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A decision-support system for forest density management within upland black spruce stand-types

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ABSTRACT

The objective of this study was to develop an enhanced modular-based structural stand density management model (SSDMM) and associated algorithmic analogue for upland black spruce (*Picea mariana* (Mill) BSP.) stand-types situated within the central portion of the Canadian Boreal Forest Region. For a given density management regime, site quality, rotation age, stock-type, cost structure and set of merchantability standards, the hierarchical-based SSDMM enabled estimation of the following metrics: overall productivity (e.g., mean annual volume, biomass and carbon increments), volumetric yields (e.g., total and merchantable volumes per unit area), log-product distributions (e.g., number of pulp and saw logs by diameter class), biomass production and carbon sequestration outcomes (e.g., oven-dried masses of above-ground components and associated carbon equivalents by diameter class), recoverable end-products and associated monetary values (e.g., volume and economic value of recovered chip and dimensional lumber products by diameter class and sawmill-type (stud and randomized length processing protocols)), and fibre quality attributes (e.g., maximum branch diameter and wood density). The core modules which were responsible for describing stand dynamics and structural change were developed using 407 (122 from natural stands and 285 from managed stands) temporal tree-list measurements obtained from 269 (142 in natural stands and managed 127 in managed stands) sample plots (note, natural stands are those that naturally regenerated following a stand-replacing disturbance and have no history of density regulation whereas managed stands are those that naturally or artificially regenerated following a stand-replacing disturbance and have a history of density regulation). The modules responsible for predicting log product distributions, and end-product volumes and values, were developed employing relationships derived from taper and sawmill simulation studies. The modules responsible for predicting biomass and carbon outcomes, and log and fibre quality attributes, were developed using data obtained from initial espacement and thinning experiments. The resultant model introduces a number of advancements over its predecessors including those that (1) ensured mathematical compatibility among yield estimates, (2) accounted for intrinsic density-independent mortality factors, response delay following thinning, and genetic worth effects, and (3) provided increased flexibility in terms of enabling end-users to change merchantability standards, specify product degrade factors, and adjust cost profiles, according to their unique requirements. As demonstrated, the decision-support model can assist in facilitating the transformative shift towards the production of high value end-products, bio-energy feed stocks, carbon credits, and ecosystem services, currently underway within the Canadian forest sector.

1. Introduction

Forest management in Canada has been undergoing a transformative change as the production of higher value end-products (e.g., Emmett, 2006) and a broader array of ecosystem services (e.g., Raudsepp-Hearne et al., 2010) have supplemented, and in some cases superceded, the traditional singular objective of volumetric yield maximization. Hence, density management which can be used to achieve these new objectives as exemplified by numerous case studies, has an important role to play. Among these studies, density management treatment effects have included the following: (1) increases in mean tree size within Norway spruce (*Picea abies* (L.) Karst.;) and Scots pine (*Pinus sylvestris* L.;) stands in Finland (Mäkinen and Isomäki, 2004a, 2004b, respectively); (2) enhancements in the quality and value of end-products within jack pine (*Pinus banksiana* Lamb; Kang et al., 2004) and black spruce

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(*Picea mariana* (Mill) BSP., Tong et al., 2005) stands in central Canada; and (3) creation of acceptable habitat for mammalian herbivores within lodgepole pine (*Pinus contorta* var. latifolia) stands in western Canada (Sullivan et al., 2010). Operationally, density management consists of regulating a stand's species composition, density-stress levels, resource competition relationships, and structural characteristics, by varying initial planting densities at the time of stand establishment (initial espacement; IE), and (or) decreasing densities at the sapling (precommercial thinning; PCT) or semi-mature (commercial thinning (CT)) stages of development.

Determining the most appropriate density management regime for a given set of objectives is a complex management proposition. A multitude of factors must be considered including decisions regarding the selection of the sites to be treated, initial planting densities, timing and intensity of thinning treatments, discount and interest rates, and fixed and variable costs. Furthermore, these decisions must be considered within a broader regulatory framework which itself can imposes additional constraints. Commonly, these constraints include attaining minimum tree size and basal area thresholds before implementing thinning treatments, maintaining stand occupancy and stability thresholds throughout the rotation, ensuring that the selected crop plan results in a positive economic return, and meeting sustainability requirements (e.g., McKinnon et al., 2006). This complexity calls for the provision of comprehensive decision-support tools which can describe the effect of density management treatments on structural stand dynamics. Information on the dynamics of change within the horizontal and vertical size distributions is a basic prerequisite for estimating size-dependent attributes of economic and environmental importance. Consequently, the modular-based structural stand density management model (SSDMM; Newton, 2009) offers a potential modelling platform for the development of such a tool. The SSDMM is a hierarchical-designed variable-density growth, yield and wood quality distribution model which evolved from the modelling approach used in the development of stand density management diagrams (SDMDs). The ecological-based SSDMM enables the estimation of volumetric productivity, log distributions, product volumes and values, and fibre quality attributes, for a given density management regime, site quality, and cost profile.

Black spruce dominates the boreal landscape and represents an important societal resource (sensu Patriquin et al., 2007). The species crown characteristics (e.g., narrow with dense foliage) along with its biomass allocation strategy, allows black spruce to efficiently utilize its allocated growing space (Van Damme and Parker, 1987; Newton and Jolliffe, 2003). Furthermore, its ability to tolerate a range of growing conditions suggests that it will continue to be an important component of the forest landscape as predicted changes in climate take effect (e.g., Chertov et al., 2009). Currently, density management continues to be the dominant intensive forest management practice employed in managing this resource (NFDB, 2009). However, comprehensive decision-support tools for density management are currently lacking which has hindered the ability of forest managers to make the transformative shift to a value-based management proposition.

Thus as part of a larger effort to develop a suite of comprehensive decision-support tools for operational use in managing commercially important boreal species employing a participatory process involving scientific, knowledge exchange, policy, informatics and end-user staff from the receiving organizations (industrial forest sector and governmental regulatory agencies (sensu McIntosh et al., 2011)), the objectives of this study were to develop a modular-based SSDMM and associated algorithmic analogue for natural (naturally regenerated stands without a history of density regulation) and managed (naturally or artificially regenerated stands with a history of density regulation) upland black spruce stand-types. This study introduces a number of analytical solutions which overcome the shortcomings of previously developed SDMD-based models including the modular-based SSDMM introduced by Newton (2009). Specifically, these enhancements consisted of (1) ensuring internal model prediction compatibility in terms of volumetric yield forecasts (e.g., constraining the cumulative chip and lumber volume estimate to be equivalent to the merchantable volume estimate in cases were such cumulative volumes exceeded this estimate), (2) accounting for density-independent mortality from extraneous factors such as insects and disease through the use of an user-specified operational adjustment factor (sensu Nussbaum, 1998), (3) integrating a crown occupancy algorithm to account for the temporal response delay effect that arises when trees within recently thinned stands are adjusting to their newly allocated space and site resources, (4) enabling the model to address growth rate changes arising from the use of genetically enhanced stock through a functional adjustment to the site-based height–age function (sensu Xie and Yanchuk, 2003), and (5) varying merchantable specifications (e.g., specifying diameter and length thresholds for pulplogs and sawlogs), product degrade rates, and fixed and variable cost profiles in order to account for changes in market requirements and economic conditions. Among these enhancements, accounting for the temporal reduction in stand dynamics following thinning (response delay effect) is one of the most consequential given that all previous models built upon on the SDMD modelling framework have lacked the ability to account for this effect within their model structures. This has been considered a major shortcoming of the SDMD modelling approach and a potential source of error in yield projections following thinning (e.g., Newton, 2003). The utility of the new model as a crop planning tool was exemplified through the comparative evaluation of a diverse set of regimes involving PCT, CT and IE treatments employing a board array of performance indices which are relevant to the value-added management proposition.

2. Materials and methods

The hierarchical-based SSDMM consisted of six sequentially-linked estimation modules, denoted as follows: Module A—Dynamic SDMD; Module B—Diameter and Height Recovery; Module C—Taper Analysis and Log Estimation; Module D—Biomass and Carbon Estimation; Module E—Product and Value Estimation; and Module F—Fibre Attribute Estimation. A schematic illustration of the structure of the SSDMM including the interrelationships and sequential flow of computations among the individual modules is provided in Fig. 1. Procedurally, Module A involved the development of stand-type-specific dynamic SDMDs via the parameterization and integration of a broad array of static and dynamic yield–density relationships employing the traditional SDMD modelling framework (Newton, 1997). Module B consisted of the development of (1) Weibull-based parameter prediction equation systems for diameter distribution recovery, and (2) composite height–diameter prediction equations for diameter-class-specific height estimation. Module C employed a dimensional-compatible taper equation derived from the literature to predict log products (number of pulp and saw logs) and stem volumes. Module D entailed the development of allometric-based composite biomass equations for each above-ground component (bark, stem, branch and foliage) from which diameter-class and stand-level biomass and associated carbon-based equivalents were predicted. Module E utilized sawmill-specific (stud and random length mill) product and value equations, derived from the literature, to predict diameter-class and stand-level chip and lumber volumes and associated monetary values. Module F encompassed the development of composite equations for estimating wood density and mean maximum branch diameter. Likewise, an algorithmic analogue of the resultant modular-based SSDMM was developed and its utility exemplified by simultaneously contrasting a set of complex density management regimes using a comprehensive set of performance measures. These measures included indices for quantifying overall productivity, log quality and product distributions, biomass production and carbon yields, quantity and value of recoverable end-products, economic efficiency, duration of optimal site occupancy, structural stability, quality of fibre attributes, and operability status.

Presentation wise, given that a number of the required relationships were previously reported in separate incremental contributions, i.e., parameter prediction equation systems (Newton and Amponsah, 2005), asymptotic size–density relationships (Newton, 2006a), and the composite height–diameter functions (Newton

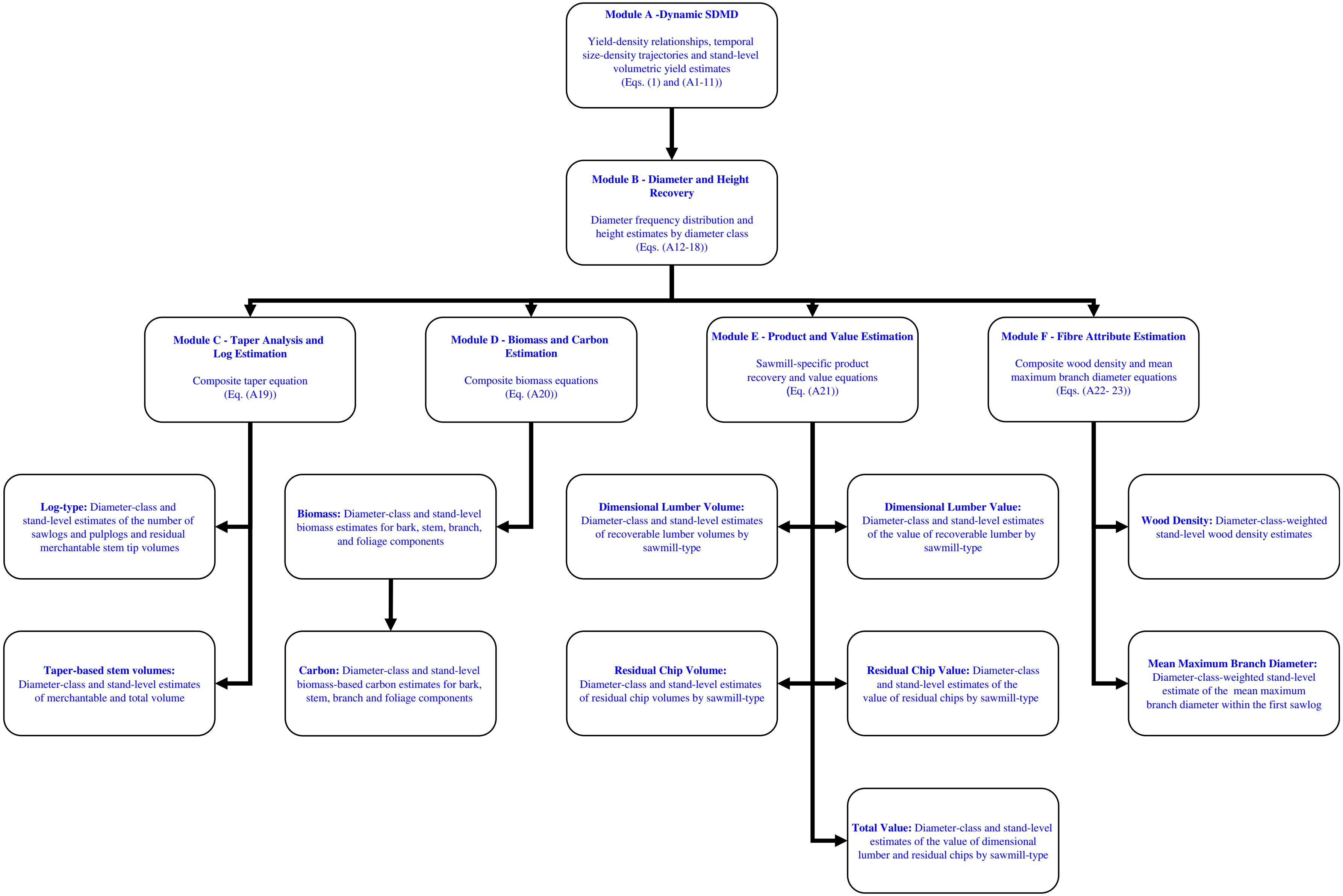

Fig. 1. Schematic illustration of the modular-based SSDMM.

and Amponsah, 2007), an abridged description of the methods and results associated with these relationships is presented. The nature of the model building approach utilized dictated that the results be presented in a sequential fashion. Analytically, not all of the required relationships could be parameterized using the core data set and hence supplemental sources were used to develop the required functions (i.e., mean live crown ratio and mean maximum branch diameter functions were developed from Nelder plot remeasurement data whereas biomass and wood density equations were parameterized using data derived from thinning trials). In cases where such data bases were unavailable, applicable literature-based functions were utilized (i.e., taper, product and value functions).

Although the development of the modular-based SSDMM for upland black spruce stand-types shares similarities with the approach used to develop the jack pine variant (Newton, 2009), a number of consequential advancements were introduced in this study. These included: (1) ensuring mathematical compatibility among yield estimates; (2) developing and integrating a crown-based occupancy algorithm in order to account for the response delay effect that occurs immediately following thinning; (3) modifying the net density change function in order to account for density-independent mortality factors during a stand's rotation via the use of an operational adjustment factor; (4) relaxing the merchantability specifications so that the log distribution output can be tailored to variable log lengths and upper stem diameters as market requirements warrant; (5) reducing product values through a product degrade factor in order to address the overestimation arising from the use of published functions; (6) incorporating genetic worth effects so that the increased growth rate achievable via the use of genetically improved seedling stock can be accounted for; (7) including additional flexibility in terms of inputting and specifying cost information which enables end-users to realistically reflect local conditions when designing their crop plans; and (8) adding an operability metric to the suite of performance measures so that the regimes can be contrasted in terms of the temporal reduction in rotation age arising from a particular density control regime. Furthermore, a VisualBasic.Net algorithmic analogue of the decision-support system was developed.

2.1. Stand-type description, data sets and preliminary calculations

Based on the forest unit descriptions and silviculture intensity classes utilized within the central portion of the Canadian Boreal Forest Region, two commercially important stand-types were defined for upland black spruce (Table 1): pure even-aged stands situated on mineral soils with no history of density manipulation (denoted $\text{PIm}_{(N)}$); and pure even-aged stands situated on mineral soils with a history of density manipulation (denoted $\text{PIm}_{(M)}$). Subsequent to conducting a comprehensive data quality review and verification procedure of the available temporary, permanent and experimental permanent sample plot records within the Province of Ontario, a total of 407 (122 in natural stands and 285 in managed stands) tree-list measurements derived from 269 (142 in natural stands and 127 in managed stands) sample plots were selected for use in this study. Geographically, the selected plots were largely concentrated within Forest Sections B-4, B-7, B-8, B-9, B-10, B-11 and B-14 of the Canadian Boreal Forest Region (Rowe, 1972). These sections fall within the northeastern, northcentral and northwestern administration regions of Ontario and are dominated by simple and complex stands of black spruce, jack pine, and (or) aspen (*Populus tremuloides* (Michx)). The temporary and permanent plots were established mostly by forest-based industrial corporations or government departments during the 1930–1990 period. To ensure approximately equal representation in terms of forest age classes and site qualities across the commercially productive forest sites, a stratified pseudo-random sampling design was used in the selection of stands for plot establishment. The majority of the experimental plots were established within density manipulated stands as part of various initial spacing and thinning experiments established by various research agencies during the 1950–2000 period. Structurally, the plots were circular, square or rectangular in shape with a mean overall area of 0.0966 ha (SD = 0.1060 ha; minimum/maximum = 0.0249/0.4047 ha). The mean number of trees measured per plot was 156 trees (SD = 90 trees/plot; minimum/maximum = 37/521 trees/plot). For analytical purposes, the plots were also differentiated based their utility in describing temporal change. Static plots were those for which only a single measurement was available and hence could not be used to derive temporal change estimates. Conversely, dynamic plots were those for which two or more sequential measurements were available and thus able to provide change estimates. A summary of the number of static and dynamic plot measurements for each stand-type is provided in Table 1.

Information available for each plot included its geographic location, disturbance and silvicultural treatment history, ecological site type, time of plot establishment and remeasurements, and measurement protocol. Briefly, plot measurements included a (1) tree-list consisting of the diameter measurements at breast-height (1.37 m or 1.3 m) − outside bark (D; ±0.25 cm) for all live trees greater than 2.54 cm in D by species, and (2) D and total height (H; ±0.30 m) measurements on a subset of black spruce sample trees ($n \approx 10$) usually selected from across the plot's diameter range. Based on the individual tree values (D and H measurements or estimates derived from species-specific allometric-based height–diameter functions) in combination with plot area information, the following stand-level variables were calculated: (1) mean dominant height (H_d; m) as defined as the mean height of the trees within the largest height quintile; (2) quadratic mean diameter (D_q; cm); (3) basal area (G; m^2/ha); (4) total volume (V_t; m^3/ha) which was calculated as the sum of the individual tree total volumes (v_T; m^3/tree) as determined from the D and H values in combination with a regional-wide standardized total volume equation ($v_T = D^2/(\beta_0 + (\beta_1/H))$ where β_0 and β_1 are species-specific constants derived from 7442 sample trees; accuracy (%) = ±17.0; Honer et al., 1983); (5) merchantable volume (V_m; m^3/ha), which was calculated as the sum of the individual tree merchantable volumes (v_M; m^3/tree) for all trees greater than 9 cm in D where v_M was determined from the D and H values, v_T estimate and specified merchantability limits (0.1524 m stump-height and a 7.62 cm merchantable top diameter (inside-bark)) according to a regional-wide standardized merchantable volume equation (Honer et al., 1983); (6) total density (N (stems/ha)); and (7) relative density index

Table 1
Stand-type-specific characteristics, plot data sources and types, and measurement frequency.

Stand-type denotation	Principal defining characteristics	Plot series and number of plots by measurement type			Measurement sequence and number		
		Series[a]	Type[b]		Number of consecutive measurements	Number of plots	Total number
			Static	Dynamic			
$\text{PIm}_{(N)}$	Even-aged upland black spruce stands situated on mineral soils. Black spruce constitutes >90% of the plot's basal area at the time of plot establishment, or >90% of the plot's density at time of establishment (regenerating stands). Includes stands which regenerated naturally following disturbance but with no history of density manipulation. Within the SP1 working group analog (Watt et al., 2001).	Boreal-Growth (TSP; OMNR)	41		1	41	122
		American-Can (PSP)		5	5	1	
		Spruce Falls (PSP)		76	6	2	
					9	1	
					10	2	
					11	1	
					12	2	
$\text{PIm}_{(M)}$	Density-manipulated even-aged upland black spruce stand-types situated on mineral soils. Black spruce constituted >90% of the plot's basal area at the time of establishment, or >90% of the plot's density at time of establishment (regenerating stands). Includes stands which were regenerated artificially via planting or stands which regenerated naturally but were subsequently thinned. Within the SP1 working group analog (Watt et al., 2001)	Boreal-Growth (TSP; OMNR)	7		1	15	285
		Spruce Falls (PSP)		19	2	11	
		Beckwith (PSP; OMNR)		202	3	61	
		New Brunswick (Anon; EPSP)		30	4	4	
		Stanley (EPSP; OMNR)		12	5	6	
		Thunder Bay (EPSP; OMNR)		15	8	1	
					11	1	

[a] Plot series denoted according to Ontario-centric nomenclature where the plot type and host organization responsible for initial plot establishment is acknowledged: plot type is delineated as a temporary sample plot (TSP), permanent sample plot (PSP) or experimental permanent sample plot (EPSP); and the host organization is denoted by the legacy corporate name or government agency (n., OMNR refers to the Ontario Ministry of Natural Resources).

[b] Dynamic plots were those for which a sequential remeasurement was recorded whereas static plots were those for which only a single measurement was recorded.

(P_r; %/100; derived from the ratio of N to the maximum N attainable in a stand with the same mean volume (Drew and Flewelling, 1979; Newton and Weetman, 1993; Newton, 2006a)). The mensurational characteristics of the datasets are summarized in Table 2.

2.2. Development of dynamic SDMDs (Module A)

Stand-type-specific dynamic stand density management diagrams were developed via the calibration and subsequent integration within the SDMD modelling framework of the following relationships: (1) asymptotic mean volume–density relationship and associated relative density index function; (2) yield–density relationships and associated isolines for quadratic mean diameter, mean dominant height, mean live crown ratio and relative density index; (3) mean volume–density relationships at the time of initial crown closure and those delineating the zone of maximum production; and (4) survivorship functions for predicting post-crown-closure size–density trajectories. A complete account of the methods used and results obtained for each relationship is provided in Appendix A. The graphical version of the dynamic SDMDs were developed for each stand-type by superimposing the following relationships on a bivariate logarithmic graph with mean volume on the ordinate axis and stand density on the abscissa: (1) asymptotic size–density relationship (self-thinning rule; Eq. (A1)); (2) isolines for relative density index, quadratic mean diameter, mean dominant height, and mean live crown ratio (Eqs. (A3), (A5), (A7) and (A9), respectively); (3) crown closure line (Eq. (A10)); (4) lower and upper P_r isolines delineating the optimal density management window ($0.32 \le P_r \le 0.45$); and (5) site-specific expected size–density trajectories for a given density management regime as predicted by the net density change function (Eq. (A11)) in association with the height–age function (Eq. (1); Carmean et al., 2006).

$$H_d = 1.3 + 16.95(S_I - 1.3)^{0.1136}\left[1 - K^{\frac{A_B}{50}}\right]^{0.6167(S_I-1.3)^{0.3116}}$$
$$\text{where } K = 1 - \left[\frac{(S_I - 1.3)}{16.95(S_I - 1.3)^{0.1136}}\right]^{\frac{1}{0.6167(S_I-1.3)^{0.3116}}} \quad (1)$$

where H_d is the predicted mean dominant height (m) at a given breast-height age (A_B) for a specified site quality as quantified by site index (S_I (m); H_d at a breast-height age of 50 yr).

Table 2
Mensurational characteristics of the trees and stands utilized to develop the SSDMM for upland black spruce stand-types.

Stand-type[a] (n_p; n_s; n_t)	Variable[b] (units)	Mean	Standard deviation	Minimum	Maximum
$PIm_{(N)}$	A (yr)	60	17	30	89
(122; 111; 1366)	H_d (m)	16.27	2.51	8.49	21.91
	D_q (cm)	11.67	2.99	5.68	17.42
	G (m^2/ha)	28.69	8.70	7.77	48.49
	$\bar{v}$ (dm^3)	71.12	42.22	9.20	176.24
	V_t (m^3/ha)	171.19	65.14	39.91	345.72
	V_m (m^3/ha)	100.84	58.83	2.96	260.13
	N (stems/ha)	3094	1618	817	9002
	P_r (%)	78.8	23.2	22.5	130.3
	S_I (m)	16.70	2.62	11.78	25.23
	D_m (cm)	2.97	1.03	1.30	7.62
	$\hat{a}$	1.75	0.96	0.01	4.35
	$\hat{b}$	9.91	3.70	2.58	17.21
	$\hat{c}$	2.45	0.97	1.00	4.04
	D (cm)	13.06	5.52	2.50	35.40
	H (m)	12.08	4.37	2.15	23.14
$PIm_{(M)}$	A (yr)	28	12	12	78
(285; 256; 5490)	H_d (m)	9.46	3.89	2.39	18.75
	D_q (cm)	9.66	3.98	1.29	20.06
	G (m^2/ha)	22.26	12.74	0.19	60.08
	$\bar{v}$ (dm^3)	40.70	43.67	0.15	226.26
	V_t (m^3/ha)	97.95	76.36	0.22	322.24
	V_m (m^3/ha)	51.38	65.80	0.00	289.76
	N (stems/ha)	2991	1210	600	7750
	P_r (%)	49.5	30.0	1.0	125.0
	S_I (m)	15.69	3.92	6.46	26.00
	D_m (cm)	2.27	1.74	0.20	10.30
	$\hat{a}$	1.14	0.94	0.05	5.43
	$\hat{b}$	8.57	3.50	0.83	16.75
	$\hat{c}$	3.29	0.96	1.00	5.88
	D (cm)	7.15	4.23	1.10	23.40
	H (m)	5.47	2.87	1.40	19.50

[a] As defined in Table 1; n_p denotes the number of plot measurements utilized to establish the relationships used in the dynamic SDMD; n_s denotes the number of plot measurements associated with the diameter distribution recovery models; and n_t denotes the number of individual diameter at breast-height (D) and height (H) measurement pairs used to establish the composite H–D relationships.

[b] A, H_d, D_q, G, $\bar{v}$, V_t, V_m, N, P_r, S_I and D_m denote the following stand-level variables: mean stand-age, mean dominant height, quadratic mean diameter, basal area, mean volume, total volume, merchantable volume, total density, relative density index, site index and minimum diameter, respectively. $\hat{a}$, $\hat{b}$ and $\hat{c}$ denote mean likelihood estimates of the location, scale and shape parameters of the 3-parameter Weibull probability density function as fitted to the diameter frequency distributions. Note, site index was determined from the function developed by Carmean et al. (2006).

2.3. Development of diameter distribution recovery and height prediction equations (Module B)

Analogous to the parameter prediction method used to develop stand-level diameter distribution yield models (*i.e.,* expressing the parameters of a probability density function characterizing the diameter frequency distribution as a function of stand-level variables (Hyink and Moser, 1983)), parameter prediction equation systems were used to recover the grouped-diameter frequency distribution from the SDMD-generated stand-level variable estimates. The systems previously developed by Newton and Amponsah (2005) were utilized. Appendix A provides a summary of methods and the model specifications used. Likewise, the previously developed regression functions by Newton and Amponsah (2007) were employed to describe the H–D relationships. Additional details are given in Appendix A.

2.4. Taper equation selection (Module C) and development of composite biomass functions (Module D)

Data limitation negated the development of stand-type-specific taper equations and hence the composite nonlinear mixed-effects variable exponent taper equation developed for black spruce by Sharma and Parton (2009) was utilized in this study (Eq. (A19); Appendix A). Composite biomass functions were developed for estimating each above-ground component (bark, stem, branch and foliage) based on a multivariate allometric model (e.g., Jolliffe et al., 1988; Newton, 2006b). Appendix A provides complete details regarding the calibration data sets, specified models, parameterization techniques used, and the resultant parameter estimates and associated regression statistics.

2.5. Selection of sawmill-specific product recovery and associated value functions (Module E) and development of composite wood density and mean maximum branch diameter functions (Module F)

Sawmill-specific product recovery and value functions by stand-type were derived from sawmill simulation studies as reported in the literature (i.e., Liu and Zhang, 2005; Zhang et al., 2006). Briefly, these functions were calibrated using results obtained from the Optitek sawing simulator (Forintek Canada Corp., 1994) employing both a conventional stud sawmill and a random length sawmill processing protocol. Procedurally, for a tree stem of given diameter, length, taper and wane, the stud sawmill processing protocol consisted of bucking the stem into sections of fixed length (2.44 m) and then sawing the resultant sections into dimensional lumber products based on an algorithm that maximized section-level lumber value recovery. The random length sawmill processing protocol consisted of optimally bucking the stem into sections of variable length (largest (4.88 m) to smallest (1.22 m)) and then sawing them into dimensional lumber products based on a bucking and cutting algorithm that maximized tree-level lumber value recovery. Employing the resultant sawdust, chip and lumber volume estimates in combination with market-based economic values for the year 2002, lumber volume, lumber value and total product value, were calculated. The employment of these virtual estimates in combination with individual tree D and H enabled the development of size-dependent prediction equations (Lui and Zhang, 2005; Zhang et al., 2006; Eq. (A21)). In reference to the fibre attribute functions for predicting mean wood density per tree and mean maximum branch diameter within the first 4.9 m sawlog per tree, multivariate allometric-based models were parameterized using data derived from density control experiments. Complete analytical details for these relationships are provided in Appendix A.

3. Results and discussion

3.1. The enhanced modular-based SSDMM and associated computational framework

Expanding the dynamic SDMD modelling framework (Module A) through the integration of the (1) Weibull-based parameter prediction equation systems and composite height–diameter functions (Module B), (2) dimensional-compatible variable exponent taper equation (Module C), (3) allometric-based component biomass functions (Module D), (4) sawmill-specific product recovery and value functions (Module E), and (5) composite fibre attribute functions (Module F), yielded the modular-based SSDMM (Fig. 1). An indepth schematic illustration and corresponding descriptive synthesis of the computational framework is presented in Appendix B. Included within this framework are the modelling advancements introduced in this study, as described below.

3.1.1. Accounting for response delay, density-independent mortality, and genetic worth effects

The Dynamic SDMD Module (Fig. B1(a)) embeds the prerequisite yield–density relationships that are used to predict the temporal site-specific size–density trajectory and associated stand-level variables for a given density management regime. The SDMD modelling approach commonly assumes that the size–density trajectory of a recently thinned stand immediately follows that of a stand which was managed at the lower post-thinned density. However, trees within recently thinned stands require a period of time to morphologically adjust to their newly allocated growing space and resources. In order to account for this adjustment period a temporal response delay function was developed. This approach was based on the difference in live crown ratios between trees within the pre-thinned and post-thinned stand as initially conceptualized by Newton (2003). To illustrate this concept by way of an example, the results from a black spruce initial spacing trial are used (i.e., Table 1 in McClain et al., 1994). Specifically, the differential in mean live crown ratio between a density stressed stand (surrogate for the thinned stand just before thinning (44%)) and a low-density-stressed stand (surrogate for the thinned stand immediately following thinning (80%)), situated on the same site and of equal age (41 yr), was 36%. However, if the density-stressed stand was thinned at an age of 41, the model would incorrectly assume there was no differential between the stands. Thus the length of time required for trees within this conceptually thinned stand to achieve a mean live crown ratio of approximately 80%, would be considered the duration of the response delay period. Extending this concept by accounting for intrinsic live crown ratio change within the lower density stand in the years immediately following thinning, the exact number of years required for the live crown ratios in both stands to converge can be determined. Computationally, this would be the number of years that the live crown ratio of the tree of mean dominant height took to rebuild its live crown ratio (based on a static live crown base) to be equivalent to that predicted for a similar tree growing at the lower density. For these response delay years, the trees within the recently thinned stand which have yet to fully occupy their newly allocated space would not be competing until their live crown ratios recovered. Consequently, the net density change function was disabled during this adjustment period.

Size–density trajectories should also account for possible age-related density-independent mortality arising from intrinsic biotic and abiotic factors (e.g., mortality due to insect and disease vectors). Consequently, a dynamic operational adjustment factor (O_A; %/yr), defined as the annual percentage of trees that are expected to incur density-independent mortality throughout the rotation, is used to modify the net density change projections. Computationally, this involves subtracting (O_A/100) N from the density estimate given by Eq. (A11), as described in the following script:

$$\textit{If}\ \ O_A > 0\ \ \textit{then}\ \ \hat{N}'_{(t)} = \hat{N}_{(t)} - (O_A/100)\hat{N}_{(t)}$$

where $\hat{N}_{(t)}$ is the predicted density (stems/ha) at time t as calculated from Eq. (A11), and $\hat{N}'_{(t)}$ is the resultant adjusted density estimate at time t after accounting for density-independent mortality factors.

Genetic worth effects, as defined as the temporary increase in dominant height growth (G_W; %/100) initiating at a specific selection age (G_A; yr) which decreases in a linear fashion until rotation age (sensu Xie and Yanchuk, 2003), was integrated into the height–age function as described by the following script.

$$\textit{If}\ G_W > 0\ \textit{then for}\ t = G_A:$$
$$\hat{H}'_{d(t)} = \hat{H}_{d(t)} + G_W \hat{H}_{d(t)},$$
$$\textit{otherwise},\ \textit{for}\ t > G_A:$$
$$\hat{H}'_{d(t)} = \hat{H}_{d(t)} + \left(G_W - \left(\frac{G_W}{T - G_A}\right)\sum_{i=G_A}^{t} 1\right)\hat{H}_{d(t)}$$
$$\textit{let}\ \hat{H}_{d(t)} = \hat{H}'_{d(t)}$$

where $\hat{H}_{d(t)}$ is the predicted mean dominant height at time t according to Eq. (1), $\hat{H}'_{d(t)}$ is the adjusted $\hat{H}_{d(t)}$, and T is the rotation length in years.

3.1.2. Ensuring compatibility among dominant height estimates

The Diameter and Height Recovery Module (Fig. B1(b)) is used to recover the grouped-diameter frequency distribution and corresponding tree height distribution employing the Weibull-based parameter prediction equation systems and composite height–diameter functions in association with stand-level variable estimates derived from the Dynamic SDMD module. The provision of two annual dominant height estimates, one from the site-specific height–age function ($\hat{H}_{d(t)}$; Eq. (1)) and the other one calculated from the diameter-class heights ($\hat{H}'_{d(t)}$; Eq. (A18)), allows for an internal comparison and correction if required on the diameter-class height predictions (Eq. (2)).

$$\hat{H}'_{d(t)} = \sum_{j=1}^{J}\hat{H}_{(t,j)}\hat{N}_{(t,j)} \Big/ \sum_{j=1}^{J}\hat{N}_{(t,j)}\ \text{for}\ \hat{D}_{(t,j)} \geq \hat{D}_{80(t)}$$
$$\text{where}\ \hat{D}_{80(t)} = \hat{b}_{(t)}[-\log_e(0.20)]^{\hat{c}_{(t)}^{-1}}) \tag{2}$$

where $\hat{H}_{(t,j)}$, $\hat{N}_{(t,j)}$ and $\hat{D}_{(t,j)}$ are the predicted height (m), number of trees (stems/ha) and midpoint diameter (cm) for the jth two-centimetre-width diameter class at time t, respectively, $\hat{b}_{(t)}$ and $\hat{c}_{(t)}$ are the predicted stand-type-specific scale and shape parameters of the 3-parameter Weibull probability density function at time t, respectively, and $\hat{D}_{80(t)}$ is the predicted diameter (cm) corresponding to the 80th percentile within the recovered diameter distribution at time t. Thus in cases where $\hat{H}'_{d(t))} \neq \hat{H}_{d(t)}$, the H–D function (Eq. (A18)) was conditionized to ensure mathematically consistency. Computationally, this involved calculating the mean diameter of trees within the upper quintile of the diameter distribution by year ($\hat{D}_{d(t)}$) and then adjusting the intercept term in Eq. (A18) accordingly,

$$\text{i.e.,}\ \hat{\lambda}'_{0(i)_{(t)}} = \frac{\hat{H}_{d(t)}}{\hat{D}_{d(t)}^{\hat{\lambda}_{1(i)}+\hat{\lambda}_{2(i)}\hat{P}_{r(t)}+\hat{\lambda}_{3(i)}\hat{H}_{d(t)}+\hat{\lambda}_{4(i)}\hat{P}_{r(t)}\hat{H}_{d(t)}}\hat{P}_{r(t)}^{\hat{\lambda}_{5(i)}}\hat{H}_{d(t)}^{\hat{\lambda}_{6(i)}}\left(\hat{P}_{r(t)}\hat{H}_{d(t)}\right)^{\hat{\lambda}_{7(i)}}},$$

where $\hat{\lambda}'_{0(i)_{(t)}}$ is the adjusted intercept parameter for the ith stand-type at time t, $\lambda_{l(i)}$, $l = 1,\ldots,7$ are parameter estimates specific to the ith stand-type, and $\hat{P}_{r(t)}$ is the predicted relative density index at time t. The revised diameter-class heights can then be estimated via Eq. (3).

$$\hat{H}'_{(t,j)} = \hat{\lambda}'_{0(i)_{(t)}}\hat{D}_{(t,j)}^{\hat{\lambda}_{1(i)}+\hat{\lambda}_{2(i)}\hat{P}_{r(t)}+\hat{\lambda}_{3(i)}\hat{H}_{d(t)}+\hat{\lambda}_{4(i)}\hat{P}_{r(t)}\hat{H}_{d(t)}}\hat{P}_{r(t)}^{\hat{\lambda}_{5(i)}}\hat{H}_{d(t)}^{\hat{\lambda}_{6(i)}}\left(\hat{P}_{r(t)}\hat{H}_{d(t)}\right)^{\hat{\lambda}_{7(i)}} \tag{3}$$

Additional computation details for the variables used in Eqs. (2) and (3) can be found in Appendices A and B (i.e., Fig. B1(a) and (b) in association with Table B1).

3.1.3. Tailoring log and volume outputs by management objective

The Taper Analysis and Log Estimation Module (Fig. B1(c)) calculates upper stem diameters for trees within each diameter class from which diameter-class and stand-level estimates of the number of sawlogs and pulplogs, residual tip volumes, and merchantable and total stem volumes are calculated, according to the specified merchantability limits. However, these limits can vary due to changes in market conditions or management objectives. For example, an integrated forest operation consisting a saw and pulp mill with a cogeneration power plant may configure their slashing operations to maximize the production of sawlogs first, pulplogs second and residual tip volumes third. Consequently, the employment of user-specified merchantability limits, in terms of log lengths and upper stem diameter thresholds, allows the user to tailor the model's output according to their specific needs (e.g., reducing the upper merchantable stem diameter from the traditional 10 cm to 4 cm in order to increase the biomass volume available for the cogeneration operation).

3.1.4. Compatibility among end-product volumes and accounting for value degrade

The Product and Value Estimation Module (Fig. B1(e)) estimates sawmill-specific recoverable chip and lumber volumes and associated market-based values at the tree, diameter-class and stand levels. According to empirical expectation, the cumulative chip and lumber volume per tree should not exceed the merchantable volume per tree estimate as calculated from the taper equation. However this is not always the case since the product and taper equations are not mathematically constrained to ensure compatibility between their predicted volumes. Thus via the use of a ratio estimator, the product volume estimates are adjusted to ensure that their additive volumes do not exceed the merchantable volume predicted from the taper equation. Likewise, the same proportionate reduction is used to adjust the resultant product values. Refer to Fig. B1(e) for the computation script associated with these adjustments.

In order to account for inflation since the time the product value equations were developed (2002), the estimates were increased using an adjustment factor based on a user-specified inflation rate (I_r; mean annual rate of inflation since 2002 (%/100)) and the calendar year in which the calculation was made (Y_s). Furthermore, the product value estimates from these equations have been shown to overestimate actual monetary values since product downgrades due to knots were not accounted for in the original studies (e.g., Liu et al., 2007; Tong and Zhang, 2009). Consequently, as shown in Fig. B1(e), a user-specified degrade adjustment factor (D_e; %) is used to address this issue explicitly.

3.1.5. Predictive ability

A majority of the principal relationships used within the estimation modules have been previously validated independently within the source publications. These included the parameter prediction equation systems for diameter distribution recovery (Module B; Newton and Amponsah (2005)), composite height–diameter functions (Module B; Newton and Amponsah (2007)), dimensional taper equation (Module C; Sharma and Parton (2009)), and product recovery and value functions (Module E; see Liu and Zhang (2005) and Zhang et al. (2006)). In addition, an assessment of the biological reasonableness of the model's predictions in relation to expected patterns derived from theoretical constructs indicated the predictions were in accord with expectation: (1) increasing rates of density-dependent mortality as the size–density trajectories approach the self-thinning line; (2) approximate convergence of size–density trajectories with the self-thinning line as density-stress levels approach their maximum; (3) increasing positive-skewness of size-distributions with increasing density-stress until self-thinning occurs, thereafter, approaching a normal-type distribution; (4) declining live crown ratios and branch sizes with increasing density; and (5) decreasing wood density with reductions in density-stress levels. Similarly, numerical thresholds obtained from the measurement of density control experiments (i.e., Nelder plots) and provincial wide permanent sample plot data bases were used to assess the reasonableness of the empirical estimates. Results indicated that the predictions did not exceed the observed maximums in terms of mean tree sizes, basal area per unit area, and merchantable and total volume productivity. A case-study assessment of the model's ability to predict recovered product volumes and associated monetary values was also carried out by comparing the model's estimates with those observed within a long term initial spacing experiment (Zhang and Chauret, 2001). Briefly, this experiment was located on a medium site quality (site index = 16.9 m (Carmean et al., 2006)) in Northwestern Ontario, and consisted of 3 initial espacement treatments (2.74 × 2.74 m, 2.0 × 2.0 m, and 1.83 × 1.83 m which corresponding to initial densities of 1329, 2500 and 2986 stems/ha). Sample trees within each treatment were destructively sampled in 1998 at an age of 52 yr and subsequently processed via a local stud mill. Differences between observed and predicted values for the 1329, 2500 and 2986 stems/ha treatments were respectively (1) −29 (under estimation), 10 and 4% for chip volume, (2) −11, 33 and 19% for lumber volume, and (3) −3, 39 and 24% for total product values. These results suggest that for this particular experiment, the model preformed adequately in terms of predicting these output metrics (i.e., overall mean differences of 5, 14, and 20% for chip and lumber volumes, and total product values, respectively). These initial assessments indicated that the model's predictions were reasonable and in general agreement with expectation. However, it should be noted that these results are preliminary and a full evaluation of the model's predictive ability will require comprehensive validation data sets consisting for the entire suite of output parameters from multiple density control experiments (e.g., volumetric yields, log distributions, biomass and carbon values, recoverable end-products and associated values, and fibre attributes from experiments that implement operationally-relevant ranges of IE, PCT and CT treatments).

3.2. An algorithmic analogue and its application in density management

In order to reduce the complexities in implementing the computational sequence required to derive volumetric yields, log assortments, biomass and carbon outcomes, recoverable products and associated values, and fibre attributes (as described in Appendix B), an algorithmic analogue of the SSDMM was developed using the VisualBasic.Net programming language. The program predicts and tabulates site-dependent annual and rotational diameter-class and stand-level estimates in terms of volumetric yields, log distributions, biomass and carbon yields, recoverable products and associated values by sawmill-type, cost profiles and fibre attributes, for each of 3 user-specified density management regimes. Specifically, for each tree within the recovered diameter distribution, the program calculates its height, number of pulp and saw logs recovered, merchantable volume, biomass and carbon equivalents for each above-ground component, sawmill-specific recoverable chip and lumber volumes and associated monetary values, and individual tree fibre attributes,

Table 3
Stand-level performance indices: denotations and computations.

Index (unit)	Computation
Mean annual merchantable volume increment: R_{MAI} (m^3/ha/yr)	$R_{MAI} = (V_m + \sum_{k=1}^{K} V_{m(k)})/A_{(T)}$ where V_m is the standing merchantable volume (m^3/ha) at rotation ($A_{(T)}$) and $V_{m(k)}$ is the merchantable volume removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$).
Mean annual biomass increment: R_{BMI} (t/ha/yr)	$R_{BMI} = (M_t + \sum_{k=1}^{K} M_{t(k)})/A_{(T)}$ where M_t is the standing total aboveground biomass (t/ha) at rotation and $M_{t(k)}$ is the total aboveground biomass (t/ha) removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$).
Mean annual carbon increment: R_{CAI} (t/ha/yr)	$R_{CAI} = (C_t + \sum_{k=1}^{K} C_{t(k)})/A_{(T)}$ where C_t is the standing total aboveground carbon (t/ha) at rotation and $C_{t(k)}$ is the total aboveground carbon (t/ha) removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$).
Percentage of sawlogs produced: R_{SL} (%)	$R_{SL} = 100[(N_{ls} + \sum_{k=1}^{K} N_{ls(k)})/((N_{ls} + \sum_{k=1}^{K} N_{ls(k)}) + (N_{lp} + \sum_{k=1}^{K} N_{lp(k)}))]$ where N_{ls} and N_{lp} are the total number of sawlogs (logs/ha) and pulplogs (logs/ha) at rotation, respectively, and $N_{ls(k)}$ and $N_{lp(k)}$ are the total number of sawlogs (logs/ha) and pulplogs (logs/ha) removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$), respectively.
Percentage of lumber volume recovered: $R_{LV(m)}$ (%)	$R_{LV(m)} = 100[(V_{l(m)} + \sum_{k=1}^{K} V_{l(k,m)})/((V_{l(m)} + \sum_{k=1}^{K} V_{l(k,m)}) + (V_{c(m)} + \sum_{k=1}^{K} V_{c(k,m)}))]$ where $V_{l(m)}$ and $V_{c(m)}$ are the lumber and chip volumes (m^3/ha) recovered employing the mth sawmill processing protocol ($m = s$ (stud mill) or r (randomized length mill)) from the merchantable-sized trees at rotation, respectively, and $V_{l(k,m)}$ and $V_{c(k,m)}$ are the lumber and chip volumes (m^3/ha) recovered employing the mth sawmill processing protocol from the merchantable-sized trees removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$), respectively.
Relative land expectation value: $E_{(m)}$ (%)	$E_{(m)} = 100\cdot\left(\frac{L_{E(m)}^{T} - L_{E(m)}^{C}}{L_{E(m)}^{C}}\right)$ where $L_{E(m)}^{T} = \frac{(P_{t(m)}^{T}(1+I_r)^{A_{(T)}} + \sum_{k=1}^{K}(P_{t(k,m)}^{T}(1+I_r)^{A_{(k)}})(1+I_r)^{A_{(T)}-A_{(k)}}) - (C_F^E(1+I_r)^{A_{(T)}} + C_{V-P}^{T}(1+I_r)^{A_{(T)}} + \sum_{k=1}^{K} C_{F-T(k)}^{T}(1+I_r)^{A_{(T)}-A_{(k)}} + \sum_{k=1}^{K} C_{V-T(k)}^{T}(1+I_r)^{A_{(T)}-A_{(k)}} + C_{V-H}^{T})}{(1+D_r)^{A_{(T)}} - 1}$ $\begin{cases} P_{t(m)}^{T} = P_{t(m)} \\ P_{t(k,m)}^{T} = P_{t(k,m)} \\ C_{F-T(k)}^{T} = c_{F-T(k)}^{T}(1+I_r)^{A_{(k)}} \\ C_{V-P}^{T} = 0 \text{ for the natural stand} - \text{type} \\ C_{V-P}^{T} = c_s N_I^T \text{ for the managed stand} - \text{type} \\ C_{V-T(k)}^{T} = (c_{V-T(k)}^{T}(1+I_r)^{A_{(k)}})\hat{V}_{m(k)} \\ C_{V-H}^{T} = (c_{V-H}^{T}(1+I_r)^{A_{(T)}})\hat{V}_{m(T)} \end{cases}$ $L_{E(m)}^{C} = \frac{P_{t(m)}^{C}(1+I_r)^{A_{(T)}} - (C_F^E(1+I_r)^{A_{(T)}} + C_{V-P}^{C}(1+I_r)^{A_{(T)}} + C_{V-H}^{C})}{(1+D_r)^{A_{(T)}} - 1}$ $\begin{cases} P_{t(m)}^{C} = P_{t(m)} \\ C_{V-H}^{C} = (c_{V-H}^{C}(1+I_r)^{A_{(T)}})\hat{V}_{m(T)} \\ C_{V-P}^{C} = 0 \text{ for the natural stand} - \text{type} \\ C_{V-P}^{C} = c_s N_I^C \text{ for the managed stand} - \text{type} \end{cases}$ $L_{E(m)}^{T}$ and $L_{E(m)}^{C}$ are the land expectation values at rotation attained employing the mth sawmill processing protocol within the density manipulated and control stands, respectively, $P_{t(m)}^{T}$ and $P_{t(m)}^{C}$ are the inflation-adjusted (to the time of simulation; Y_s) total product values (\$/ha) recovered employing the mth sawmill processing protocol from the merchantable-sized trees within the density manipulated and control stands at rotation, respectively, $P_{t(k,m)}^{T}$ is the inflation-adjusted total product value (\$/ha) recovered employing the mth sawmill processing protocol from the merchantable-sized trees removed during the kth thinning entry ($k = 1,\ldots,K$; $K = 4$), C_F^E is the fixed costs (\$/ha) incurred at the time of stand establishment (e.g., regeneration assessment or vegetation management expenses), C_{V-P}^{T} and C_{V-P}^{C} are the variable costs for planting for the treated and control stand, respectively, and are equivalent to the number of seedlings planted (N_I^C and N_I^T are the initial planting density (stems/ha) within the control and treated stand, respectively) multiplied by the cost per planted seedling (c_s; \$/seedling), $C_{F-T(k)}^{T}$ is the inflation-adjusted fixed costs (\$/ha) incurred during the kth thinning entry (e.g., precommercial thinning cost or logistical costs such as those associated with transporting thinning equipment to CT sites), c_{V-H}^{C} and C_{V-H}^{C} are the inflation unadjusted and adjusted variable costs (dollars per cubic metre of merchantable volume harvested (\$/m^3)), respectively, associated with crown charges (stumpage and renewal fees), harvesting, transportation, processing and manufacturing at the time harvest within the control stand, similarly, c_{V-H}^{T} and C_{V-H}^{T} are the inflation unadjusted and adjusted variable costs (\$/m^3), respectively, at the time of harvest within the treated stand, and $c_{V-T(k)}^{T}$ and $C_{V-T(k)}^{T}$ are the inflation unadjusted and adjusted variable costs (\$/m^3), respectively, at the time of the kth thinning entry within the treated stand, I_r and D_r are the inflation and discount rate, respectively, and $A_{(k)}$ and $A_{(T)}$ are the stand ages at the time of the kth thinning entry and rotation, respectively.
Duration of optimal site occupancy: S_O (%)	$S_O = 100(Y_O/Y_N)$ where S_O is the percentage of rotation that the size–density trajectory was within the conceptual optimal relative density management zone ($0.32 \le P_r < 0.45$), Y_O is the number of years in which the size–density trajectory was within the conceptual optimal relative density management zone, and Y_N is the rotation length in years.

Mean height/diameter ratio: S_s (m/m)	$S_S = \frac{1}{(T-T_A)}\sum_{t=T_A}^{T}\left(\frac{\sum_{j=\hat{D}_{80(t)}}^{J}\left(\frac{H_{(t,j)}}{100\cdot D_{(t,j)}}\right)N_{(t,j)}}{\sum_{j=\hat{D}_{80(t)}}^{J} N_{(t,j)}}\right)$ where $\begin{cases} T_A = \text{stand age at the time of the last treatment, otherwise zero} \\ D_{80(t)} = \hat{b}_{(t)}[-\log_e(0.20)]^{\hat{c}_{(t)}^{-1}} \end{cases}$ where $\hat{D}_{80(t)}$ is the 80th percentile of the recovered diameter frequency distribution at time t as calculated from the Weibull (1951) scale and shape parameters (Bailey and Dell, 1973).
Mean wood density: $\overline{W}_D$ (g/cm^3)	$\overline{W}_D = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{\sum_{j=5}^{J}\overline{w}_{D(t,j)}N_{(t,j)}}{\sum_{j=5}^{J}N_{(t,j)}}\right)$ where $\overline{w}_{D(t,j)}$ is the stem cross-sectional area-weighted mean wood density at time t of trees within the jth merchantable size diameter class ($D_{(t,j)} \geq 10$).
Mean maximum branch diameter: $\overline{B}_D$ (cm)	$\overline{B}_D = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{\sum_{j=8}^{J}\overline{b}_{D(t,j)}N_{(t,j)}}{\sum_{j=8}^{J}N_{(t,j)}}\right)$ where $\overline{b}_{D(t,j)}$ is the mean maximum branch diameter within the first 4.9 m sawlog at time t within the jth sawlog-sized diameter-class ($D_{(t,j)} \geq 16$).
Time to operability status: O_T (yr)	$O_T = t$ when $\begin{cases} O_{1(t)} \leq O_{1-T} \text{ where } O_{1(t)} = \hat{N}_{m(t)}/\hat{V}_{m(t)} \\ \text{and} \\ O_{2(t)} \geq O_{2-T} \text{ where } O_{2(t)} = \hat{V}_{m(t)} \end{cases}$

where O_T is the minimum number of years that a stand requires to reach a target piece size, O_{1-T} (number of merchantable stems per cubic metre of merchantable volume), and merchantable yield threshold, O_{2-T} (merchantable volume per unit area (includes thinning yields)), and $O_{1(t)}$ and $O_{2(t)}$ are the piece size and merchantable yield of the stand at time t, respectively.

from which cumulative diameter-class and stand-level values, and performance indices, are derived.

Productivity, quantity and quality of recoverable products, economic efficiency, degree of optimal site occupancy, structural stability, wood quality and operability status, are among the most important elements considered when designing a crop plan. Thus in order to simplify the decision-making process, a key set of stand-level performance indices was formulated. These indices enabled the contrasting of alternative density management regimes in terms of the following: (1) overall productivity as measured by the mean annual merchantable volume increment (R_{MAI}; m^3/ha/yr), mean annual biomass increment (R_{BMI}; t/ha/yr) and mean annual carbon increment (R_{CAI}; t/ha/yr); (2) sawlog production potential (R_{SL}; %); (3) end-products produced expressed as the percentage of lumber volume recovered via the mth sawmill processing protocol ($R_{LV(m)}$; %); (4) economic efficiency as quantified by relative land expectation value (i.e., the maximum an investor could pay for bare land to achieve a specified rate of return (discount rate) of a given manipulated regime relative to the control regime, employing the mth sawmill processing protocol ($E_{(m)}$; %)); (5) duration of optimal site occupancy (S_O; %); (6) stand stability as quantified by the mean height/diameter ratio for the dominant crown class population (S_S; m/m); (7) fibre quality attributes as reflected by mean wood density ($\overline{W}_D$; g/cm^3) and mean maximum branch diameter ($\overline{B}_D$; cm); and (8) operability status as measured by the number of years that a stand requires to reach harvestable status as defined by target piece size (number of merchantable stems per cubic metre of merchantable volume) and merchantable yield (merchantable volume per unit area) thresholds (O_T; yr). Computational details for each of these indices are provided in Table 3.

Operationally, deriving the optimal density regime or crop plan for a given set of objectives is a challenging management proposition considering the number of the decision variables that a resource manager must evaluate. These include decisions on which stand-types and site qualities are to be treated, what initial densities to plant at, the number, intensity (removable densities), timing and type (systematic, selective, thinning-from-below) of thinning treatment to implement, when to conduct the final harvest (rotation age), inflation and discount rates, and applicable fixed and variable cost values. Furthermore, the selected regime must also adhere to regulatory guidelines as issued by governing bodies (e.g., candidate stands for CT treatments must achieve threshold structural conditions such as minimum basal areas and live crown ratios before thinning can commence). In order to exemplify the utility of the model within this operational context, the software program was used to evaluate the consequences of implementing thinning treatments (PCT and CT) within natural black spruce stands, and reducing initial espacement regimes below the commonly employed 2500 seedlings/ha planting standard. These density management scenarios reflect current discussions regarding forest management practices within the central portion of the Canadian Boreal Forest Region. Briefly, the goal of implementing PCT treatments within density-stressed stands is to shorten the time to operability status. The objective underlying CT is to minimize merchantable volume losses that would be normally attributed to density-dependent mortality at the later stages of stand development while at the same time reducing the technical rotation age for the production of high quality wood products (McKinnon et al., 2006). The purpose of lowering planting densities is to increase economic efficiencies through the reduction of planting costs and avoiding the expense of subsequent thinning treatments.

3.2.1. Natural stand-types − PCT + CT treatments

Conceptually, preferable CT density management regimes are those which (1) increased mean tree size without incurring declines in stand volume growth, (2) do not unacceptably increase the risk of volume losses to wind, snow, insects, and disease, and (3) avoid high rates of density-dependent mortality within the merchantable-sized tree classes which enables the recovery of some the expected merchantable volume losses. Operationally, the CT treatment should occur within density regulated stands approximately 15–20 yrs from rotation age, reduce basal areas by 30–35% from an initial minimum basal area of 25 m^2/ha, be implemented only when density-dependent mortality is occurring or imminent within the merchantable-sized classes, and only in stands where mean live crown ratios exceed 35% (McKinnon et al., 2006). Thus within this context, 3 stands with initial densities of 5000 stems/ha (N_I) established on good quality sites ($S_I = 18$) which were subjected to (1) no thinning treatments (Regime 1; control), (2) a single PCT treatment (Regime 2), and (3) a dual treatment consisting of both a PCT and CT treatment (Regime 3), were contrasted over a 65 yr rotation. The PCT treatments were identical in both Regime 2 and 3 and consisted of a thinning-from-below protocol in which 2500 stems/ha were removed at age 10. The CT treatment consisted of removing 1000 stems/ha at age 45 which represented a 30% reduction in basal area at the time of thinning. To account for density-independent mortality throughout the rotation, an operational adjustment factor (O_A) of 1% was specified for all 3 regimes. The fixed costs included a $0.1K/ha regeneration assessment fee applicable at the time of establishment, $0.3K/ha charge for the PCT treatment (e.g., labour and supplies for equipment), and $0.1/ha for the CT treatment (e.g., transportation costs associated with equipment transfer). Variable costs associated with stumpage and renewal fees, harvesting, transportation and manufacturing differed by regime in order to reflect the nominal cost reductions arising from larger piece sizes and spatial uniformity within the treated stands. The time of simulation, rate of inflation and discount rate were set to 2011, 2% and 4%, respectively. Similar to a sawlog management objective in which there is a bias towards the production of larger but few trees at rotation, the operability targets were set at a piece size and merchantable volume yield threshold of 10 stems/m^3 and 130 m^3/ha, respectively. All the required input parameter values are listed in Table 4.

The temporal mean volume–density trajectories for these regimes within the context of the traditional SDMD mean volume – density graphic are illustrated in Fig. 2(a). Note, the stands at the time of the PCT treatment (10 yr) were below the x-axis in Fig. 2(a) and hence not shown. However, the tabular output from the software indicated that the stands had a mean

Table 4
Stand-type specific input parameters used in the SSDMM simulations.

Input parameter (unit) [symbol]	Stand-type[a] and treatment					
	$PIm_{(N)}$			$PIm_{(M)}$		
	Regime 1: Control	Regime 2: PCT	Regime 3: PCT + CT	Regime 1: Control	Regime 2: CT	Regime 3: Low IS
Simulation year [Y_s]	2011	2011	2011	2011	2011	2011
Site index [S_I]	18	18	18	18	18	18
Rotation age (yr) [T]	65	65	65	50	50	50
Initial density (stems/ha) [N_I]	5000	5000	5000	2500	2500	1500
Genetic worth and selection age (%/yr) [G_W/G_A]	–	–	–	15/10	15/10	15/10
Merchantable specifications						
Pulplog length (m) [l_p]	2.59	2.59	2.59	2.59	2.59	2.59
Pulplog minimum diameter (cm) [d_p]	10	10	10	10	10	10
Sawlog length (m) [l_s]	5.03	5.03	5.03	5.03	5.03	5.03
Sawlog minimum diameter (cm) [d_s]	14	14	14	14	14	14
Merchantable top diameter (cm) [d_m]	4	4	4	4	4	4
Rates						
Interest rate (%) [I_r]	2	2	2	2	2	2
Discount rate (%) [D_r]	4	4	4	4	4	4
Operability Targets						
Piece-size (stems/m^3) [O_{1-T}]	10	10	10	10	10	10
Merchantable yield (m^3/ha) [O_{2-T}]	130	130	130	200	200	200
Assessment fee and (or) site preparation ($/ha) [$C_F^E$]	100	100	100	300	300	300
Planting ($/seedling) [$c_s$]	–	–	–	0.6	0.6	0.6
Operational adjustment factor (%) [O_A]	1	1	1	0	0	0
Product degrade (%) [D_e]	5	5	5	5	5	15
Variable cost ($/$m^3$) [$C_{V-H}^C$ or C_{V-H}^T]	90	80	70	80	75	70
PCT Treatment						
Time of treatment [$T_{2_{A(1)}}$]	–	10	10	–	–	–
Density removed (stems/ha) [$T_{2_{N(1)}}$]	–	2500	2500	–	–	–
Fixed cost of PCT ($/ha) [$C_{F-T(1)}^T$]	–	0.3	0.3	–	–	–
CT Treatment						
Time of treatment [$T_{3_{A(2)}}$ or $T_{2_{A(1)}}$]	–	–	45	–	30	–
Density removed (stems/ha) [$T_{3_{N(2)}}$ or $T_{2_{N(1)}}$]	–	–	1000	–	805	–
Fixed cost of CT ($/ha) [$C_{F-T(2)}^T$ or $C_{F-T(1)}^T$]	–	–	100	–	100	–
Variable cost ($/$m^3$) [$C_{V-H}^T$]	–	–	80	–	80	–

[a] As defined in Table 1

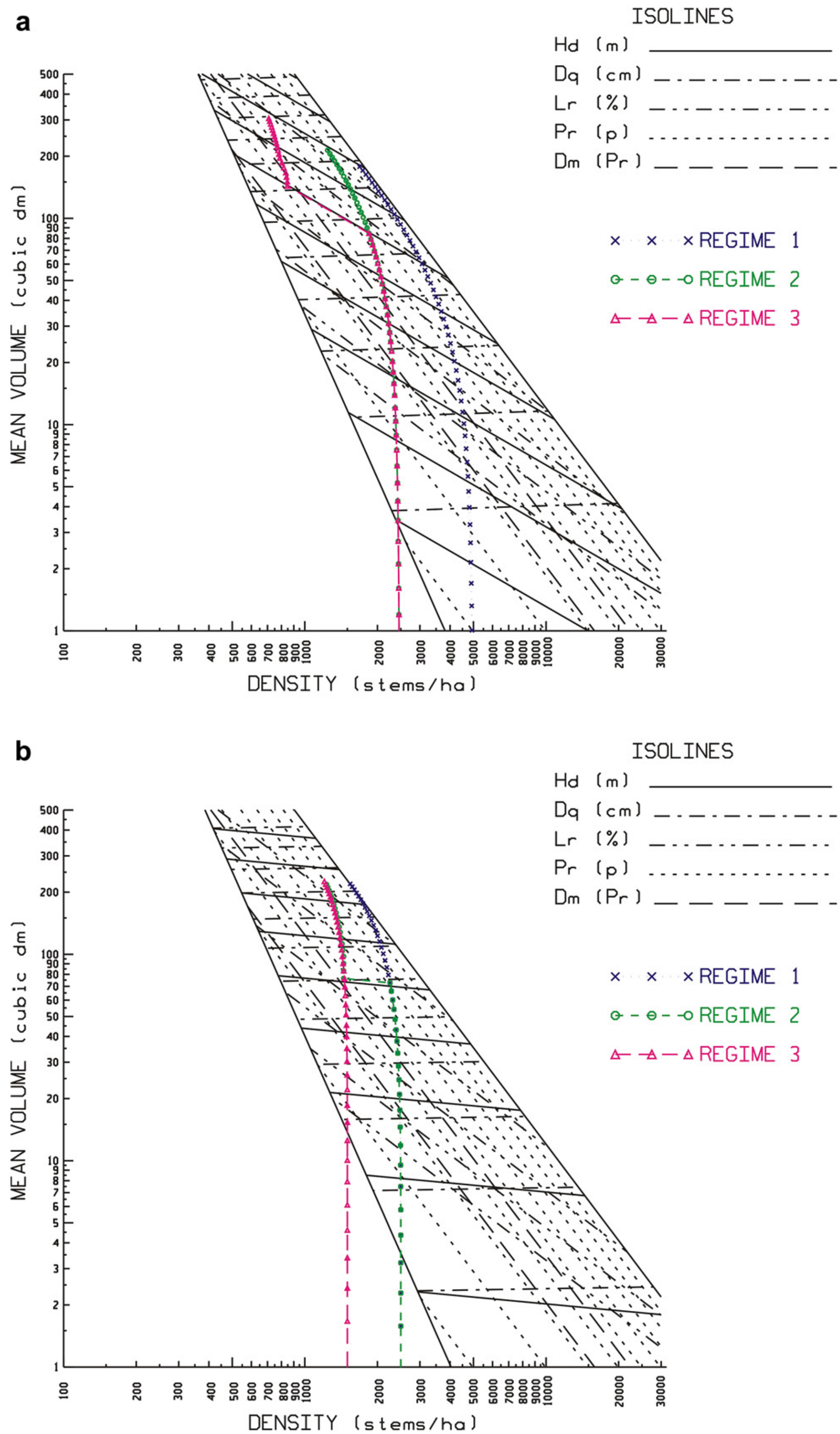

Fig. 2. (a) SDMD graphic for the natural black spruce stand-type. Note the following principal components of the SDMD: (1) isolines for mean dominant height (Hd; diagonal lines ranging from a minimum of 6 m at the bottom of the graphic to a maximum of 22 m at the top of the graphic separated by 2 m increments), quadratic mean diameter (Dq; horizontal-line lines ranging from a minimum of 4 cm at the bottom of the graphic to a maximum of 24 cm at the top of the graphic separated by 2 cm increments), mean live crown ratio (Lr; 35, 40, 50,..., 80% (diagonal lines)), relative density index (Pr; 0.1–1.0 by 0.1 intervals (diagonal lines)); (2) crown closure line (lower diagonal solid line) and self-thinning rule at a $Pr = 1.0$ (upper diagonal solid line); (3) lower and upper Pr diagonal isolines delineating the optimal density management window (Dm; $0.32 \leq Pr \leq 0.45$); and (4) expected 65 year size–density trajectories with 1 year intervals denoted by a vertical line for each of the 3 user-specified density management regimes, for stands situated on good quality

dominant height (Hd) of 3.1 m, density of 4965 stems/ha, a mean volume of 0.3 dm^3, quadratic mean diameter (Dq) of 1.4 cm, basal area of 0.8 m^2/ha and relative density index (Pr) of 0.04, just before treatment. Furthermore, the stands had yet to achieve crown closure status. Later at the time of the CT treatment, as observable from trajectory for Regime 3 in Fig. 2(a), the stand had (1) just intersected the 16 m dominant height isoline, (2) was slightly more then midway between the 12 and 14 quadratic mean diameter isolines, (3) exactly midway between the 0.6 and 0.7 relative density index isolines, and (4) slightly above the 0.4 live crown ratio (Lr) isoline. The corresponding interpolated mean volume, density and basal area values were 84.6 dm^3, 1845 stems/ha and 25.1 m^2/ha, respectively. Hence, according to the guidelines given in McKinnon et al. (2006), the stand was a candidate for a CT treatment: i.e., previously density regulated (i.e., PCT at age 10), pre-treatment basal area >25 m^2/ha, live crown ratio >35%, and imminent density-dependent mortality expected within the merchantable size classes (e.g., projected to occur at age 51 yr). The resultant thinning and rotational yield estimates are provided in Table 5 whereas the stand-level performance indices are given in Table 6.

Results indicated that the PCT treatments occurred during the stage of development during which the crowns had yet to close (i.e., size–density trajectories were below the crown closure line at the time of treatment). However, the effect of PCT was to extend the open grown period of stand development by another 5 years, as indicated by the occurrence of crown closure status at age 17 for the PCT stands. Given that the dominant height of the stands would be 6 m at age 17 and hence most of the branches within the first 5.03 m sawlog would have been formed, this additional growing space may have contributed to the slightly greater mean maximum branch diameters observed within the thinned stands (c.f., 2.65 cm versus 2.70 cm for the control and thinned stands, respectively; Table 6). Comparing Regime 2 against Regime 1, indicated that on the positive side, the PCT treatment (1) shorten the time to stand operability status by 7 years, (2) produced trees of larger mean size at rotation (i.e., increases in mean volume of 25%, quadratic mean diameter of 10%, and mean total biomass of 19%), (3) increased the percentage of sawlogs produced by 13%, and (4) enhanced overall structural stability (e.g., reducing the height/diameter ratio by 7%). On the negative side, however, the single PCT treatment resulted in lower per unit area yields for merchantable volume (10% less), biomass (14% less) and carbon (14% less). The PCT treatment did, however, result in a gain in economic efficiency (11%) at rotation when employing a stud mill processing protocol. Furthermore, the reduction in the time to operability status would also increase the economic gain given that the stands would be harvested at age 46 rather than at an age of 53 yr. In summary, the PCT treatment resulted in (1) earlier stand operability status which may have translated into substantial economic gains if the stand was harvested at the age of operability, (2) larger but fewer trees at rotation, (3) increased duration of the period of optimal site occupancy, (4) enhanced structural stability, (5) lower overall per unit area yields, and (6) a slight decline in log quality in terms of potential knot size and wood density.

For Regime 3, the CT treatment consisted of removing 7.5 m^2/ha of the basal area at age 45. This mid-rotation partial harvest resulted in the recovery of approximately 31 m^3/ha in merchantable volume. Density-dependent mortality rates within the merchantable size classes of the CT stand were considerably lower than that within the control stand during the post-CT period (c.f., 151 stems/ha versus 303 stems/ha over the 20 yr period). In terms of site occupancy, the CT stand extended the percentage of the rotation in which it was within the optimal density management window: 5% over that of the stand that was only PCT, and 9% over the untreated control stand. Relative to the control and PCT stand, the CT treatment also resulted in larger but fewer trees at rotation, increased proportion of sawlogs, extended period of optimal site occupancy, and enhanced structural stability. However, a decline in overall productivity and slight reduction in log quality were evident. The economic indices indicated that compared to the control stand, relative land expectation values remained unchanged for the random length mill processing protocol compared to an approximate 22% increase for the stud mill processing protocol.

Although specific to these selected crop plans and conditional on the economic assumptions employed, these results suggest that relative to unthinned density-stressed natural black spruce stands, thinning may be a viable treatment option. Particularly, in regards to accelerating stand operability status (as shown by the PCT treatment), capturing expected mortality within the merchantable-sized tree classes, increasing the proportion larger-sized trees and the resultant number of sawlogs produced, and improving of stand stability (as shown by the dual PCT and CT treatments).

3.2.2. Plantations – IE + CT with incorporation of genetic worth effects

The standard planting density for boreal species in the central portion of the Canadian Boreal Forest Region is approximately 2500 seedlings/ha (i.e., 2 × 2 m square spacing). As discussed above, reducing planting densities below this threshold is increasing being debated due to economic constraints. However, given the density-dependent nature of the relationship between site occupancy and stand level productivity, lower planting densities may result in reduced productivity and declines in economic value. Although less dense stands may incur lower mortality losses and produce trees of larger mean size, the quality of commercially-relevant fibre attributes could decline due to the increased production of juvenile wood and larger knot sizes. In order to evaluate the consequences of reducing initial espacement levels, stand development trajectories and associated 50 year rotational ($T = 50$) outcomes for 3 plantations established employing improved stock on good quality sites ($S_I = 18$) were compared. Specifically, the 2500 seedlings/ha planting standard (Regime 1) was contrasted with a (1) plantation also established at a density of 2500 seedlings/ha but with a CT treatment at age 30 yr (i.e., removing 805 stems/ha employing a thinning-from-below

sites ($S_I = 18$). Specifically: Regime 1 – establishment density of 5000 stems/ha with no thinning; Regime 2 – establishment density of 5000 stems/ha with a precommercial thinning (PCT) of 2500 stems/ha at 10 yr; and Regime 3 – establishment density of 5000 stems/ha with a PCT of 2500 stems/ha at 10 yr and a commercial thinning of 1000 stems/ha at 45 yr. (b) SDMD graphic for the managed black spruce stand-type. Note the following principal components of the SDMD: (1) isolines for mean dominant height (Hd; horizontal-like lines ranging from a minimum of 4 m at the bottom of the graphic to a maximum of 20 m at the top of the graphic separated by 2 m increments), quadratic mean diameter (Dq; horizontal-line lines ranging from a minimum of 4 cm at the bottom of the graphic to a maximum of 26 cm at the top of the graphic separated by 2 cm increments), mean live crown ratio (Lr; 35, 40, 50,…, 80% (diagonal lines)), relative density index (Pr; 0.1–1.0 by 0.1 intervals (diagonal lines)); (2) crown closure line (lower diagonal solid line) and self-thinning rule at a Pr = 1.0 (upper diagonal solid line); (3) lower and upper Pr diagonal lines delineating the optimal density management window (Dm; $0.32 \leq Pr \leq 0.45$); and (4) expected 50 year size–density trajectories with 1 year intervals denoted by a vertical line for each of the 3 user-specified density management regimes for plantations situated on good quality sites ($S_I = 18$). Specifically: Regime 1 – initial planting density of 2500 stems/ha with no thinning; Regime 2 – establishment density of 2500 stems/ha with a commercial thinning of 805 stems/ha at 30 yr; and Regime 3 – establishment density of 1500 stems/ha with no thinning.

Table 5
Rotational yield estimates for density-manipulated black spruce stand-types situated on good quality sites: (1) high density natural stands subjected to precommercial thinning (PCT) and commercial thinning (CT) treatments; and (2) plantations established at varying initial espacement (IE) levels with one subjected to a commercial thinning treatment. Values in parenthesis denote yields derived from the thinning treatments (ordered by time of treatment).

Attribute[a] ($t = T$)	Stand-type[b] and treatment[c]					
	$PIm_{(N)}$			$PIm_{(M)}$		
	Regime 1: Control	Regime 2: PCT	Regime 3: PCT + CT	Regime 1: Control	Regime 2: CT	Regime 3: Low IS
$A_{(t)}$ (yr)	65	65	65	50	50	50
$\hat{H}_{d(t)}$ (m)	19.9	19.9	19.9	17.2	17.2	17.2
$\hat{D}_{q(t)}$ (cm)	17.5	19.2	22.4	20.6	20.8	20.8
$\hat{G}_{(t)}$ (m^2/ha)	41	35	27	51	41	41
$\hat{\bar{v}}_{(t)}$ (dm^3)	178	222	324	219	225	225
$\hat{V}_{t(t)}$ (m^3/ha)	300	270 (3)	261 (3,35)	338	327 (53)	272
$\hat{V}_{m(t)}$ (m^3/ha)	285	256 (−)	245 (−,31)	319	305 (48)	256
$\hat{N}_{(t)}$ (stems/ha)	1687	1215	695	1541	1215	1205
$\hat{P}_{r(t)}$ (%/100)	0.96	0.80	0.58	1.0	0.8	0.8
$\hat{N}_{lp(t)}$ (logs/ha)	3515	2262 (−)	1314 (−,271)	2458	2315 (523)	1778
$\hat{N}_{ls(t)}$ (logs/ha)	608	873 (−)	790 (−,0)	1041	862 (0)	858
$\hat{V}_{r(t)}$ (m^3/ha)	59	38 (−)	31 (−,9)	43	48 (10)	38
$\hat{M}_{p_{(t)}}$ (t/ha)	20	17 (−)	17 (−,3)	20	21 (3)	17
$\hat{M}_{s_{(t)}}$ (t/ha)	194	164 (−)	149 (−,26)	187	178 (25)	152
$\hat{M}_{b_{(t)}}$ (t/ha)	6	6 (−)	7 (−,2)	9	11 (3)	8
$\hat{M}_{f_{(t)}}$ (t/ha)	10	11 (−)	16 (−,4)	14	20 (5)	15
$\hat{M}_{t_{(t)}}$ (t/ha)	230	197 (−)	189 (−,34)	230	230 (37)	192
$\hat{C}_{p_{(t)}}$ (t/ha)	10	9 (−)	9 (−,2)	10	10 (2)	9
$\hat{C}_{s_{(t)}}$ (t/ha)	97	82 (−)	73 (−,13)	94	89 (13)	76
$\hat{C}_{b_{(t)}}$ (t/ha)	3	3 (−)	4 (−,1)	5	6 (2)	4
$\hat{C}_{f_{(t)}}$ (t/ha)	5	6 (−)	8 (−,2)	7	10 (3)	7
$\hat{C}_{t_{(t)}}$ (t/ha)	115	99 (−)	95 (−,17)	115	115 (18)	96
$\hat{V}_{c(s)_{(t)}}$ (m^3/ha)	132	109 (−)	100 (−,21)	138	140 (26)	113
$\hat{V}_{l(s)_{(t)}}$ (m^3/ha)	150	134 (−)	123 (−,11)	150	138 (13)	124
$\hat{V}_{c(r)_{(t)}}$ (m^3/ha)	113	93 (−)	89 (−,19)	118	122 (24)	97
$\hat{V}_{l(r)_{(t)}}$ (m^3/ha)	167	149 (−)	136 (−,13)	166	154 (16)	138
$\hat{P}_{c(s)_{(t)}}$ ($K/ha)	7	6 (−)	5 (−,1)	8	9 (2)	6
$\hat{P}_{l(s)_{(t)}}$ ($K/ha)	30	28 (−)	27 (−,2)	31	29 (2)	24
$\hat{P}_{t(s)_{(t)}}$ ($K/ha)	37	34 (−)	32 (−,3)	39	37 (4)	30
$\hat{P}_{c(r)_{(t)}}$ ($K/ha)	7	5 (−)	4 (−,1)	6	6 (1)	4
$\hat{P}_{l(r)_{(t)}}$ ($K/ha)	41	37 (−)	36 (−,4)	44	42 (4)	34
$\hat{P}_{t(r)_{(t)}}$ ($K/ha)	47	42 (−)	40 (−,5)	50	47 (5)	37
$L_{E(s)}$ ($K/ha)	3.5	3.9	4.2	5.4	5.4	4.7
$L_{E(r)}$ ($K/ha)	6.7	6.6	6.7	10.0	9.9	8.1

Notes: (1) in cases where the diameter distribution could not be recovered, incalculable size-dependent values are denoted by a dash; and (2) volumetric, log number, biomass, carbon, lumber and chip volume, and product values (undiscounted) per unit area values include thinning yields.
[a] As defined in Table B1 with the exception of $L_{E(s)}$ and $L_{E(r)}$ which are the land expectation values for stud and randomization length sawmill processing protocols, respectively, as given in Table 3.
[b] As defined in Table 1.
[c] As defined in Table 4.

protocol; Regime 2), and (2) plantation established at a substantially lower density of 1500 seedlings/ha but with no subsequent thinning treatments (Regime 3). Note, the number of trees removed during the CT treatment was set so that the post-treatment density and the density of plantation established at the lowest IE treatment would be equivalent at age 31 yr. This allows one not only to compare the effect of the lower IE treatment but also demonstrate the response delay concept as introduced in this study.

Specifically, for these simulations, density-independent mortality throughout the rotation was assumed to be inconsequential and hence the operational adjustment factor was set to zero. A fixed cost of $0.3K/ha was used to cover regeneration assessment and site preparation costs at the time of plantation establishment. Variable costs were regime-specific in order to reflect harvesting, transportation and manufacturing cost reductions associated with increased piece size, spatial pattern uniformity and reduced size variability, arising from the thinning treatments. Similarly, product value degrade factors differed given the expected development of larger branch diameters and by inference larger knot sizes with increasing spacing. The increasing use of genetically improved stock in reforestation programs dictated that the simulations be based on a genetic worth setting of 15% at a selection age of 10 yr. A complete list of input parameters are given in Table 4.

The temporal mean volume–density trajectories for each planting regime within the context of the traditional SDMD mean volume – density graphic are presented in Fig. 2(b). As inferred by the intersection of the size–density trajectories with the crown closure isoline, initial crown closure status was attained at ages 13 for Regimes 1 and 2, and 18 for Regime 3. As shown in Fig. 2(b), the size–density trajectory at the time of the CT treatment (age 30; Regime 2) was (1) just slightly above the 12 m dominant height (Hd) isoline, (2) slightly below the 14 cm quadratic mean diameter (Dq) isoline, and (3) slightly above the 0.7 relative density (Pr) and

Table 6
Stand-level performance indices for density-manipulated black spruce stand-types situated on good quality sites: (1) high density natural stands subjected to precommercial thinning (PCT) and commercial thinning (CT) treatments; and (2) plantations established at varying initial espacement (IE) levels with one subjected to a commercial thinning treatment.

Index[a]	Stand-type[b] and treatment[c]					
	$Plm_{(N)}$			$Plm_{(M)}$		
	Regime 1: Control	Regime 2: PCT	Regime 3: PCT + CT	Regime 1: Control	Regime 2: CT	Regime 3: Low IS
R_{MAI} (m^3/ha/yr)	4.4	3.9	3.8	6.4	6.1	5.1
R_{BMI} (t/ha/yr)	3.5	3.0	2.9	4.6	4.6	3.8
R_{CAI} (t/ha/yr)	1.8	1.5	1.5	2.3	2.3	1.9
R_{SL} (%)	15	28	38	30	27	33
$R_{LV(s)}$ (%)	53	55	55	52	50	52
$R_{LV(r)}$ (%)	60	62	61	59	56	59
$E_{(s)}$ (%)	–	11	22	–	Nil	−1
$E_{(r)}$ (%)	–	−2	Nil	–	−13	−19
S_O (%)	10	14	19	12	12	20
S_S (m/m)	103	96	90	72	71	72
$\overline{W}_D$ (g/cm^3)	0.48	0.49	0.49	0.48	0.49	0.49
$\overline{B}_D$ (cm)	2.65	2.69	2.71	2.64	2.67	2.69
O_T (yr)	53	46	46	35	36	42

[a] As defined in the Table 3.
[b] As defined in Table 1.
[c] As defined in Table 4.

the 40% live crown ratio (Lr) isolines. The corresponding interpolated mean volume, density and basal area values were 72.8 dm^3, 2254 stems/ha and 33.8 m^2/ha, respectively. Accordingly, the stand is a candidate for CT based on the guidelines given in McKinnon et al. (2006): i.e., history of density regulation (i.e., planted), pretreatment basal area >25 m^2/ha, a mean live crown ratio >35%, and imminent density-dependent mortality within the merchantable size classes\(e.g., predicted to occur at age 31 yr).

The actual CT treatment resulted in reducing the basal area by 33% (11.1 m^2/ha) and yielded an interim merchantable volume harvest of 47.8 m^3/ha. At rotation, all 3 plantations had achieved a mean dominant height of 17.2 m, quadratic mean diameter slightly greater than 20 cm, live crown ratio between 31 and 34%, and high level of site occupancy (relative densities between 0.80 and 1.0). The resultant rotational and thinning yield estimates are listed in Table 5 whereas Table 6 summarizes the resultant stand-level performance indices. Although self-thinning occurred within all 3 regimes indicating full occupancy had been achieved, the rate of density-dependent mortality increased with increasing planting density. Based on the stand-level performance indices, productivity increased with increasing planting density: merchantable volume production for the stand with a planting density of 2500 seedlings/ha without the CT treatment was 5% greater than the same stand with the CT treatment, and 20% greater than the stand planted at lowest density of 1500 seedlings/ha. Biomass and carbon productivity for the stand with the lower planting density was 17% less than that of the other 2 regimes. Although Regime 3 produced the highest proportion of sawlogs over the rotation, the differences were less than 5% among all the regimes. Similarly, the lumber volume produced at rotation was approximately equivalent across the 3 regimes irrespective of the sawmill processing protocol utilized. The net revenue derived from the CT treatment nor the benefits arising from the lower planting costs associated with planting 1500 stems/ha versus 2500 stems/ha standard, did not translate into significant gains in economic efficiency. In fact, the stand established at the lower planting density, exhibited a 10% decline in economic efficiency, relative to the planting standard (Regime 1). This difference can be attributed to the greater quantity of products recovered (chip and lumber volumes) and the associated increases in revenue: e.g., approximately 21% and 25% increase in the volume and value of products produced, respectively, for the plantation established at 2500 stems/ha relative to plantation established at 1500 stems/ha. Although Regime 3 had the longest duration of optimal site occupancy, differences among the regimes in terms of stand stability, wood density and branch diameter were largely inconsequential. In terms of operability status, the time to harvestable status was extended by 7 years when planting at the lowest density (1500 stems/ha).

Similar to the example provided for the natural stand-type, these results are specific to this crop plan and the associated economic assumptions employed. Nevertheless, the comparisons did suggest that relative to the standard practice of planting 2500 stems/ha (control regime), planting at densities substantially below this threshold may result in declines in merchantable volume, biomass and carbon yields, quantity, quality and value of recoverable products, economic efficiency, and operability status.

Apart from the operational context of this example, the comparison of two regimes with convergent size–density trajectories immediately following thinning, provides an opportunity to illustrate the response delay concept. Comparing Regime 2 which was planted at the higher density but with a CT treatment at age 30 with Regime 3 that was planted at a lower density and not thinned, in terms of their live crown ratios immediately after thinning, revealed that the length of the response delay lasted until age 33. The live crown ratio at age 30 within the lower density stand was 47% versus 42% within the higher density stand. At ages 31, 32 and 33 the live crown ratios (%) were 43.3, 44.4 and 43.3 within the CT stand versus 45.8, 44.5 and 43.4 within the lower density stand, respectively. Thus in this example, it took 3 years for the trees within the CT stand to rebuild their crowns and fully occupy their newly allocated growing space.

3.2.3. Summary

As exemplified through these crop planning simulations, the modelling advancements introduced in this study will enable users to: (1) produce mathematical compatible yield estimates; (2) account for intrinsic density-independent mortality factors that were expected to affect survival rates during the rotation; (3) allow for a temporal period for trees within recently thinned stands to readjust morphologically through the application of the response delay algorithm; (4) incorporate the projected increase in growth rates arising the use of genetic enhanced stock; and (5) tailor their simulations and output to their unique circumstances by modifying the merchantability thresholds, product degrade factors, and cost profiles. Furthermore, apart from the decision-support role that the SSDMM provides, these examples also demonstrate that it can be utilized as a variable-density growth, yield and wood quality distribution model. For example, although not shown, annual estimates for all yield attributes listed in Table 5 are also provided by the software at both the diameter-class and stand levels.

The model's output provides the prerequisite information to compare alternative crop plans and subsequently select the optimal regime for a given set of management objectives and constraints. Although the potential utility of the enhanced model and the associated algorithmic analogue in density management decision-making is only partially demonstrated via these operational examples, it is evident that the model can play a consequential role as management objectives shift towards the production of high value end-products, bio-energy feed stocks, and carbon credits.

3.3. *Evolution, significance and overall utility of the new modular-based SSDMM*

The new modular-based SSDMM represents a plateau in terms of the evolutionary developmental pathway of SDMD-based decision-support models. The historical lineage of model development can be conceptualized as consisting of a three-stage incremental process in which the model architecture has steadily increased in complexity over a period of approximately 50 years. The first stage involved the development of static SDMDs for commercially important species (Japanese red pine (*Pinus densiflora* Siebold and Zucc.), Sugi (*Cryptomeria japonica* D. Don.), Hinoki cypress (*Chamaecyparis obtusa* Siebold and Zucc.) and Japanese larch (*Larix leptolepis* (Siebold and Zucc.)) in Japan during the 1960–1975 period (Ando, 1962, 1968; Aiba, 1975a,b)). These SDMDs were based on a number of quantitative relationships derived from plant population biology and ecological plant experimentation which included the reciprocal equations of the competition–density and yield–density effect (Kira et al., 1953; Shinozaki and Kira, 1956), self-thinning rule (Yoda et al., 1963), relative density index functions (Ando, 1962), and size–density functions for quadratic mean diameter, dominant height, mean volume, and mean live crown ratio. Later in western North America, Drew and Flewelling (1979) realized the potential of these decision-support aids in industrial forest management and subsequently developed a static SDMD for use in managing coastal Douglas Fir *(Pseudotsuga menziesii* (Mirb.) Franco) plantations. Of significance was (1) the introduction of the zone of imminent-competition mortality that was used to delineate the size–density space in which density-dependent mortality was likely to occur, and (2) quantitatively linking key stages of stand development as predicted by the SDMD to site occupancy zones according to Langsaeter's forest production theory. These incremental advancements enabled them to derive a density management framework for coastal Douglas Fir plantations. The framework consisted of four basic tenets: (1) stands below the crown closure line are not fully occupying the site and hence densities could be increased without decreasing mean tree growth; (2) stands at or slightly below the crown closure line will result in the attainment of maximum mean tree sizes but will conversely cause substantial reductions in per unit area merchantable yields; (3) stands between the lower bound of the zone of imminent competition-mortality (relative density index of 0.55) and a relative density index of 0.40 will result in an increase in per unit area stand growth but will yield considerably smaller sized trees than stands managed at lower densities; and (4) stands should not be allowed to enter the zone of imminent competition-mortality until just before rotation age in order to avoid the occurrence of self-thinning within the merchantable size classes.

The second stage of development consisted of the introduction of the dynamic SDMD model variant by Newton and Weetman (1993, 1994). These models incorporated a site-dependent size–density trajectory sub-model in order to explicitly account for mortality losses arising from self-thinning. To date, numerous SDMDs have been developed for commercially important species throughout the boreal, temperate and tropical forest regions. For example, SDMDs have been developed for (1) Japanese red pine in South Korea (Kim et al., 1987), (2) Monterey pine (*Pinus radiata* D. Don.) in New Zealand (Drew and Flewelling, 1977) and Spain (Castedo-Dorado et al., 2009), (3) Douglas fir in Spain (López-Sánchez and Rodríguez-Soallerio, 2009), (4) lodgepole pine (*Pinus contorta* var. latifolia Engelm.) in the western USA (McCarter and Long, 1986; Smith and Long, 1987) and the Pacific Northwest (Flewelling and Drew, 1985), (5) slash pine (*Pinus elliottii* Engelm. var. elliottii) and loblolly pine (*Pinus taeda* L.) in the southern USA (Dean and Jokela (1992) and Dean and Baldwin (1993), respectively), (6) teak (*Tectona grandis* L.) in India (Kumar et al., 1995), (7) pedunculate oak (*Quercus robur* L.) in Spain (Anta and González, 2005), (8) Scots pine (*Pinus sylvestris* L.) and Austrian black pine (*Pinus nigra* Arn.) in Bulgaria (Stankova and Shibuya, 2007), (9) Merkus pine (*Pinus merkusii* Jungh. et de Vriese) plantations in Indonesia (Heriansyah et al., 2009), and (10) *Eucalyptus globulus* and *Eucalyptus nitens* short rotation plantations in southwestern Europe (Pérez-Cruzado et al., 2011). For comprehensive reviews of the conceptual basis and description of the common functional and empirical quantitative relationships utilized in the development of static and dynamic SDMDs, refer to Drew and Flewelling (1977, 1979), Jack and Long (1996) and Newton (1997).

The third stage of development was the introduction of structural SDMD-based models by Newton et al. (2004, 2005). These models were subsequently enhanced resulting in the modular-based structural model variants (Newton, 2009; this study). The first structural models were developed by expanding the dynamic SDMD modelling architecture through the incorporation of a Weibull-based parameter prediction equation system. The system enabled the model to recover a stand's diameter distribution at any point in its development. This provided the quantitative foundation for predicting size-dependent attributes at the diameter-class level. In addition to the models developed for natural and managed black spruce stands (Newton et al. (2004) and (2005), respectively) in the Canadian Boreal Forest Region, a structural model was also subsequently developed for Austrian black pine plantations for use in eastern Europe (sensu Stankova and Zlatanov (2010)). Expanding the structural model further through the integration of additional prediction modules for estimating tree height, biomass, carbon, end-product volumes and value, and fibre attributes, gave rise to the modular-based SSDMM (Newton, 2009). To date, this model has been calibrated for natural and managed jack pine stands, and natural black spruce and jack pine mixed stands, for use within the central portion of the Canadian Boreal Forest Region (Newton (2009) and (2012), respectively).

The most recent variant of the modular-based SSDMM as presented in this study, overcomes the previous shortcomings of SDMD-based models. Specifically, the provision of analytical solutions for ensuring mathematical compatibility among yield estimates, accounting for intrinsic density-independent mortality factors, response delay following thinning and genetic worth effects, and providing enhanced flexibility in terms of allowing end-users to change merchantability standards, specify product degrade factors, and adjust cost profiles, collectively comprise a consequential contribution to this modelling area. Furthermore, the decision-support algorithm allows resource managers to more realistically estimate the consequences of density management decisions across a wide array of productivity, end-product, economic and ecological metrics. This enhanced model retains the advantageous elements of the previous static, dynamic, and structural model forms, particularly in regards, to maintaining their ecological foundation through the continued employment of functional and empirical relationships derived from quantitative ecology, plant population biology and forest production theory.

The introduction of the analytical solutions to overcome the previous shortcomings of SDMD-based models represents an important step towards their deployment in operational forest management. As exemplified via the use of operational relevant crop plans, the model enabled the determination of the most applicable regime for a given set of management objectives. Based on the scenarios considered, thinning within natural density-stressed black spruce stands was found to be viable treatment option for accelerating stand operability and avoiding merchantable volume losses at the later stages of stand development. Similarly, substantially lowering planting densities below the 2500 stems/ha threshold would result in declines in productivity, economic efficiency and stand operability status.

The model presented here represents an important contribution to the development of modular-based SSDMMs for boreal conifers. More generally, the model increments the growing portfolio of comprehensive density management simulators that are able to address both volumetric and end-product outcomes simultaneously. These simulators include those developed by Di Lucca (1999; SYLVER) for Douglas fir and other coniferous species in western Canada, by Pretzsch et al. (2002; SILVA) for Norway spruce (*Pinus abies* (L.) Karst.) and other conifers and deciduous species in central Europe, by Hynynen et al. (2005; MOTTI) for Scots pine (*Pinus sylvestris* L.) and other conifers in Finland, and by Kotze and Malan (2007; FORSAT) for *Pinus patula* (Schiede ex Schlect. & Cham.) in South Africa. As forest management migrates from its traditional volumetric yield maximization focus to one based on the product diversification including the provision of a wider array of ecosystem services (Emmett, 2006; Raudsepp-Hearne et al., 2010), development of such comprehensive models will become a basic necessity for optimally managing our forest resources.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.envsoft.2012.02.019.

References

Aiba, Y., 1975a. Effects of cultural system on the stand growth of Sugi-plantations (*Cryptomeria japonica*). II. A tendency of the constant in final stem volume yield of stands under actual stand density (in Japanese; English abstract). Journal of the Japanese Forestry Society (Tokyo, Japan) 57, 39–44.

Aiba, Y., 1975b. Effects of cultural system on the stand growth of Sugi-plantations (*Cryptomeria japonica*). III. Estimate of the stem volume yield under actual stand density (H-D-p-V diagram) (in Japanese; English abstract). Journal of the Japanese Forestry Society (Tokyo, Japan) 57, 67–73.

Ando, T., 1962. Growth analysis on the natural stands of Japanese red pine (*Pinus densiflora* Sieb. et. Zucc.). II. Analysis of stand density and growth (in Japanese; English summary). Government of Japan, Bulletin of the Government Forest Experiment Station (Tokyo, Japan), No. 147. 77 pp.

Ando, T., 1968. Ecological studies on the stand density control in even-aged pure stands (in Japanese; English summary). Government of Japan, Bulletin of the Government Forest Experiment Station (Tokyo, Japan). No. 210.

Anta, M.B., González, J.G.Á., 2005. Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. Forestry 78, 209–216.

Bailey, R.L., Dell, T.R., 1973. Quantifying diameter distributions with the Weibull function. Forest Science 19, 97–104.

Carmean, W.H., Hazenberg, G., Deschamps, K.C., 2006. Polymorphic site index curves for black spruce and trembling aspen in northwest Ontario. Forestry Chronicle 82, 231–242.

Castedo-Dorado, F., Crecente-Campo, F., Álvarez-Álvarez, P., Barrio, A.M., 2009. Development of a stand density management diagram for radiate pine stands including assessment of stand stability. Forestry 82, 1–16.

Chertov, O., Bhatti, J.S., Komarov, A., Mikhailov, A., Bykhovets, S., 2009. Influence of climate change, fire and harvest on the carbon dynamics of black spruce in Central Canada. Forest Ecology and Management 257, 941–950.

Dean, T.J., Baldwin Jr., V.C., 1993. Using a Density Management Diagram to Develop Thinning Schedules for Loblolly Pine Plantations. Government of the United States of America, Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, Louisiana. Research Paper SO-275. 12 pp.

Dean, T.J., Jokela, E.J., 1992. A density-management diagram for slash pine plantations in the lower coastal plain. Southern Journal of Applied Forestry 16, 178–185.

Di Lucca, C.M., 1999. TASS/SYLVER/TIPSY: systems for predicting the impact of silvicultural practices on yield, lumber value, economic return and other benefits. In: Barnsey, C. (Ed.), Stand Density Management Planning and Implementation Conference. Edmonton, Alberta. Clear Lake Publishing Ltd., Edmonton, Alberta, Canada, pp. 7–16.

Drew, T.J., Flewelling, J.W., 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. Forest Science 23, 517–534.

Drew, T.J., Flewelling, J.W., 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science 25, 518–532.

Emmett, B., 2006. Increasing the value of our forest. Forestry Chronicle 82, 3–4.

Flewelling, J.W., Drew, T.J., 1985. A stand density management diagram for lodgepole pine. In: Baumgarter, D.M., Krebill, R.G., Arnott, J.T., Weetman, G.F. (Eds.), Lodgepole Pine: The Species and Its Management. Washington State University, Pullman, Washington, USA, pp. 239–244.

Forintek Canada Corp., 1994. Optitek: User's Guide. Forintek Canada Corp., Sainte-Foy, QC, Canada, 185 pp.

Heriansyah, I., Bustomi, S., Kanazawa, Y., 2009. Density effects and stand density management diagram for merkus pine in the humid tropics of Java, Indonesia. Journal of Forestry Research 5, 91–113.

Honer, T.G., Ker, M.F., Alemdag, I.S., 1983. Metric Timber Tables for the Commercial Tree Species of Central and Eastern Canada. Government of Canada, Department of Agriculture, Canadian Forestry Service, Maritimes Forest Research Centre, Fredericton, New Brunswick. Information Report M-X-140.

Hyink, D.M., Moser, J.W., 1983. A generalized framework for projecting forest yield and stand structure using diameter distributions. Forest Science 29, 85–95.

Hynynen, J., Ahtikoski, A., Siitonen, J., Sievanen, R., Liski, J., 2005. Applying the MOTTI simulator to analyse the effects of alternative management schedules on timber and non-timber production. Forest Ecology and Management 207, 5–18.

Jack, S.B., Long, J.N., 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. Forest Ecology and Management 86, 205–220.

Jolliffe, P.A., Eaton, G.W., Potdar, M.V., 1988. Plant growth analysis: allometry, growth and interference in Orchardgrass and Timothy. Annals of Botany 62, 31–42.

Kang, K.-Y., Zhang, S.Y., Mansfield, S.D., 2004. The effects of initial spacing on wood density, fibre and pulp properties in jack pine (*Pinus banksiana* Lamb.). Holzforschung 58, 455–463.

Kim, D.K., Kim, J.W., Park, S.K., Oh, M.Y., Yoo, J.H., 1987. Growth Analysis of Natural Pure Young Stand of Red Pine in Korea and Study on the Determination of Reasonable Density (in Korean; English Abstract), vol. 34. Government of Korea, Research Reports of the Forestry Institute (Seoul, Korea), 32–40 pp.

Kira, T., Ogawa, H., Sakazaki, N., 1953. Intraspecific competition among higher plants. I. Competition-yield-density interrelationship in regularly dispersed populations. Journal of the Institute of Polytechnics (Osaka City University, Japan), Series D 4, 1–16.

Kotze, H., Malan, F., 2007. Further progress in the development of prediction models for growth and wood quality of plantation-grown *Pinus patula* sawtimber in South Africa. In: Dykstra, D.P., Monserud, R.A. (Eds.), Forest Growth and Timber Quality: Crown Models and Simulation Methods for Sustainable Forest Management. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, USA, General Technical Report, PNW-GTR-791. pp. 113–123.

Kumar, B.M., Long, J.N., Kumar, P., 1995. A density management diagram for teak plantations of Kerala in peninsular India. Forest Ecology and Management 74, 125–131.

Liu, C., Zhang, S.Y., 2005. Models for predicting product recovery using selected tree characteristics of black spruce. Canadian Journal of Forest Research 35, 930–937.

Liu, C., Zhang, S.Y., Ruel, J.-C., Cloutier, A., Rycabel, T., 2007. Development of lumber volume recovery correction models for stem deformations of natural black spruce trees. Scandinavian Journal of Forest Research 22, 415–421.

López-Sánchez, C., Rodríguez-Soalleiro, R., 2009. A density management diagram including stand stability and crown fire risk for *Pseudotsuga menziesii* (Mirb.) Franco in Spain. Mountain Research and Development 29, 169–176.

Mäkinen, H., Isomäki, A., 2004a. Thinning intensity and growth of Scots pine stands in Finland. Forest Ecology and Management 201, 311–325.

Mäkinen, H., Isomäki, A., 2004b. Thinning intensity and growth of Norway spruce stands in Finland. Forestry 77, 349–364.

McCarter, J.B., Long, J.N., 1986. A lodgepole pine density management diagram. Western Journal of Applied Forestry 1, 6–11.

McClain, K.M., Morris, D.M., Hills, S.C., Buse, L.J., 1994. The effects of initial spacing on growth and crown development for planted northern conifers: 37-year results. Forestry Chronicle 70, 174–182.

McIntosh, B.S., Ascough II, J.C., Twerym, M., Chew, J., Elmahdi, A., Haase, D., Harou, J.J., Hepting, D., Cuddy, S., Jakeman, A.J., Chen, S., Kassahun, A., Lautenback, S., Matthews, K., Merritt, W., Quinn, N.W.T., Rodriguez-Roda, I., Sieber, S., Stavenga, M., Sulis, A., Ticehurst, J., Volk, M., Wrobel, M., van Delden, H., El-Sawah, S., Rizzoli, A., Voinov, A., 2011. Environmental decision-support systems (EDSS) development – Challenges and best practices. Environmental Modelling and Software 26, 1389–1402.

McKinnon, L.M., Kayahara, G.J., White, R.G., 2006. Biological Framework for Commercial Thinning Evenaged Single-Species Stands of Jack Pine, White Spruce, and Black Spruce in Ontario. http://www.forestresearch.ca/Projects/fibre/FrameworkCTofPjSwSb.pdf.

Newton, P.F., 1997. Stand density management diagrams: review of their development and utility in stand-level management planning. Forest Ecology and Management 98, 251–265.

Newton, P.F., 2003. Yield prediction errors of a stand density management program for black spruce and consequences for model improvement. Canadian Journal of Forest Research 33, 490–499.

Newton, P.F., 2006a. Asymptotic size–density relationships within self-thinning black spruce and jack pine stand-types: parameter estimation and model reformulations. Forest Ecology and Management 226, 49–59.

Newton, P.F., 2006b. Forest production model for upland black spruce stands—optimal site occupancy levels for maximizing net production. Ecological Modelling 190, 190–204.

Newton, P.F., 2009. Development of an integrated decision-support model for density management within jack pine stand-types. Ecological Modelling 220, 3301–3324.

Newton, P.F., 2012. Development and utility of an ecological-based decision-support system for managing mixed coniferous forest stands for multiple objectives. In: Zhang, W.-J. (Ed.), Ecological Modeling (Chapter 7). Environmental Science, Engineering and Technology Book Series. Nova Scientific Publishers, pp. 100–160.

Newton, P.F., Amponsah, I.G., 2005. Evaluation of Weibull-based parameter prediction equation systems for black spruce and jack pine stand types within the context of developing structural stand density management diagrams. Canadian Journal of Forest Research 35, 2996–3010.

Newton, P.F., Amponsah, I.G., 2007. Comparative evaluation of five height–diameter models developed for black spruce and jack pine stand-types in terms of goodness-of-fit, lack-of-fit and predictive ability. Forest Ecology and Management 247, 149–166.

Newton, P.F., Jolliffe, P.A., 2003. Aboveground dry matter partitioning responses of black spruce to directional-specific indices of local competition. Canadian Journal of Forest Research 33, 1832–1845.

Newton, P.F., Weetman, G.F., 1993. Stand density management diagrams and their utility in black spruce management. Forestry Chronicle 69, 421–430.

Newton, P.F., Weetman, G.F., 1994. Stand density management diagram for managed black spruce stands. Forestry Chronicle 70, 65–74.

Newton, P.F., Lei, Y., Zhang, S.Y., 2004. A parameter recovery model for estimating black spruce diameter distributions within the context of a stand density management diagram. Forestry Chronicle 80, 349–358.

Newton, P.F., Lei, Y., Zhang, S.Y., 2005. Stand-level diameter distribution yield model for black spruce plantations. Forest Ecology and Management 209, 181–192.

NFD (National Forestry Database), 2009. Silviculture – Jurisdictional Tables. http://nfdp.ccfm.org/silviculture/jurisdictional_e.php.

Nussbaum, A., 1998. Operational Adjustment Factors for Use in TIPSY. Ministry of Forests, Research Branch, Government of British Columbia. http://www.for.gov.bc.ca/hre/gymodels/tipsy/oafsv8.htm.

Patriquin, M.N., Parkins, J.R., Stedman, R.C., 2007. Socio-economic status of boreal communities in Canada. Forestry 80, 279–291.

Perez-Cruzado, C., Merino, A., Rodriguez-Soalleiro, R., 2011. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass and Bioenergy 25, 2839–2851.

Pretzsch, H., Biber, P., Dursky, J., 2002. The single tree-based stand simulator SILVA: construction, application and evaluation. Forest Ecology and Management 162, 3–21.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. PNAS 107, 5242–5247.

Rowe, J.S., 1972. Forest Regions of Canada. Government of Canada, Department of Environment, Canadian Forestry Service, Ottawa, Ontario. Publication No. 1300.

Sharma, M., Parton, J., 2009. Modeling stand density effects on taper for jack pine and black spruce plantations using dimensional analysis. Forest Science 55, 268–282.

Shinozaki, K., Kira, T., 1956. Intraspecific competition among higher plants. VII. Logistic theory of the C-D effect. Journal of the Institute of Polytechnics (Osaka City University, Japan), Series D 12, 69–82.

Smith, F.W., Long, J.N., 1987. Elk hiding and thermal cover guidelines in the context of lodgepole pine stand density. Western Journal of Applied Forestry 2, 6–10.

Stankova, T.V., Shibuya, M., 2007. Stand density control diagrams for Scots pine and Austrian black pine plantations in Bulgaria. New Forests 34, 123–141.

Stankova, T.V., Zlatanov, T.M., 2010. Modeling diameter distribution of Austrian black pine (*Pinus nigra* Arn.) plantations: a comparison of the Weibull frequency distribution function and percentile-based projection methods. European Journal of Forest Research 129, 1169–1179.

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., Ransome, D.B., 2010. Long-term responses of mammalian herbivores to stand thinning and fertilization in young lodgepole pine (*Pinus contorta* var. latifolia) forest. Canadian Journal of Forest Research 40, 2302–2312.

Tong, Q.J., Zhang, S.Y., 2009. Development of lumber recovery correction models for plantation-grown *Pinus banksiana* trees. Scandinavian Journal of Forest Research 24, 417–424.

Tong, Q.J., Zhang, S.Y., Thompson, M., 2005. Evaluation of growth response, stand value and financial return for pre-commercially thinned jack pine stands in Northwestern Ontario. Forest Ecology and Management 209, 225–235.

Van Damme, L., Parker, W.H., 1987. Selection of *Picea mariana* for growing space efficiency. Canadian Journal of Forest Research 17, 421–427.

Watt, W.R., Parton, J., Chen, H., Lucking, G., Houle, N., Levesque, S., Luke, A., 2001. Standard Forest Units for Northeastern Ontario Boreal Forests. Ontario Ministry of Natural Resources, Northeast Science and Technology Unit. Information Report (Draft dated 14/02/01).

Weibull, W., 1951. A statistical distribution function of wide applicability. Journal of Applied Mechanics 18, 293–297.

Xie, G.Y., Yanchuk, A.D., 2003. Breeding values of parental trees, genetic worth of seed orchard seedlots, and yields of improved stocks in British Columbia. Western Journal of Applied Forestry 18, 88–100.

Yoda, K., Kira, T., Ogawa, H., Hozumi, K., 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions. Journal of Biology (Osaka City University, Japan) 14, 107–129.

Zhang, S.Y., Chauret, G., 2001. Impact on Initial Spacing on Tree and Wood Characteristics, Product Quality and Value Recovery in Black Spruce (*Picea mariana*). Canadian Forest Service Report No. 35. Forintek Canada Corp., Sainte-Foy, Quebec, 47 pp.

Zhang, S.Y., Liu, C., Jiang, Z.H., 2006. Modeling product recovery in relation to selected tree characteristics in black spruce using an optimized random sawing simulator. Forest Products Journal 56, 93–99.