Ontario's forest growth and yield modelling program: Advances resulting from the Forestry Research Partnership

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ABSTRACT

The province of Ontario holds approximately 70.2 million hectares of forests: about 17% of Canada's and 2% of the world's forests. Approximately 21 million hectares are managed as commercial forests, with an annual harvest in the early part of the decade approaching 200 000 ha. Yield tables developed by Walter Plonski in the 1950s provide the basis for most wood supply calculations and growth projections in Ontario. However, due to changes in legislation, policy, and the planning process, they no longer fully meet the needs of resource managers. Furthermore, Plonski`s tables are not appropriate for the range of silvicultural options now practised in Ontario. In October 1999, the Canadian Ecology Centre-Forestry Research Partnership (CEC-FRP) was formed and initiated a series of projects that collectively aimed at characterizing, quantifying and ultimately increasing the economically available wood supply. Comprehensive, defensible, and reliable forecasts of forest growth and yield were identified as key knowledge gaps. The CEC-FRP, with support from the broader science community and forest industry, initiated several new research activities to address these needs, the results of which are outlined briefly in this paper. We describe new stand level models (e.g., benchmark yield curves, FVS^{Ontario}, stand density management diagrams) that were developed using data collected from permanent sample plots and permanent growth plots established and remeasured during the past 5 decades. Similarly, we discuss new height–diameter equations developed for 8 major commercial tree species that specifically account for stand density. As well, we introduce a CEC-FRP-supported project aimed at developing new taper equations for plantation grown jack pine and black spruce trees established at varying densities. Furthermore, we provide an overview of various projects undertaken to explore measures of site productivity. Available growth intercept and site index equations are being evaluated and new equations are being developed for major commercial tree species as needed. We illustrate how these efforts are advancing Ontario's growth and yield program and supporting the CEC-FRP in achieving its objective of increasing the supply of fibre by 10% in 10 years while maintaining forest sustainability.

Key words: permanent sample plots (PSPs), permanent growth plots (PGPs), normal yield tables, sustainable forest management, NEBIE plot network, forest inventory, Forest Vegetation Simulator

RÉSUMÉ

On retrouve environ 70,2 millions d'hectares de forêt dans les limites de la Province de l'Ontario, soit 17 % des forêts du Canada ou encore 2 % des forêts du globe. Environ 21 millions d'hectares de ces forêts sont aménagées en tant que forêts commerciales pour lesquelles la récolte annuelle au début de la décennie atteignait près de 200 000 ha. Les tables de rendement développées par Walter Plonski dans les années 1950 ont constitué la base de la plupart des calculs d'approvisionnement en bois et de projections de croissance en Ontario. Cependant, suite à des modifications de la législation, des politiques et des processus de planification, ces tables ne répondent plus à tous les besoins des aménagistes de la ressource. De plus, les tables de Plonski ne s'appliquent pas à l'ensemble des options sylvicoles mises en pratique en Ontario. En octobre 1999, le Centre écologique du Canada–Partenariat pour la recherche forestière (CEC-PRF) a été mis sur pied et a amorcé une série de projets qui visaient collectivement à décrire, quantifier et en fin de compte à accroître l'approvisionnement en bois économiquement disponible. L'obtention de prévisions complètes, défendables et fiables de la croissance et du rendement des forêts a été identifiée comme étant la principale lacune. Le CEC-PRF, avec l'appui de la communauté scientifique en général et l'industrie forestière, a démarré plusieurs nouvelles activités de recherche pour répondre à ces besoins dont les résultats sont brièvement soulignés dans cet article. Nous décrivons de nouveaux modèles de peuplement (par ex., les courbes de rendement de référence, FVS^{Ontario} , les diagrammes d'aménagement de la densité du peuplement) qui

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ont été élaborés au moyen des données recueillies à partir des parcelles échantillons permanentes et des parcelles permanentes d'étude de la croissance mises en place et remesurées au cours des 5 dernières décennies. De même, nous discutons des nouvelles équations hauteur-diamètre élaborées pour 8 importantes espèces commerciales qui sont spécifiquement retenues dans le calcul de la densité du peuplement. De plus, nous présentons un projet appuyé par le CEC-PRF visant à élaborer de nouvelles équations de défilement pour le pin gris et l'épinette noire en provenance de plantations de différentes densités. De plus, nous effectuons un survol des différents projets entrepris pour déterminer les mesures de la productivité d'une station. Les équations disponibles d'intervalle de croissance et d'indice de la station sont présentement sous évaluation et de nouvelles équations sont en voie d'élaboration pour les plus importantes espèces commerciales en fonction des besoins. Cet article illustre comment ces efforts permettent de faire progresser le programme de croissance et de rendement de l'Ontario et démontre comment le CEC-PRF cherche à atteindre son objectif d'accroissement de l'approvisionnement en fibre de 10 % en 10 ans tout en maintenant la durabilité des forêts.

Mots clés : parcelles échantillons permanentes (PEP), parcelles permanentes de croissance, tables de rendement normal, aménagement forestier durable, réseau de parcelles NEBIE, inventaire forestier, simulateur de végétation forestière

Introduction

The province of Ontario holds approximately 70.2 million hectares—about 17% of Canada's and about 2% of the World's forests. Of that, approximately 21 million hectares are managed as commercial forests (OMNR 2001) following the legislative requirements of the Crown Forest Sustainability Act and the Environmental Assessment Act. Approximately 200 000 ha of forest are harvested annually so that within an 80-year-period about 16.0 million ha will be manipulated following directions provided by the Forest Management Planning Manual for Ontario's Crown Forests (OMNR 2004).

Forest growth and yield research in Ontario dates back to the late 1940s when the first coordinated provincial studies began. The significant products of these studies were normal yield tables for the major commercial tree species (Plonski 1956) and associated provincial cull tables (Morawski *et al.* 1958). These yield tables were later updated and converted to metric units (Plonski 1981). Since then, numerous permanent sample plots (PSPs) have been established to investigate stand dynamics, forest productivity, and basic biological processes. However, data from these plots have often had limited value to providing a province-wide understanding of forest productivity because they were often established within a narrow geographical range, had limited scope with respect to species and sites considered, and frequently lacked replication. More recently, it was identified that Plonski's normal yield tables no longer met all the needs of foresters trying to ensure a continuous flow of products and values from forested land (OMNR 1993) as they failed to account for the role of silviculture in manipulating stand composition and structure.

In October 1999, the Canadian Ecology Centre-Forestry Research Partnership (CEC-FRP) was formed with the objective of producing a sustainable 10% gain in wood supply within 10 years from Tembec's licenses in Ontario (CEC-FRP 2000). Achieving this goal required defensible predictions of stand growth and yield across a range of silvicultural activities. Key growth and yield knowledge gaps were subsequently identified, and research activities initiated.

The objectives of this paper are to summarize: (1) the status of Ontario's Growth and Yield (G&Y) program, (2) knowledge gaps that existed when the CEC-FRP was established, and (3) completed or ongoing research programs/activities undertaken to fill these gaps.

Background: Status of Ontario's Growth and Yield Program

In the early 1990s, OMNR identified the need for accurate, timely, and relevant G&Y information to underpin the sustainable development of Ontario's forests (OMNR 1993). It recognized that public accountability and transparency in decision-making were crucial to achieving public trust and confidence in the forest management system, and that efforts to increase environmental security needed to be founded on a solid knowledge base. To this end, OMNR embarked on a comprehensive G&Y program to provide the long-term consistent data necessary to monitor, model, and predict the growth and status of Ontario's vast forest resources.

The G&Y program was tasked with developing and maintaining an ecologically based network of PSPs (approximately 4300 plots on a 5-year remeasurement cycle), and producing a suite of operational (suitable for use within Ontario's system of forest management) growth, yield, and productivity models. Emphasis was on developing predictive models (both for short-term response to treatment and for long-term stand development and succession), and practical (in terms of use, application, and input requirements) quantitative tools for assessing site productivity from this data stream. During the mid 1990s, the program was rescaled to a network of approximately 1100 PSPs (Fig. 1), and the planned remeasurement interval was extended to a minimum of 10 years.

Also recognized was the need to develop shared stewardship responsibilities for the collection, management and use of G&Y data and information. The CEC-FRP spurred many G&Y-related activities such as further implementation of the plot network, the development of benchmark yield curves, the calibration of density management diagrams, the investigation of growth intercept models, and the evaluation and calibration of FVS$^{\mathrm{Ontario}}$ (Lacerte *et al.* 2004). FVS$^{\mathrm{Ontario}}$ is the Ontario variant of the Forest Vegetation Simulator (FVS), the official growth model of the United States Forest Service. As well, a large co-operative venture was formed through the Forest Ecosystem Science Co-op's Growth and Yield Science Unit (Forest Co-op) to promote the establishment of a comprehensive plot network and stimulate G&Y technology development and transfer. Through these relationships, a significant network of permanent growth plots[9] (PGPs) has been established throughout the province (Table 1, Fig. 1) and remeasurements have largely remained on the desired 5-year cycle.

Information from the provincial PSP network compliments data collected by the Forest Co-op and follows a parallel methodology. The provincial plots, however, provide a broader suite of forest and tree attributes and can be used to support diverse modelling activities. Their larger size in particular supports the modelling of regular mortality (although the realized remeasurement cycle somewhat compromises this objective). Both data sources have been used to develop and calibrate Ontario-specific G&Y models.

Not all data necessary for G&Y modelling can be obtained from PSPs. To support tree-level modelling (e.g., taper functions) and various measures of site productivity (site index, growth intercept) a series of 50 plots has been established in jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* [Mill.] BSP) plantations from which approximately 2400 trees have been selected for detailed stem analysis. These data are being used to develop density-dependent plantation taper functions and to evaluate published growth intercept models for these species.

Most G&Y plot networks are established to support modelling and quantitative silviculture and although perfectly valid for these purposes, are less useful for provincial- scale monitoring. To enhance G&Y monitoring, a network of approximately 1400 (400-m^2) plots is being established on a 20 × 20 km grid throughout the forested landbase. These provincial forest inventory ground plots (PFIGPs) will be established over the next 10 years and be remeasured on a 10-year cycle.

Although G&Y programs can be viewed as little more than expensive plot networks, this is only true if the data are not used to support forest management. To this end, the CEC-FRP, in partnership the Forest Co-op, has made substantial progress in information management, and are actively working to turn the legacy of G&Y data within Ontario into useable products. Through this exercise, hundreds of additional sample plots (collectively referred to as historic PSPs as shown in Fig. 1) have been discovered/recovered, brought up to current standards, and added to the provincial database. These core data are now being used to support a range of modelling activities, make informed forest management decision, demonstrate public accountability, and identify additional knowledge gaps.

The Partnership's Growth and Yield Objectives and Identified Knowledge Gaps

One of the first initiatives of the CEC-FRP was a workshop to explore the assumption that more intensive silviculture could be used to offset reductions in the managed forest landbase by identifying what was already known and what new knowledge was likely needed about intensive forest management (IFM) to adapt it for use in Ontario's forests. The workshop provided a forum to: (1) develop a common level of understanding of the principles, practices, and possibilities for IFM in Ontario, (2) provide managers with a basis for making informed decisions about resource expenditures, and (3) identify education, training, and/or research needs associated with implementing IFM. Many participants recommended the development of a wood supply strategy that would include accurate predictions of growth and yield for a range of species, on different soil types, under various management intensities. They also recommended that the province commit to reviving existing PSP networks and establishing new ones, particularly in managed forests. A few participants suggested formalizing and regulating training for thinning practitioners and mandating the use of density management diagrams (DMDs) (Bell *et al.* 2000).

In 2000, the CEC-FRP prepared a strategic plan that identified its mission as *developing and implementing ecologically sound and scientifically defensible leading edge forestry practices required to maintain and enhance an economically viable supply of quality fibre to Tembec mills, and to the communities those mills support, over the long term* (Bruemmer 2008, this issue). Flowing from this mission was a number of desired outcomes or objectives. A primary objective was to reduce uncertainty around current and future wood supply, with the underlying goal of facilitating corporate capital decision-making. Two specific areas were identified as priorities. The first was the development of inventory science to facilitate accurate continuous inventories of the existing forest resource. The second was to develop models with precisely calibrated inputs whose outputs could accurately forecast allowable cut, ecological sustainability, community stability, and economic viability. The partners recognized that these models would require ongoing refinement and maintenance.

The primary data sources available for G&Y model development at the individual-tree level were the Ontario PSP network, the Forest Co-op PGP network, plot networks from adjacent provinces, particularly Quebec, and published studies. Review of these data indicated that a wealth of information was available for model development, particularly for species such as jack pine and black spruce. However, further analyses identified gaps in the data for managed stands; particularly lacking were data for managed stands older than 50 years. Specific stand conditions such as mixedwoods were also underrepresented and gaps in geographical representation of plots were evident for all stand conditions.

Table 1: Ontario Permanent Growth Plots (PGPs) established and remeasured by the Forest Ecosystem Science Co-op – Growth and Yield Science Unit between 1998 and 2007

	Permanent Growth Plots (#)	
Year	**Established**	**Remeasured**
1998	10	–
1999	80	–
2000	307	–
2001	483	–
2002	523	9
2003	494	–
2004	303	87
2005	247	289
2006	80	541
2007	60	471
Total	**2587**	**1397**

[9]PSPs and PGPs are closely related plot designs. A PGP consists of a single 400-m^2 circular plot in which all trees with DBH ≥ 2.5 cm are tagged and evaluated. A PSP consists of a cluster of 3 PGPs nested within a larger 6400-m^2 circular plot used to assess tree mortality and snag dynamics.

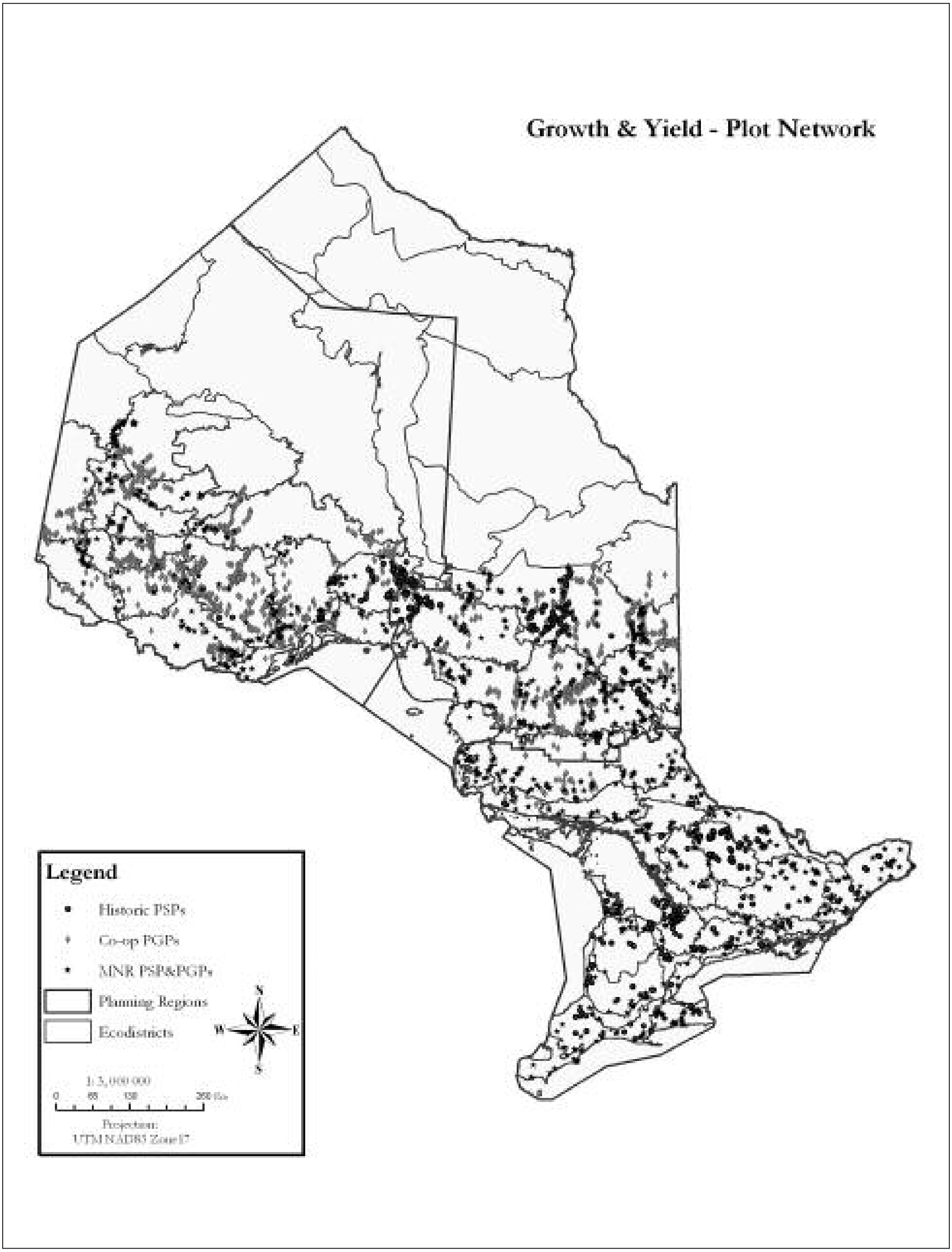

Fig. 1. Locations of Ontario's historic growth and yield permanent sample plots (PSPs) (used as calibration data in FRP modelling projects) as well as Forest Ecosystem Science Co-op permanent growth plots (PGPs) and MNR PSPs and PGPs (used as validation data in FRP modelling projects).

Benchmark yield curves

Yield curves are used to estimate the amount of wood growing in a stand/forest at a given time. These curves are developed using field data (i.e., tree characteristics such as diameter, height, and crown class, and stand characteristics representing basal area/ha, trees/ha, and site index). Forest management plans in Ontario rely on yield curves to estimate present and future wood supply (OMNR 2004), and must be developed for all strata. Forest management planning has moved from stratifying forests on the basis of working groups (a leading species approach with legacy ties to Plonski's Normal Yield Tables), to more ecologically derived forest units. A forest unit is defined as "an aggregation of forest stands for management purposes which have similar species composition, develop in a similar manner (both naturally and in response to silvicultural treatments) and are managed under the same silvicultural system" (OMNR 2004).

Since 1956, Plonski's yield tables (Plonski 1956, 1981), or variants of them, have been used for forest management planning on public lands in Ontario. These yield tables have undergone several undocumented modifications and are available in tabular form. Equations have been fit to the tabular data (Payandeh 1991) but, as the site classes are not necessarily of equal width, and there is polymorphism across site classes, the tabular data remain the definitive source for predictions. In response to the recognized need for additional yield curve development, and the availability of an extensive plot network, the CEC-FRP initiated a project to: (1) develop empirical yield curves for use in forest management planning, (2) test these curves against independent data, and (3) compare the precision and accuracy of these new yield curves against existing yield predictions. These curves were developed specifically for NE Ontario (for the forests of interest to CEC-FRP; McPherson *et al.* 2008, this issue).

The data used in the yield curve development were from all PGP and PSP data collected in Ontario (Fig. 1). In addition, the Quebec government generously shared data from their extensive plot network, representing more than 12 000 PGPs with over 26 000 measurements. These data (used in Quebec to develop yield tables [Pothier and Savard 1998]) in conjunction with the Ontario data, provided a solid basis for developing species-specific empirical yield curves (Penner *et al.* 2008, this issue).

In addition to available PGP data, recent science developments including site index curves (Carmean *et al.* 2001, 2006), taper models (Zakrzewski 1999) and cull estimates by species (OMNR 1978) were used. The yield curves were tested against an independent data set (subset of data not used in curve development). For unmanaged, natural-origin stands, the predictions associated with gross total volume were, on average, within 5% of the actual volumes, except for lowland hardwood stands and the mixed coniferous-deciduous stand forest unit.

In the case of lowland hardwoods, few data were available to build the model as this condition is relatively uncommon in boreal Ontario. The results from the mixed coniferous–deciduous forest unit were not entirely unexpected as this forest unit comprises a diverse range of species and sites, including stands with multiple age cohorts. Forest unit-level yield curves are not well-suited to describing heterogeneous conditions. As a result of the poor predictions, this forest unit was further stratified by leading species. This reduced the gross total volume prediction bias for the validation data set from 20% to less than 1%. These predictions were compared with those from other common yield tables in Ontario.

The new yield curves showed a substantial reduction in bias in the prediction of gross total volume compared to historic yield tables. However, they are limited by the data currently available. This limitation is less serious for unmanaged stands as the data range is close to that of the productive forest except for a few minor forest units. The limitations are more significant for managed stands. Few plantations are currently older than 50 years, and most tend to be well-stocked, single-species stands. The recent trend towards establishing mixed species plantations at lower planting densities is not well represented in the database.

While these new yield curves are an improvement on previous models used in Ontario, they remain a work in progress. Ongoing remeasurement of existing plots and establishment of new plots in underrepresented conditions is still required to support their development and maintenance. Efforts are now underway to use the same methods to develop benchmark yield curves for northwestern Ontario forest units.

Forest Vegetation Simulator (FVS)

Ontario's G&Y program began evaluating suitable G&Y models compatible with the province's varied range of species and silvicultural practices, and the type of data and information available. The Prognosis-FVS (Stage 1973) family of models seemed most attractive to Ontario resource managers. FVS is the official growth model of the United States Forest Service, which is a robust modelling framework constructed to support a class of G&Y models that are single-tree, aspatial, empirical simulators. The specific model functions used to describe various components of tree regeneration, growth, and mortality are typically developed or adapted locally, and the collective suite of functions is known as an FVS variant. FVS is consistent with existing data and comprehensive with respect to the range of species and silvicultural systems addressed. The FVS shell also provides a ready means to integrate existing G&Y products (taper models, site index curves, etc.) thereby capitalizing on these resources and reducing overall development costs. FVS also met an identified need of providing a "gaming" or "what-if" tool to develop and compare various strategic silviculture options and a potential tool to update provincial inventory information.

As discussed, benchmark yield curves have been developed for even-aged and relatively pure species stands. These curves are less suitable for mixed species stands, or stands with multiple age-classes. A model being adapted for mixed species conditions in Ontario is FVS$^{\text{Ontario}}$ (www.fvsontario.ca; Lacerte *et al.* 2004), which is the Ontario variant of the FVS. FVS$^{\text{Ontario}}$ is based on the Lake States (LS) variant (Bush and Brand 1995) and uses the metric version of FVS known as Prognosis$^{\text{BC}}$ developed by the British Columbia Ministry of Forests (Snowdon 1997).

Efforts were undertaken by research modellers to use Ontario G&Y plot data to determine how well the LS variant growth equations represented growing conditions north of the model's US Lake States origins. Results of the validation exercise (Lacerte *et al.* 2004) indicated that the LS variant did not adequately represent growing conditions throughout Ontario for the species evaluated, and that model calibration would be required. A calibration of FVS was undertaken with a moderate number of Ontario G&Y plots (Lacerte *et al.* 2006a) that improved performance of the new model forms. These findings were documented in a validation report (Lacerte *et al.* 2006b). Late in 2006, Ontario's maturing government–industry cooperative G&Y efforts provided the FVS^{Ontario} team with a data set of over 172 000 remeasurement observations (Woods and Penner 2007)—about 66% more observations than were available to Lacerte in 2004. Accordingly, the sub-models were recalibrated and re-evaluated. Based on the additional data, many model forms were modified from those of Miner *et al.* (1988) and Lacerte *et al.* (2006a).

Modifications and additions to the original Prognosis^{BC} user interface have been completed, adding additional functionality required for Ontario species and silvicultural systems. The FVS^{Ontario} interface includes entry forms for site quality information, tree lists or bare ground regeneration input, juvenile spacing treatments, different thinning methods, and partial harvesting systems (single-tree selection, uniform shelterwood and seed tree). In addition, 2 forms were created to permit manual keyword entry to allow users access to the full flexibility of the FVS modelling system. FVS^{Ontario} provides tabular and graphical output summaries and also include linkages to tree and stand visualization through a stand visualization system (McGaughey 2002).

FVS^{Ontario} has been developed through a cooperative partnership among OMNR, BC Ministry of Forests and Range, USDA Forest Service, ESSA Technologies Ltd., Canadian Forest Service (CFS), and Forest Analysis Ltd. All of these groups have openly provided software, advice or expertise to develop FVS^{Ontario}. This admirable arrangement has permitted Ontario to quickly develop a modelling system that will permit empirically based growth estimates to provide support to sustainable resource management decisions now and into the future. Ongoing successful partnership efforts with Michigan Technological University are continuing the evolution of FVS model algorithms (http://www.fvs.mtu.edu/glfvs/). Recent efforts include modelling tree mortality, investigating the effect of measurement error in some predictor variables, and a detailed analysis of the base functions used in individual-tree, aspatial models like FVS^{Ontario}.

Stand density management diagrams

Yield curves and FVS are G&Y models that can be used to estimate the amount of wood in a forest stand. Stand density management diagrams (SDMDs), on the other hand, are innovative decision-support tools for managing even-aged, pure-species stands. SDMDs are average stand-level models that graphically illustrate the dynamic relationships among stand density, tree size, and wood volume, at various stages of stand development.

Density management is the process of controlling resource competition through the regulation of the number and arrangement of individual trees on a given forest site via initial spacing and (or) a temporal sequence of thinning events to realize specified management objectives. At the stand level, density management may (1) accelerate stand operability (i.e., minimize the time to achieve an operable volume and merchantable tree size [Erdle 2000]); (2) increase spatial and structural uniformity of the residual stand, facilitating subsequent thinning operations (Weetman 1997); and (3) increase individual tree size and improve wood quality, increasing end product value (Zhang *et al.* 2002).

At the forest level, density management may increase volumetric annual allowable cut via the allowable cut effect. It may also ameliorate potential wood supply deficits via the early arrival of operable stands in the harvesting queue (Weetman 1997, Erdle 2000). Density management also affects species composition, succession vectors, coarse wood levels, wildlife habitat, and overall biodiversity at both the stand and forest level.

Given the many options a forest manager must evaluate when designing a density management regime (i.e., forest management objectives, strategic practices, and tactical prescriptions), density management is a complex process (BCMFR 1999). These complexities are greatly reduced by SDMDs (Ando 1962, Drew and Flewelling 1979). Basically, SDMDs are used to determine the density regime required to realize a given management objective. Structurally, SDMDs are presented in a 2-dimensional graphical format that embeds many quantitative functional and empirical relationships. These relationships collectively represent the cumulative effect of various underlying competition processes on tree and stand yield parameters (e.g., the self-thinning rule). The temporal dependency of these processes is governed by the intensity of competition and site quality as expressed by relative density index and site index, respectively.

Through various collaborative research programs among OMNR, CFS, Forest Products Innovation (FPInnovations – Forintek), and the CEC-FRP, SDMDs have been developed for a number of commercially important Ontario species, e.g., jack pine (Archibald and Bowling 1995, Sharma and Zhang 2007), upland black spruce (Newton and Weetman 1994), red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.; Smith and Woods 1997). Furthermore, PC-based software programs have been developed to eliminate graphical interpolation errors and facilitate the use of SDMDs in operational stand-level management planning (e.g., Newton 1997, 2003; Woods 1998).

Recently, to address the paradigm shift in management focus from one of volumetric yield maximization to one of product value maximization (as exemplified by corporate trends and new government initiatives in Canada [e.g., Brunsdon 2000, Emmett 2006]), the structural SDMD (SSDMD) was introduced (Newton *et al.* 2005). SSDMDs expand on the existing SDMD modelling framework by incorporating a diameter distribution recovery submodel (i.e., a parameter prediction equation system). Basically, SSDMDs enable the user to estimate the underlying diameter distribution and predict size-dependent product assortments and values at any point in a stand's development. Current research efforts include the development of enhanced SSDMDs and associated software for jack pine stand types via a collaborative project involving the Canadian Wood Fibre Centre (CWFC), OMNR, the CEC-FRP, and key forest industry representatives throughout Ontario.

Height–diameter equations

Most G&Y models are based on measured tree and stand characteristics. Therefore, information on diameter at breast height (DBH) and total tree height are fundamental to both developing and applying these models. Tree DBH can be measured quickly, easily, and accurately, but the measurement of total tree height is relatively complex, time-consuming, and expensive. Therefore, diameter is normally measured for all trees comprising the sample but height is typically measured for only selected trees. Height–diameter relationship models are then used to estimate the heights of the remaining trees.

A number of height–diameter equations have been developed for Ontario species using only DBH as the predictor variable for estimating total height (Peng 1999, Jayaraman and Zakrzewski 2001, Peng *et al.* 2001, Zhang *et al.* 2002). However, the relation between the diameter of a tree and its height varies among stands (Calama and Montero 2004) and depends on the growing environment and stand conditions (Sharma and Zhang 2004a). Because of greater competition among individuals, trees growing at higher densities generally have smaller diameters for a given height than those growing in less dense stands (Lopez Sanchez *et al.* 2003, Calama and Montero 2004). This height–diameter relationship is also not constant through time, even within the same stand (Curtis 1967). Therefore, to accurately estimate the height of the trees, a unique height–diameter model is required for stands with different stand conditions. To avoid having to establish individual height–diameter relationships for every stand, generalized height–diameter models can be developed by including additional predictor variables (Temesgen and Gadow 2004).

Sharma and Zhang (2004a) incorporated stand density (trees/ha and basal area/ha) and site index information to develop generalized height–diameter models for jack pine and black spruce trees in boreal Ontario. They reported that the Chapman-Richards function (Richards 1959, Chapman 1961) with the asymptote and rate parameters expressed in terms of basal area and trees/ha, respectively, was superior to other models for estimating heights of these species. Newton and Amponsah (2007) evaluated 5 nonlinear models that described height–diameter relationship of jack pine and black spruce trees grown in different stand types. They found that incorporating stand-level variables in the height–diameter equations improved model accuracy.

Finally, Sharma and Parton (2007) presented generalized height–diameter relationship models for 8 major commercial tree species (balsam fir (*Abies balsamea* [L.] Mill.), balsam poplar (*Populus balsamifera* L.), black spruce, jack pine, red pine, trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), and white spruce (*Picea glauca* [Moench] Voss)) in boreal Ontario by modifying the Chapman-Richards function. They expressed the asymptote in their models in terms of dominant stand height (average of dominant and codominant heights) and the rate parameter as a function of stand density and basal area. They found these models superior to the ones available for these species in terms of fit characteristics and predictive accuracy. Height-diameter equations for other species will be developed as required.

Taper equations

While height–diameter equations are fundamental to G&Y models, taper equations are important for estimating individual tree volumes and product yields. Product recovery can be optimized by calculating the amounts (volumes) of various products (e.g., sawlogs, pulp) obtainable from a tree. Taper equations can be applied only if DBH and total tree height measurements of individual trees are available. Tree DBH can be easily measured and total height can be estimated using a height–diameter equation. Diameters along the bole at a given tree height are estimated using taper equations first, and individual tree volume can then be calculated based on these diameters and corresponding heights. Product recovery from different trees with the same total volume can be substantially different depending on the shape of the stem and thus have significantly different economic value.

Historically, OMNR's G&Y program has relied on taper equations developed from data derived from natural stands. One such commonly used taper equation in Ontario was presented by Zakrzewski (1999). Although sufficient for natural stands, using these equations to calculate individual stem volumes for plantation-grown trees has the potential to introduce bias (generally an overestimate), and this bias will be magnified when used in association with Ontario's new benchmark yield curves.

The shape of a tree is influenced by stand density (Gray 1956, Larson 1963)—a variable not included in current taper functions. Similarly, the stem form may not be the same for different tree species growing in the same environment or stand conditions. For example, Sharma and Zhang (2004b) reported that taper profiles for jack pine, black spruce, and balsam fir trees grown in natural stands in eastern Canada differed significantly. They further reported that the stem forms for black spruce trees grown in natural stands at different stand densities also differed. Stand density can be regulated either by planting the trees at different initial spacings or by thinning stands to different densities. However, the trees of a particular species grown in a plantation and in a natural stand thinned to the same density may not have the same form, especially if the thinning occurs later in stand development (Sharma and Zhang 2004b).

Stem analysis data are generally used in developing taper equations. However, discrepancies among methodologies used to collect stem analysis data present a challenge. The number of trees used to fitting taper equations has varied from as few as 50 to tens of thousands. Similarly, both the number and location of measurements along a stem are not consistent among studies. Little consensus exists on how many trees are required to adequately model stem taper. Optimum numbers and locations of measurements within a tree also remain undefined. Since costs associated with collecting stem-analysis data increase as a multiple of the number of trees sampled and number of samples within a tree assessed, determining relative sources of variation within this sampling chain is required. A study is underway to address these issues and to develop new and more appropriate taper functions for plantation-grown jack pine and black spruce trees by incorporating stand density (trees/ha and/or basal area/ha) and other tree and stand characteristics.

Site index/intercept

In addition to individual tree height and diameter, site index (SI) is another important parameter used in modelling G&Y and developing and using SDMDs. It is generally defined as the height of a site tree at breast height age 50. A site tree is the largest diameter tree of a target species on a 0.01-ha plot; the tree has to be healthy, free of breakage or damage, and free from competition (dominant tree). More intensive forest management requires accurate estimates of site quality and the potential G&Y. A variety of quantitative tools can be used to determine site quality including site index curves, growth intercepts, and site index comparison or conversion between major tree species and site factors (e.g., soil nutrient and moisture regimes).

Polymorphic site index curves have been developed for black spruce and trembling aspen (Carmean *et al*. 2006) in northwestern Ontario and jack pine (Carmean and Lenthall 1989, Carmean *et al*. 2001) in northern Ontario. In addition, relationships between jack pine site quality, soil, and topography were studied in northern Ontario. Through the collaborative environment of the CEC-FRP, these existing models were incorporated into the G&Y products under development; however, several significant knowledge gaps were also identified. In particular, the need for research to evaluate site quality for tolerant hardwood and mixedwood forests in the Great Lakes–St. Lawrence forest region was acknowledged (Buda and Wang 2006). In addition, it was recognized that existing site index curves are only appropriate for natural stands with breast-height age 50 years and older.

Variable growth intercept (GI) models are increasingly used to give reliable site index estimates for young stands and plantations by relating the average annual height growth of trees to site index. Those models have the advantages of being developed specifically to predict site index in young stands. In British Columbia, growth intercept is extensively used for young plantations of major conifer species such as interior lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia*), white spruce, Sitka spruce (*Picea sitchensis* [Bong.] Carr.), coastal and interior Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco), western larch (*Larix occidentalis* Nutt.), black spruce, and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Nigh and Love 2000), and especially for some species without distinct annual branch whorls such as western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) (Nigh 1996). Relationships between jack pine growth and site variables were reported for plantations in New Brunswick using the growth intercept approach (Hamilton and Krause 1985). Recently, GI models were developed for natural young stands of black spruce, jack pine, and balsam fir in Quebec (Mailly and Gaudreault 2005). In Ontario, GI models had been developed for white spruce plantations (Thrower 1987), jack pine (Guo and Wang 2006) and black spruce plantations (M. Kwaiton and J. Wang, Lakehead University, unpublished data). These GI models have yet to be used in practice.

Next Steps

Participants of the 1999 IFM science workshop also recommended that (1) the PSP network be extended to include intensively managed stands and address canopy trees as well as advance growth and seedlings, (2) research on wood quality, including specific gravity and fibre length, both important to pulp, and diameter, knot size, and height, all important to sawlogs, be linked to the full suite of harvest-to-harvest practices, rather than single treatments, and (3) benchmark yield curves and succession models for the full range of stand conditions (natural, extensive, basic, intensive, and elite [NEBIE] silvicultural scenarios) be developed with data from the PSP network (Bell *et al*. 2000).

It is important that the new models be incorporated into the forest management planning process and that the modellers continue to improve their products. The latter is recommended for a couple of reasons: (1) existing models for managed stands are based on plantations less than 50 years old, and (2) because G&Y programs frequently monitor plantations after age 20, the models may not based on current silvicultural practice (i.e., plots provide a retrospective assessment of historical silvicultural practices that may not be current). The lack of data from older plantations can only be solved through the remeasurement of existing plot networks. However, more active sampling should be pursued in younger plantations to assess effects of changing silvicultural practices.

The Forest Management Planning Manual (OMNR 2004) directs forest managers to link strategic silviculture options with expected forest response. The models described here are based on plantations established prior to 1980 and, hence, dated silvicultural practices. Substantial efforts have been made to improve silviculture within the last 20 years (Bell *et al*. 2008, this issue) in terms of stand composition and resource management. For example, mixed-species plantations are more common than they were 20 years ago and tree improvement programs now produce enough first-generation seeds for basic silvicultural programs for jack pine and black spruce across most of Ontario's forested landbase. As well, efforts were made to increase growth by ensuring crop trees received a much greater proportion of site resources through site preparation, vegetation management, and density regulation. Although data from many experimental research plots are available, this information is currently not used in G&Y modelling efforts in Ontario. This means delays of 20 years or more between the implementation of new silvicultural practices and the development of models that reflect resulting changes in growth and yield.

To expedite the opportunity to have data that reflect the most recent silviculture practices, the CEC-FRP along with other forest industry partners are expanding the G&Y plot network into younger plantations and have initiated an experimental plot network throughout the boreal and Great Lakes–St. Lawrence forests of Ontario to study the effects of a range of intensities of silvicultural practices (Bell *et al*. 2008, this issue). The combination of monitoring and experimentation is expected to address key knowledge gaps in growth and yield to support future modelling efforts.

Summary

The CEC-FRP has provided a catalyst for G&Y modelling efforts in Ontario. Much of the G&Y data collected over the past 5 decades have been analyzed for the first time and new stand- and tree-level models are now becoming available to resource managers in Ontario. As well, data gaps have been identified and new monitoring and experimental research initiated to fill these gaps.

Stand-level models such as the benchmark yield curves and FVS$^{\text{Ontario}}$ will contribute substantially to achieving CEC-FRP objectives by reducing the uncertainties in predicting present and future wood supply. On the other hand, stand density management diagrams (e.g., SSDMDs) will enable the forest industry to estimate underlying diameter frequency distribution and predict size-dependent product assortments and values at any point in the development of a forest stand.

Since individual-tree models (height–diameter, taper, and site index/intercept equations) are the building blocks for developing and applying most G&Y models, the more accurate and efficient the individual sub models, the lower the uncertainty that results from using stand-level models in predicting present and future wood supply. These improved models are helping CEC-FRP partners to obtain more accurate information on the quantity of wood in their forest stands and thus better predict wood supply.

We hope that the current network of plots and resulting data will be a legacy to future resource managers and researchers and will help to ensure that Ontario's G&Y program remains responsive to the needs of the public, and to the management organization(s) that it supports.

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