC is expressed as potential tree height at 50 years breast height age. SI provides standardized comparisons of productive potential between sites across a broad range of existing stand conditions. It is used to prescribe treatments and analyze investments. SI also serves as the main driver for many GY models (from SiteTools help[6]).

Nigh et al. (2004) and Nigh (2006) examined the impact of climate on the SI of coastal and interior Douglas-fir, lodgepole pine, and white spruce. One option for incorporating the effects of climate change on tree growth is to use climate-sensitive SI relationships within GY models.

SI can be estimated using SiteTools or the Provincial Site Productivity Layer. More information on these is given in section 11.1.4 and 11.1.5.

4.4.2 Taper/volume/biomass equations/net downs

Most GY models are calibrated using raw and compiled data from field plots. Most of the compilation routines use Kozak's taper model (Kozak 2004) to estimate stem volume from Dbh and height. Volume equations are also available (Nigh 2016). These tree models can be used to estimate total and merchantable stem volume. Kozak's taper model is also used to estimate gross total and merchantable stem volume within VDYP.

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[5] https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/mpb_changes_to_veg_2015.pdf

[6] SiteTools is available for download at https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/field-forms-and-software/software-download

Biomass is estimated in TASS using the equations of Ung et al (2008) which used stem analysis data collected in the 1980s. Sample sizes for some species are small. For example, 25 Douglas-fir trees were sampled.

The two main methods for accounting for decay and waste at the tree level are Loss Factor (LF) and Net Factoring (NF). LFs are used in VDYP. NF is used in the VRI compiler.

5 Assessment of Current Models

TASS, TIPSY and VDYP are assessed for use in BC for various conditions.

5.1 Even-aged, pure species stands

TASS is designed to predict the growth of single species, even-aged stands from bare ground or from a tree list. It is calibrated for most of the important timber species in the geographic regions where they primarily occur. The only version of TASS that is publicly available is TASS III and is for lodgepole pine, white spruce and mixtures of the two. The range of TASS calibration data (geographic, age, site index) is not publicly available. Most of the calibration data come from younger stands and the reliability of projections to older ages is unknown. The projections of managed coastal Douglas-fir were graphically compared to independent spacing trial data (Mitchell and Cameron 1985).

TIPSY is available for the same conditions as TASS. It has a user interface that is very easy to use. TIPSY has an existing stand option. In theory, this could be used to project managed stands in an inventory. However, the existing stand option is only available in interactive TIPSY, making it impractical for inventory projection. It can simulate the effects of thinning, fertilization and genetic improvement. The reliability of the predictions to older ages is not known other than for coastal Douglas-fir (Mitchell and Cameron 1985)

VDYP is calibrated to project the growth of the primary layer of unmanaged stands. It is calibrated for the entire province and is used primarily to project the inventory and produce yield curves for unmanaged stands. VDYP is publicly available and can be run with minimal computer resources but does require some level of training. It does not have a graphical user interface and is generally run from the command line. Documentation is available. VDYP does not include any treatment options.

The current GY models project even age, pure species stands for managed and unmanaged stands in BC and managed mixtures of spruce/pine. The calibration data for managed stands is limited to relatively young (< 60 year old) stands.

5.2 Complex stands

Complex stands include mixtures of species, stands with layers, stands with a range of tree sizes and stands with non-random spatial arrangements.

TASS III includes a dynamic light model which regulates growth and mortality and can simulate species interactions, different spatial arrangements and tree sizes. Calibration is currently limited to lodgepole pine and white spruce.

TIPSY projects the growth of species mixtures as a species composition weighted average of pure species curves. Essentially TIPSY assumes species composition is constant over time and there is no interaction between species. Spatial arrangements can be natural, clumped or planted. Each species can have its own SI but stands are assumed to be a single age, spatial arrangement and density.

VDYP projects the primary layer and assumes the species composition is constant. This may be adequate for short term projections of complex stands. The primary and secondary species can have different ages and heights and therefore different SIs.

The projection of complex stands using current GY models is limited to short term projections of unmanaged stands (VDYP) and projections of single species managed and unmanaged stands (TASS & TIPSY). TASS III is capable of modelling the development of species mixtures but calibration is currently limited to managed mixtures of lodgepole pine and spruce.

5.3 Management

TASS is capable of projecting different establishment spatial arrangements (natural, clumped and planted), thinning, fertilization, snag removal, variable retention harvesting and genetic improvement. It is also capable of projecting species mixtures. Most of the current limitations of TASS are calibration limitations rather than inherent model limitations.

TIPSY supports the same establishment spatial arrangements as TASS. Commercial thinning is only available for pure stands of coastal Douglas-fir and interior lodgepole pine. The timing of pre-commercial thinning is fixed to occur when the stand height is 4m in the interior and 6m on the coast. Users can overlay graphs from different management scenarios when comparing silvicultural options.

VDYP does not project managed stands.

TASS and TIPSY can be used to develop and compare yield curves for different management regimes for pure species stands including economic analysis.

Prediction of the effects of management is limited to even-aged, pure species stands and mixtures of lodgepole pine and spruce.

5.4 Disturbances

TASS can predict the impact of spruce weevil, root rot and mountain pine beetle. It also predicts the effects of western gall rust (Sattler et al. 2019) and Commanda blister rust on lodgepole pine.

VDYP works relatively well for projecting MPB-impacted stands, given appropriate adjustments to basal area and trees/ha[7].

Following stand replacing disturbances, areas are surveyed to assess post-disturbance establishment (see section 5.6).

Non-stand replacing disturbances, such as wind events or partial harvests, generally result in an overstory as well as understory component and are difficult to survey and project. VDYP has limited capacity to model layers and there is currently no interaction between layers. TASS III has good potential to model layers but calibration is currently limited even age conditions.

5.5 Climate change

None of the models (TASS, TIPSY, VDYP) explicitly incorporate climate effects. The TASS architecture should be capable of incorporating the predicted changes in tree growth resulting from climate change.

5.6 Linkages to inventory and ground surveys

VDYP is designed to project unmanaged stands in an inventory. It is not designed to project young stands including summaries from REporting Silviculture Updates and Land status Tracking System (RESULTS). RESULTS was designed to support free-growing declarations and not to initialize GY model runs.

TASS/TIPSY are not designed to project inventories[8]. Recently, Batch TIPSY has been modified to predict yield curves from RESULTS. Stand Development Monitoring (SDM) data can be assembled into a TASS input file and projected. These are important developments but the reliability of the projections has not been assessed. Using models and databases in ways they were not designed for incurs risk.

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[7] Wenli Xu, pers. Comm.

[8] https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/land-based-investment/forests-for-tomorrow/procedures_for_initializing_tipsy_with_silvsurvey_data_sss_27mar13.pdf

BC is developing and implementing LiDAR enhanced forest inventories. These may provide additional/better information about forest structure, heights and volumes, potentially at the pixel level rather than the polygon level and ultimately at the tree level. GY modellers should be working with the people involved in inventory and survey design (VRI, YSM, SDM, RESULTS) as well as users of model outputs including silviculturalists and timber supply analysts.

5.7 Ease of use

VDYP is relatively easy to run. The main challenge is formatting the input and control files. The software, documentation as well as a training example are available on-line.

TASS III is easy to run and has an extensive help file to assist in use.

TASS II is not publicly available and is only run by a small number of expert users.

TIPSY is easy to run and has an extensive help file to assist in use. The software and a tutorial are available on-line. Stand Development Monitoring staff spend a significant proportion of time providing training workshops, outreach and user support. In 2019/2020, staff held two training workshops, three GY sessions for regional cooperatives in BC and four presentations to broader audiences.

5.8 Summary

GY models are available to predict the growth of managed and unmanaged single species, even-age stands for most of BC as well as pine/spruce mixtures.

The main gaps are the projection of complex stands, particularly species mixtures, and the projection of stands under climate change. Given data and resources, TASS should be capable of addressing these gaps. The development of TASS is limited by staff, budgets and data. Suggestions for using genetic studies to link growth to climate and recent research on response to fertilization (Jang et al 2019) have not yet been incorporated into TASS or TIPSY.

It was relatively easy to summarize TASS, TIPSY and VDYP in terms of their basic type (e.g., tree level vs. stand level) and intended use, their projection capabilities (e.g., short term inventory update vs. longer term stand development), the inputs needed to initiate the model (e.g., tree list vs. stand level polygon description) and their outputs (gross total volume, size class distributions, biomass, structure, etc.).

It was more difficult to get information on model scope, the conditions covered (e.g., stand types including species mixtures and age and height structure, geographic coverage), management and disturbance capabilities (e.g., range of silvicultural options, MPB), known weaknesses (e.g., validation against empirical data, comparison to other models), and current research efforts.

When interviewing people about the current GY models, those involved in TASS development and its use were very positive about TASS and its potential to meet BC's GY needs. This is a very small group. The rest of the people interviewed were very frustrated with the limitations of the versions of TASS and TIPSY that are publicly available, the slow pace of development and the lack of documentation and training. These people are interested in looking at other models and calibrating them for BC conditions to address short and medium term needs. The people interviewed were not a representative sample of model users. The sample intentionally targeted people critical of the current GY models.

6 Potential Models

BC is lacking GY models for most complex conditions including mixed species stands and stands with complex vertical and horizontal structure. Additional gaps include growth responses to climate change and disturbances. This section examines the potential of FVS, SORTIE and MGM to address these gaps. Both FVS and SORTIE were calibrated in BC by Ministry staff but are no longer maintained by the province. MGM has been calibrated in northern BC. All models have current research efforts outside the Ministry. More details of FVS, SORTIE and MGM as well as additional models are given in the appendix.

FVS, SORTIE and MGM are all tree level models and project the growth of individual trees. These tree lists can be linked to existing taper/volume/biomass models (section 4.4.2) to produce stand or area-based estimates compatible with existing provincial methods and standards.

6.1 FVS

The Forest Vegetation Simulator (FVS) has potential to address some of the model needs in BC. It is a single-tree, distance independent model. The main model is the large tree diameter growth model. FVS has good potential to address species mixtures that are relatively homogenous in the xy plane but with vertical structure. It accounts for differences in tree species and size but not horizontal spatial arrangements. FVS has extensions that address many of the identified needs including the following.

Complex stands – As noted, FVS had good potential for stands that have a mixture of species and sizes but have relatively homogenous horizontal arrangements. For most variants, individual tree growth is influenced by other trees through some measure of overall site occupancy (stand density) as well as the presence of larger trees (basal area of trees larger than the target tree). Individual tree growth is affected by the presence and size of competing trees but not their species.

Insects and disease – FVS has a number of extensions that may be of interest including the mountain pine beetle extension and the western root disease model (*Heterobasidion annosum, Annosus, Armillaria* spp. and *Phellinus weirii*). Part of the reason for developing the BC variant of FVS in the 1990s was the availability of the western root disease model (chapter 6 in Frankel 1998).

Fire behavior – The Fire and Fuels Extension (FFE) simulates fuel dynamics and potential fire behaviour over time in the context of stand development and management. It includes a snag model which can be useful for wildlife considerations.

Carbon accounting – Using the FFE, FVS can report the carbon stored in various carbon pools including below ground and coarse woody debris.

Climate FVS - Climate FVS accounts for stand level impacts of climate change by i) linking mortality and regeneration by species to climate variables, ii) linking site index to climate and modifying growth rates and, iii) adding functions that account for changing growth rates due to climate-induced genetic responses (Crookston et al. 2010).

Staff at the Forest Management Service Centre in Fort Collins, Colorado, part of the U.S Department of Agriculture Forest Service, are responsible FVS maintenance, enhancement, validation, training and support. The source code for FVS is available. FVS has a large user community in the U.S. Documentation, training and support are available at www.fs.fed.us/fvs/.

FVS has been calibrated in BC for the ICH and IDF subzones. Legacy models are available for the ESSF, MS and PP. Partial development occurred for the SBS and SBPS. The following extensions have been linked in BC but have had minimal testing:

- FFE-Carbon (uses northern Idaho parameters).
- Climate – FVS.
- Western root disease.
- Dwarf Mistletoe.
- Douglas-fir and western spruce budworm.

In the 1990s, FVS was calibrated for the southern interior in BC (Prognosis^{BC}). Prognosis^{BC} has not been enhanced since the release of the Windows VISTA operating system. ESSA is working with Bianca Eskelson at UBC to overhaul Prognosis^{BC}. This will include updating the source code to synchronize with US models, adapting FVS-Online for use in BC and updating database linkages. FVS-Online runs on a local PC or a remote server.

Potential for BC

Inventory update – The potential of FVS for inventory update is limited because FVS requires a tree list as input.

Timber supply analysis & Silviculture planning – FVS has good potential for development of yield curves. It is not designed to be initiated from bare ground but rather from tree lists. It does have an *establishment* extension but in the short term it could be initiated from tree lists from ground surveys including YSM or SDM plots. FVS has good potential to predict the effects of spatially uniform treatments (pre-commercial thinning, uniform shetlerwood) but not treatments such as group selection or row thinnings. It has potential to incorporate the effect of climate change on growth and mortality.

Requirements

Calibrating FVS to a new condition (species, geographic region) involves, at a minimum, calibrating the small tree height growth model, the large tree Dbh growth model, the Dbh-height model, the mortality model and the crown change model.

FVS is initiated by a tree list. Linking FVS to information sources such as the VRI or RESULTS would require some way of generating a tree list. Most work has focused on imputing a tree list from a reference dataset, including work at UBC (Temesgen et al. 2003).

6.2 SORTIE

SORTIE is a distance dependent, individual tree model (Figure 2). The spatial distribution and size of trees determines the spatial distribution of light. Competition for light is assumed to be the main driver of growth on a given site for seedlings and saplings and competition for light and underground resources drive growth for adult trees. The main growth model is the diameter growth model. Growth rates are also one of the inputs used to predict mortality. SORTIE is designed for mixed species stands and incorporates horizontal and vertical structure. It uses a combination of empirical and mechanistic relationships to predict forest dynamics based on field experiments that measure fine-scale and short-term interactions among individual trees. In particular, SORTIE/BC combines short-term empirical studies with the SORTIE model framework to provide insight into long-term forest response to silvicultural strategies (Coates et al. 2003).

Growth and mortality of individual trees and the recruitment of new trees depends on the spatial arrangement, size and species of neighbouring stems. SORTIE is capable of accounting for species interactions, response to partial disturbances such as thinning, mixtures of tree species and sizes and various spatial arrangements.

Complex stands – SORTIE is designed to simulate the development of complex stands including species mixtures and spatial arrangements. The recruitment model has good potential to address partial disturbances including patch cutting and insects and disease.

Insects and disease – SORTIE has good potential for simulating the effects of insect and disease including recruitment following mortality of part of the overstory. In the mid-2000s, the SORTIE research program in northern BC shifted to issues around projecting stand dynamics after MPB in sub-boreal spruce forests of central BC.

Carbon accounting – SORTIE outputs can be used to calculate carbon. The Bulkley Valley Research Centre (BVRC) has a project to evaluate this method against data from Date Creek[9] in the ICH. Work is also underway to collect data across a fire chronosequence to examine the effect of post-fire rehabilitation on carbon and wildlife habitat.

Climate change – SORTIE does not have climate inputs in BC. Work in other jurisdictions (Buechling et al. 2017) has incorporated climatic effects (temperature and precipitation) as growth modifiers.

[9] https://www.for.gov.bc.ca/hfd/pubs/docs/Lmh/Lmh38.pdf

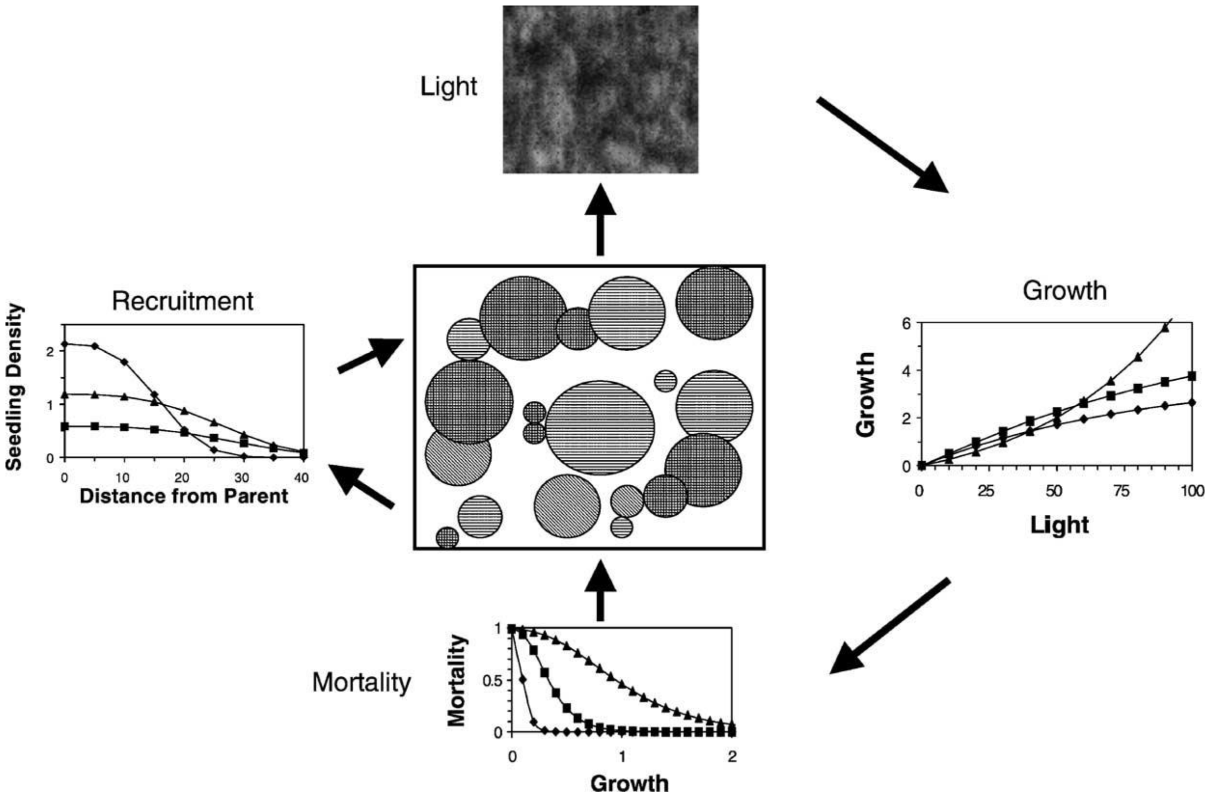

Figure 2. Schematic diagram of the SORTIE-BC model for a hypothetical forest with three species. The spatial distribution of trees in the forests (central panel) determines both the spatial distribution of light (light submodel) and the spatial distribution of new seedlings (recruitment submodel). Spatial variation in light levels determines growth (growth submodel), and growth rates are used to predict mortality rates (mortality submodel), which in turn determine the distribution of trees at the beginning of the next time step. (From Coates et al 2003).

SORTIE is parameterized for subalpine fir, aspen, birch, cottonwood, interior hemlock, interior cedar, amabilis fir, lodgepole pine and interior spruce. It is parameterized for sub-boreal spruce forests in northern BC, particularly the SBSmc2, and for the Kispiox interior temperate rainforest (ICHmc2). SORTIE is currently parameterized for mesic sites, but parameter files are being developed across site series in the SBS. Work is underway to augment the current user interface with an R user interface and to look at response to climate change using temperature and precipitation to modify growth.

For adapting the model to additional geographic areas (and species), it may be possible to focus on parameterization of key functions expected to be affected by local effects not explicitly included. Other functions (e.g., seed dispersal) may be more general and not require geographic localization.

The advantages of SORTIE include the following:

- Historic work in the SBS and ICH and with MPB.
- SORTIE accounts for species interactions and spatial arrangements through light and competition models that account for the size, species and location of neighbouring trees.
- SORTIE has an explicit recruitment model calibrated using data from the Date Creek Study in the Kispiox district.
- SORTIE has active research in BC (BVRC and UBC) and elsewhere (Cary Institute or Ecosystem Studies, New York). The source code is available.

The disadvantages of SORTIE include the following:

- SORTIE has had limited calibration and testing in BC. The extent to which the model can be transferred across site series is not known.

- SORTIE requires either a tree list or a Dbh distribution and is likely not a good option for inventory update or projection.

Potential for BC

Inventory update – The potential of SORTIE for inventory update is limited because it requires a tree list or Dbh distribution as input.

Timber supply analysis & Silviculture planning – SORTIE has good potential for development of yield curves for stands with mixed species, sizes and spatial arrangements. It is capable of predicting the response to treatments such as partial harvesting including variable retention harvesting. SORTIE can be initiated from a spatial tree list, aspatial tree list or a Dbh distribution. For aspatial tree lists and Dbh distributions, it generates random tree locations. SORTIE has a recruitment submodel that predicts the establishment of seedlings. A current project is looking at incorporating the effects of climate change on growth and mortality using a temperature/precipitation gradient.

Requirements

Calibrating SORTIE to a new condition (species, geographic region) requires diameter growth data from stem mapped field plots.

SORTIE can be initiated with a tree list, a Dbh distribution or from bare ground.

6.3 Mixedwood Growth Model (MGM).

MGM (https://mgm.ualberta.ca/) is a deterministic, distance-independent, individual tree-based stand growth model for the boreal forest. MGM is capable of modelling pure or mixed stands of white spruce, trembling aspen, lodgepole pine, jack pine, and black spruce.

MGM is a “height-driven model” that uses SI curves (i.e. height-age-SI models) to predict the maximum annual height increment for each tree. Then, each tree is ranked by social status to determine competition-adjusted height increment, diameter increment and survival. The competition adjustment varies with the species of the competing trees. Dominant trees grow quickly and are more likely to survive. Suppressed trees grow slowly and are less likely to survive.

MGM accounts for interactions between adjacent strata with an adjacency model. The adjacency model reduces the growth as a result of shading from adjacent strata. This can be used, for example, to model the effect of unharvested strips on the growth in cut strips within a cut block.

MGM has good potential for the following.

Complex stands – MGM has good potential for predicting growth of species mixtures that are relatively homogenous in terms of spatial arrangement. It is capable of predicting growth response to uniform removals such as uniform shelterwood. MGM is capable of projecting growth following strip cutting, using a light model to modify growth due to shading of adjacent strips.

Climate change MGM includes a climate moisture index to incorporate the effects of climate change.

The advantages of MGM include the following:

- MGM is calibrated in Alberta with some historic work in BC (SWBS and SBS)
- There is active research and development of MGM at the University of Alberta.
- MGM is used by companies in Alberta. It will be adopted by Saskatchewan as the provincial wood supply model and for short term inventory forecasting.
- MGM may be a good option for developing yield curves, given a tree list.
- MGM can be initialized from SDM and YSM field plots.
- MGM may be a good option for exploring the effects of retaining a larger deciduous component.

The disadvantages of MGM include the following:

- MGM is not spatially explicit so it requires spatially homogenous strata.

- MGM requires a tree list and is likely not a good option for inventory update or projection.

Potential for BC

Inventory update – The potential of MGM for inventory update is limited because it requires a tree list as input.

Timber supply analysis & Silviculture planning – MGM has good potential for development of yield curves for stands with mixed species and sizes. It is capable of predicting the response to treatments that are spatially relatively uniform (e.g., precommercial thinning, uniform shelterwood) as well as strip cutting. MGM is initiated with an aspatial tree list which may be available from ground surveys including YSM and SDM plots. MGM incorporates the effects of climate change on growth through a climate moisture index.

Requirements

The MGM developers recommend, prior to any calibration efforts in BC, MGM should be tested against BC data to determine where the model is working well and where it requires adjustment.

MGM is initiated with an aspatial tree list.

7 Additional Considerations

In discussions with modellers and consultants, it is clear there is a great deal of expertise in BC and a lot of model development is occurring. However, there is not a lot of communication. Don Robinson of ESSA suggested it would be very productive for the MFLNRO&RD to host an informal meeting each year, inviting researchers, academics and modellers from BC and elsewhere to share their current work and future plans. This communication would encourage collaboration, reduce duplication and encourage sharing of data.

Collaboration has many benefits.

- Industry involvement and consultation helps ensure models meet operational needs.
- Provincial government, as the landowner, should be involved in model development to ensure models meet regulatory requirements.
- Academic involvement helps to keep research relevant, ensure results are published, expose undergraduates to GY models and train graduate students to become future researchers.
- The most successful PSP programs tend to be those associated with cooperatives. Data, particularly from PSPs, is essential to model development.

Data standards, sampling design and compilation routines are very important but often neglected and misunderstood. Sample design and protocols are sometimes developed prior to knowing how they will be used. Compilation routines should be thoroughly tested and documented.

8 Summary

The biggest short- and medium-term GY model needs in BC are for mixed species conditions, complex silviculture such as partial harvests, partial disturbances (e.g., MPB, fire), climate change and initializing managed stand yield curves (creating inputs from performance surveys and silviculture packages). According to one person interviewed, model development is progressing linearly while model needs are increasing exponentially. The gap between what models can do and what users want is increasing. Resources are limited. Some resources should continue to be allocated to documentation and training to ensure models are used correctly. GY model users should be intelligent, informed and observant.

TASS, TIPSY and VDYP are calibrated and supported in BC. Prognosis^{BC} has been calibrated for most subzones in the IDF and ICH and some subzones in the SBS and SBPS. MGM has been calibrated for northeast BC and SORTIE-ND in the SBS and ICHmc2. With the exception of MGM, all have active research projects in BC. Current calibration of MGM includes BC PSP data (winter 2020 release).

TASS has good potential to meet short-, medium- and long-term needs in BC. It is capable of handling mixtures of species, sizes and spatial arrangements. The TASS architecture should accommodate many of the predicted changes in tree growth and mortality under different climate change models. The fundamental biological relationships underlying tree growth and stand development are expected to remain stable. The main limitations to TASS are that few people are trained in its use, it is only calibrated for one species mixture and model development is limited by staff, resources and data. There is a need for more documentation on the calibration data, validation of the model and training on its use. TASS III needs to be expanded to include more species mixtures. TASS III is a great start but limited to pine/spruce mixtures. TASS is a complex model and model development and maintenance is costly.

TIPSY has good potential to meet short- and medium-term needs in BC if it can be expanded to species mixtures. Recent work linking a simplified version of TIPSY to RESULTS information is promising. Significant disconnects remain between RESULTS and TASS/TIPSY. TIPSY was not designed to project existing stands and RESULTS was not designed to be compatible with TIPSY. As with TASS, documentation is required on the calibration data and the robustness of the predictions. Training and standardization on the use of TIPSY in timber supply is required.

Prognosis^{BC}, MGM and SORTIE all have potential to address short- and medium-term needs in BC. All have capabilities to model species mixtures, complex canopies, partial disturbances and climate and have active research efforts.

There are fundamental differences between TASS/TIPSY and the potential models (Table 1) including the fundamental drivers (crown vs. Dbh and height), the primary initialization (bare ground vs. established stand) and the detail of the outputs (wood quality vs. tree size).

The decision of where to allocate GY resources is not clear. All the models examined have capabilities to address the main GY needs identified in section 3.1. How well they currently meet the needs is unknown. None of the models have had recent (last 10 years) validation in BC. There is little documentation on the calibration data or statistical properties of any of the models for use in BC. The reliability required of the models for various applications is also unknown. As a consequence, it is not possible to estimate the data and modeling efforts required for each model to address the user needs.

The next step should be to validate TASS, TIPSY. VDYP, Prognosis^{BC}, MGM and SORTIE-ND. This involves identifying and prioritizing the main conditions of interest (forest types and silviculture) and developing evaluation criteria for the main uses. Then each model should be evaluated against validation datasets representing the conditions of interest using the evaluation criteria, perhaps similar to Goudie[10].

Currently BC has VDYP for unmanaged stands and TASS/TIPSY for managed stands. There are no other options. Making additional GY models available will mean that GY staff will be asked to recommend which model should be used where. This makes validation and documentation of calibration data, model features and model robustness very important. If more than one model is available, users will want to know which model is better under which circumstances.

There are significant barriers to using any models other than those provided by the ministry. There is no process for getting approval for use of an external model in timber supply analysis. Current data sharing agreements give the ministry access to any models developed so there are no commercial benefits for developers. Consequently, there is little or no model development in the private sector. BC is moving toward allowing access to many provincial datasets[11]. However, it is unknown whether the Ministry will require products derived from the data to be made available in the public domain.

There is frustration in the user community about the slow pace of development of TASS and TIPSY.

[10] https://www.for.gov.bc.ca/hre/pubs/pubs/0567.htm
[11] https://www2.gov.bc.ca/gov/content/data/open-data

Table 1. The requirements and capabilities of the main GY models are compared.

Attribute	VDYP	TASS	TIPSY	Prognosis[BC]	MGM	SORTIE
Model type	Stand level	Spatial, individual tree	Yield tables derived from TASS	Aspatial, individual tree	Aspatial, individual tree	Spatial, individual tree
Fundamental driver	SI, BA, quadratic mean Dbh and Lorey height	Crown-driven	See TASS	Large tree Dbh growth – empirical function of species, size, site and competing trees	Height-driven – empirical function of species, size, site and competing trees	Large tree Dbh potential growth moderated by competing trees, small tree recruitment – a function of seed source, substrate and available light
Initialization – primary	Inventory polygon description	Bare ground Species, SI, spatial arrangement	See TASS	Established stand aspatial tree list – species, Dbh, height (optional), SI, age	Established stand aspatial tree list – species, Dbh, height, age (optional) and SI	Established stand – Dbh distribution
Initialization alternatives		Spatial or aspatial tree list – species, Dbh, height, SI	Limited ability to initiate from existing stand information	Some work on tree list generation		Spatial or aspatial tree list Ongoing work to initialize from bare ground
Primary calibration	By inventory type group	By species	See TASS	Species within geographic region	Species within geographic region	Species within geographic region
Outputs	Stand level attributes including height, BA, various stand level volumes	All tree-level models output a tree list at each time step. This tree list includes species, Dbh and height. Available taper/volume/biomass equations can be used to convert the tree list to standard compilations of volume and biomass to various utilization levels. External estimates of decay, waste and breakage can also be applied.				
Additional outputs	Biomass	Wood quality, snags, coarse wood debris	See TASS	Extensions for Fire and Fuels and some insects and diseases		Crown radius and length, Regeneration
Climate	No	Recommendation to use genetics studies as a first approximation	See TASS	Climate extension links climate to mortality and regeneration, site index and growth rates	Climate Moisture Index (CMI) affects mortality/ survival. Current work on incorporating CMI into growth functions.	Current work to calibrate across a temperature/ precipitation gradient
Inventory update	Yes	None of the tree-level models link well to the current inventory. All would benefit from a tree list, either imputed from the inventory or from an individual tree inventory (potentially from LiDAR)				

Attribute	VDYP	TASS	TIPSY	Prognosis^{BC}	MGM	SORTIE
Timber Supply Analysis	Yes, for unmanaged forests	No	Yes, limited calibration for species mixtures	Yes, limited calibration and no recent work in BC	Yes, limited calibration in BC	Has potential but limited applications to date in BC
Silviculture planning	No	Yes, limited calibration for species mixtures	Yes, limited calibration for species mixtures	Yes, limited to horizontally uniform treatments Limited calibration in BC	Yes, limited to horizontally uniform treatments Limited calibration in BC	Yes, limited calibration in BC

The proposed strategic goals in the growth and yield modelling strategy for BC prepared in 1997[12] remain relevant today.

Ensure that the organizational framework for GY allows for the development of "corporate" approaches to GY and engenders long-term support for GY modelling activities in BC.

Secure sufficient resources (including funding, skills and personnel) to pursue GY initiatives of strategic importance in a timely manner.

Ensure that application related needs are identified and prioritized.

Ensure that model inputs and required data are being collected to use GY models.

Provide specific GY models that meet the needs of clients.

Develop and maintain a user/model interface that is menu-driven, user friendly and easy to understand

Improve the skills of GY practitioners and clients to ensure that appropriate and optimal use is made of existing GY models.

Improve GY clients' level of awareness of GY program and initiatives and provide user support at levels which ensure that optimal use is made of existing GY models.

Ensure that accepted standards and guidelines for the development, application, maintenance and monitoring of GY models are developed and communicated to GY clients.

9 Recommendations

Step 1 – Document Provincial models

TASS, TIPSY and VDYP require more documentation. Lack of documentation is a significant barrier to model acceptance and use. Documentation should include:

- A description of the basic model architecture and its intended application (e.g., yield curves, comparing silvicultural options).
- A description of the underlying assumptions and calibration data including the conditions covered (e.g., stand types including species mixtures, age and height structure, geographic range) and management and disturbance capabilities (e.g., range of silvicultural options, MPB).
- An assessment of model performance and the reliability of the predictions (e.g., validation against empirical data, comparison to other models).
- Availability of the model including training and recommended use.
- Supporting literature, particularly peer-reviewed literature.
- Current research efforts.

Step 2 – Prioritize needs

The GY needs identified in Section 3 are broad. The next step should be to prioritize specific needs and conditions. For instance, not all species mixtures are of equal importance. Some specific conditions with high levels of uncertainty may potentially have a large impact on wood supply while other conditions may have lower impact. TASS has been parametrized for complex relationships over a narrow range of species conditions. TASS III development could focus on adding more complexity such as adding climate change effects or focus on broadening the range of species in TASS III.

The scope of the needs should be identified. For instance, the impacts of a changing climate are longer term and affect all species and regions of the province. In contrast, some diseases have local, short term impacts.

[12] "A Growth and Yield Modelling Strategy for British Columbia" Draft November 1997 Prepared by Forum Consulting Group in association with D.R. Systems, Inc.

Existing research on climate change should be incorporated into TASS and TIPSY. Fertilization results that have not been incorporated should be incorporated

GY needs include training of more model developers and model users and acquiring more data from long term remeasured field plots.

Step 3 – Identify resources

The available resources need to be identified. Resources include the current and potential models. This also includes published research such as the impact of fertilization on growth. The data available to calibrate models should be summarized as it will limit model development. Resources, human and financial, should be summarized including potential funding sources and collaborators.

The people interviewed were in that agreement the FAIB modelling group is understaffed and underfunded.

Step 4 – Assess Models

The reliability of TASS, TIPSY. VDYP, Prognosis^{BC}, MGM and SORTIE should be evaluated against the needs and conditions of interest in step 2. The evaluation should include quantitative measures (bias, precision) as well as subjective criteria such as model logic. Each model should be evaluated against validation datasets representing the conditions of interest, using the evaluation criteria.

The FAIB should host a meeting of people involved in GY research including those involved with TASS. TIPSY, VDYP, Prognosis^{BC}, SORTIE and possibly MGM. The models should be summarized as well as the research efforts. Ideally this would be an annual meeting, possibly as a formal working group.

After the initial meeting, FAIB should decide whether to allocate resources outside of the currently supported models. If so, it is recommended FAIB further investigate the use of Prognosis^{BC}, SORTIE and MGM in BC. It is likely that in the short term, calibration of Prognosis^{BC}, SORTIE or MGM will be less expensive and cover more conditions than development of TASS. In the longer term, additional TASS development has the potential to cover more conditions and produce more detailed output including wood quality.

Step 5 – Develop a plan

Given the needs, model assessments and the available resources (including current models, potential models, research, and calibration data), a GY plan should be developed. For each need, the plan should summarize the model options, the data required and its availability, the resources required and the timing. An example summary is given in Table 2.

Table 2. Examples are given of model needs, model options to address the needs, the data requirements, the lead organization as well as the timing.

Model need	Model options	Data requirements	Lead	Timing
TIPSY documentation	NA	NA	MFLNRO&RD	Short term
Spruce/aspen mixtures in NE BC	TASS/TIPSY MGM	PSP data for calibration and validation	External, depends on model	Depends on availability of data & resources
Climate change	FVS	PSP data Climate model		Medium term, possibly short term for IDF
	SORTIE	PSP along a climate gradient		Longer term

A realistic time frame for TASS and TIPSY development should be constructed and updated as necessary.

FAIB should develop a plan to encourage model development, targeted at specific needs. This plan should include data sharing, financial and in-kind support of external projects as well as internal model development.

BC is committed to sustainable management of its forests, requiring GY models covering the range of forest conditions and management activities in BC. Staff and resources are needed to maintain current models. Additional resources are required to address gaps. Without additional resources, the gap between GY model capabilities and user needs will continue to increase.

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11 Appendix A – More detailed model descriptions

First the models supported by the MFLNRO&RD are described followed by external models.

11.1 Current Models

The Government of BC develops and maintains models and tools to predict the GY of the province's forests. These predictions play a key role in supporting sustainable forest management decision making by government and its forest licencees in many areas, including:

- Forest and timber-supply analysis for Timber Supply Areas and Tree Farm Licences.
- Forest inventory (including annual projection of the provincial inventory)
- Silviculture planning (including comparison of alternatives)

The main GY models are TASS, TIPSY and VDYP.

11.1.1 Tree and Stand Simulator (TASS)

TASS is a spatially explicit, individual tree model that provides GY estimates of key attributes for the managed forests of BC[13]. It is a crown driven model and is calibrated by species and is independent of geographic region. It predicts volume, biomass and carbon yields under different management scenarios.

TASS simulates the growth of individual trees and stands in three dimensions. The crowns of individual trees expand and contract asymmetrically in response to internal growth processes, the crowns of competitors, environmental factors and silvicultural practices. The crowns add a shell of foliage each year. The volume increment produced by the foliage is distributed over the bole annually.

TASS is based on detailed stem and crown analysis and growth trends observed in fully stocked research plots growing in a relatively pest free environment. The yields will be very close to the potential of a specific site, species and management regime.

TASS III, the newest version, supports and complex structures and mixtures of lodgepole pine and white spruce and is the first publically distributed, MS-Windows™ version of TASS.

TASS II predicts the potential GY of even-aged, single-species managed stands for 10 commercial tree species:

The coastal species are Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), sitka spruce (*Picea sitchensis*) and red alder (*Alnus rubra*). The interior species are Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), western hemlock (*Tsuga heterophylla*), lodgepole pine (*Pinus contorta* var. *latifolia*), white spruce (*Picea glauca*) and trembling aspen (*Populus tremuloides*).

TASS is the core of a suite of programs developed and maintained by the Stand Development Modelling Group. TASS is linked to models in the Silviculture impacts on Yield, Lumber Value and Economic Return (SYLVER) system that predicts log and lumber yields.

TASS and SYLVER generate the database of yield tables stored and reported by TIPSY. TIPSY is the user-friendly table interpolation program used in most TASS operational applications.

Basic type

TASS is an individual tree, spatially explicit (distance dependent) growth model.

Projection capabilities

TASS III is approved for use in all applications requiring managed stand yields of lodgepole pine and white spruce in BC. It may be used for projecting stand development for managed pine and spruce monocultures,

[13] https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/growth-yield/iufro_2019_poster_presentation_mariodilucca.pdf

TASS may also be used to project early stages of stand development for pine and spruce mixtures but users should exercise caution when interpreting late-rotation projections. TASS III Windows is publicly available.

TASS II is calibrated for single-species, managed stands. TASS II is not publicly available.

Inputs

TASS is primarily designed to be initiated from bare ground with species, site index, plantation density and spatial arrangement, as well as ingress. It can also be initialized with a spatially explicit tree list.

Outputs

TASS can output a tree list as well as stand level attributes. Tree attributes include Dbh, height, crown area and length and foliar volume.

Scope

TASS is intended to provide GY estimates for managed stands and is also a research tool.

The core purpose of TASS is to predict silvicultural treatment response by modelling individual tree crown dynamics and their relationship to bole growth and wood quality. This focus on crown dynamics makes TASS particularly well suited for predicting response to treatments such including initial spacing, fertilization, pruning and pre-commercial and commercial thinning.

Climate change is expected to affect tree growth and mortality. The fundamental biological relationships underlying tree growth and stand development are expected to remain stable (BC Ministry of Forests and Range 2010). As a result, TASS may be capable of simulating conditions it hasn’t been calibrated for, including a changing climate. For example, TASS may be able to simulate the effect of Swiss needle cast through a reduction of the foliage layers.

TASS can simulate the growth of irregularly spaced, mixed species plantations because it is spatially explicit and has detailed crown models.

Most of the plantation data come from plantations established in 1960 or later.

Calibration and validation

Many of TASS’s component growth relationships were derived from detailed stem analyses of tree boles, branches and foliage. The resulting model was then calibrated with data from approximately 15,000 permanent sample and research plots in BC, Alberta, the U.S. Pacific Northwest, Europe and New Zealand.

Goudie (1998) compared pre-commercial and commercial thinning response predictions from TASS against data from many long-term research installations in BC, Alberta and Washington State. He concluded that “while growth and yield models cannot be proved valid, models must be evaluated or tested against available data to identify potential biases. The [TASS] system generally performs very well but may moderately overestimate the response to thinning in some cases."

Goudie (1996) also compared lodgepole pine managed stand yield tables generated by TASS against data and a yield model from Sweden (Elfving, 1990). He concluded that the appearance of higher productivity in Sweden, relative to BC, is due largely to the absence of natural, unmanaged stands in Sweden, where lodgepole pine is an introduced exotic. Comparing managed stands, he found similar upper productivity limits and similar standing volumes at common stages of stand development. Thinning yields produced by two very different models (TASS and the model by Elfving 1990) are quite similar for standing volume, the culmination of mean annual increment and total production.

Management and disturbance simulation capabilities

TASS has many potential applications[14]:

- Analyzing managed stand yield curves at the forest level to support allowable annual cut (AAC) determinations and forest management planning. Examples include:
  - Timber supply review (FAIB)
  - Forest Development Plans (licensees)
- Planning and analysis of silviculture investment. Examples include:
  - The Ministry's Forests for Tomorrow and Land Based Investment programs
  - Silviculture Strategy development
  - Stocking Standards development under the BC *Forest and Range Practices Ac*t
  - Stand-level prescriptions
- Exploring questions involving tree growth and stand dynamics. For example:
  - Evaluating proposed silvicultural treatments and policies in the absence of conclusive field data
- Assessing impacts on wood quality and value
- Projecting carbon sequestration and biomass production
- Analyzing pest and disease yield impacts,
- Teaching and demonstrating the principles of growth, yield and stand dynamics

Known weaknesses

In TASS II, all over-topped trees die. As a consequence, TASS II has limited ability to simulate multi-layered canopies and other complex stands.

TASS is a complex model and few people have the expertise to prepare the input files for meaningful simulations. TASS can be initiated from bare ground with relatively basic information. Initiating a TASS run for an existing stand requires a spatial tree list, something not available from the VRI or from silvicultural surveys.

TASS is viewed as a black box – users would like more documentation on the model components, calibration data and validation as well as training on its use.

TASS is not publically available and cannot be used by other researchers to investigate, for example, climate effects.

TASS does not link well to performance surveys and stocking standards. Regeneration surveys are the responsibility of the Resources Practices Branch (not FAIB) and the primary use is in evaluating free-growing status and not to initiate GY projections.

Although not a model weakness, most of the TASS expertise is concentrated in a few people who are close to retirement. This may limit future model development and support.

Current Research Efforts

TASS III

- A light model (tRAYci) simulates relative light levels within the canopy.
- Height growth and other driving functions are responsive to relative light levels.
- Development of coastal Douglas-fir and hemlock mixed species functionality.

TASS II

- Building a new edition of TASS II for all species, incorporating many improvements in the model algorithm.

[14] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/growth-and-yield-modelling/tree-and-stand-simulator-tass

Methods to incorporate climate change into TASS have been investigated[15] leading to a recommendation to examine provenance trials to address questions about tree growth and climate. An example is given in O'Neill and Nigh (2011). These climate/growth relationships could then be incorporated into TASS. Another option is to predict the effect of climate on SI (e.g., Nigh et al. 2004). Realized gain trials have been established to corroborate the height estimates from progeny trials and estimate volume gains. Realized gain trials are in place for Douglas-fir (coastal and interior), western hemlock (coastal), lodgepole pine, interior spruce and larch. Results for age 12 for Douglas-fir have been reported but more meaningful results as the trees get older (over age 20).[16]

A pilot study is planned to use a LiDAR-based inventory to initialize TASS.

11.1.2 Table Interpolation Program for Stand Yields (TIPSY)

TIPSY provides access to TASS-generated, managed-stand yield tables, which support many operational applications in BC. TIPSY is based on growth trends observed for up to 70 years in fully stocked research plots growing in a relatively pest free environment. The yields are expected to be very close to the potential of a specific site, species and management regime. These yields are generally not attainable under operational conditions. However, they are the only source of data for managed stands subjected to various silvicultural treatments. TIPSY predicts the yields of the best managed stands with reasonable confidence.

The reduction necessary to approximate the yield of the average managed stand is not known. The best estimate suggests that the productivity of the average managed stand will be about 15% below the unadjusted yields generated by TIPSY. TIPSY includes Operational Adjustment Factors (OAFs) which are used to adjust (lower) yields for abiotic and biotic factors that cause TIPSY predictions to differ from operational yields. OAF1 is a constant multiplier. OAF2 is progressive multiplier that increases linearly with age from 0% at age 0 to the user specified value (the default is 5%) at age 100 and older. For forest planning purposes, the TIPSY online help feature recommends yields be reduced by 15% and 5% for OAF 1 and OAF 2 respectively, unless there is strong evidence that local conditions warrant a different value. These OAFs should be reduced if other adjustment factors such as decay, waste and breakage are used.

TIPSY includes a batch processing feature to generate yield tables for large multi-stand datasets, like those used in timber supply analysis. It handles most of the treatments and variables that interactive TIPSY does, provided they impact volume.

Basic type

TIPSY is a stand level GY model.

Projection capabilities

TIPSY is provides managed stand yield tables for use in timber supply analysis. It is used to generate yield curves and compare silvicultural regimes. For these applications, TIPSY works well for relatively pure, even-aged conditions. Recent work has improved the integration of early performance surveys and yield curves leading to the improvement of the analysis unit curves for young stands.

TIPSY is used by Forests for Tomorrow (FFT). The FFT Program is administered by the Resource Practices Branch and was established by the Province of BC in 2005 to respond to the catastrophic wildfires that occurred in the southern and central interior, and to the mountain pine beetle epidemic. Investments focus on reforestation (on land that would otherwise remain unproductive) and timber supply mitigation (mitigating

[15] Stearns-Smith & Associates. Incorporating climate change into TASS predictions: a problem analysis. Draft prepared for BC Ministry of Forests, Mines and Lands. March 2011.

[16] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/forest-genetics/research-projects/realized-genetic-gain-trials#:~:text=Progeny%20tests%20are%20conducted%20on,quality%20of%20a%20tree's%20offspring.&text=Realized%20genetic%20gain%20trials%20have,on%20a%20per%2Dhectare%20basis.

impacts on mid-term timber supply caused by catastrophic disturbance through a program of stand treatments). The investments are evaluated using TIPSY.

Inputs

The inputs include the BEC zone, species, site index, origin (planted, natural or clumped), genetic worth and initial density. The user can also specify treatments including pre-commercial thinning, commercial thinning and fertilization. In interactive mode, TIPSY can be initiated with information from an existing stand.

Outputs

TIPSY outputs stand level attributes including volume to various utilization levels, top height, basal area, Dbhq, live crown percent, biomass and carbon. TIPSY output is readily transferred to the graphing program PLOTSY and the financial analysis program FAN$IER.

Scope

TIPSY has no tables for scenarios combining planted and natural ingress or mixed species. It projects the growth of species mixtures as the species composition weighted average of the pure species growth.

Reliability

The yield information in TIPSY was calibrated with more than 15 000 permanent sample plots. The number of plots varies greatly by species, treatment, and site index. The reliability estimates in Table 3 are based on the number of plots by species, experience, and basic knowledge of tree growth and stand development. Reliability also varies by treatment, stand age and other factors.

Table 3. The reliability (G = good, M = medium and P = poor) of the TIPSY predictions varies with species and site index (For coastal species High =35, Average =25, Low=15. For interior species High=20, Average=15, Low=10). From TIPSY 4.4 help.

	Site Index		
Species	High	Average	Low
Douglas-fir (coastal)	G	M	P
Western hemlock (coastal)	G	M	P
Sitka spruce	M	M	P
Western redcedar	P	P	P
Lodgepole pine	G	G	M
White spruce	M	M	P
Douglas-fir (interior)	M	M	P
Western hemlock (Interior)	P	P	P
Red alder	P	P	P
Trembling Aspen	M	G	P

Management and disturbance capabilities

Like TASS, TIPSY provides managed stand yield tables for single-species, even-aged stands. TIPSY also provides mixed-species yield tables (without species dynamics) by using simple, area-weighted averaging of single-species yields. TIPSY functions primarily as a “bare ground” model like TASS, with the same inputs.

Although TIPSY is less flexible than TASS, it still supports a variety of silviculture treatments including fertilization, genetic gain, pre-commercial and commercial thinning and variable retention harvesting.

Three spatial distributions (square, random and clumped) and a broad range of initial densities (69 to 10,000+ stems/ha) are supported.

TIPSY predicts attributes important in predicting fire behaviour and suppression including mean crown base height, mean crown length, and crown bulk density.

Known weaknesses

TIPSY is initialized at stand establishment. It can be used to project existing stands. Essentially, TIPSY recreates the conditions leading to the existing stand. TIPSY takes the density, site index and age (or height) and estimates the initial density. The effects of any silvicultural treatments such as thinning must also projected backwards. The estimated initial conditions are then grown and the silvicultural treatments applied. The existing stand option is not available in batch TIPSY.

TIPSY is the main model used for managed stands in timber supply analysis. TIPSY is calibrated for pure species and pine/spruces mixtures. There is managed stand data for some species up to about age 60 for some species, younger data for other species. However projections in timber supply can run up to 300 years for things such as caribou. The implications of extrapolating beyond the range of data are unknown.

Current Research Efforts

TIPSY benefits from TASS research. Work is underway to incorporate fertilization effects (Jang et al. 2019).

Work is ongoing to create TIPSY input files from harvest openings (from the RESULTS layer). This input file contains information on planted species and density. SI can be obtained from the PSPL. The input file works for TASS and TIPSY. A stripped-down version of TIPSY was created to handle the large number of openings. A yield curve is generated for each opening which can then be reviewed by an analyst and then used in timber supply.

11.1.3 Variable Density Yield Projection (VDYP)

VDYP is a stand level model, used to project unmanaged stands. VDYP was developed by Dr. Jim Flewelling and the Resources Inventory Branch (now the FAIB of the MFLNRO&RD) using subjectively located permanent sample plots as well as temporary sample plots that cover a wide range of unmanaged conditions. VDYP projects the average yield of naturally regenerated stands which have not been treated. The empirical yields from VDYP are generally lower than the potential yields given by TASS and TIPSY, although TIPSY yields can be adjusted for operational conditions. The current version of VDYP is the result of close to a decade of research, development and testing to prepare and fit the model using temporary sample plot data (52,000 plots) and permanent sample plot data (9,300 plots). Additionally, inventory audit samples (2,700 plots) were used to validate the model.

Basic type

VDYP is a stand level growth model designed to project inventories over the short term. It is intended to be used for naturally regenerated stands. It does not generate the full set of outputs for short, young stands until they reach a minimum size. Stands that are less than 6 – 8m and have a Dbhq < 7.5 cm will not be assigned volumes.

Projection capabilities

VDYP is intended mainly for short term inventory updates and is designed to start with an inventory stand description. VDYP is also used for developing yield tables for unmanaged stands for use in timber supply.

Yields are projected by incrementing density attributes, including basal area (BA) and Dbhq, as well as incrementing age and growing height.

VDYP uses BA as a direct measure of stand density. Therefore VDYP can be used to model catastrophic mortality (e.g. stands affected by mountain pine beetle), or selectively harvested stand through changes in BA.

VDYP generates a wide variety of outputs. Five different volume types (whole stem volume; close utilization; close utilization net decay; close utilization net decay and waste; and close utilization net decay, waste and breakage) are generated at five different diameter limits (Table 4). The 4.0 cm+ diameter limit allows for more accurate estimation of forest biomass. The distribution of volume by size class can be important information for industry.

Table 4. The utilization classes in VDYP are defined.

Utilization code	Dbh range (cm)
-1	4.0 ≤ Dbh < 7.5
0	7.5 ≤ Dbh
1	7.5 ≤ Dbh < 12.5
2	12.5 ≤ Dbh < 17.5
3	17.5 ≤ Dbh < 22.5
4	22.5 ≤ Dbh

VDYP growth and yield functions are fit by BEC zone. This is consistent with the ecologically-based taper equations and loss factors that predict more accurate volumes.

Layers. Stands may have multiple layers. The layer designated the primary (P) layer is grown. Additionally there may be an overstory (V) layer, which can include "veteran" layers in the FIP standard. At present, all trees in the V layer are estimated to have Dbh's > 22.5 cm. Attributes for the V and Dead layers are estimated but not projected. The full set of attributes for the primary layer are projected. For the remaining layers (not primary, not V, not dead), age and height are projected.

Utilization class. There are yield statistics for various utilization levels within each species group by layer combination. The utilization classes are based on Dbh (Table 4).

Most plot data used in fitting the growth equations were collected with protocols which excluded trees having DBH < 7.5 cm. Lorey height (HL) is computed for utilization classes -1 and 0. HLs are weighted means of total tree heights, using tree basal area as the weight.

VDYP stand descriptions are created by all the VDYP modules. Stand descriptions could also be compiled from ground sample data. This may require assigning sample trees to layers when appropriate, and a method to estimate the net volumes of the individual trees.

VDYP includes six modulus. VDYPGrow is the main module.

VDYPGrow VDYPGrow takes a VDYP stand description and projects it to future years through annual growth increments. The primary driving equations increment site height, basal area and quadratic mean diameter. A secondary series of equations update basal area and trees/ha by species and utilization class. All volumes are updated to reflect the increments in basal area, quadratic mean diameter and height. Species percentages of basal area do not change during a projection using the recommended default parameter settings.

VDYPGrow can handle multiple layers. Veteran overstory layers are not grown (age is incremented). The primary layer is grown with a full suite of attributes by layer, species group and utilization level. Attributes include basal area, trees/ha, lorey height and five volumes (whole stem volume, close utilization volume, close utilization volume net decay, close utilization volume net of decay and waste, and close utilization net of decay, waste and breakage)

VRIStart VRIStart takes stand descriptions from inventories using the VRI standard and completes the required model inputs required including HL.

FIPStart FIPStart takes stand descriptions from legacy Forest Inventory Protocol (FIP) standard inventories that have crown closure rather than basal area.

VRIYoung VRIYoung is a sub-component of VRIStart. VDYPGrow requires basal area and tree/ha as inputs. These are defined for utilization class 0, which includes all trees with DBH ≥ 7.5 cm. For young stands, the yield statistics are often zero, and give no useful indication of stocking or mean tree size. Full VDYP stand description for young ages would be mainly zeros and not provide a useful starting point for the growth components. Therefore, VRIYoung projects the growth of a subset of the attributes of young stands until they meet minimal conditions.

VRIStart checks whether VRIYoung should be invoked. Generally, VRIStart is used for young stands without a BA. Age, site index, and site curve number are the primary inputs. The current age and a series of annual increments are examined. At each age, site height is determined from the site curve, and BA is predicted with an empirical equation. At each age, the predicted site height and BA are compared against minimum targets. The first age where the targets are met becomes the age at which a full VDYP description is made. The minimum targets are breast height age 6, site height 6 m, and BA of about 2.0 m^2/ha.

VDYPBack VDYPBack takes a VDYP stand description, estimates the condition of the primary layer at some earlier age, and interpolates at intermediate ages. The earlier age is chosen such that the site curves will indicate a site height of about 9 m. No consideration is given to the history of the overstory layer. Long term planning processes used by the Ministry and the previous version of VDYP (VDYP6) required yield curves for each stand. VDYPBack is designed to create plausible yield curves which include the current stand condition. These curves allow the present planning process to be continued with minimal change. However, the curves derived in this way are far from perfect; there may be better ways to estimate yield curves for future rotations

VRIAdjst The VRI was designed to collect data suitable for the unbiased estimation of many different quantities at some aggregate levels, such as that of a Tree Farm License. VDYP provides estimates of quantities such as basal area and volume for each stand. A sampling estimator can be used to calculate an unbiased estimate of the totals for a population. Typically this involves obtaining an independent, unbiased estimate of the population total from a set of randomly selected plots. Then a ratio of means is estimated as the ratio between the average attribute measured on the ground sample and the average attribute estimated in the VRI for the same ground samples. The sampling estimator for the population total is the product of the ratio of means and the VRI population estimate.

The sampling estimator is for population means and totals. It does not indicated how the population estimates should be distributed to individual stands in the population. The same ratio of means can be used to adjust each attribute independently at the polygon level. However, this may not preserve logical relationships between the attributes. In general the adjustment algorithm in VDYP is not used.

Inputs

The main growth module, VDYPGrow, requires a VDYP stand description. At the stand level, the required attributes are year, BEC and percent forest land. At the layer level, the required attributes include BA, trees/ha, species group and their proportion of BA and, for at least one species group, site height, site index, total age, abreast-height age and years to breast height. The VRIStart and FIPStart modules are used to complete the inputs.

Outputs

The VDYP system generates estimates of stand volume, basal area, and mean diameter. Estimates can be obtained to several utilization standards and diameter limits. Some yield estimates include reductions for decay. VDYP estimates stand level biomass using volume to biomass conversion factors.

Scope

VDYP is used for inventory projection of all unmanaged stands in BC. It is used in timber supply analysis for naturally regenerated, unmanaged stands.

Management and disturbance capabilities

VDYP is intended to be used for unmanaged, even-aged stands. The system does not explicitly model treatment and stand history effects. VDYPBack can be used for backward projection (past growth) and VRIYoung can be used to project a limited suite of attributes for young stands.

Known weaknesses

VDYP is calibrated by growth type groups. A 50/50 spruce/pine mixture is in a different growth type group than a 50/50 pine/spruce mixture leading to different growth projections.

The species composition is static. There is no interaction between layers – each layer is projected (or not projected, in the case of the veteran layer) independently.

There is no regeneration option. The two main conditions of interest are regeneration following stand-replacing disturbances and regeneration following partial disturbances.

VDYP is working well for its intended uses, even for MPB stands. It is an older model, much of which is in FORTRAN 77. There are few people who understand the model well and fewer who can code and make changes to VDYP. There is interest in rewriting the code in a more current programming language.

Current Research Efforts

Work is ongoing to model the growth of, and interaction between, layers. The VRI contains information by horizontal layers. A polygon may have up to 5 layers – 1, 2, 3, S (silviculture) and V (veteran). There is generally at least a difference of 40 years in age and 10m in height between layers. What is the influence of an overstory residual layer on the understory layer?

Options for using VDYP to project growth after partial disturbances (such as MPB) are being evaluated. There is ongoing work on post-MPB regeneration. The main focus is on the mortality rate from MPB and the advance regeneration species composition and growth rate, as affected by the overstory.

11.1.4 SiteTools

SiteTools is a comprehensive SI calculator for BC tree species. Although SiteTools does not deal with volume (generally one of the most important outputs of a GY model), it is discussed here because it is an integral component of TASS and VDYP. SiteTools is developed and maintained independently.

SiteTools is a user-friendly SI calculator for Windows. It provides access to many SI related functions for 24 tree species in BC by location (coast/interior) and regeneration method (natural/planted).

SiteTools includes:

- SI (height-age) equations
- Years-to-breast-height equations
- Growth intercept equations
- SI conversion equations

Other functions include:

- Enabling age input/output as total tree age or breast height age
- Providing an alternative (growth intercept) to SI equations for ages younger than 50 years.
  Note: This function is only available for some species
- Predicting the SI of one species from the SI of another (SI conversion equations)
  Note: This function is available for only some species pairs
- Providing multiple equations for some species

Note: Ministry recommended equations are identified in SiteTools. These are the default equations used in most Ministry GY applications including TIPSY and VDYP.

SiteTools produces custom SI tables and graphs and functions as a SI calculator. It includes a separate batch routine for processing large data files.

There are gaps in the SI conversion equations (e.g., interior red cedar).

Nigh et al. (2004) and O'Neill and Night (2006) predicted SI for from climate variables for lodgepole pine, interior spruce and interior Douglas-fir.

Gord Nigh was responsible for most of the SI research in the province and has recently retired.

11.1.5 Provincial Site Productivity Layer

The Provincial Site Productivity Layer (PSPL) is a spatial database of SIs for commercial species for the province. It was created in response to a need for improved accessibility to SI information. The SI estimates in the PSPL were obtained from either the SI by BEC (SIBEC) model coupled with an ecological map or from a biophysical model (Nigh and de Jong 2015).

The PSPL conceptually divides BC into 1-ha cells using the provincial Resource Inventory Standard approved grid[17]. A SI for each species potentially growing in the grid cell is estimated and assigned to the cell based on the ecological, biophysical, and/or climatic conditions at the centroid of the cell. Each grid cell can have a SI for up to 22 species. Usually cells have much fewer than 22 SIs because not all species grow in every area of the province and/or because SI estimates are lacking for some species.

Nigh and de Jong (2015) compared the PSPL SI against SI measured on field plots. They tested the overall bias and whether there was 1:1 correspondence between the predicted and observed SI. As a whole and by model type (biophysical or SIBEC), the PSPL passed the validation tests. When the layer was stratified by species, species x model type, and species x BEC zone, slightly more than half the strata passed the equivalence test for unbiasedness but few were validated for 1:1 correspondence. When a strata is not validated, it means there is not enough information to validate the layer.

The SIBEC database includes some young trees and there are differences between growth intercept and SI estimates for young trees, especially shade tolerant species. In general, for shade tolerant species the growth intercept estimate of SI for young trees is lower than the SI curve estimate for the same age and height.

11.1.6 Individual Tree volume estimates

Most of the current models are calibrated using ground plots and a compilation routine. Most of the compilation routines use Kozak's taper model (Kozak 2004) although volume equations are also available (Nigh 2016). These taper and volume models can be used to estimate total and merchantable stem volume. Kozak's taper models are also used to estimate gross total and merchantable stem volume within VDYP.

There are two main methods for accounting for decay and waste at the tree level – Loss Factor (LF) and Net Factoring. LFs are used in VDYP. NF is used in the VRI compiler to obtain unbiased estimate of net volume.

Biomass is estimated in TASS using the equations of Ung et al (2008), using stem analysis data collected in the 1980s. 573 trees were sampled in BC including. Sample sizes for some species are small. For example, 25 Douglas-fir trees were sampled.

11.2 Potential Models

The models discussed here have potential for use in BC. They are not approved for use in timber supply review and are not supported by the MFLNRO&RD.

11.2.1 FVS/PrognosisBC

Most of the discussion focuses on FVS. The BC variant of FVS is Prognosis^{BC}. Development of Prognosis^{BC} ended more than 10 years ago.

Model name – Forest Vegetation Simulator (FVS), the BC variant is called Prognosis^{BC}.

Background and development history

The Forest Vegetation Simulator (FVS) is a distance-independent, individual-tree forest growth model widely used in the United States to support management decision-making. Stands are the basic projection unit, but the spatial scope can be many thousands of stands. The temporal scope is several hundred years at a resolution of 5–10 years. Projections start with a tree list. FVS contains a self-calibration feature that uses measured growth rates to modify predictions for local conditions. Component models predict the growth and mortality of individual trees and extensions to the base model represent disturbance agents including insects, pathogens, and fire. The component models differ depending on the geographic region. The models for different geographic areas are referred to as regional variants. The differences are due to data availability and the applicability of existing models. FVS supports management rules such as thinning if density is too high. The

[17] https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nr-laws-policy/risc/raster_standard.pdf

rules can be extended to represent other factors. For example, the effect of climate change on stand development can be simulated by entering rules that specify how growth and mortality will change in response to changing climate (Crookston and Dixon 2005).

In the 1990's, BC investigated the use of FVS (known then as PROGNOSIS). The self-calibration feature of FVS was used to predict the ratio between growth rates in the northern Idaho variant of the FVS and growth rates observed in long-term permanent sample plots (PSPs) in the Nelson, Kamloops and Cariboo forest regions of BC. This was released as Prognosis^{BC} (Zumrawi et al 2002). Prognosis^{BC} has been parameterised for the IDF (Interior Douglas-fir), ICH (Interior Cedar Hemlock), SBS (Sub-boreal Spruce) and SBPS (Sub Boreal Pine Spruce) zones[18] [19].

Type of model – FVS is a distance independent, individual tree model. It is based largely on empirical relationships. The core models in FVS are the large tree Dbh increment model, the large tree height model and the small tree height growth model. In Prognosis^{BC}, large tree height growth is predicted using ht-Dbh equations. In some variants, potential height growth is predicted and then modified by tree and stand conditions (Crookston & Dixon 2005).

Inputs

FVS is initialized with an aspatial tree list. This includes species and Dbh. As part of the Prognosis^{BC} development, there were efforts in the early 2000s to calibrate tree list generation models by Hailemariam and LeMay[20][21]. Additional efforts were undertaken in 2015[22]. Generally two approaches have been taken – i) generating a parametric size class distribution from inventory attributes and ii) imputing a tree list from a library of tree lists using some sort of nearest neighbour or other nonparametric matching technique, using inventory attributes. Both approaches use inventory attributes and are limited by the weak associations between inventory attributes and tree lists, particularly tree lists by species.

The user can specify thinning actions.

Outputs

The outputs include a tree list and individual tree volumes as well as stand summaries.

Model evaluation

Marshall et al. (2008) evaluated the ability of the Prognosis^{BC} (Version 3.0) growth model to predict tree and stand growth against a series of remeasured permanent sample plots in the dk3 subzone of the IDF BEC, including some which had been precommercially thinned. In addition, the model was evaluated for logical consistency across a variety of stand structures using simulation. The model generally performed well against the test data at both the single tree and the stand level. Although predicted Dbh values for individual trees appeared to match closely with actual values in an 11-year period following precommercial thinning, Dbh growth following thinning was clearly overestimated. The simulations produced results under a wide variety of

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[18] https://essa.com/explore-essa/tools/fvsprognosis/

[19] https://www.researchgate.net/publication/266559292_Prognosis_BC_Version_43_variant_description?enrichId=rgreq-bb5ce08fc96bcebbb8cc642287c66565-XXX&enrichSource=Y292ZXJQYWdlOzI2NjU1OTI5MjtBUzoxNDk3ODU0MjgzNjk0MDhAMTQxMjcyMzAzNzc5NQ%3D%3D&el=1_x_2&_esc=publicationCoverPdf

[20] Possible approaches for relating growth and yield models to aerial information. Part I – Literature review and data sources. Prepared by T. Hailemariam and V. LeMay for B. Snowdon, BC Ministry of Forests. Jan. 31, 2000. 21p.

[21] Possible approaches for relating growth and yield models to aerial information. Part II Example using audit data. Prepared by T. Hailemariam and V. LeMay for B. Snowdon, BC Ministry of Forests. March. 31, 2000. 26p.

[22] Data types for tree list imputation. Prepared by M. Penner for S. Otukol, BC Ministry of Forests, Lands and Natural Resource Operations. March 2015. 12p.

stand structures which were consistent with the authors' understanding of stand dynamics. The authors concluded Prognosis[BC] was acceptably robust for the range of conditions examined.

FVS has been widely calibrated and is the standard model used by the USDA Forest Service.

Capabilities

Work on FVS is ongoing. Some FVS extensions may be of interest.

Fire and Fuels Extension (FFE)[23] – The FFE simulates fuel dynamics and potential fire behaviour over time. Submodels include fire behaviour, fire effects and snag and fuel dynamics. Outputs include estimates of stored carbon and coarse woody debris. The FFE extension is in most FVS variants including the Pacific Northwest Coast and Central Rockies variants. The main use of FFE is to support fuel management and post fire treatment decision. FFE projects measures of fire hazard over time as stands develop in response to management actions and other disturbances.

The fire simulation model, FSIM, has been integrated into FVS[24].FSIM simulates large wildfires (20,000 – 100,000 ha) on large landscapes (1 – 5 million ha) under various management scenarios. It was applied in central Oregon.

Regeneration establishment – Work is ongoing to develop full establishment models for all FVS variants[25]. ESSA did some work around 2008[26] but further documentation is unavailable.

Information and data needs.

FVS can automatically calibrate internal models to reflect local deviations from the regional growth trends represented in the variant. If three or more tree records for a species have measured heights, the model parameters of the height–diameter function for that species are adjusted. If qualifying growth increment data are provided on five or more sample trees per species, parameters of the large-tree diameter increment model, the small tree height increment model, or both will also be scaled. To qualify, diameter increment observations are used from trees that were larger than a threshold Dbh (generally 7.6 cm) at the start of the growth measurement period. Height increment observations are accepted only from trees with Dbh < 12.7 cm at the end of growth period (Crookston and Dixon 2005).

There is a FVS validation subcommittee as well as validation protocols (https://www.fs.fed.us/fvs/documents/validation.shtml).

Sensitivity to inputs, particularly climate attributes.

Climate-FVS (Crookston et al. 2010) is a modification to the Forest Vegetation Simulator designed to take climate change into account when predicting forest dynamics at decadal to century time scales.

Climate-FVS contains components that modify mortality and establishment and growth rates. Specifically, FVS was modified by:

- adding functions that link mortality and regeneration of species to climate variables expressing climatic suitability,
- constructing a function linking site index to climate and using it to modify growth rates, and
- adding functions accounting for changing growth rates due to climate-induced genetic responses.

Crookston et al. (2010) found projections were the most sensitive to mortality. The loss of trees of a dominant species heavily influenced stand dynamics.

[23] https://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/FFEguide.pdf
[24] https://www.fs.fed.us/rm/pubs_journals/2017/rmrs_2017_ager_a003.pdf
[25] https://www.fs.fed.us/pnw/pubs/pnw_gtr931/pnw_gtr931_027.pdf
[26] https://www.fs.usda.gov/rmrs/publications/development-external-regeneration-models-fvs-another-wrench-toolkit

Climate-FVS is available for western US states.

Degree of active use.

Prognosis^{BC} is not in active use in BC. FVS is the standard model used by the USDA Forest Service.

Current state of model development and support

USDA FS staff in Fort Collins, Colorado maintain, develop and provide training for FVS.

Current research efforts

The FVS Steering Team provide strategic guidance for development and enhancement of FVS.

Efforts are underway at UBC to package Prognosis^{BC} in R as well as produce an online version similar to FVS-online. Prognosis^{BC} will be tested against results from a partial cutting trial in the Kootenays as well as the Knife Creek Block at the UBC Research Forest. The project will look at the regeneration extension as well as the fire and fuels extension.

Researchers at UBC are preparing an NSERC Alliance grant proposal. Part of that proposal involves a sub-project on incorporating climate-sensitivity into Prognosis^{BC} and FVS^{Ontario}.

Ease of use and training

FVS staff provide many types of training including self-paced, instructor-led and web-based training.

Addressing short and medium term BC needs

Prognosis^{BC} was calibrated for the southern interior of BC and should work well for projecting pure species and species mixtures in that region. The use of FVS for inventory projection is limited by its input requirement of a tree list.

Requirements to calibrate, maintain and support the model in BC

To be used for inventory projection, FVS would require a module to generate a tree list (species, Dbh) from the inventory description.

To be used for yield curve development, FVS would need to be linked to a regeneration extension or initiated from a tree list for an existing stand (e.g., from YSM or SDM field plots).

FVS can be used to in silviculture planning to project the growth of species mixtures and response to thinning and other partial harvests.

See “current research efforts”.

Literature related to the model

There is extensive documentation for FVS on the FVS website.

11.2.2 SORTIE-ND

Name – SORTIE-ND

Background and development history

SORTIE-ND is an individual tree, spatially explicit model of forest dynamics. It originated from the small scale disturbance model SORTIE developed and tested in the early 1990's for transitional oak-northern hardwood forests in the northeastern U.S. In 1995 Dave Coates, Phil LePage, Elaine Wright and other scientists from the Research Section of the British Columbia Forest Service in Smithers, BC began collaborating with Charles Canham of the Cary Institute of Ecosystem Studies, Millbrook, New York to develop SORTIE/BC (Coates et al. 2003, Coates et al. 2009).

In the mid-2000s research in northern BC shifted to issues around projecting stand dynamics after the massive MPB epidemic in the sub-boreal spruce (SBS) forests. This research programme, undertaken by the Bulkley

Valley Research Centre and the BC Forest Service, included the establishment of a series of experiments and large stem-mapped plots in SBS forests.

Type of model – individual tree, spatially explicit model. SORTIE-ND is designed to provide growth predictions for individual trees in multi-species complex structured stands. It uses a combination of empirical and mechanistic behaviours to predict forest dynamics based on field experiments that measure fine-scale and short-term interactions among individual trees. SORTIE-ND has an intermediate position between purely empirical and process-based models. It is capable of simulating management activities including planting and partial harvesting and natural disturbances such as MPB and wildfire.

The model does not need to be initiated by a spatial tree list. It has provisions for generating a random distribution of trees by user set diameter classes.

SORTIE-ND is open source with the core modules written in C++.

Output – the model outputs a tree list including species, Dbh, height and crown size. It does not predict biomass, carbon or wood products but the tree list can be linked to individual tree taper equations and biomass estimation models. SORTIE-ND includes a recruitment submodel that predicts the number and spatial distribution of seedlings.

Model evaluation SORTIE-ND was evaluated for use in Timber Supply Review[27], focusing on sub-boreal spruce forest affected by MPB. Two general stand types were simulated – mixed aspen/spruce stands and pine-dominated stand after an MPB attack. The website does not have the final report but the interim results are the following.

- Relatively small levels of uncertainty about parameter estimates can lead to large levels of variation in model predictions. The model predictions were most sensitive to small changes in the adult neighbourhood competition index (NCI) growth parameters (especially alpha) and the allometry parameters (empirical equations used to convert tree Dbh to height).
- Young (< 40 years old), intermediate age (40 – 100) and older (100+ year) stand dynamics were evaluated. At higher densities, mortality was higher than expected but easily fixed with a minor adjustment to the NCI.
- The projected growth of single-species plantations of lodgepole pine, interior spruce and subalpine fir at various densities were compared to TIPSY predictions. The growth projections were very similar at intermediate densities (1,000 – 2,000 stems/ha).
- Model outputs were compared to 54 PSPs in the SBSmc2 subzone that had been measured for 30 years. The results were highly dependent on the species composition.

Based on the results, the adult mortality and adult tree growth behaviours were selected for calibration.

Logic - Most of the components of SORTIE are documented in peer-reviewed papers. Developers feel the key growth, mortality and recruitment relationships are explicit in SORTIE-ND, making it adaptable for a wider range of species and conditions.

Calibration data - SORTIE is parameterized for subalpine fir, aspen, birch, cottonwood, interior hemlock, interior cedar, amabilis fir, lodgepole pine, interior spruce.

It is parameterized for sub-boreal spruce forests in northern BC, particularly the SBSmc2, and for the Kispiox interior temperate rainforest (ICHmc2). SORTIE is currently only parameterized for mesic sites, but parameter files are currently being developed for 4 site series in the SBS.

Statistical properties -See model evaluation.

Capabilities SORTIE is an individual tree, spatially explicit model. It is capable of simulating management activities including planting and partial harvesting and natural disturbances such as MPB and wildfire.

[27] https://bvcentre.ca/files/SORTIE-ND_reports/SORTIE-ND_Executive_Summary_Year_End_Report_April_2009.pdf

Information needs

- SORTIE-ND requires remeasured field plot data to develop and localize functions. The component submodels may be calibrated independently. All component models are species-specific but some are more general (e.g., seedling dispersal) while others are more affected by local conditions (e.g., tree growth is affected by climatic and edaphic conditions).
- The model is initiated by a tree list or can generate a tree list from a Dbh distribution. If the tree list does not have spatial locations, SORTIE-ND has provisions for generating a random distribution of trees by user set diameter classes.
- The individual components of the model can be evaluated and validated but ideally, the model would also be validated using long term PSP data and evaluated for logical consistency by subject matter experts.

Sensitivity to model inputs SORTIE-ND does not have climate inputs in BC. Work in other jurisdictions (Buechling et al. 2017) have incorporated climatic effects (temperature and precipitation) as growth modifiers.

Active use SORTIE-ND development in BC slowed around 2010 and SORTIE-ND is not in active use. There is now funding and active work on SORTIE-ND in BC. The primary users of SORTIE-ND are ecologists who use it to perform simulations for research purposes.

Current state of model development & Research. In BC, model development is being undertaken at the Bulkley Valley Research Centre (BVRC). The SORTIE-ND home is www.sortie-nd.org.

The Forest Carbon Imitative (FCI) is funding two initiatives. The first initiative has 4 parts:

1. The BVRC and ESSA (In collaboration with Bianca Eskelson -UBC) are developing a frontend for SORTIE in R to make it more accessible to users. Delivery date Fall 2020.
2. Carbon accounting in SORTIE is being evaluated against data from Date Creek Research Forest in the Kispiox district.
3. Using SORTIE, model different partial cutting scenarios over time and develop yield tables.
4. Using SORTIE, incorporate stand yield tables (or directly link models) into landscape modelling scenarios for carbon management. This is a collaboration with the Pacific Forestry Centre – Spatial Discrete Even Simulation.

The second initiative is to collect data across a chronosequence of fires that have been planted and naturally regenerated to examine the carbon consequences (and change to wildlife habitat) following wildfire, and then modelling the results forward in time using SORTIE

SORTIE-ND has a recruitment module that has potential to predict recruitment following disturbances such as MPB and wildfire. Work is underway to be able to project “bare ground” scenarios.

Previous field studies are being incorporated into SORTIE to parameterize the model along an ecological gradient, improve the crown allometry for pine, and evaluate how understory light is being modelled.

Work is ongoing to look at response to climate change through using temperature and precipitation to modify growth – need data from a temperature/precipitation gradient for calibration.

Ease of use and Training. The SORTIE-ND model, code, user’s manual and other useful information are available at https://bvcentre.ca/index.php/sortie-ndhttp://www.sortie-nd.org/. The BVRC and ESSA (In collaboration with Bianca Eskelson -UBC) are developing a frontend for SORTIE in R to make it more accessible to users. Delivery date - fall 2020

Address Short and Medium term needs in BC. SORTIE has the potential to compare complex ecological scenarios including complex stand structures, complex silviculture and climate change. In the short term, SORTIE is available for local (SBS and ICHmc2) areas. In the medium term, results may be available for more areas and more applications, including climate effects.

Requirements in terms of staff time, expertise and data Model calibration is largely occurring at the BVRC and universities. The main role of the requirements from the Ministry are data (PSPs). If the model becomes an approved tool, the Ministry would need to provide training and help desk support.

Literature. The main literature is at http://www.sortie-nd.org/research/pubs.html. Coates et al. (2003) provides a good overview of the model.

11.2.3 Mixedwood Growth Model (MGM).

Model Name – Mixedwood Growth Model (MGM)

Background

MGM model development is supported through funding and data from the WEStern BOreal GY Association (WESBOGY) and is now a project team of the Forest Growth Organization of Western Canada (FGrOW).

Model type MGM (https://mgm.ualberta.ca/) is a deterministic, distance-independent, individual tree-based stand growth model for the boreal forest. MGM is capable of modelling pure or mixed stands of white spruce, trembling aspen, lodgepole pine, jack pine, and black spruce.

It is an empirical model. MGM's growth and survival functions are in a user-installable MS Office "Addin" with a University of Alberta digital certificate. MGM's user interface works within MS Excel (32-bit). Support for MS Excel (64-bit) in Office 2019 and Office 265 will be available in fall 2020.

MGM is a "height-driven model" that uses SI curves (i.e. height-age-SI models) to predict the maximum annual height increment for each tree. Then, each tree is ranked by social status to determine competition-adjusted height increment, diameter increment, and survival. The competition adjustment varies with the species of the competing trees. Dominant trees grow quickly and are more likely to survive. Suppressed trees grow slowly and are less likely to survive. Tree-level height, diameter, survival, basal area, and volume are updated annually using competition-adjusted growth information. Then, tree-level characteristics are summarized for each stand to determine stand-level height, diameter, density, basal area, volume, etc.

MGM's growth and survival relationships are based on data from across the western boreal (Table 5). Regional variants of MGM are available for Alberta, BC, Saskatchewan, and Manitoba (Table 6). These variants allow the use of local species codes, SI curves, and tree volume equations. Recent submodel updates have been published in Strimbu et al. (2017), Cortini et al. (2017), and Oboite (2018).

Table 5. Data origin for MGM's height increment and diameter increment submodels by species. These submodels apply to all regional variants. The survival model (Alaska to Manitoba) comes from Cortini et al. (2017).

Species	Height Increment	Diameter Increment
White Spruce	Alberta (Stadt unpubl.)	Alberta (Stadt unpubl.)
Lodgepole Pine	Alberta	Alberta
Jack Pine	Alberta, Saskatchewan and Manitoba (Strimbu et al. 2017)	Alberta, Saskatchewan and Manitoba (Strimbu et al. 2017)
Trembling Aspen	Alberta (Stadt unpubl.)	Alberta (Stadt unpubl.)
Black Spruce	Alaska to Manitoba (Oboite 2018)	Alaska to Manitoba (Oboite 2018)

Table 6. MGM's SI and volume equations by regional variant.

Regional Variant (Region Code)	SI Curves	Volume Equations
Alberta (1)	GYPSY SI Curves (Huang et al. 2009)	Natural Subregion Taper Equations (Huang 1994)
British Columbia (2)	British Columbia Provincial SI Curves	BEC (SWBS and SBS) Taper Equations

Regional Variant (Region Code)	SI Curves	Volume Equations
Saskatchewan (3)	Saskatchewan Provincial SI Curves (Cieszewski et al. 1993)	Saskatchewan Provincial Taper Equations
Manitoba (4)	Saskatchewan Provincial SI Curves (Cieszewski et al. 1993)	Saskatchewan Provincial Taper Equations

Model outputs MGM outputs charts and yield tables that portray averages and totals for the conifer and deciduous components. Tree-level data may also be exported from MGM. MGM can output stand-level graphics through a linkage to the Stand Visualization System (SVS) developed by the US forest service for visualizing FVS output.

Model evaluation

Farnden[28] investigated the use of MGM to build yield curves for the Dawson Creek Timber Supply Area. The intent of these yield curves was to test harvest flow sensitivity to patterns of stand succession. The standard VDYP derived yield curves were considered not adequate for these conditions. Unfortunately, yield projections from the version of MGM tested were found to be unreliable for the stand conditions being simulated and the original goal was abandoned. In the interim, however, much was learned about the how the model might be used in the future, and how application of the model can be facilitated through other processes.

MGM was evaluated by Bokalo et al. (2013). They found the model effectively simulated juvenile and mature stages of stand development for both pure and mixed species stands of aspen and white spruce in Alberta. MGM overestimates increment in older stands likely due to age-related pathology and weather-related stand damage. They identified underestimates of deciduous density and volume in Saskatchewan. MGM performs well for increment in postharvest stands less than 30 years of age

Validation is ongoing. An “up to date” validation based on the MGM’s new black spruce growth functions, jack pine growth functions, and climate-sensitive survival suite is available on the MGM website. Validation is re-run with each change in the components of MGM.

The Alberta government is currently performing behavioural testing of MGM as part of an approval process.

Capabilities – MGM projects individual tree growth in species mixtures. Individual tree growth depends on the size and species of the competing trees. MGM can model thinnings. It does not explicitly include forest health or other disturbance agents or genetic improvement.

The primary uses of MGM are for timber supply and silviculture planning.

Timber supply – One application is to establish a random sample of temporary sample plots and project them using MGM. The resulting projections can be aggregated by strata to produce strata level yield curves.

Crop planning – MGM can be used to evaluate different silviculture scenarios including species mixtures, thinnings, and partial harvests.

Information and data needs

- MGM has provincial variants. It contains the BC SI curves as well as taper models for the SWBS and SBS ecozones. The diameter increment model has not been calibrated for BC. If local diameter increment data is available for some trees in the tree list to be projected, MGM can calculate a simple ratio-of-means to scale the diameter increment function.
- MGM requires a tree list to initialize and run models as well as a management scenario or crop plan.

[28] Farnden, C. 1999. An attempt to build TSR yield curves using the Mixedwood Growth Model. A report submitted to Larry Badowski, Prince George Forest Region.

- MGM was evaluated by Bokalo et al. (2013). They found the model effectively simulated juvenile and mature stages of stand development for both pure and mixed species stands of aspen and white spruce in Alberta. MGM overestimates increment in older stands likely due to age-related pathology and weather-related stand damage. They identified underestimates of deciduous density and volume in Saskatchewan. MGM performs well for increment in postharvest stands less than 30 years of age

The individual submodels can be calibrated using independent data. The tree height and Dbh increment models require repeated measures or stem analysis. MGM also requires SI curves and tree volume equations. MGM now includes climate sensitive survival functions for white spruce, black spruce, lodgepole pine, jack pine, trembling aspen, balsam poplar and balsam fir (Cortini et al 2017).

MGM is initialized with a tree list or stand table (i.e. species, height, and Dbh) within representative area-based plots (preferred). Tree-level measurements should include suppressed trees <1.3m tall. Synthetic tree lists may also be developed for juvenile stands (Trees < 25 years) using MGM's Treelist Generator and plot summary statistics. (MGM's Treelist Generator requires: Trees/ha, top height, average height, average DBH, the standard deviation of height, and the standard deviation of Dbh for each species.)

MGM requires accurate SI. SI may be determined using local height-age information and regional SI models. Approximate SI estimates may also be determined using local ecosite guides.

MGM is very sensitive to vertical complexity (vertical structure). MGM also has capabilities to model horizontal complexity. This has been used to model *understory protection* (Grover et al. 2014). This is used in aspen/spruce mixtures. In understory protection, the harvester creates a machine corridor (MC) that is essentially a clearcut that will regenerate back to aspen. The extraction corridors (EC) are adjacent to the machine corridor and the harvester reaches in to extract merchantable aspen and spruce. The buffer strip (BS) in the interior of the EC for windthrow. The arrangement of the strips BS – EC – MC – EC – BF – EC – MC and so on. Within each strip or strata, MGM functions as normal. However, additional growth reductions are applied to account for shading from adjacent strips or strata. To model the interactions between the strips or strata, there is a light model with ray tracing to account for the shading of the adjacent corridor. So some degree of horizontal structure can be handled using this multi-strata model. This has not yet been validated.

Mean Climate Moisture Index (Hogg et al. 2013) from 1981-2010 is also required to run MGM. Climate Moisture Index may be determined using direct calculations from ClimateNA (Wang et al. 2016) data (preferred) or the "MGM CMI Lookup Tool". Stand-level latitude, longitude, and elevation (m) are required to calculate mean CMI from ClimateNA data.

Sensitivity to inputs, particularly climate attributes.

See discussion of CMI in the previous section. The CMI is in the mortality/survival functions (not yet in growth functions). Work is underway to test the inclusion of climate variables in the growth functions and maximum density equations (fall 2020), with a plan to include updated functions in the 2021/2022 release of MGM. A project is currently underway to explore use of MGM in estimating impacts of climate change on stand growth in one FMA in northeastern Alberta. However, additional work will be required to develop the model to deal with dynamic climate variables and to develop tools and the user interface to allow most users to examine climate change impacts. Additional work to develop or refine growth functions will also likely be needed. Consequently, it will likely take a few years to make MGM fully functional for modeling climate change effects.

Degree of active use

MGM is used in Alberta by Alcan, Mercer and West Fraser (in the interior of BC) and is being adopted by Saskatchewan as its provincial wood supply model and for short term inventory forecasting. The Alberta government is reviewing MGM for use in forest management planning and regeneration surveys. Approval from the Government of Alberta is essential to future use by industry.

Current state of model development and support

MGM development and support resides at the University of Alberta and has an active model development team. The most recent version, MGM 18, was released June 30, 2019. The winter 2020 release will include PSP data from BC in the calibration of the growth and mortality functions.

The involvement of the University of Alberta in MGM has been key. In Alberta, the partnership between government, industry, and academia has been complementary and has aided MGM's development. The Government of Saskatchewan has also supported the development of MGM in Saskatchewan through both direct funding (e.g. for calibration of MGM for jack pine) and through their funding of WESBOGY.

Current research efforts

MGM has a four person development team at the University of Alberta. Development include research (adding new features) as well as calibration for new conditions (e.g., Saskatchewan, jack pine). The new features in MGM include adding results from recent research (height and Dbh increment functions for jack pine and black spruce and climate-sensitive survival functions).

MGM is being calibrated to become the provincial wood supply model in Saskatchewan.

There will be an autumn 2020 release of MGM which will include SI curves for white spruce, aspen and black spruce from SiteTools 4.1 and lodgepole pine from Nigh[29].

The winter 2020 release will include BC PSP data in the calibration of growth and mortality functions (lodgepole pine, spruce, aspen, and balsam fir).

MGM staff are working on a batch processing version that will interact with R or SAS to execute large numbers of runs and summarize results.

Ease of use

MGM is well-documented and includes training workbooks. MGM18 is available at mgm.ulberta.ca. This includes the model as well as extensive documentation and examples of use (including crop plan development).

Ability to address short and medium term needs in BC.

MGM models tree-level growth in mixed-species stands. This tree-level / mixed-species architecture allows MGM to model multi-cohort stands (Grover et al. 2014), managed-stand treatments (Bokalo et al. 2013; Comeau 2014; Comeau and Fraser 2018), and fire-origin boreal forests (Bokalo et al. 2013). MGM also has the ability to model discrete spatial treatments like understory protection (Grover et al. 2014). MGM includes climate-sensitive survival functions (Cortini et al. 2017).

MGM should work well for aspen, spruce and pine – in pure stands and in mixtures – in central and NE BC. It is capable of simulating release after MPB mortality. It is very responsive to vertical structure and can be used to predict growth following thinning as well as selection and shelterwood cutting.

Requirements to support the model in BC

The first step to adopting MGM for use in BC is to validate the current model using BC data to identify where the model is working well and where local calibration is required. The next step would be to evaluate the BC data available to calibrate the model.

The best bets for the quick application of MGM in BC are likely in the sub-boreal and boreal regions. Steve Titus did a lot of work to set up MGM for use in the SBS and BWBS zones. The current lodgepole pine, white spruce and aspen growth functions are based on Alberta data, while black spruce growth functions were developed using data from BC, Alberta, Yukon, NWT, Saskatchewan and Manitoba. Growth functions in a

[29] Nigh, G. 2017. Development of a lodgepole pine site index model with the grounded-Generalized Algebraic Difference Approach (g-GADA). BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, FAIB, Victoria, BC, Res. Rep. 31, 24 p.

future release of MGM (late 2021 early 2022) are being developed using BC PSP data together with data from the other western provinces and territories (lodgepole pine, white spruce, black spruce, aspen and balsam fir). While Douglas-fir is available for BC in MGM18, it is grown using white spruce SI, white spruce growth functions, and white spruce survival functions. Subalpine fir and balsam fir are partially modeled. Subalpine fir and balsam fir are grown using white spruce SI, white spruce growth functions, and balsam fir/subalpine fir survival functions. Douglas-fir, subalpine fir, and balsam fir volume is calculated using species-specific taper functions from Kozak (1994).

Literature related to the model

See https://mgm.ualberta.ca/mgm18/references/

11.2.4 GYSPY

Model name Growth and Yield Projection System (GYPSY).

Type of model GYPSY is a stand level growth model with spatial and non-spatial versions. It is an empirical model. It generates a size class distribution (stems/ha by Dbh class).

Background and development history

The Alberta Department of Agriculture and Forestry developed GYPSY to forecast the GY of forest stands. One of the predominant reasons for developing GYPSY was to link the growth and yield of post-harvest stands to Alberta's Regeneration Performance Survey Standards and Alternative Regeneration Standards.

The first version of GYPSY was released in 2001 and was limited to pure lodgepole pine stands. It now forecasts the growth of four species groups (Table 7).

Table 7. The species groups projected by GYPSY.

Group	Includes
Aspen group	balsam poplar (*Populus balsamifera*) trembling aspen (*Populus tremuloides*)
Black spruce group	black spruce (*Picea mariana*)
Pine group	jack pine (*Pinus banksiana*) lodgepole pine (*Pinus contorta v. latifolia*) tamarack/larch (*Larix laricina*)
White spruce group	alpine fir (*Abies lasiocarpa*) balsam fir (*Abies balsamea*) Douglas-fir (*Pseudotsuga menziesii*) Engelmann spruce (*Picea engelmannii*) white spruce (*Picea glauca*)

GYPSY will also predict future growth based on reforestation survey results.

Model Output – GYPSY output stand level yields including volume by species group. Outputs can be generated to various utilization standards.

Model Evaluation - The submodels of GYPSY were evaluated using an internal Alberta dataset[30]. The dataset is not described, limiting the interpretation of the results.

The conditions covered by the model are given in Table 7, for Alberta. In the documentation[31], fit statistics are given for the ht-Dbh submodels.

[30] Validation Summary of GYPSY Sub-modes – "Internal" validation. Prepared for the Forest Resources Improvement Association of Alberta by The Forestry Corp. June 16, 2009. 67p.
[31] GYPSY – A growth and yield projection system (GYPSY) for natural and post-harvest stands in Alberta. Techn. Rep. Pub. No: T/216 by Huang, S., Meng, S., Yang, Y. May 21, 2009. 20 P + app.

Capabilities to address impacts of forest health and other disturbance agents, silvicultural treatments, genetic enhancements, etc.

GYPSY is designed for natural-origin stands as well as post-harvest stands. If alternative or enhanced forest management practices such as thinning, herbicides, fertilization and/or genetic improvement are applied, rather than having GYPSY estimate the basal area it is recommended that the user supply basal area.

Information and data needs

Most of the models are provincial. The top-height submodel is a mixed-effects model and Alberta subregion models are available.

The non-spatial version of GYPSY requires SI and initial density. The spatial version of GYPSY requires top height, total age, density, percent stocking and, optionally, basal area, as inputs.

Sensitivity to inputs

GYPSY is very sensitive to SI. Volume/ha is relatively insensitive to initial density but volume/tree is sensitive to initial density. GYPSY does not include any climate variables.

GYPSY is the provincial wood supply model for Alberta and is not used elsewhere.

State of model development

GYPSY is maintained and supported by the Alberta Government.

Ease of use.

There are two Excel implementations of GYPSY – the GYPSY Yield Table Generator Tool and the Performance Age Silvicultural Scenario (PASS) Tool. The yield table generator is more flexible and produces yield tables and other key outputs from starting conditions at any age. The PASS tool is simpler to use and provides graphical and summary outputs specifically in support of reforestation surveys for stands aged 12 – 14.

Ability to address short and medium term needs in BC.

GYPSY covers relatively pure species stand conditions and these are covered by TIPSY. The linking of the model to performance surveys may be of interest.

Staff and Data requirements

Calibration of GYPSY requires remeasured PSP data, not necessarily stem-mapped.

Literature

https://www.alberta.ca/growth-and-yield-projection-system.aspx#toc-3

11.2.5 ORGANON

ORGANON[32] is a distance independent individual tree growth model developed for Southwest Oregon, Northwest Oregon, and red alder plantations in Oregon and Washington. It will project stand development for a variety of species mixes, stand structures and management activities. It was developed by David Hann and his graduate students and cooperators at Oregon State University.

The equations in ORGANON are applicable to complex stand structures (e.g., single and multi-storied even-aged stand structures, and uneven-aged stand structures). One reason for this flexibility results from the choice not to use stand (or tree) age in any of the equations. The only use of stand age in ORGANON is to label the output and calculate MAI for even-aged stands. ORGANON makes the assumption that tree dynamics are a function of tree size rather than tree age. ORGANON does require SI which is generally estimated from height and age. ORGANON uses crown ratio and both one sided and two sided competition variables in the

[32] http://www.cof.orst.edu/cof/fr/research/organon/orginf.htm

equations. ORGANON is an individual tree model applicable to pure and mixed species stands provided the necessary equations have been calibrated for each of the species of interest.

11.2.6 SPS/FPS

The Forest Projection and Planning System (FPS)[33] was developed by Jim Arney of the Forest Biometrics Research Institute. It includes a distance dependent GY model for projection of even-aged and uneven-aged stands for more than 26 North American tree species. It includes options for thinning, fertilization genetic worth. SPS is the distance-independent version of FPS.

11.2.7 FORECAST

FORECAST[34] is an ecosystem-based, stand-level, forest growth simulator. The model was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics, and various biophysical indicators of non-timber values. The model uses a hybrid approach combining local GY data (often from TASS/TIPSY) with other data to derive estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species. FORECAST uses relatively simple measures of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth and ecosystem dynamics under changing management conditions (Figure 3). Growth occurs in annual time steps. Depending on the species, plant populations within the model can be initiated from seed and/or vegetatively, and stand development can occur with or without competition from non-target tree species and understory populations. Details of FORECAST calibration and its application are provided in Kimmins et al. (1999), and Seely et al. (1999).

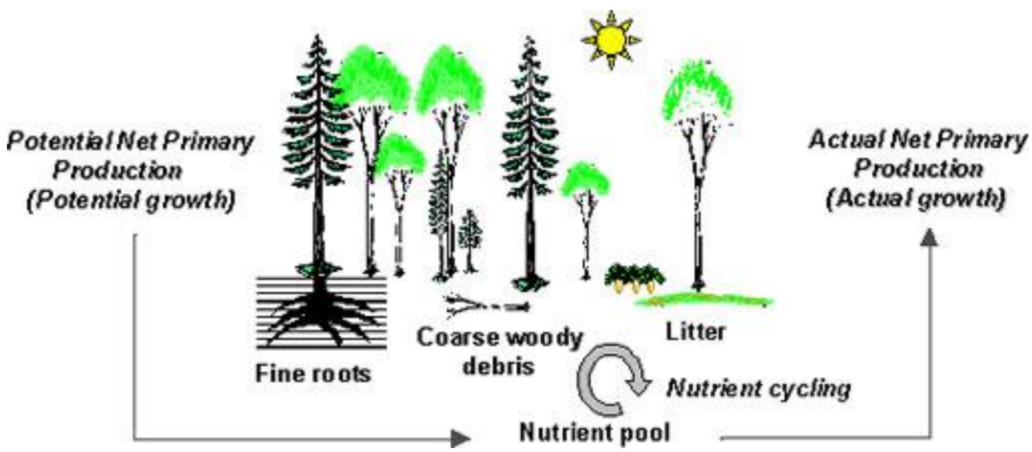

Figure 3. Schematic of basic ecosystem processes represented in FORECAST.

As a management model, FORECAST can simulate a wide variety of activities such as fertilizer application, brushing, partial harvesting, and mixedwood management. Disturbances such as fire and insect defoliation can also be represented. Timber volume projections generated by FORECAST are ultimately constrained by the potential yields of single species stands as specified in the calibration data for a range of site qualities. GY in complex stands is based on a simulated partitioning of limited resources (light and nutrients) among species and age cohorts. The biological properties of individual species, as defined by the input data, determine their relative competitiveness for limited resources.

To date, the FORECAST model has been calibrated and used in variety of forest ecosystems, both in Canada and elsewhere (Table 8). In BC it has been used in conjunction with various landscape level models for projecting the spatial and temporal dynamics of a wide range of stand attributes in forests subjected to

[33] https://fbrinstitute.org/home-page/what-is-forest-projection-systems-fps-software/
[34] http://web.forestry.ubc.ca/ecomodels/moddev/forecast/forecast.htm

alternative management strategies. The output of such analyses is being used to support the development of sustainable forest management plans.

Table 8. Current applications of the FORECAST model.

Location		Project	Applications
Canada	Arrow TSA (BC)	Arrow IFPA Project	GY projection in complex stands, long-term site productivity, indicators of non-timber values
	Canfor TFL 48 (BC)	Development of SFM plan, Certification	GY projection in complex stands, long-term site productivity, indicators of non-timber values, carbon sequestration
	Alberta	Oil sands reclamation	Ecosystem recovery, long-term site productivity
	Saskatchewan	Boreal mixedwood management	GY projection in aspen / spruce mixedwoods, economic analyses, decision support tool
International	Scotland	Plantation forestry	Projection of treatment response in sitka spruce stands, long-term site productivity
	Norway	Plantation forestry	Projection of treatment response in Norway spruce stands, long-term site productivity
	China	Plantation forestry	Projection of treatment response in Chinese fir stands, long-term site productivity

11.2.8 Stand Density Management Diagrams (SDMDs)

Stand density management diagrams (SDMDs) graphically depict the temporal relationships between stand density, top height, quadratic mean Dbh and mean tree volume and are typically used to develop and compare crop plans involving initial spacing and thinning prescriptions (Farnden 1996). Farnden (1996) developed SDMDs for lodgepole pine, white spruce and interior Douglas-fir in BC based on TIPSY runs.

12 Appendix B - Additional considerations

12.1 Model Data needs

12.1.1 Calibration and validation data

"The information available from the historical time series data from study sites is essential for a comprehensive understanding of systems and model evaluation." (Pretzch 2009)

Establishment and measurement of permanent sample plots (PSPs) is not reviewed here but PSPs are an integral part of model development, calibration and validation. As climate, forests and forest management change, it is critical that a network of PSPs is maintained for model development and monitoring. This network should be dynamic with PSPs continually being established in conditions of interest. The PSP design should be compatible with the growth models. TASS requires tree locations so PSPs intended for calibration and evaluation of TASS should be stem mapped.

The raw data should be complete and correct and compiled correctly. The data should be analyzed correctly including consideration of the error structure (time series and nested designs).

GY models must meet internal Ministry standards. GY models should also satisfy external standards including those of third party forest certification and carbon accounting.

The GY database, including research trials, needs to be used or the data may be lost.

12.1.2 Climate Change

Linking climate to forest growth can be done a number of ways from coarse correlations of temperature to growth to linking meteorological stations with growth plots and monitoring water deficits, pollutants, etc.

Climate is expected to affect growth rates but the largest effects are expected to be on tree establishment and survival and on disturbance events.

Sensitivity to climate change should be built into GY models. Forecasting forest growth under climate change also requires models of climate that can be linked to GY models.

12.2 Model Development

12.2.1 Partnerships

The Bourgeois et al. (2018a) report recommended establishing a GY partnership. Ideally this would involve, the provincial & federal government, industry and academia. Companies and co-ops need to see a return on investment. This generally involves some input into project goals and objectives as well as to data and results. Academia is a great place for research as well as a training ground for future researchers and GY support staff.

12.2.2 Human resources

Growth models require human resources for model development, model maintenance and training and communication. Models are used for scenarios with no historic equivalent or empirical data for validation. Local experts act as a coarse filter to identify model behaviors and outputs that appear unreasonable in a given ecosystem (Shifley et al. 2017).

In 1997, a draft Growth and Yield Modelling Strategy[35] noted “there are only a small number of GY experts in the province” and, referring the Ministry, industry, private consulting and academic institutions “some organization are seeing increased staff burnout, slow process on some initiatives, the occurrence of too many projects sometimes managed of a single desk, and initiatives faltering when a project “champion” leaves or retires”. These comments are still relevant.

12.2.3 Training and documentation

Well-informed model users are more likely to use models appropriately and also give feedback.

12.2.4 Empirical vs. process models

The following is taken from Burkhart and Tomé (2012).

> Often growth models are characterized as either empirical or process-based. In general, empirical models are developed using statistical techniques and calibrated with data representing the population of interest. Process-based models describe the behaviour of a system in terms of functional relationships and interactions. Both types of models have some level of empiricism (calibration using data). Generally, empirical models are calibrated at the same level they are used, usually at the tree or stand level. In contrast, process-based models are generally modelled and calibrated at a finer level than the tree or stand, for example at the leaf or crown level. In terms of objectives, the goal of process-modelling is more to understand the process while empirical models are aimed at prediction. Most modelling efforts combine aspects of empirical and process modelling.

For the same level of accuracy, as the projection length increases, the model resolution should decrease (Kahne 1976) implying tree-level models are likely more appropriate for shorter term projections while stand level models may be more appropriate for long term projections

12.3 Integration with other programs

The main uses of GY model include inventory update and timber supply analyses. As a result, it is important GY models are integrated with the VRI as well as silvicultural surveys and provide the outputs needed for timber

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[35] Forum Consulting Group in association with D.R. Systems, Inc. A Growth and Yield Modelling Strategy for British Columbia. Nov. 1997 Draft. 80p + app.

supply including net merchantable volumes to various utilization limits as well as information on non-timber values such as habitat and fire risk.

12.3.1 VRI

The new VRI will be LiDAR-based for most attributes. Initially, area-based attributes will be available at the pixel level (usually 20 x 20m) which can be aggregated to the polygon level. Research is ongoing into delineating individual trees from LiDAR and developing individual tree inventories. Tree-based inventories have the potential to provide spatial tree lists for initializing GY models.

VDYP and TIPSY are used to develop yield curves and it is important that there is compatibility between the VRI and GY models in terms of attributes and scale. In future, the inventory may provide tree lists to initialize TASS.

12.3.2 Linking to Silvicultural surveys

A number of the people consulted stressed the importance of being able to link GY models to silvicultural surveys.

The Reporting Silviculture Updates and Land Status Tracking System (RESULTS)[36] tracks silviculture information which then becomes part of the VRI.

There were concerns that regeneration surveys and standards are aimed at answering the question “is it green” and not providing the information needed to put the area on a growth curve. There is a need to develop regeneration standards that can be linked to a growth curve.

There are concerns about integrating silviculture records from RESULTS when they are brought into the inventory Bourgeois et al (2018a). Specifically, blending polygons to the block level (versus “standard unit” level) introduces avoidable errors such as generalizing species composition, over/under estimating species components, losing complex stand structural data such as mature retention areas being recorded as depleted, or depleted units being recorded as mature.

The current procedure is to assign the attributes associated with the largest stratum in RESULTS to each cutblock as a whole. FAIB staff deemed this is necessary due to difficulties in reconciling RESULTS stratum-level linework with cutblock boundaries identified in the inventory.

In Alberta, GYPSY has been linked to performance surveys. This may be an opportunity to benefit from Alberta’s experience.

12.4 Model evaluation

GY models are used in a variety of applications. It is important models are evaluated on their own against independent data. It is also important that model performance is evaluated in the context of its use including timber supply analysis and inventory projection.

12.4.1 Validation

As soon as more than one model is available, model evaluation is critical. Ideally, at the provincial level, model evaluation would result in recommendations on which model to use under which conditions.

Model evaluation requires

- access to the model and model documentation,
- validation data (clean, compiled), and
- evaluation criteria.

[36] https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/silviculture-reporting-results

Regulatory agencies such as the MFLNRO&RD should specify the evaluation criteria in terms of requirements or acceptance criteria. Model developers can report the evaluation results and let the user decide whether the results are acceptable.

The results of the model evaluation should indicate the conditions under which a model should be used.

12.4.2 Monitoring

Periodic monitoring should be implemented to identify deviations from trends predicted by models used in the timber supply review and annual allowable cut processes[37].

There are three main monitoring programs in BC – SDM, YSM and the Change Monitoring Inventory (CMI).

SDM 2.0[38] is a result of a collaborative effort between FAIB and the Forest and Range Evaluation Program (FREP). Like FAIB's YSM program, SDM samples mid-rotation stands collecting mensuration and forest health data. The difference is that YSM is designed to monitor change at a given point on the landscape while SDM is designed to capture within stand variability at a given point in time. YSM is designed to provide stratum level averages while SDM is designed to score the performance of individual blocks within a defined post free growing population. The philosophy behind the development of the SDM 2.0 protocol is that performance of a stand is more readily assessed at projected harvest rather than mid-rotation. The protocol was therefore designed so the data collected could be projected by a growth and yield model.

Specifically, the objectives of SDM 2.0 are:

- to capture the variability in tree size and forest health condition across a mid-rotation stand;
- for the performance of an individual stand to be assessed at projected harvest;
- for the population sampled to be scalable from stands of a given leading species, BGC zone, Landscape Unit or watershed up to an entire management unit or Resource District;
- to collect a statistically robust sample; and
- once compiled the data collected is compatible with compilations of data from the YSM program.

The goal of the Provincial CMI program is to provide land cover and forest attribute information relevant to needs for natural resources decision making and monitoring change at a broad, landscape scale and at regular time intervals by using well known and understood survey sampling methods. Specific objectives for the Provincial CMI program include:

- Calculate point-in-time statistics of land cover and forest attributes for the most current inventory.
- Calculate change in broad land cover/land use classes where change is calculated over one time period from the most current inventory and the last inventory.
- Calculate net change, components of change, and average annual change statistics of forest attributes, where change is calculated over one time period from the most current inventory and the last inventory.
- Assess the accuracy of forest attribute estimates from various inventory datasets.
- Validate growth model projections with an independent dataset.

Data collection for the Provincial Change Monitoring Inventory (CMI) program began in 2013 and includes plots on all intersections of the National Forest Inventory (NFI) 20km by 20 km grid. The Provincial CMI project is a large-landscape-level initiative aimed to estimate forest and land cover attributes over large areas.

The Provincial YSM program is also a landscape-level initiative with the goal of providing information on young stand growth, as relevant to needs for natural resources decision making at regular time intervals by using well known and understood survey sampling methods. Specific objectives for the YSM program include:

- Calculate point-in-time forest attributes of young stands.

[37] Watt, M. and Britneff, A. 2018. A Submission to the Forest Inventory Review Panel. 105 p + app.
[38] Stand Development Monitoring Protocol: Field and Office Procedures for Stand Development Monitoring Surveys, SDM Technical Committee, September 2018. 30p + app.

- Calculate net change, components of change, and average annual change statistics of forest attributes between the most current inventory and the last inventory.
- Report incidence and severity of forest health issues in young stands.
- Help evaluate if young stands will meet future timber supply expectations.

YSM data collection originally began on a subset of TFL's in 2000; with the provincial expansion of YSM data collection to TSA's in 2011.

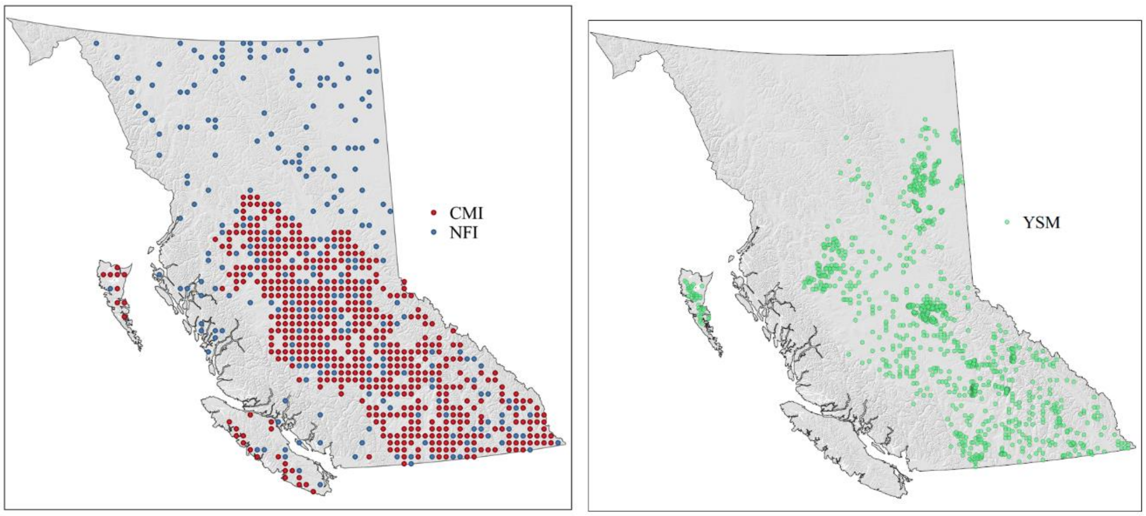

Figure 4. The location of the established CMI and NFI plots on the 20 x 20 km grid (left) and the established YSM plots (right)[39].

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