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A Decision-Support Model for Regulating Black Spruce Site Occupancy Through Density Management

P. F. Newton

*Canadian Wood Fibre Centre, Canadian Forest Service, Natural Resources Canada
Canada*

1. Introduction

Regulating site occupancy through stand density management has been a cornerstone of silvicultural practice since it was first introduced in forestry by Reventlow in 1879 (Pretzsch, 2009). Density management continues to be a dominant intensive forest management practice throughout boreal and temperate forest regions (e.g., Canada (CCFM, 2009) and Finland (Peltola, 2009) treat over 500,000 ha annually). Operationally, density management consists of manipulating initial planting densities at the time of establishment (initial espacement; IE) and (or) reducing stand densities during subsequent stages of stand development (e.g., precommercial thinning (PCT) at the sapling stage, and (or) commercial thinning (CT) at the semi-mature stage). As documented by numerous case studies, density management can result in a wide array of benefits at the tree, stand and forest levels. These include increased growth and resultant yields leading to enhanced end-products (e.g., Kang et al., 2004), attainment of early stand operability status (e.g., Erdle, 2000), reduced density-dependent mortality losses (e.g., Pelletier & Pitt, 2008), increased spatial and structural uniformity resulting in lower extraction, processing and manufacturing costs (e.g., Tong et al., 2005), and increased carbon sequestration rates (e.g., Nilsen & Strand, 2008). Density management also has consequential effects on other important non-timber values. These include regulating the production of coarse woody debris to meet wildlife habitat requirements (e.g., pine marten (*Martes americana*) (Sturtevant et al., 1996)), provision of thermal protection and hiding requirements for ungulates by regulating stand structure (e.g., elk (*Cervus elaphus nelsonii*) and mule deer (*Odocoileus hemionus*) (Smith and Long, 1987)), controlling successional pathways in order to prevent the establishment and development of ericaceous shrub species (e.g., Lindh and Muir, 2004), and increasing biodiversity (e.g., Verschuyt et al., 2011). Although thinning effects are largely positive in nature, inappropriate treatments can have serious detrimental implications. These include (1) PCT treatments which result in an extended period of openness in which individual trees are allowed to build up extensive crowns resulting in an increase in juvenile wood production and larger knot sizes (e.g., Tong et al., 2009), and (2) CT treatments which are implemented within structurally unstable stands resulting in increased mortality during high wind or heavy ice and snow events.

Determination of the optimal density management regime for a given objective is a complex process given the multitude of variables that a forest manager needs to consider. For

example, deciding on initial establishment densities, the timing of thinning entries and associated removables, discount and interest rates, and fixed and variable cost values. Furthermore, the selected regime must be considered within the broader regulatory framework which can impose additional constraints on the decision-making process (e.g., specific minimum pre-treatment tree size and basal area requirements before CT treatments can be implemented (McKinnon et al., 2006)). Fortunately, however, the complexity of decision-making has been greatly reduced for traditional volumetric-based objectives with the advent of stand density management diagrams (SDMDs; Ando, 1962; Drew & Flewelling, 1979; Jack & Long, 1996; Newton, 1997).

Briefly, SDMDs are graphical decision-support tools that are used to determine the density management regime required for the realization of a specified mean tree size or volumetric yield objective. Recently, in order to address the evolving paradigm shift in management focus from a singular volumetric yield maximization objective to a focus on a multitude of diverse objectives, including the end-product quality (Barbour & Kellogg, 1990), product value maximization (Emmett, 2006), bioenergy and carbon sequestration potential, and ecosystem services, the SDMD modeling framework was expanded. Specifically, Newton (2009) introduced the modular-based structural stand density management model (SSDMM) for jack pine (*Pinus banksiana* Lamb.) stand-types. The model has a hierarchical design in which 6 integrated estimation modules collectively enable the estimation of volumetric productivity, log distributions, product volumes and values, and fibre attributes, for a given density management regime, site quality, and cost profile.

The objectives of this study were to describe the upland black spruce (*Picea mariana* (Mill.) BSP) variant of the modular-based SSDMM and demonstrate its utility in designing density management regimes within an operational context. More specifically, the stand-level examples are placed within the broader context of sustainable management at the landscape level in which a portion of the productive forest land base is allocated and managed for timber related objectives (i.e., early operability within natural-origin stands, and production of enhanced end-products within plantations) and the remainder, for non-timber related objectives (i.e., production of coarse woody debris (CWD) for maintenance of wildlife habitat).

2. Methods

2.1 Modular-based SSDMM for upland black spruce stands

The SSDMM for upland black spruce stands was developed by expanding the dynamic SDMD modelling framework through the incorporation of diameter, height, log-type, biomass, carbon, product and value distribution, and wood quality recovery modules (Figure 1). Analytically, the principal steps involved the development of a dynamic SDMD and the subsequent incorporating of (1) a parameter prediction equation (PPE) system for diameter distribution recovery, (2) a composite height-diameter prediction equation for height estimation, (3) a composite taper equation for recovering log product distributions and calculating stem volumes, (4) composite biomass equations for estimating above ground components and their carbon mass equivalents, (5) sawmill-specific product recovery and associated product value functions, and (6) composite wood density and maximum mean branch diameter equations. Computationally, Module A (Dynamic SDMD) provides a set of annual stand-level variables which are required as input to Modules B-F. Module B utilizes the PPE system and the composite height-diameter function to recover the grouped-diameter frequency distribution and estimate corresponding tree heights for each diameter

class (Diameter and Height Recovery Module), and similar to Module A, provides prerequisite input to the remaining modules. The taper equation is used to derive estimates of the upper stem diameters for each tree within each diameter class from which the number of sawlogs and pulplogs, residual tip volumes, and merchantable and total stem volumes, are calculated (Taper Analysis and Log Estimation Module). The composite biomass equations are used to predict masses and carbon equivalents for each above-ground component (Biomass and Carbon Estimation Module). The product recovery and value functions are used to predict sawmill-specific (stud mill (SM) and randomized length mill (RLM)) chip and lumber volumes and associated market-based monetary values (Product and Value Estimation Module). The composite fibre attribute functions are used to estimate mean wood density for merchantable-sized (≥ 10 cm diameter classes) trees, and the mean maximum branch diameter within the first 5 m sawlog for trees ≥ 15.1 cm in diameter (Fibre Attribute Estimation Module). Refer to Newton (2012a) for a complete description of the approach used in the development and calibration of the modular-based SSDMM for upland black spruce stands.

Given the model's complexity and the computation burden associated with its use, an algorithmic analogue was developed in the Visual Basic (VB.NET (Ver. 1.1); Microsoft Corporation) programming language. Denoted, Croplanner, the program predicts and tabulates site-dependent annual and rotational diameter-class and stand-level estimates of volumetric yields, log distributions, biomass and carbon outcomes, recoverable products and associated values by sawmill-type, economic efficiency profiles and fibre attributes, for 3 density management regimes per simulation. The user is required to specify the following information for each simulation: (1) provincial region (e.g., Ontario); (2) stand-type (natural origin or plantation); (3) simulation year; (4) site quality (site index); (5) rotational age; (6) establishment densities; (7) expected ingress during the establishment period (n., applicable to plantations only); (8) merchantable specifications (i.e., length and upper threshold diameters for pulp and saw logs, and merchantable top diameter); (9) interest and discount rates; (10) operability targets (i.e., number of merchantable trees per cubic metric of merchantable wood, and total merchantable volume per unit area); (11) establishment costs (e.g., fixed site assessment or preparation expenses and planting costs); (12) genetic worth effects and selection ages (n., applicable to plantations only); (13) operational adjustment factors; (14) product degrade estimates; (15) variable cost estimates accounting for stumpage and renewal charges, harvesting, transportation and manufacturing expenses at the time of harvest; and (16) regime-specific thinning treatments and associated costs (i.e., time of entry (stand age), type of thinning (PCT or CT), removal densities (stems/ha) or basal area (%) reductions, and fixed and variable thinning cost values).

For each year, the program recovers the grouped-diameter frequency distribution and for each recovered diameter class, calculates height, number of pulp and saw logs, merchantable and total volumes, biomass and carbon equivalents for each above-ground component (bark, stem, branch and foliage), sawmill-specific recoverable chip and lumber volumes and associated monetary values, and mean tree fibre attributes. Cumulative stand-level values and performance indices are subsequently derived. The output is presented in both tabular and graphical formats and consists principally of a traditional SDMD graphic, regime-specific annual estimates at the individual diameter-class level and stand-levels, regime-specific treatment and rotational summaries, and across-regime rotational comparisons. The comparisons employ a comprehensive set of performance indices which include measures of (1) overall productivity as measured by the mean annual merchantable

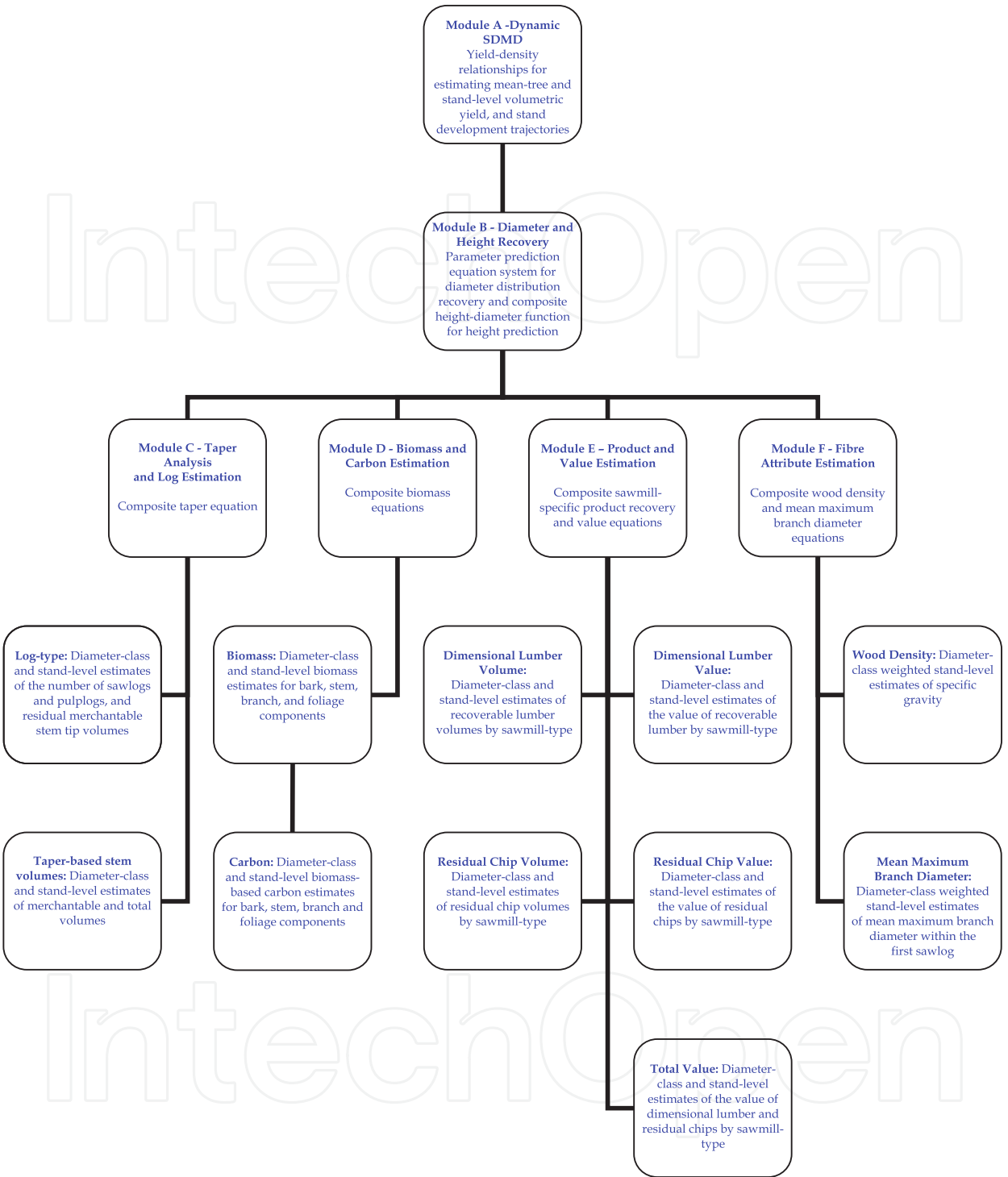


Fig. 1. Schematic illustration of the modular-based SSDMM.

volume increment ($\text{m}^3/\text{ha}/\text{yr}$), mean annual biomass increment ($\text{t}/\text{ha}/\text{yr}$) and mean annual carbon increment ($\text{t}/\text{ha}/\text{yr}$), (2) log production in terms of the percentage by sawlogs produced, (3) end-products recovered as quantified by the percentage of lumber volume produced by each sawmill type, (4) economic efficiency based on land expectation values (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 for each

sawmill type), (5) optimal site occupancy (number of years that a size-density trajectory was within an optimal production zone as delineated by relative density indices of 0.32 and 0.45 (Newton, 2006)), (6) stand stability as reflected by the mean height/diameter ratio for trees within the dominant crown class, (7) fibre quality attributes as summarized by mean wood density and mean maximum branch diameter, (8) accelerated operability based on the reduction in the number of years that a stand took to reach harvestable status as defined by target piece size and merchantable yield thresholds, and (9) time to full occupancy as quantified by the number of years required to reach initial crown closure status.

2.2 Simulations

The treatment regimes as stated within an operational forest management plan are used to exemplify the utility of model. Specifically, the silvicultural matrix presented in the 2009-2019 forest management plan developed for the Romeo Malette Forest in the Timmins District of the Northeastern Region of Ontario, Canada, by Tembec Inc. (Anonymous, 2009), was used. These ecosite-specific treatment regimes reflect best management practices for a given stand and forest management objective as defined within the NEBIE silvicultural intensity framework (Bell et al., 2008).

For the natural regenerated stand-type (forest unit SP1 (Ecosite 2)), an extensive silvicultural intensity employing an early operability objective, was evaluated. For the plantations (forest unit SP1 (Ecosite 5f)), an elite silvicultural intensity with an enhanced end-product value objective, was evaluated. These objectives reflect ongoing discussions regarding the management of boreal conifers in the central portion of the Canadian Boreal Forest Region: (1) implementing PCT treatments within density-stressed natural-origin stands in order to shorten the time to operability status; and (2) employing CT treatments within genetically-improved plantations so that merchantable volume losses normally attributed to density-dependent mortality at the later stages of stand development are minimized, and reducing the technical rotation age in regards to the production of high quality wood products.

The protocol for implementing the CT treatments followed the provincial recommendations as espoused by McKinnon et al. (2006). Specifically, 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) minimize the rate of density-dependent mortality within the merchantable-sized classes during the later stages of stand development thus enabling the recovery of some of the expected merchantable volume losses through thinning. Operationally, the CT treatment should occur within previously density regulated stands which are approximately 15-20 yrs from rotation age. The CT treatment should reduce basal areas by a maximum of 30-35% from an initial minimum basal area of 25 m²/ha and be implemented only when density-dependent mortality is occurring or imminent within the merchantable-sized classes. Lastly, CT treatments should only occur within stands where the mean live crown ratio exceed 35%. Table 1 provides a summary of the input parameters required to run these scenarios with the Croplanner algorithm.

3. Results and discussion

3.1 Extensive silviculture: Natural-origin black spruce stand-types subjected to PCT

The resultant mean volume-density trajectories for the natural-origin black spruce stands within the context of the traditional SDMD graphical format are illustrated in Figure 2. It is

Input Parameter (unit)	Stand-type and Treatment					
	Natural-origin Stands subjected to PCT			Plantations subjected to IE+PCT+CT with genetic worth effects		
	Regime 1 -	Regime 2 -	Regime 3 -	Regime 1 -	Regime 2 -	Regime 3 -
	Control	PCT	PCT	Control	PCT	PCT+CT
Silvicultural intensity	Extensive			Elite		
Objective	Early operability			End-product value		
Simulation year	2011	2011	2011	2011	2011	2011
Site index (Carmean et al., 2006)	16	16	16	18	18	18
Rotation age (yr)	80	80	80	50	50	50
Initial density (stems/ha)	5000	5000	5000	2750	2750	2750
Ingress density (stems/ha)	-	-	-	0	0	0
<i>Merchantable specifications</i>						
Pulplog length (m)	2.59	2.59	2.59	2.59	2.59	2.59
Pulplog minimum diameter (cm)	10	10	10	10	10	10
Sawlog length (m)	5.03	5.03	5.03	5.03	5.03	5.03
Sawlog minimum diameter (cm)	14	14	14	14	14	14
Merchantable top diameter (cm)	4	4	4	4	4	4
<i>Rates</i>						
Interest rate (%)	2	2	2	2	2	2
Discount rate (%)	4	4	4	4	4	4
<i>Operability Targets</i>						
Piece-size (stems/m ³)	10	10	10	10	10	10
Merchantable yield (m ³ /ha)	130	130	130	200	200	200
Site preparation (\$/ha)	100	100	100	300	300	300
Planting (\$/seedling)	-	-	-	0.6	0.6	0.6
Genetic worth (%)	-	-	-	15	15	15
Selection age (yr)	-	-	-	15	15	15
Operational adjustment factor (%)	1	1	1	1	1	1
Product degrade (%)	15	5	5	15	10	5
Variable costs for harvesting, stumpage, renewal, transportation and manufacturing (\$/m ³)	100	80	80	75	65	55
<i>PCT Treatments</i>						
Time of treatment (yr)	-	14	14	-	13	13
Number of trees removed (stems/ha)	-	1943	2943	-	907	907
Fixed cost of PCT (\$/ha)	-	300	300	-	300	300
<i>CT Treatment</i>						
Time of treatment (stems/ha)	-	-	-	-	-	30
Number of trees removal (stems/ha)	-	-	-	-	-	604
Fixed cost of CT (\$/ha)	-	-	-	-	-	100
Variable cost for harvesting, stumpage, transportation and manufacturing for volume removed (\$/m ³)	-	-	-	-	-	65

Table 1. Stand-type specific input parameters used in the Croplanner simulations.

instructive to familiarize oneself with the overall structure of the diagram, particularly, in relation to the static and dynamic components. Essentially, the yield-density isolines are used for positioning a given stand in the size-density space and deriving corresponding yield estimates. The size-density trajectories in combination with the isolines provide a graphical pictorial of overall stand dynamics (density changes due to thinning treatments and density-dependent and independent mortality) in addition to enabling users to derived structural characteristics at various key phases of stand development, through interpolation. For example, the intersection of the size-density trajectories with the diagonal line denoting crown closure status indicated that the stand thinned to a residual density of 3000 trees (stems/ha; Regime 2) re-attained crown closure status by an age of 18 yr whereas the stand thinned to a residual density of 2000 trees (stems/ha; Regime 3) re-attained crown closure status by an age of 22 yr. Knowing the period of time a stand is open-grown is an important metric when attempting to control early branch development within the lower portion of the stem through density regulation.

The graphic also shows that at an approximate mean dominant height value of 10 m, the stands enter a period of accelerated self-thinning, as evident from the degree of curvature of the size-density trajectories. The degree of self-thinning was most pronounced in the control stand and less so for the PCT treated stands. Numerically, from the time of treatment to rotation, the unthinned control stand lost 3373 trees (stems/ha; Regime 1) compared with only 1746 trees (stems/ha) for Regime 2, and 1124 trees (stems/ha) for Regime 3. By the time the stands reached rotation age (80 yr) they were positioned just below the 20 m mean dominant height isoline. The control stand was just below the 18 cm quadratic mean diameter isoline, just above the 0.9 relative density index isoline, and just below the 35% mean live crown ratio isoline. For the thinned stand PCT to a residual density of 3000 stems/ha (Regime 2), the trajectory terminated at a position that was slightly above the 18 cm quadratic mean diameter isoline, just above the 0.8 relative density index isoline, and slightly below the 35% mean live crown ratio isoline. Similarly, for the thinned stand PCT to a residual density of 2000 stems/ha (Regime 3), the trajectory terminated at a position that intersected the 20 cm quadratic diameter isoline, just above the 0.7 relative density index isoline, and intersected the 35% mean live crown ratio isoline. Although the graphic is very useful in terms of understanding and visualizing stand development, the algorithmic revision readily facilitates the estimation of a much broader array of yield, end-product, economic, and wood fibre attribute metrics (Table 2), and associated performance measures (Table 3), at various temporal scales (annual, periodic and rotational).

The thinning treatments resulted in an increase in the duration of the pre-crown-closure period by 4 and 8 yr for Regimes 2 and 3, respectively. Given that the dominant height of the stands would be in the 5.5 to 6.5 m range at time of re-closure, most of the branches within the first 5 m long sawlog would have been formed by then. As inferred by the minimal differential in mean maximum branch diameters at rotation between the stands (c.f., 2.65 cm versus a mean of 2.70 cm for the control and thinned stands, respectively; Table 3), suggest that this extended period of openness did not consequentially affect branch development within this economically-important portion of the stem. Comparing Regimes 2 and 3 against Regime 1, indicated that on the positive side, the PCT treatment (1) shorten the time to stand operability status by an average of 8 years, (2) produced trees of large mean size at rotation (i.e., average increases in mean volume of 32%), (3) increased the percentage of sawlogs produced by an average of 12%, and (4) enhanced overall structural stability

(e.g., reducing the height/diameter ratio by an average of 10%). On the negative side, however, the single PCT treatment resulted in lower per unit yields for merchantable volume (average of 12% less), and biomass and carbon production (average of 18% less). Economically, however, the PCT treatments did result in gains in economic efficiency (an average of 88% increase) at the specified rotation age of 80 yr, irrespective of sawmill type. These economic differences can be largely attributed to the lower product degrade values specified for the thinned stands, and to the assumed reduction in variable costs at the time of harvest arising from decreased harvesting and manufacturing expenses due to increased piece-size,

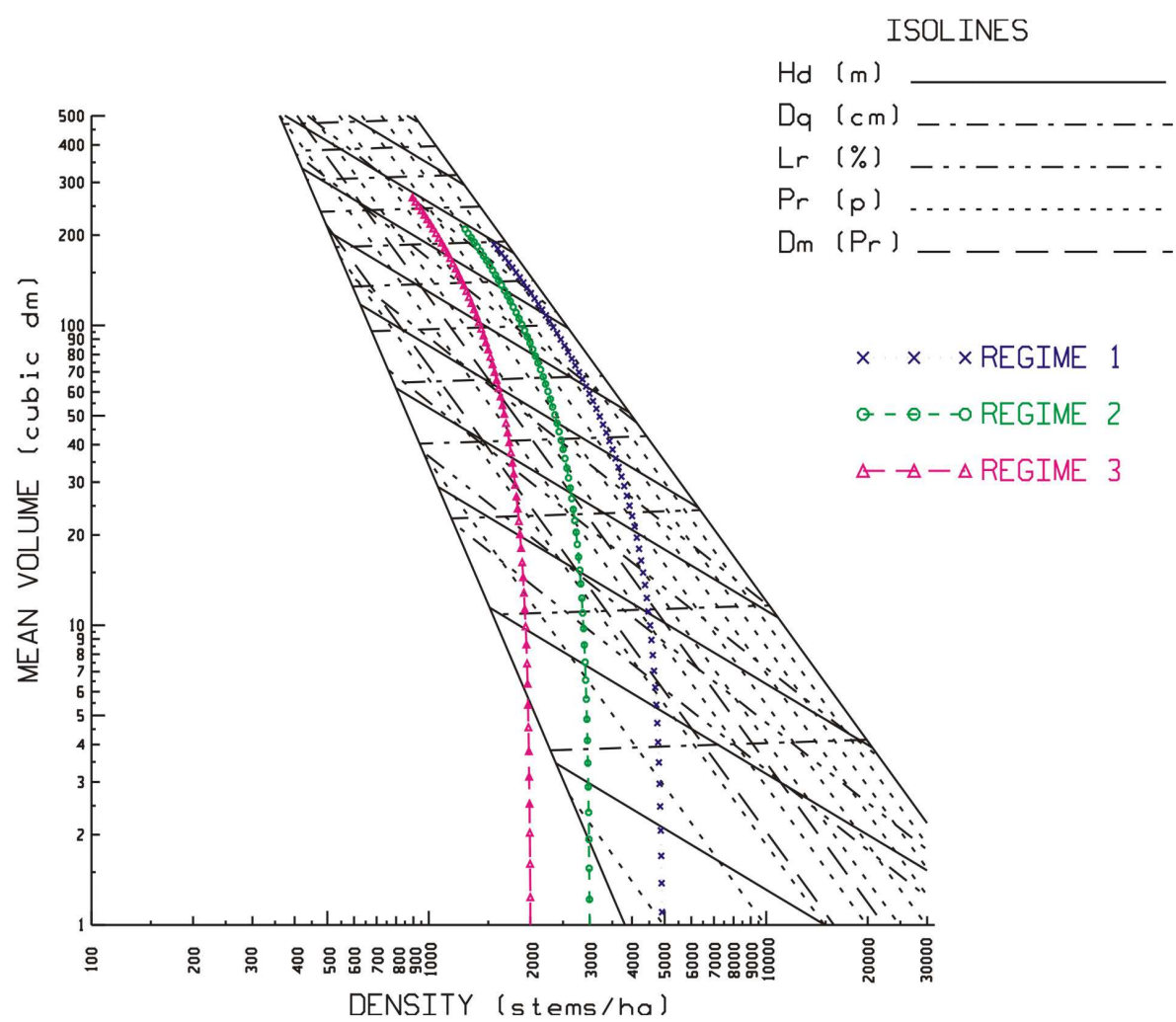


Fig. 2. Dynamic SDMDs for natural-origin upland black spruce stand-types managed under an extensive silvicultural intensity. Graphically illustrating (1) isolines for mean dominant height (Hd; 6-22 m by 2 m intervals), quadratic mean diameter (Dq; 4-26 cm by 2 cm intervals), mean live crown ratio (Lr; 35, 40, 50,..., 80%), and relative density index (Pr; 0.1-1.0 by 0.1 intervals), (2) the self-thinning line at a Pr = 1.0, and initial crown closure line (lower solid diagonal line); (3) lower and upper Pr values delineating the optimal density management window (Dm; 0.32 ≤ Pr ≤ 0.45); and (4) expected 80-yr size-density trajectories with 1 year intervals denoted for 3 user-specified density management regimes for stands situated on a medium site quality (site index = 16).

reduced size variation, and more uniform spatial patterns. In terms of provision of wildlife trees, the number of large standing snags (trees/ha), as approximated by the number of merchantable-sized abiotic trees which died during the last decade before harvest, was 41% less in the PCT stands as compared to the control stand.

Attribute (unit)	Regime 1 - Control	Regime 2 - PCT (thinning yields)	Regime 3 - PCT (thinning yields)
Mean dominant height (m)	19.9	19.9	19.9
Quadratic mean diameter (cm)	18	19	20
Basal area (m ² /ha)	39	35	32
Mean volume per tree (dm ³)	186	216	252
Total volume (m ³ /ha)	291	272 (4)	242(6)
Total merchantable volume (m ³ /ha)	276	257 (0)	229(0)
Density (stems/ha)	1561	1254 (1943)	876 (2943)
Relative density index (%/100)	0.91	0.81	0.66
Mean live crown ratio (%)	33	34	35
Number of pulplogs (logs/ha)	3149	2345 (-)	1531 (-)
Number of sawlogs (logs/ha)	724	846 (-)	782 (-)
Residual log tip volume (m ³ /ha)	53	39 (-)	28 (-)
Bark biomass (t/ha)	19	17 (-)	15 (-)
Stem biomass (t/ha)	188	164 (-)	139 (-)
Branch biomass (t/ha)	6	6 (-)	6 (-)
Foliage biomass (t/ha)	11	11 (-)	12 (-)
Total biomass (t/ha)	224	198 (-)	172 (-)
Bark carbon (t/ha)	10	9 (-)	8 (-)
Stem carbon (t/ha)	94	82 (-)	70 (-)
Branch carbon (t/ha)	3	3 (-)	3 (-)
Foliage carbon (t/ha)	5	5 (-)	6 (-)
Total carbon (t/ha)	112	99 (-)	86 (-)
Chip volume - SM (m ³ /ha)	127	110 (-)	90 (-)
Lumber volume - SM (m ³ /ha)	149	133 (-)	122 (-)
Chip volume - RLM (m ³ /ha)	108	94 (-)	77 (-)
Lumber volume - RLM (m ³ /ha)	166	148 (-)	134 (-)
Chip value - SM (\$K/ha)	6	6 (-)	5 (-)
Lumber value - SM (\$K/ha)	27	27 (-)	26 (-)
Total product value - SM (\$K/ha)	33	33 (-)	31 (-)
Chip value - RLM (\$K /ha)	6	5 (-)	4 (-)
Lumber value - RLM (\$K /ha)	36	37 (-)	35 (-)
Total product value - RLM (\$K/ha)	42	42 (-)	39 (-)
Land expectation value - SM (\$K/ha)	1.2	2.7	2.6
Land expectation value RLM - (\$K/ha)	3.2	4.7	4.3

Table 2. Rotational yield estimates for upland black spruce natural-origin stands subjected to PCT. Values in parenthesis denote yields derived from the PCT treatment (n., a dash line indicates an incalculable value).

Index (unit)	Regime 1 - Control	Regime 2 - PCT	Regime 3 - PCT
Mean annual volume increment (m ³ /ha/yr)	3.4	3.2	2.9
Mean annual biomass increment (t/ha/yr)	2.8	2.5	2.1
Mean annual carbon increment (t/ha/yr)	1.4	1.2	1.1
Percentage of sawlogs produced (%)	19	27	34
Percentage of lumber volume recovered - SM (%)	54	55	57
Percentage of lumber volume recovered - RLM (%)	61	61	64
Relative land expectation value - SM (%)	-	138	49
Relative land expectation value - RLM (%)	-	129	36
Duration of optimal site occupancy (%)	9	11	16
Mean height/diameter ratio (m/m)	103	96	90
Mean wood density (g/cm ³)	0.48	0.49	0.49
Mean maximum branch diameter (cm)	2.65	2.68	2.72
Time to operability status (yr)	64	58	55
Time to initial crown closure (yr)	14	14	14
Age of crown re-closure post-PCT (yr)	-	18	22
Number of large standing snags (trees/ha)	332	228	165

Table 3. Stand-level performance indices for density-manipulated upland black spruce natural-origin stands subjected to PCT.

In summary, this specific simulation indicated that PCT resulted in (1) earlier stand operability status, (2) larger but fewer trees at rotation, (3) an increased in the duration of optimal site occupancy, (4) enhanced structural stability, (5) a decline in overall merchantable volume productivity, and (6) production of fewer wildlife trees.

3.2 Elite silviculture: Genetically-improved upland black spruce plantations subjected to PCT and CT

Similar to the PCT treatments within the natural-origin stands, the resultant mean volume-density trajectories for elite treatments are graphically illustrated within the context of the SDMD graphic (Figure 3). Table 4 lists the rotational and thinning yield estimates whereas Table 5 lists 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. The PCT treatments extended the period of openness by approximately 3 yr, however the effect of branch development was minimal (c.f., 2.65 cm for the control stand versus 2.69 and 2.72 cm for the PCT and PCT+CT stands, respectively). The trajectories also revealed that the thinned stands spent a greater portion of the rotation in the optimal site occupancy zone: 20% and 44% for the PCT and PCT+CT regimes, respectively, versus 12% for the control stand. This suggest that the thinned stands, particularly the stand that received a dual treatment (Regime 3), the rate of carbon sequestration and biomass production was close to an optimal level for a considerable portion of the rotation. Essentially, stands below the zone are not fully utilizing the site and consequently site resources are going unused in terms of forest biomass production (e.g., resource supply exceeds demand). Stands above the zone are over-occupying the site resulting in intensive asymmetric resource competition among local neighbors and subsequent mortality through self-thinning.

Further examination of the SDMD revealed that the size-density trajectories intersected the crown closure isoline slightly above the 4 m mean dominant height isoline. This corresponds to an age of 13 yr for this site quality and represents the target PCT age. The yield-density isolines indicated that the stands were slightly above the 4 cm quadratic mean diameter isoline and the 0.1 relative density isoline, at the time of the PCT treatment. The corresponding interpolated mean volume, density and basal area values were 2.9 dm³, 2707 stems/ha and 4.0 m²/ha, respectively. Similarly, the size-density trajectories at the time of the CT treatment were slightly above the 12 m mean dominant height isoline, 14 cm quadratic mean diameter isoline, 0.5 relative density isoline, and the 40% live crown ratio isoline. The corresponding interpolated mean volume, density and basal area values were 77.9 dm³, 1604 stems/ha and 25.4 m²/ha, respectively. Accordingly, the stands would be candidates for CT treatments based on the guidelines given by McKinnon et al. (2006): CT candidate stands must have been previously managed in terms of density control treatments (e.g., IE with PCT), have a pretreatment basal area of greater than 25 m²/ha, a mean live crown ratio greater than 35%, and where density-dependent mortality within the merchantable size classes is imminent. In case of the PCT stands, this last requirement was projected to occur at an age of 31 yr.

The mean dominant height at rotation age was 17.2 m for all 3 plantations. Respectively, for Regimes 1, 2 and 3, the rotational values for mean live crown ratio were 33, 34 and 38% and cumulative merchantable volume were 284, 240 and 211 m³/ha. The CT treatment consisting of removing 35% (8.8 m²/ha) of basal area at age 30 resulted in a mid-rotation harvest of approximately 39 m³/ha of merchantable volume. Density-dependent mortality rates within the merchantable size classes of the CT stand was considerably lower than that within both the control and PCT stand during the post-CT period (c.f., 204 stems/ha within the PCT+CT stand versus 710 and 389 stems/ha within the control and PCT stands, respectively, over the 20 yr period). Although, relative to the control and PCT stand, the CT treatment resulted in larger but fewer trees of slightly inferior quality at rotation, the dual treatment did extend period of optimal site occupancy and substantially increased the economic worth of the stand at rotation. Relative to the control stand, the number of large standing snags (trees/ha) at rotation was approximately 39% and 73% less in the PCT and PCT+CT treated stands, respectively.

In summary, relative to the unthinned plantation, the thinning treatments resulted in (1) lower overall productivity in terms of merchantable volume (16 and 26% less for the PCT and PCT+CT plantations, respectively), and biomass and carbon production (8 and 11% less for the PCT and PCT+CT plantations, respectively), (2) extended the time to operability status by 6 and 12 yr for the PCT and PCT+CT plantations, respectively, (3) larger (mean volume) but fewer trees at rotation, (4) increased economic efficiency (36 and 54% less for the PCT and PCT+CT plantations, respectively), and (5) increased durations of optimal site occupancy (8 and 36% more for the PCT and PCT+CT plantations, respectively). With respect to the single core objective of increasing the production of high-value end-products through thinning, the results were not fully supportive. For the 2 mill configurations assessed, the thinned plantations produced lower volumes of chip (13 and 18% less for the PCT and PCT+CT plantations, respectively) and dimensional lumber products (9 and 20% less for the PCT and PCT+CT plantations, respectively). The removal of the merchantable-sized trees during the CT contributed to the decline in sawlogs and associated dimensional lumber volumes at rotation. In terms of product values, the

thinned stands produced generally lower monetary values due to the decreased end-product volumes. However the differences were not large and in some cases were nil (c.f., product values for the RLM configuration for the thinned versus control plantation (Table 4)). The largest benefit from thinning was in terms of an increase in economic efficiency as inferred from the ratio of land expectation values between the control and the treated plantations (Table 5). The lower product degrade values employed and the assumed lower variable costs arising from a more uniform piece-size distribution, largely contributed to this positive economic result.

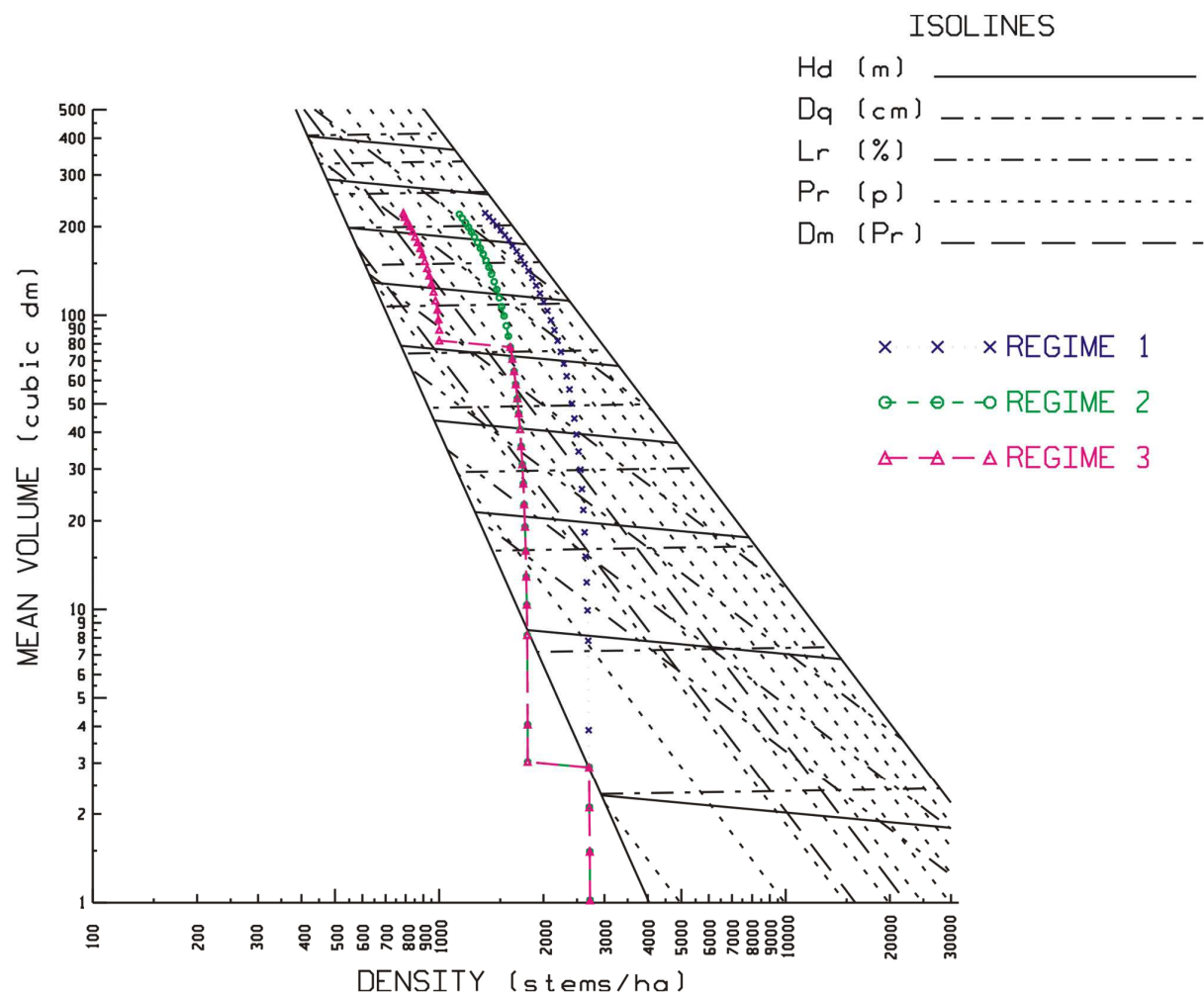


Fig. 3. Dynamic SDMD for genetically enhanced upland black spruce plantations managed under an elite silvicultural intensity. Graphically illustrating: (1) isolines for mean dominant height (Hd; 4-20 m by 2 m intervals), quadratic mean diameter (Dq; 4-26 cm by 2 cm intervals), mean live crown ratio (Lr; 35, 40, 50,..., 80%), relative density index (Pr; 0.1-1.0 by 0.1 intervals); (2) self-thinning line at a Pr = 1.0 and initial crown closure line (lower solid diagonal line); (3) lower and upper Pr values delineating the optimal density management window (Dm; 0.32 ≤ Pr ≤ 0.45); and (4) expected 50 year size-density trajectories with 1 year intervals denoted for 3 user-specified density management regimes for plantations situated on a good site quality (site index = 18).

Attribute (unit)	Regime 1 - Control	Regime 2 - PCT (thinning yields)	Regime 3 - PCT+CT (thinning yields)
Mean dominant height (m)	17.2	17.2	17.2
Quadratic mean diameter (cm)	21	21	21
Basal area (m ² /ha)	46	38 (1)	27 (1,9)
Mean volume per tree (dm ³)	222	227	237
Total volume (m ³ /ha)	302	255 (2)	183 (2,43)
Total merchantable volume (m ³ /ha)	284	240 (0)	173 (0,39)
Density (stems/ha)	1358	1120 (907)	773 (907,604)
Relative density index (%/100)	0.89	0.74	0.53
Mean live crown ratio (%)	33	34	38
Number of pulplogs (logs/ha)	1982	1667 (0)	1203 (0,464)
Number of sawlogs (logs/ha)	909	824 (0)	643 (0,0)
Residual log tip volume (m ³ /ha)	42	35 (0)	25 (0,9)
Bark biomass (t/ha)	18	17 (0)	14 (0,3)
Stem biomass (t/ha)	164	144 (1)	110 (1,21)
Branch biomass (t/ha)	9	8 (1)	8 (1,3)
Foliage biomass (t/ha)	14	15 (2)	16 (2,5)
Total biomass (t/ha)	205	184 (5)	147 (5,31)
Bark carbon (t/ha)	9	8 (0)	7 (0,1)
Stem carbon (t/ha)	82	72 (1)	55 (1,10)
Branch carbon (t/ha)	4	4 (1)	4 (1,1)
Foliage carbon (t/ha)	7	8 (1)	8 (1,3)
Total carbon (t/ha)	103	92 (2)	74 (2,16)
Chip volume - SM (m ³ /ha)	123	107 (0)	79 (0,22)
Lumber volume - SM (m ³ /ha)	131	120 (0)	94 (0,11)
Chip volume - RLM (m ³ /ha)	106	92 (0)	68 (0,20)
Lumber volume - RLM (m ³ /ha)	146	133 (0)	105 (0,13)
Chip value - SM (\$K/ha)	7	6 (0)	5 (0,1)
Lumber value - SM (\$K/ha)	25	24 (0)	21 (0,2)
Total product value - SM (\$K/ha)	32	30 (0)	26 (0,3)
Chip value- RLM (\$K /ha)	4	4 (0)	3 (0,1)
Lumber value- RLM (\$K /ha)	34	34 (0)	29 (0,5)
Total product value - RLM (\$K/ha)	38	38 (0)	32 (0,5)
Land expectation value - SM (\$K/ha)	3.7	5.5	6.4
Land expectation value - RLM - (\$K/ha)	7.3	8.9	9.8

Table 4. Rotational yield estimates for upland black spruce plantations established at fixed IE levels subjected to PCT and CT treatments with genetic worth effects incorporated. Values in parenthesis denote yields derived from the thinning treatment(s) (ordered by time of treatment).

Index (unit)	Regime 1 - Control	Regime 2 - PCT	Regime 3 - PCT+CT
Mean annual volume increment (m ³ /ha/yr)	5.7	4.8	4.2
Mean annual biomass increment (t/ha/yr)	4.1	3.8	3.7
Mean annual carbon increment (t/ha/yr)	2.1	1.9	1.8
Percentage of sawlogs produced (%)	31	33	28
Percentage of lumber volume recovered - SM (%)	52	53	51
Percentage of lumber volume recovered - RLM (%)	58	59	57
Relative land expectation value - SM (%)	-	49	74
Relative land expectation value - RLM (%)	-	22	34
Duration of optimal site occupancy (%)	12	20	48
Mean height/diameter ratio (m/m)	72	72	70
Mean wood density (g/cm ³)	0.48	0.49	0.50
Mean maximum branch diameter (cm)	2.65	2.69	2.72
Time to operability status (yr)	35	41	47
Time to initial crown closure (yr)	13	13	13
Age of crown re-closure post-PCT (yr)	-	16	16
Number of large standing snags (trees/ha)	350	214	93

Table 5. Stand-level performance indices for density-manipulated upland black spruce plantations established at fixed IE levels subjected to PCT and CT treatments with genetic worth effects incorporated.

3.3 Extension of the model to address non-timber objectives

Conservation of biological diversity is the cornerstone of sustainable forest management (OMNR, 2005). Although the broader issues of forest-level structural complexity and connectivity, and overall wildlife habitat requirements were assumed to have been addressed at the landscape level during the forest management planning process, density management treatments are expected to affect biodiversity at both the stand and forest levels (Thompson et al, 2003). Specifically, at the stand-level, biodiversity would decline as a direct consequence of the reduction in structural complexity arising from IE, PCT and CT treatments, principally through the (1) establishment of monocultures, application of herbicides and species-specific thinning treatments which would reduce species diversity, (2) regulation of intertree spacing which would result in a decrease in spatial complexity, and (3) truncation of the diameter distribution due to the thinning-from-below treatment protocol which would reduce the degree of horizontal and vertical structural heterogeneity. Employment of improved planting stock would also result in a reduction in genetic diversity. Lastly, the lowering of the intensity of resource competition through IE, PCT and CT would result in a reduction in the rate of self-thinning and hence a decrease in the production of abiotic components (e.g., snags and coarse woody debris). However, the question remains as to the degree of impact that a reduction in biodiversity arising from density management would have. In an extensive literature review of previous biodiversity impact studies augmented by model projections, Thompson et al., (2003) concluded that (1) the presence of large sturdy and standing snags was most important to the vertebrate population in terms of providing nesting and denning site, (2) the quality of coarse woody debris (CWD) in terms of its decay stage and size were more important than

quantity in relation to providing cover, feeding areas, and den sites for wildlife, (3) having a diverse vertical structure combined with the presence of fruiting species within the understory was most conducive to the songbird populations, and (4) canopy cover was important for many vertebrate species in regards to avoiding avian predators. However, it is evident that some of these requirements are specific to a given wildlife species and hence are inversely related (c.f., (3) and (4)). Consequently, achieving an optimal stand structure which complies with all the wildlife habitat requirements would be largely illusive. Thus regulating stand densities in order to realize biodiversity objectives will likely involve various tradeoffs.

The modular-based SSDMM can be used to provide direct or indirect structural metrics that address biodiversity objectives. For example, at any point in a stand's development the model provides estimates of horizontal and vertical structure (e.g., diameter and height distributions). Similarly, the degree of canopy closure and crown heights can be inferred from crown closure line or calculated from the live crown ratio isoline as presented in the SDMD graphic (Figures 2 and 3). Estimates of the approximate number, age and size of CWD components produced during stand development can be derived from the model using the density and total volume estimates (Newton, 2006). Once the threshold values for these biodiversity-based structural metrics are explicitly quantified, they could be added to the suite of performance measures. Hence, the SSDMM could be used to determine if a specific crop plan complied with not only volumetric, end-product, or economic objectives, but also biodiversity goals.

For example, consider the plantation scenarios but now with a CWD requirement superimposed. Although CWD requirement has yet to be defined in terms of absolute volumes, sizes and decay classes, it is evident that a CT treatment will remove a substantial amount of the larger-sized trees that would have naturally incurred mortality during the later stage of the rotation. In fact, relative to the control stand, 506 fewer merchantable-sized trees per hectare experienced mortality during the post-CT period. Hence this differential in CWD production is of concern given the importance of CWD to maintaining biodiversity. However, one approach in overcoming this CWD deficit is to leave more of the CT trees on site at the time of the treatment. Specifically, by changing the merchantability thresholds of the trees to be removed, more of the stem can be left behind on the forest floor. The minimum diameter of CWD has been defined as 7.5 cm in Ontario (OMNR, 2010) and hence by decreasing log length and increasing the minimum threshold diameters for both sawlogs and pulplogs, the residual amount of stem volume left on the site will increase.

To demonstrate, the third scenario was re-run with the following modifications: (1) all log lengths were set to 2.59 m; (2) the minimum diameter for pulplogs was increased from 10 to 12 cm; and (3) the diameter defining the merchantable top was set to 7.5 cm. Effectively, this increases the residual stem tip volume left behind given that this volume is defined as the volume between the top of the upper most log removed and the top of the merchantable stem. Table 6 lists a subset of the resultant yields and performance metrics for this modified regime relative to the previous PCT+CT regime where the CWD requirement was not explicitly addressed (Tables 4 and 5).

This comparison reveals that the production of large volumes of CWD via CT did result in a decline in merchantable volume productivity, economic efficiency and operability status. However, the treatment was profitable given that the revenue generated from the approximately 9 m³/ha of merchantable wood that was removed from the site exceeded the costs of acquiring and processing it. The CT treatment resulted in a substantial increase of

relatively large CWD components (varying log lengths with diameters ranging from a minimum of 7.5 to a maximum of 12 cm). This CWD contribution should provide acceptable habitat to various wildlife species, particularly, the pine marten. Although not identical in terms of the volume of CWD produced, this scenario is similar to that proposed by Sturtevant et al. (1996) for pine marten habitat in western Newfoundland: i.e., providing old-growth stand structural attributes through the use of CT to generate downed CWD, which created denning and resting sites, subnivean access for cover, prey access, homeoiothermic regulation, and prey biomass (principally voles (genera *Microtus* and *Myodes*)), for the pine marten.

Index (unit)	Regime 3 - PCT+CT	Difference
Residual tip volume left on site at time of CT treatment (m ³ /ha)	24	+15
Total merchantable volume removed from the site via CT (m ³ /ha)	9	-30
Net Revenue arising from the CT treatment - SM (\$K/ha)	0.1	-0.6
Net Revenue arising from the CT treatment - RLM (\$K/ha)	0.4	-1.6
Relative land expectation value at rotation - SM (%)	74	-49
Relative land expectation value at rotation - RLM (%)	34	-38
Time to operability status (yr)	47	+2

Table 6. Subset of CT yield metrics and stand-level performance indices for upland black spruce plantations managed for the production of CWD.

3.4 Utility of SDMD-based decision-support models in forest management

SDMDs have an extensive history of development and use in forest management throughout many of the world’s temperate and boreal forest regions. The SDMD developed by Ando (1962) for Japanese red pine (*Pinus densiflora* Siebold and Zucc.) in Japan was the first model to explicitly incorporate the reciprocal equations of the competition-density (C-D) and yield-density (Y-D) effect (Kira et al., 1953; Shinozaki & Kira, 1956) and the self-thinning rule (Yoda et al., 1963), into an integrated model framework. The reciprocal equation describes the relationship between mean tree size (C-D effect) or per unit area yield (Y-D effect) and density at specific stages of development within stands not incurring density-dependent mortality. The self-thinning rule describes the asymptotic relationship between mean tree size and density within stands undergoing density-dependent mortality. These core relationships were derived from empirical results and associated mathematical formulations arising from numerous plant competition experiments conducted during the 1950s and 1960s (e.g., Donald (1951), Kira et al. (1953), Hozumi et al., (1956), Shinozaki & Kira (1956), Holliday (1960), Yoda et al. (1963)). The SDMD is presented as a 2-dimensional bivariate graphic with density on the x-axis and mean volume on the y-axis upon which the reciprocal equations and self-thinning line are superimposed. Ando (1962) used the SDMD to design thinning schedules which would yield a specified quadratic mean diameter at rotation.

Following the successful introduction of the SDMD by Ando in 1962, Tadaki (1963) developed a SDMD for Sugi stands (*Cryptomeria japonica* D. Don.) in Japan and extended the utility of the model by illustrating how the reciprocal equation of the C-D effect could be used to estimate thinning yields. Later in 1968, Ando (1968) introduced a new set of SDMDs

for Japanese red pine, Sugi, Hinoki cypress (*Chamaecyparis obtuse* (Siebold and Zucc.) Endl.) and Japanese larch (*Larix leptolepis* (Siebold and Zucc.) Gord.) stands in Japan. Using these new models, Ando demonstrated how they could be used as a decision-support tool in terms of evaluating the potential yield outcomes to various thinning treatments. In order to extend the applicability of the mean size – density relationship represented by the reciprocal equation of the C-D effect to stands incurring density-dependent mortality, Aiba (1975a,b) modified the Ando (1968) SDMD model for Sugi stands by replacing the reciprocal equation of the C-D effect with an empirical-based function where mean volume was expressed as function of both density and diameter.

Acknowledging the utility of the SDMD in forest management and silviculture decision-making, Drew and Flewelling (1979) introduced SDMDs to the forest management community in the Pacific Northwest through the development of a SDMD for coastal Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco.) stands. Since their introduction to the English-based forest science literature, numerous diagrams have been developed and utilized in stand-level management planning. These included SDMDs for Japanese red pine in Japan (Ando, 1962, 1968) and South Korea (Kim et al., 1987), Monterey pine (*Pinus radiata* D. Don.) in New Zealand (Drew & Flewelling, 1977) and Spain (Castedo-Dorado et al., 2009), Douglas fir in Spain (López-Sánchez & Rodríguez-Soallero, 2009), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in the western USA (McCarter & Long, 1986; Smith & Long, 1987) and the Pacific Northwest (Flewelling & Drew, 1985), slash pine (*Pinus elliottii* Engelm. var. *elliottii*) and loblolly pine (*Pinus taeda* L.) in the southern USA (Dean & Jokela (1992) and Dean & Baldwin (1993), respectively), black spruce in the eastern and central Canada (Newton & Weetman, 1993, 1994), teak (*Tectona grandis* L.) in India (Kumar et al., 1995), pedunculate oak (*Quercus robur* L.) in Spain (Anta & González, 2005), Scots pine (*Pinus sylvestris* L.) and Austrian black pine (*Pinus nigra* Arn.) in Bulgaria (Stankova & Shibuya, 2007), Merkus pine (*Pinus merkusii* Jungh. et de Vriese) plantations in Indonesia (Heriansyah et al., 2009), and *Eucalyptus globulus* and *Eucalyptus nitens* short rotation plantations in Southwestern Europe (Pérez-Cruzado et al., 2011).

Analytically, the development of SDMDs has been characterized by a sequence of continuous incremental advancements in which increasingly complex and innovative model variants have been proposed. Acknowledging the paradigm shift in management focus from volumetric yield maximization to end-product recovery and value maximization (e.g., Barbour and Kellogg, 1990; Emmett 2006), and realizing the limitations of traditional SDMDs in addressing these new management objectives, the structural SDMD was introduced (Newton et al., 2004, 2005). Specifically, the structural model incorporated a parameter prediction equation system for recovering diameter distributions within the SDMD model architecture. More recently, an expanded version of the structural model was developed in order to address stand-level volumetric, end-product, economic and ecological objectives. To date, modular-based SSDMMs has been developed for jack pine (*Pinus banksiana* Lamb.) (natural-origin stands and plantations; Newton, 2009), black spruce and jack pine mixtures (natural-origin stands; Newton, 2011), upland black spruce (natural-origin stands and plantations; Newton, 2012a), and lowland black spruce (natural-origin stands; Newton, 2012b). These models were calibrated using extensive measurement data sets derived from hundreds of permanent and temporary sample plots situated throughout the central portion of the Canadian Boreal Forest Region. Consequently, the model and associated software suite (Croplanner) represents an operational and enterprise ready decision-support tool.

Essentially, these modular-based SSDMMs retain the ecological and empirical foundation of the original SDMD models, but in addition, incorporate estimation modules for predicting diameter, height, biomass, carbon, log, end-products and associated value distributions, and fibre quality attributes, at any point during a stand's development. The model allows managers to predict the consequences of a given crop plan in terms of realizing specified volumetric, end-product, economic or ecological objectives. In terms of its ability to forecast productivity, end-product and economic, the consequences of various density management treatments, the modular-based SSDMMs share a number of similarities to some of the existing stand-level density management decision-support models. Among others, these include SYLVER (Di Lucca, 1999) which was calibrated for Douglas fir and other coniferous species for use in western Canada, SILVA which was developed for Norway spruce (*Picea abies* (L.) Karst.) and other conifers and deciduous species for use in central Europe (Pretzsch et al., 2002), and MOTTI (Hynynen et al., 2005) which was developed for Scots pine and other conifers for use in Finland.

The SSDMM model architecture in which yield-density and allometric relationships provide the quantitative linkage among the component modules is readily adaptable in addressing new and evolving forest management objectives, as exemplified in the examples considered in this study. Given the large number of existing SDMDs combined with the transformative shift in management focus from volumetric yield maximization to product diversification, suggests that the modular-based SSDMM platform may have wide applicability in resource management.

4. Conclusion

The objectives of this study were to describe an enhanced stand-level decision-support model for managing upland black spruce stand-types, and demonstrate its operational utility in evaluating complex density management regimes involving IE, PCT and CT treatments. The traditional SDMD modeling approach along with its embedded ecological foundation is retained within the modular-based SSDMM structure. For a given density management regime, site quality, and cost profile, the model provides a broad array of yield metrics. These include indices of (1) overall productivity (mean annual volume, biomass and carbon increments), (2) volumetric yields (total and merchantable volumes per unit area), (3) log-product distributions (number of pulp and saw logs), (4) biomass production and carbon sequestration outcomes (oven-dried masses of above-ground components and associated carbon equivalents), (5) recoverable end-products and associated monetary values (volume and economic value of recovered chip and dimension lumber products) by sawmill-type (stud and randomized length), (6) economic efficiency (land expectation value), (7) duration of optimal site occupancy, (8) structural stability, (9) fibre attributes (wood density and branch diameter), and (10) operability status.

The utility of the model was exemplified by contrasting operationally relevant crop plans using a broad array of performance metrics. Specifically, the likelihood of (1) realizing an early operability objective via the use of PCT treatments within density-stressed natural-origin stand-types, and (2) enhancing end-product value through the use of PCT and CT within plantations, was evaluated. As demonstrated through these simulations, this ecologically-based model enables forest practitioners to rank alternative crop plans in order to select the most applicable one for a given objective. Additionally, the model provides annual and rotational estimates of volumetric, biomass and carbon yields, log distributions,

recoverable products and monetary values, and fibre attributes, at both the diameter-class and stand levels. Although the results of these simulations are largely dependent on the input parameter settings (e.g., treatments (establishment densities, thinning treatments, site classes, rotation ages, product degrade values, variable and fixed cost profiles), the results readily illustrates the potential utility of the model in sustainable forest management.

The importance of the model in managing forest resources for the production high value solid wood products, bio-energy feed stocks, carbon credits, and ecosystem services including biodiversity, is explicitly acknowledged in the model's structure and output. Consequently, the model should be of utility as forest managers migrate to a value-added management proposition and attempt to address diverse objectives under varying constraints.

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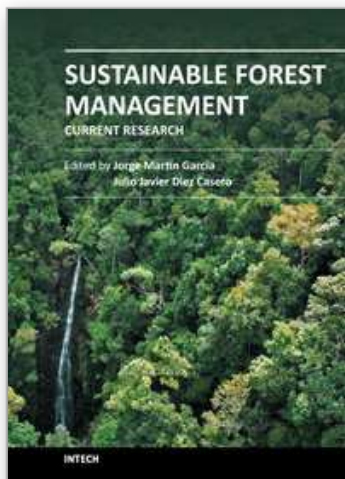
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Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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