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Croplanner: A Stand Density Management Decision-Support Software Suite for Addressing Volumetric Yield, End-Product and Ecosystem Service Objectives When Managing Boreal Conifers

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Abstract: The objectives of this study were to develop a stand density management decision-support software suite for boreal conifers and demonstrate its potential utility in crop planning using practical deployment exemplifications. Denoted CP_{DSS} (CroPlanner Decision-support Software Suite), the program was developed by transcribing algorithmic analogues of structural stand density management diagrams previously developed for even-aged black spruce (*Picea mariana* (Mill) BSP.) and jack pine (*Pinus banksiana* Lamb.) stand-types into an integrated software platform with shared commonalities with respect to computational structure, input requirements and generated numerical and graphical outputs. The suite included 6 stand-type-specific model variants (natural-origin monospecific upland black spruce and jack pine stands, mixed upland black spruce and jack pine stands, and monospecific lowland black spruce stands, and plantation-origin monospecific upland black spruce and jack pine stands), and 4 climate-sensitive stand-type-specific model variants (monospecific upland black spruce and jack pine natural-origin and planted stands). The underlying models which were equivalent in terms of their modular structure, parameterization analytics and geographic applicability, were enabled to address a diversity of crop planning scenarios when integrated within the software suite (e.g., basic, extensive, intensive and elite silvicultural regimes). Algorithmically, the Windows® (Microsoft Corporation, Redmond, WA, USA) based suite was developed by recoding the Fortran-based algorithmic model variants into a collection of VisualBasic.Net® (Microsoft Corporation, Redmond, WA, USA) equivalents and augmenting them with intuitive graphical user interfaces (GUIs), optional computer-intensive optimization applications for automated crop plan selection, and interactive tabular and charting reporting tools inclusive of static and dynamic stand visualization capabilities. In order to address a wide range of requirements from the end-user community and facilitate potential deployment within provincially regulated forest management planning systems, a participatory approach was used to guide software design. As exemplified, the resultant CP_{DSS} can be used as an (1) automated crop planning searching tool in which computer-intensive methods are used to find the most appropriate precommercial thinning, commercial thinning and (or) initial espacement (spacing) regime, according to a weighted multivariate scoring metric reflective of attained mean tree size, operability status, volumetric productivity, and economic viability, and a set of treatment-related constraints (e.g., thresholds regarding intensity and timing of thinning events, and residual stocking levels), as specified by the end-user, or (2) iterative gaming-like crop planning tool where end-users simultaneously contrast density management regimes using detailed annual and rotational volumetric yield, end-product and ecological output measures, and (or) an abbreviated set of rotational-based performance metrics, from which they determine the most applicable crop plan required for attaining their specified stand-level objective(s). The participatory approach, modular computational structure and software platform used in the formulation of the CP_{DSS} along with its exemplified utility, collectively provides the prerequisite foundation for its potential deployment in boreal crop planning.

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Keywords: CP_{DSS}; automated and iterative; initial espacement; precommercial thinning; commercial thinning; climate change; Fortran and VB.NET®; rotational performance metrics; stand visualization

1. Introduction

Stand density management is the process of controlling stand dynamics and successional pathways through the regulation of population densities, self-thinning rates and size-density trajectories, horizontal and vertical stand structure developmental patterns, species composition and intra-specific and inter-specific intertree competitive relationships, via the deployment of informed site occupancy manipulation treatments. In the temperate and boreal forest biomes of Canada these treatments have consisted principally of initial espacement (IE; initial spacing), precommercial thinning (PCT) and commercial thinning (CT) [1]. Operationally, these treatments should be implemented in accordance with rotational-based crop plans that have been designed to achieve specified volumetric yield, end-product and ecological-based stand-level objectives. Optimally, these stand-level objectives should be derived within a forest-level context and hence their realization ultimately contributes to the attainment of estate-level management objectives (sensu [2,3]). Representative examples include (1) increasing annual allowable cut allocations through the allowable cut effect arising from IE-induced accelerated growth, (2) mitigating the effects of forecasted wood supply deficits by accelerating the attainment of stand operability status via PCT, and (3) enhancing overall fiscal worth and operational viability through increased diversification of end-product potential via CT.

Historically, stand density management decision-making has been guided by universal theoretical forest production constructs (e.g., [4–6]), empirical inferences extracted from species, locale, site and treatment specific field experiments (e.g., [7–12]), site and age invariant spacing indices (e.g., [13,14]), and empirical variable-density yield tables (e.g., [15–17]). More recently, a range of comprehensive modelling platforms that enable the simultaneous forecasting and contrasting of site-specific volumetric yield, end-product and (or) ecosystem service outcomes to a broad array of density management scenarios, have been advanced. Such examples include (1) individual-tree distance-independent models such as TIPSY (Table Interpolation Program for Stand Yields) and MGM (Mixedwood Growth Model) developed for conifers in western Canada (sensu [18,19], respectively), (2) stand-level distance-independent average-tree yield models such as SDMDs (Stand Density Management Diagrams) developed for intensively managed conifers in central and eastern Canada (e.g., [20–26]), and (3) hybrid stand-level distance-independent average tree and size-distribution yield models such as SSDMDs (Structural SDMDs) developed for boreal conifers in central Canada [27–30]. Irrespective of the analytical approach, the complexity of these models requires the provision of user-friendly software analogues in order to facilitate their deployment in operational forest management planning (e.g., formulating stand-level rotational crop plans inclusive of density management treatments (IE planting densities and the intensity and timing of thinning treatments)). Optimally, such software tools should be designed in accordance with the specific requirements of the end-user community (e.g., industrial and governmental silviculturists and forest practitioners; sensu [31]) in order to facilitate statutory approval and operational acceptance within provincially regulated forest management planning systems (e.g., TIPSY in British Columbia [18], MGM in Alberta [19], and static SDMDs in Ontario [25]).

Currently, however, with respect to the dynamic SDMD and SSDMD variants developed for boreal stand-types in central Canada, only Fortran-based algorithmic analogues have been developed to date [27–30,32–37]. Although computationally efficient, the numeric and tabular reporting focus of these programs along with their lack of interactive graphical user interface (GUI) functionalities, has hinder their operational deployment. Consequently, more robust and user-friendly software programs are required to enable their successful adoption. Additionally, the processing power of conventional desktop and laptop computers has evolved to a level where the development of on-board searching algorithms for identifying optimal crop plans for given stand-level objectives, is now readily achievable. Such computational advancements in which computer-intensive searching applications can identify optimal crop plans can supplement and (or) replace the traditional time-consuming iterative (gaming-like) crop planning procedures, frequently deployed when using SDMD-based models. Consequently, the goal of this study was to present such a solution to these software-related challenges through the introduction of the CroPlanner Decision-support Software Suite (denoted CP_{DSS}). Specifically, the objectives of this study were to describe the development of this stand density management decision-support system and associated algorithmic analogue, and subsequently demonstrate its potential utility in boreal crop planning. More precisely, the overall programming approach and the associated algorithmic structure of the suite is summarized and operationally relevant exemplifications that demonstrate the suite's potential utility in stand-level management planning are presented, inclusive of both automated and iterative crop planning examples.

Preliminaries: Analytical History, Model Structure and Computational Flow of SSDMDs

The historical lineage of the SSDMD modelling approach can be characterized as a systematic progression of increasing analytical complexity demarcated by 3 principal model variants [38]: 2-dimensional (size-density) static SDMDs [25,39,40] $\rightarrow$ 3-dimensional (size-density-time) dynamic SDMDs [20,41] $\rightarrow$ n-dimensional (size-density-time-distributional) structural SDMDs [27–30,42]. Briefly, deploying theoretical constructs and associated functional yield-density relationships derived from density control experiments established during the 1950′s (e.g., reciprocal equations of the competition-density and yield-density effect [43,44], and the $-3/2$ power law for self-thinning [45]), Japanese researchers were the first to mathematically formulate and introduce the SDMD to the forest science and management communities (e.g., [39]). Although volumetric-based objectives were well addressed by the static and dynamic SDMD variants (e.g., [20,21,25,40,41,46]), management requirements for accommodating additional end-product and ecosystem service objectives, eventually lead to the development of a much more analytically complex model variant: the structural SDMD (e.g., [27]). This latest iteration of the SDMD modelling concept arose principally through model expansion. Specifically, a Weibull-based size distribution parameter prediction equation system was integrated into the dynamic SDMD modelling framework which enabled the recovery of the underlying diameter distribution at any point in a stand's size-density trajectory [47,48]. Later through the introduction of additional modules for recovering height, log, biomass, carbon, and end-product distributions, yielded the modular-based structural SDMD [27]. Currently such structural model variants have been parameterized for 6 boreal stand-types deploying Ontario-centric data bases: upland natural-origin (naturally regenerated stands without a history of density regulation) and managed (naturally or artificially regenerated stands with a history of density regulation) jack pine (*Pinus banksiana* Lamb.; [27]; henceforth denoted PNb_N and PNb_M, respectively) and black spruce (*Picea mariana* (Mill) BSP) stand-types; [30]; henceforth denoted PIm_N and PIm_M, respectively), upland natural-origin black spruce and jack pine mixtures ([29]; henceforth denoted $PImPNb_N$), and lowland natural-origin black spruce stands ([28]; henceforth denoted $PIm_{LL\text{-}N}$). Additionally, in order to account for changes in growing environments arising from anthropogenic climate change effects, climate-sensitive variants for the upland black spruce and jack pine natural-origin and plantation stand-types have also been developed (henceforth denoted $PIm_{N(CC),}$ $PNb_{N(CC)}$, $PIm_{M(CC)}$ and $PNb_{M(CC)}$, respectively; sensu [36]).

Analytically, the hierarchical-based structural SDMD consists of six sequentially linked estimation modules, denoted as follows (sensu Figure 1; [27–30]): 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. Paralleling the traditional modelling approach used to develop dynamic SDMDs (sensu [49]), Module A integrates a broad array static and dynamic yield–density relationships most of which are graphically presented within the traditional SDMD graphic. More specifically, based on yield-density relationships (e.g., reciprocal competition-density equation surrogate, self-thinning rule, relative density function), regime-specific temporal size-density trajectories are generated according to the specified site quality (site index), establishment density, genetic worth effect, type and intensity of thinning treatments, density-dependent mortality rate, density-independent mortality rate (operational adjustment factor), and climate change scenario. Genetic worth and thinning growth responses and climate change effects are all embedded within the site-specific height–age models (e.g., [36,50,51], respectively). Collectively, this computational sequence yields an array of annual mean tree and stand level mensurational-based outcome metrics for each specified crop plan (regime). Module B embeds a stand-type-specific (1) parameter prediction equation system for diameter distribution recovery (sensu [52]; parameterized using the cumulative density function regression approach [53]) which enables the prediction of the parameters of the Weibull [54] probability density function from stand-level variables [55], and (2) allometric-based multivariate height-diameter prediction equation for prediction of diameter-class-specific heights [56]. Computationally, the 3-parameter Weibull parameter prediction equation system is populated using output from Module A and subsequently used to recover the grouped diameter-class frequency distribution for each year in a given rotation. Likewise, utilizing Module A output to populate the composite allometric-based multivariate height–diameter function in conjunction with the recovered diameter frequency distribution, enabled the generation of the corresponding height distribution. Module C deploys species-specific nonlinear dimensional-compatible taper equations (i.e., functions developed jack pine and black spruce by Sharma and Zhang [57] and Sharma and Parton [58], respectively) for predicting stem product yields (number of pulp and saw logs) and total and merchantable stem volumes at the individual tree, diameter class and stand levels. Computationally, the composite taper equation is populated using output from Modules A and B, thus enabling the estimation of upper stem diameters for each tree within each recovered diameter-class. In accord with end-user-defined merchantability specifications, annual and rotational estimates of the number and type of logs potentially extractable along with total and merchantable stem volume estimates, are subsequently generated at the diameter-class and stand levels. Module D entailed the employment of species-specific composite multivariate allometric-based biomass equations from which the above-ground total and component (bark, stem, branch and foliage) biomass (i.e., Newton's equations (2006) for black spruce [35] and Newton's equations (2009) for jack pine [27]) and associated carbon-based equivalent mass estimates, are generated at the individual tree level and subsequently scaled to the diameter-class and stand levels. Computationally, the composite multivariate allometric-based biomass equations are populated using output from Modules A and B, thus yielding annual and rotational biomass estimates, and associated carbon-based mass equivalents. Module E utilizes species and sawmill (stud and random length mill) specific product and value equations to predict diameter-class and stand-level estimates of recoverable volumes of chip and lumber products along with their associated monetary worth values (n., derived from Optitek sawing simulator [59] output [27,60,61]). These composite sawmill-specific product recovery and value equations are similarly populated using output from Modules A and B. Furthermore, product fiscal values are adjusted for inflation based on the year of simulation, and used in conjunction with establishment, thinning and harvesting (stumpage, logging, transportation and manufacturing) variable and fixed cost estimates, to generate a set of economic performance metrics for each sawmill-processing protocol (e.g., land expectation value). Module F encompasses the employment of species-specific (1) composite functions for estimating mean whole-stem wood density, and mean maximum branch diameter within the 1st-order 5 m sawlog, and (2) hierarchical mixed-effects prediction models [37,62] for estimating rotational end-product-related fibre quality attributes (wood density, microfibril angle, modulus of elasticity, fibre coarseness, tracheid wall thickness, tracheid radial diameter, tracheid tangential diameter and specific surface area values at the breast-height (1.3 m) stem position; sensu [63]). Computationally, these prediction equations are populated using output from Modules A and B which ultimately enables the generation of diameter-class-specific and (or) weighted mean stand-level estimates for (1) whole-stem wood density, (2) maximum branch diameter for 1st-order sawlogs, and (3) a suite of Silviscan-based xylem fibre attributes (i.e., wood density, microfibril angle, modulus of elasticity, fibre coarseness, tracheid wall thickness, tracheid radial and tangential diameters and specific surface area).

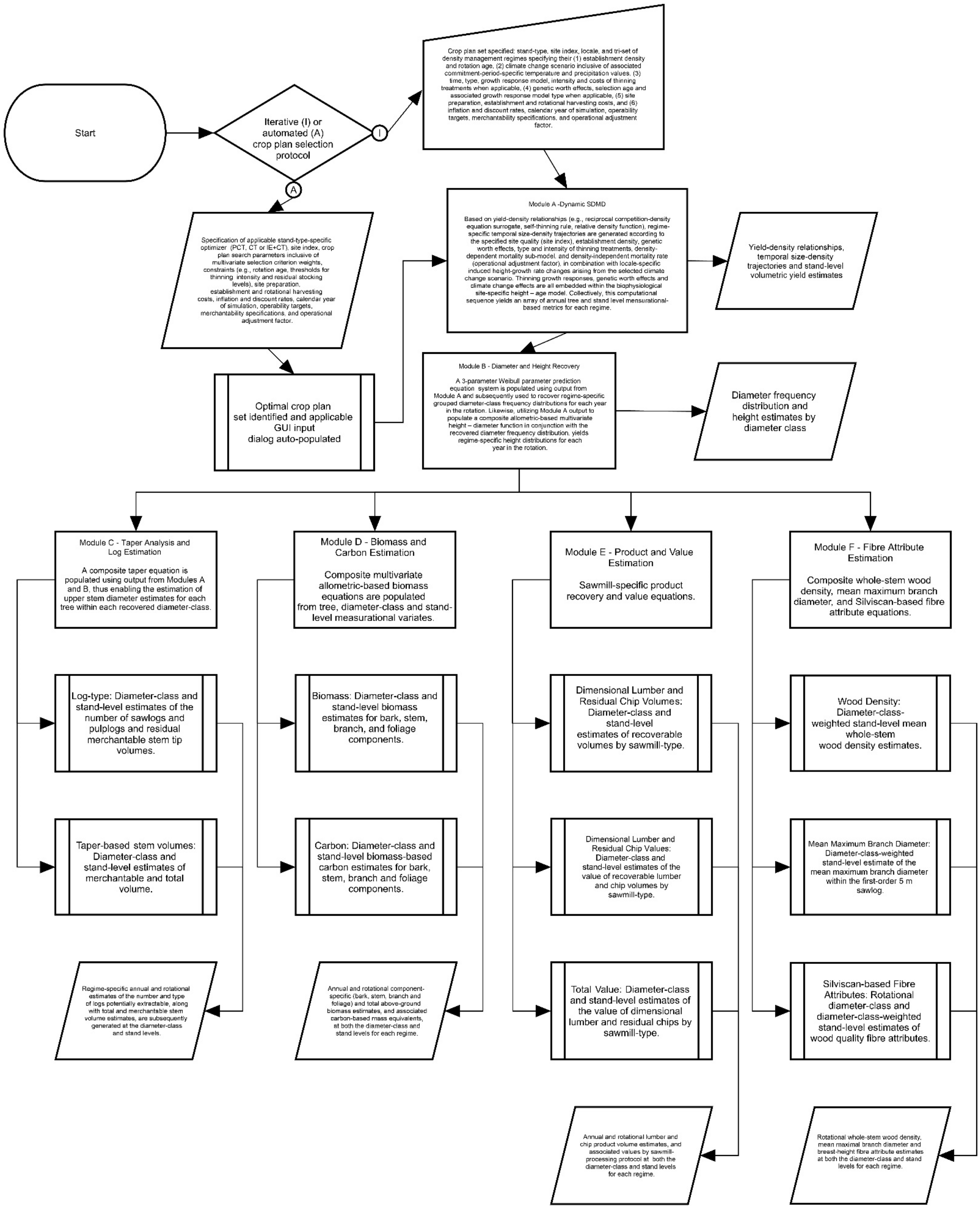


Figure 1. Schematic illustration of the CP_{DSS}: flowchart of the computational sequence and hierarchical algorithmic structure inclusive of input requirements, decisional pathways and output produced.

Collectively, this analytical and computational framework enables the prediction of a multitude of annual and rotational metrics related to volumetric productivity, biomass and carbon outcomes, log product distributions, sawmill-specific chip and lumber recoverable product volumes and associated monetary values, and commercial-relevant fibre quality attributes underlying end-product potential. Thus providing the prerequisite information for evaluating and comparing crop plans in terms of their ability of attaining specified volumetric yield, end-product and ecological-based stand-level management objectives. Furthermore, when augmented by the inclusion of biophysical site index functions, the structural SDMD provides the functionality to crop plan under various climate change scenarios.

2. Materials and Methods

2.1. Guiding Principles Underlying Software Design

Five important considerations governed the approach used to design and develop the CP_{DSS}. Firstly, the suite had to be consistent with the needs of the potential end-user community which was identified as operational silviculturists, stand-level management planners, and practicing foresters. This requirement was attained by implementing a participatory process in which recommendations from an Ontario-centric interagency advisory team consisting of scientists, knowledge exchange enablers, policy and informatics specialists, and forest practitioners, from the primary receiving organizations (industrial forest sector corporations and governmental regulatory agencies), were used to guide software design (sensu [31]; see Acknowledgements). Secondly, the resultant algorithm had to have the capability of being utilized as a gaming-type simulation model in which end-users could iteratively determine their optimal crop plan for given volumetric yield, end-product and ecological based objectives, by simultaneously contrasting regime-specific density management outcomes using detailed annual output metrics and/or an abbreviated set of rotational-based performance indicators. Thirdly, the algorithm had to also provide an alternative computer-intensive option for determining the optimal regime for a set of commonly considered density management scenarios, in order to leverage the computational power of conventional desktop and laptop computers. Specifically, this was achieved through the development and subsequent integration of a set of optimization applications for automatically determining the optimal PCT, CT or IE+CT based density management regime according to the end-user-specified multivariate selection criteria and constraint set. Fourthly, as a prerequisite to algorithm formulation, the analytics of each SSDMD had to be successfully vetted and subsequently presented within the peer-reviewed scientific literature (e.g., [27–30,35–37,47,48,50,51,55,56,62,64]). Fifthly, all supporting material including publication reprints, numerical yield table output, graphical evaluation results and variable definition and interpretation guides, were to be explicitly included within the suite, graphical user interfaces would be self-explanatory via the use of supplemental on-screen cursor-activated textual descriptions, and program execution and operation would be intuitive and easily to comprehend by the targeted end-user community without the need for extensive training or referral inquires.

2.2. Algorithm Formulation

The first step was to develop an updated Fortran 95/90/77-compliant software suite deploying the Lahey/Fujitsu Fortran 95 compiler (Lahey Computer Systems Inc., Incline Village, NV, USA) in which all previously developed SSDMD algorithmic analogues [27–30] and associated computational and modelling enhancements developed to date, were recoded and merged into a single integrated algorithm. These enhancements specifically included the following: (1) computational advancements which ensured mathematical compatibility among yield predictions, allowance for density-independent mortality via the implementation of an operational adjustment factor, accounting for response delay following thinning using a crown occupancy based criterion, and increased flexibility in terms of input parameter settings for merchantability standards, product degrade factors to account for the potential overestimation of the recoverable chip and lumber product volumes and associated fiscal worth estimates that can arise when using of equations parameterized utilizing virtual-based output derived from sawmill simulation studies, and fixed and variable cost assumptions (c.f., [27] versus [30]); (2) integration of sub-models for genetic worth effects that accounted for user-specified age-specific selection gains via a height-growth modifier in combination with a temporal phenotypic juvenile-mature correlative decay function [50]; (3) similar to (2), integration of sub-models for thinning response effects that account for anticipated growth rate increases arising from the release of density-dependent repression effects via the deployment of a height growth modifier [51]; (4) incorporation of climate-driven biophysical site index functions [65] within the upland black spruce and jack pine SSDMDs [36], yielding new climate-sensitive variants for simulating localized crop plans under end-user-specified emission scenarios over 3 commitment periods (2010–2040, 2041–2070, 2071–2100; see [36] for a complete analytical description); and (5) integration of mixed-effects hierarchical fibre attribute equation suites for predicting commercially-relevant wood quality metrics that underlie end-product potential (i.e., wood density, microfibril angle, modulus of elasticity, fibre coarseness, tracheid wall thickness, tracheid radial and tangential diameters and specific surface area [37,62]).

Although the underlying SSDMDs were developed and calibrated with boreal Ontario-centric data bases, the geographic scope of the CP_{DSS} was provisionally expanded by introducing regional-specific site index functions. Specifically, end-users who wish to deploy the suite in other parts of the Canadian boreal forest region, can select their respective provincial-specific site index models through the regional setting within the GUI input dialog panel. To briefly summarize, once the region is specified, the program will simulate the crop plan set using one of the following species-specific site index models that is unique to one of the four provincial jurisdictions considered: (1) Ontario and Manitoba non-climate-sensitive simulations deploy either Sharma's [65,66] or Carmean's [67,68] species-specific functions for 5 upland stand-types (PIm_N, PIm_M, PNb_N, PNb_M and $PImPNb_N$) in accord with the end-user specified choice, and Newton's function for the lowland black spruce stand-type ($PIm_{LL\text{-}N}$) [69]; (2) Ontario climate-sensitive simulations utilize Sharma's species-specific functions [65] for the monospecific natural-origin and managed upland stand-types ($PIm_{N(CC)}$, $PNb_{N(CC)}$, $PIm_{M(CC)}$ and $PNb_{M(CC)}$); (3) Quebec simulations deploy species-specific functions developed by Pothier and Savard [70] for 5 upland stand-types (PIm_N, PIm_M, PNb_N, PNb_M and $PImPNb_N$), and Newton's function for the lowland black spruce stand-type ($PIm_{LL\text{-}N}$) [69]; (4) New Brunswick simulations employ species-specific functions developed by Ker and Bowling for the 4 monospecific upland stand-types (PIm_N, PIm_M, PNb_N, and PNb_M) [71]; and (5) insular Newfoundland simulations for the 2 upland black spruce stand-types (PIm_N and PIm_M) utilize the function developed by Newton [72]. End-users should note that the suite's regional applicability and resultant yield prediction accuracy requires verification when used outside of the concentrated geographic scope of the data sets utilized during the parameterization of the underlying SSDMDs (i.e., boreal Ontario).

2.3. Optimizers

The suite was augmented by the inclusion of computer-intensive optimization applications (Fortran 95/90/77-compliant executable algorithms) designed to automatically determine the optimal crop plan for 3 common crop planning challenges. Specifically, the first application addresses PCT decision-making with regard to determining crop plans that require the least amount of time to attain operability status as defined by threshold piece-size and merchantable volume thresholds. In eastern and central Canada, applying a single PCT treatment within over-stocked juvenile stands which regenerated naturally following a stand-replacing disturbance, is a frequently deployed silvicultural strategy used to accelerate stand operability status (harvestability). Thus potentially assisting in mitigating the effects of forecasted future wood-supply deficits arising from unbalanced forest age structures via the allowable cut effect. The second application is for CT decision-making within well-stocked plantations where the stand-level objectives are to capture expected merchantable volume losses arising from density-dependent mortality within the larger size classes during the later stages of stand development, and enhance rotational fiscal worth through end-product diversification. Although similar to the second application, the third application is for assisting novel crop planners in determining the optimal IE and CT combination that yields the greatest increases in mean tree size, merchantable volume productivity and economic worth, relative to unthinned plantations. Even though the required searching input parameters across all 3 applications share commonalities with respect to information pertaining to site quality, initial establishment densities, rotation ages, operational adjustment and product degrade factors, economic assumptions, and merchantability specifications, they do differ in their analytical focus, stand-type applicability, and treatment specifics (density manipulations) and associated searching intensities that are unique to IE, PCT, and CT. Consequentially, as follows, a detailed description is provided for each optimizer.

The first application which is applicable to natural-origin stand-types (PIm_N, PNb_N, $PImPNb_N$ and $PIm_{LL\text{-}N}$) of boreal Ontario and denoted the PCT operability optimizer, essentially involves the selection of the optimal PCT regime in terms of the timing (stand age) and intensity (number of trees per unit area removed) of thinning treatments required to achieve operability status in the least amount of time. More precisely, this application searches and finds the optimal site-specific crop plan deploying a weighted criterion-based metric derived from relative differences between thinned and comparable untreated natural-origin stands. The metric is based on the differentials in the time required to attain operability status, mean tree size (quadratic mean diameter), and land expectation values, between the PCT and non-PCT stands that have identical crop planning settings in terms of site index, initial establishment density, maximum rotation age, operational adjustment and product degrade factors, economic assumptions and merchantability specifications. Quantitatively, this involves the calculation of a composite (tri-variate) proportional-based relative score (I_{PCT}; Equation (1)): relative difference between the *i*th PCT regime and the corresponding unthinned regime in the time required to attain operability status multiplied by it's importance weight, plus the relative difference between the *i*th PCT regime and the corresponding unthinned regime in the attained quadratic mean diameter multiplied by it's importance weight, plus the relative difference between the *i*th PCT regime and the corresponding unthinned regime in attained mean land expectation value (average of the values generated under the stud and random length sawmill processing protocols) multiplied by it's importance weight.

$$I_{PCT} = \left(\frac{T_{OS(C)} - T_{OS(i)}}{T_{OS(C)}} \right) \cdot O_W + \left(\frac{D_{Q(i)} - D_{Q(C)}}{D_{Q(C)}} \right) \cdot S_W + \frac{\left(\frac{L_{E(S)}^{T(i)} - L_{E(S)}^{C}}{L_{E(S)}^{C}} \right) + \left(\frac{L_{E(R)}^{T(i)} - L_{E(R)}^{C}}{L_{E(R)}^{C}} \right)}{2} \cdot E_W \quad (1)$$

where $T_{OS(C)}$ and $T_{OS(i)}$ are the time to operability status (yr) of the control regime and the *i*th PCT regime, respectively, O_W is the specified relative importance weight for operability (proportion), $D_{Q(C)}$ and $D_{Q(i)}$ are the quadratic mean diameter (cm) at time of the attainment of operability status, of the control regime and the *i*th PCT regime, respectively, S_W is the specified relative importance weight for mean tree size (proportion), $L_{E(m)}^{C}$ and $L_{E(m)}^{T(i)}$ are the land expectation values at time of the attainment of operability status for the *m*th sawmill processing protocol (stud and randomized length denoted by S and R, respectively), for the unthinned control stand and the *i*th PCT stand, respectively, and E_W is the specified relative importance weight for economic efficiency (proportion). Computationally, for a given stand-type, site quality, initial density, rotation age, cost structure, range of thinning ages and removal densities, operability criteria, set of merchantability criteria, threshold height-diameter limit and proportional-based importance weights for each of the 3 core criteria (reduction in time to operability, and increases in mean tree size and economic worth), the optimizer evaluates all potential regimes within the designated search space and selects the best one relative to comparable unthinned control stands. Note, the treated regimes involve a single PCT treatment and the simulations can accommodate either of the 2 thinning growth response sub-models (minimum and maximum) along with a null model option (sensu [51]).

The second application which is applicable to the managed stand-types (PIm_M and PNb_M) of boreal Ontario and denoted the value management CT optimizer, involves the selection of the optimal commercial thinning regime within either black spruce or jack pine plantations. Specifically, the CT-optimizer searches and finds the optimal site-specific crop plan deploying a weighed criterion-based metric derived from the relative differences in mean tree size (quadratic mean diameter), merchantable volume productivity (mean annual increment), and land expectation values, between the candidate thinned plantation and the corresponding unthinned plantation. The underlying simulations deploy identical crop planning settings with respect to site index, initial establishment density, rotation age, genetic worth and selection age, operational adjustment and product degrade factors, economic assumptions, and merchantability specifications. Quantitatively, the composite proportional-based relative scoring metric is calculated as follows (I_{CT}; Equation (2)): the relative difference between the ith CT regime and the comparable unthinned regime in quadratic mean diameter at rotation multiplied by the specified importance weight for mean size, plus the relative difference between the ith CT regime and the corresponding unthinned regime in mean annual merchantable volume increment over the rotation multiplied by the specified importance weight for volumetric productivity, plus the relative difference between the ith CT regime and the corresponding unthinned regime in mean land expectation value (average of the values generated under the stud and random length sawmill processing protocols) multiplied by the specified importance weight for economic efficiency.

$$I_{CT} = \left(\frac{D_{Q(i)} - D_{Q(C)}}{D_{Q(C)}}\right) \cdot S_W + \left(\frac{V_{M(i)} - V_{M(C)}}{V_{M(C)}}\right) \cdot V_W + \frac{\left(\frac{L_{E(S)}^{T(i)} - L_{E(S)}^{C}}{L_{E(S)}^{C}}\right) + \left(\frac{L_{E(R)}^{T(i)} - L_{E(R)}^{C}}{L_{E(R)}^{C}}\right)}{2} \cdot E_W \quad (2)$$

where $V_{M(C)}$ and $V_{M(i)}$ are the mean annual increment (m^3/ha/yr) at rotation for the control regime and the ith CT regime, respectively, and V_W is the specified relative importance weight for merchantable volumetric productivity (proportion). Computationally, for a given stand-type, site quality, initial spacing, rotation age, genetic worth and selection age, operational adjustment factor, product degrade value, cost structure, range of CT thinning times and CT removal densities, operability criteria, merchantability specification set, maximum height-diameter ratio threshold, minimum required thinning yield, and set of proportional-based importance weights for the 3 core criteria (increases in mean tree size, merchantable volume productivity and economic worth), the optimizer will search all potential CT regimes and select the best one (i.e., crop plan with the maximum weighted proportional score that complies with the minimum pre-treatment basal area of 25 m^2/ha and live crown ratio of 35% regulatory-based thresholds [73]). Note, the treated regimes involve a single CT treatment and the simulations can accommodate the 2 genetic worth response sub-models (temporary or permanent) along with a null response model option (sensu [50]).

The third application which is applicable to the managed stand-types (PIm_M and PNb_M) of boreal Ontario and denoted the value management IE+CT optimizer, involves the selection of the IE and CT treatment combination that yields the maximum CT response with respect to comparable untreated plantations (e.g., equivalent crop plan settings in terms of site index, initial establishment density, rotation age, genetic worth and selection age, operational adjustment and product degrade factors, economic assumptions, and merchantability specifications). Specifically, the IE + CT optimizer searches and finds the optimal site-specific crop plan deploying a weighted criterion-based metric derived from the relative differences in mean tree size (quadratic mean diameter), merchantable volume productivity (mean annual increment), and land expectation value. Computationally similar to that described for the CT-optimizer, the IE + CT optimizer firstly calculates the optimal CT treatment in terms of the time and intensity of treatment for each initial espacement level via the deployment of the composite (tri-variate) proportional-based relative scoring metric (Equation (2)). The resultant scores for each initial espacement regime are then compared and the one yielding the maximum value is considered optimum in terms of generating the largest relative thinning response with respect to comparable unthinned plantations among all IE regimes considered. The input search parameters are similar to those specified for the CT optimizer and deploy identical selection criteria with respect to the CT-based regulatory thresholds [73]. Information with respect to the maximum IE level and the IE searching interval, are the only 2 additional inputs required. It is important to note, that this optimizer does not explicitly compare the relative merits of different initial espacement treatments, rather it identifies the IE density and associated CT treatment combination that would yield the greatest CT-induced increase when measured against a comparable unthinned plantation.

3. Results and Discussion

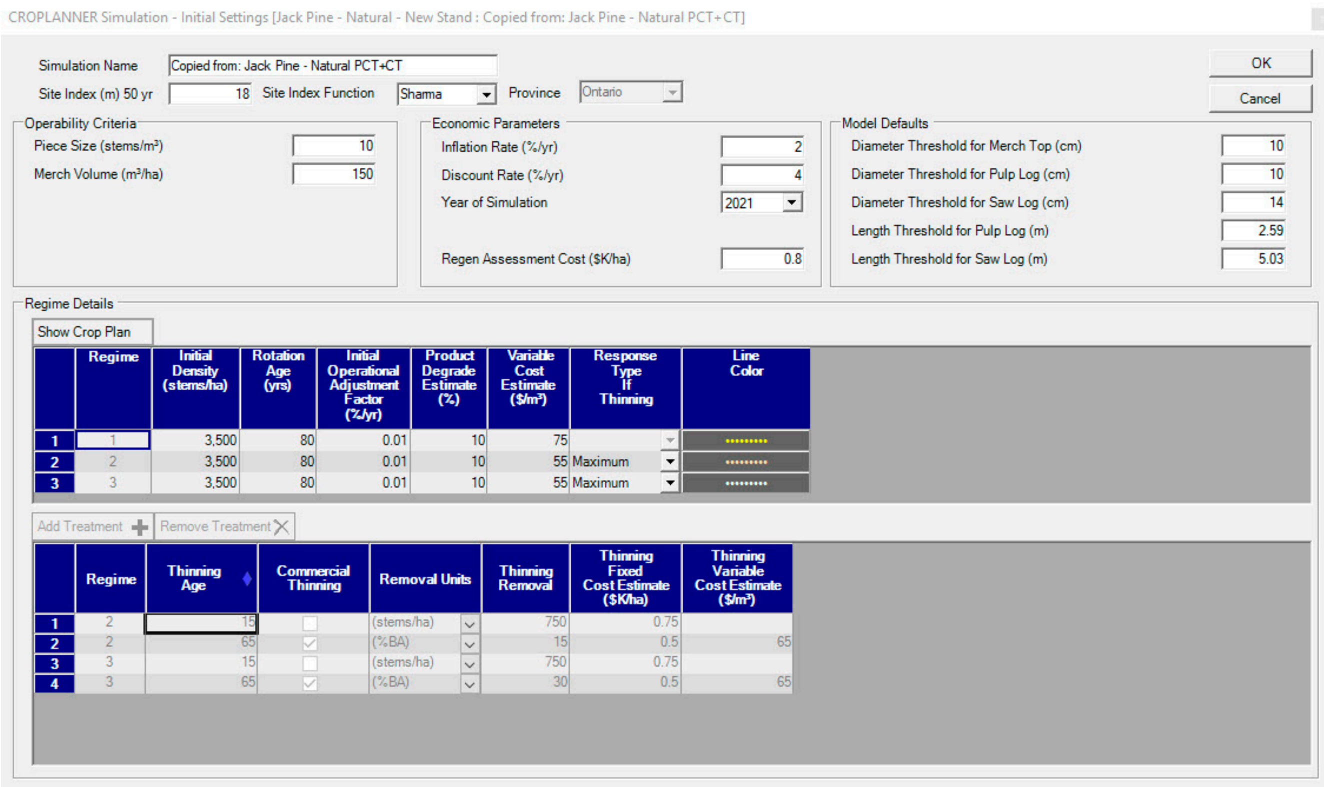
3.1. The Resultant CP_{DSS}: Core Algorithmic Components, Geographic Applicability and Shared Commonalities of Input Requirements, Output Metrics and Reporting Capabilities across All Stand-Type-Specific Variants

Algorithmically, the updated Fortran 95/90/77-compliant software algorithms were translated into the Visual Basic® (VB.NET (Microsoft Corporation, Redmond, WA, USA)) programing language. Interactive input GUI dialogs were designed as per the participatory process and subsequently integrated within the resultant VB.NET (Microsoft Corporation, Redmond, WA, USA) coded program. A third-party open-access tool for visually examining crop plans in terms of their temporal structural dynamics was also embedded. Specifically, the stand visualization system originally developed for the Forest Vegetation Simulator (FVS) software program by McGaughey [74], enables end-users to visualize their selected crop plans in terms of 4-dimensional structural development patterns (temporal (stand age; t) spatially explicit (positional Cartesian coordinates; x-y) tree height (z) structural profiles). Furthermore, within the Visual Studio (VS.NET, Version 2003 (Microsoft Corporation, Redmond, WA, USA)) development environment, enhanced tabular and charting tools were also incorporated (i.e., ProEssentials, Version 6 (Gigasoft Inc., Keller, TX, USA) and Input Pro for Windows Forms, Version 2.5 (FarPoint Technologies Inc., Morrisville, NC, USA), respectively). Executable variants of each of the 3 Fortran-based optimization applications were then integrated along with the necessary input GUI dialog panels (i.e., PCT operability optimizer applicable to natural-origin stand-types, and the value management CT and IE+CT optimizers applicable to the managed stand-types (plantations)). This latter approach retained the computational efficiency of the underlying Fortran-based searching algorithms without the added burden of extensive Fortran-to-VB program code translations. The collective execution of all of these programming steps ultimately yielded the Windows®-based (Microsoft Corporation, Redmond, WA, USA) CP_{DSS} for the Ontario-centric PIm_N, $PIm_{N(CC)}$, PIm_M, $PIm_{M(CC)}$, PNb_N, $PNb_{N(CC)}$, PNb_M, $PNb_{M(CC)}$, $PImPNb_N$ and $PIm_{LL\text{-}N}$ stand-types. Furthermore, by regionalizing the site index functions and thereby potentially expanding the geographic scope of the CP_{DSS}, yielded provisional variants applicable to (1) 6 stand-types in boreal Manitoba and Quebec (PIm_N, PIm_M, PNb_N and PNb_M and $PImPNb_N$ and $PIm_{LL\text{-}N}$), (2) 4 stand-types in New Brunswick (PIm_N, PIm_M, PNb_N and PNb_M), and (3) 2 stand-types in insular boreal Newfoundland (PIm_N and PIm_M).

Although the density management treatment regimes can be explicitly specified by the end-user or predetermined via the computationally intensive optimizers, all CP_{DSS} simulations share a set of core input requirements and produce similar tabular and graphical outputs, irrespective of stand-type or region. Specifically, in terms of input requirements after the selection of the automated crop planning functionality (Optimizers), end-users are required to select 1 of the 3 optimizer offerings (PCT in natural-origin stand-types, CT within plantation stand-types, or IE + CT within plantation stand-types) and enter the specific information requested via the optimizer-specific GUI input dialog screen. For the Operability Optimizer, the required input includes the specification of the stand-type, site index, initial density, rotation age, operational adjustment and product degrade factors, rotational variable cost estimates, range of thinning ages and removal densities, minimum residual crop density following PCT, fixed cost estimate for PCT, operability targets (minimum number of merchantable sized trees per cubic metre of merchantable volume (piece size); and minimum total merchantable volume per hectare), inflation and discount rates, year of simulation, set of merchantability specifications, rotational threshold height-diameter limit and proportional-based importance weights for each of the 3 core selection criteria (time to operability, mean tree size attained, and economic efficiency). For the Value Management Optimizer–CT, the required input includes the specification of the stand-type, site index, initial planting density, rotation age, genetic worth parameters (expected increased at the specified selection age), operational adjustment and product degrade factors, rotational variable cost estimates, range of thinning ages and removal densities, fixed and variable CT cost estimates, minimum residual crop density following CT, minimum merchantable volume removed during CT, operability targets (minimum number of merchantable sized trees per cubic metre of merchantable volume (piece size); and minimum total merchantable volume per hectare), inflation and discount rates, year of simulation, planting and site preparation costs, set of merchantability specifications, threshold height-diameter limit, and proportional-based importance weights for each of the 3 core selection criteria (mean tree size attained, merchantable volume productivity, and economic efficiency). For the Value Management Optimizer–IE + CT, the required input includes all which is specified for the Value Management Optimizer–CT, plus specification of the maximum planting density to consider along with the planting density interval width that ultimately governs the number of initial density regimes to assess. For example, deploying a minimum and maximum initial density limits of 1000 stems/ha and 3000 stems/ha, respectively, and an 100 stems/ha planting density interval, yields consideration of a total of 21 initial espacement levels (i.e., 1000, 1100, 1200, . . . , 3000 stems/ha).

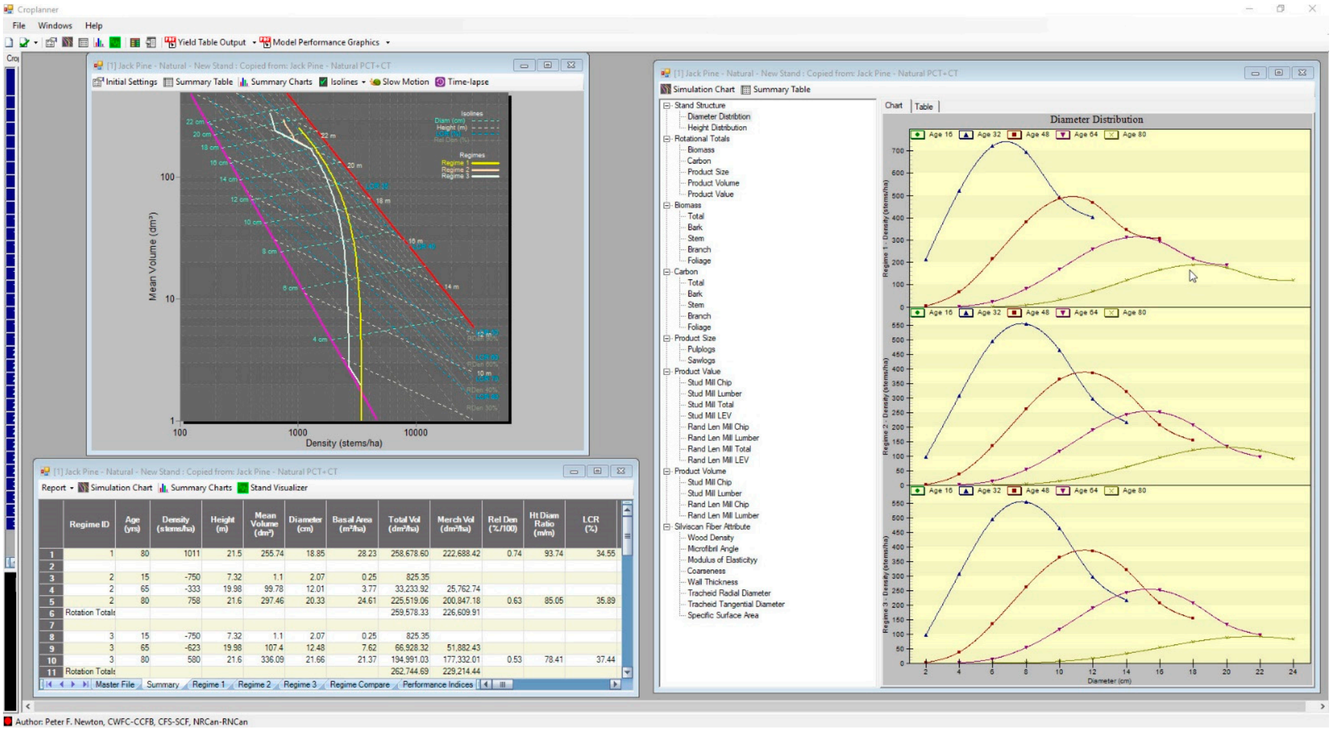
Computationally, the optimizers evaluate all possible crop plans based on the specified initial conditions (e.g., stand-type, site index and establishment densities in the operability variant) and treatment characteristics (e.g., time of CT treatments and removal thinning densities in the CT and IE+CT variants) and then selects the optimal set of crop plans based on their adherence to the imposed constraints and the associated maximum scores achieved. These optimizers are essentially searching algorithms that evaluate all plausible crop plans within the defined search space and selects the one(s) that achieves the maximum composite score while complying with the imposed constraints. Analytically, these optimizers could be characterized as sequential multivariate searching algorithms (sensu Knuth [75]).

Similarly, when deploying the iterative crop plan selection functionally, end-users are required to interactively enter the following information via the GUI input dialog screen: (1) province; (2) stand-type (i.e., natural-origin or managed (plantation) upland black spruce and jack pine stands with or without consideration of localized anthropogenic climate change effects, natural-origin mixed black spruce and jack pine stands, or natural-origin lowland black spruce stands); (3) calendar year and simulation type (i.e., establishment to rotation (new) or simulating partial rotation lengths based of surveyed stand information (existing)); (4) site quality (species, stand-type and regional specific site index); (5) merchantable specifications (i.e., lengths and upper threshold diameters for pulp and saw logs, and the merchantable top diameter threshold), interest and discount rates, operability targets (i.e., maximum number of merchantable trees per cubic metric of merchantable wood (piece size) and minimum total merchantable volume per hectare), and establishment costs (e.g., fixed site assessment or preparation expenses and planting costs); (6) 3 regime-specific crop plans, detailing for each, the length of the rotation, establishment density if executing a new stand simulation or current density and stand age if executing a partial rotational stand simulation, expected ingress during the establishment period (n., potentially most applicable to the managed stand-types), genetic worth effects and associated selection age and response model type for plantation stock if applicable, operational adjustment factor, product degrade estimate, composite variable cost estimates which collectively accounts for stumpage fees, renewal charges, and harvesting, transportation and manufacturing expenses, at the time of final harvest, regime-specific thinning treatments and associated cost information including the time of entry (stand age), type of thinning (PCT or CT), removal density (stems/ha) if PCT, or either removal density (stems/ha) or basal area (m^2/ha or % of pre-treatment stand basal area) reduction(s) if CT, and associated fixed and variable thinning expenses; and (7) if selecting the climate sensitive variants, additional information is required for each regime; specifically, for a given climate change scenario the end-user inputs the location-specific precipitation and temperate values for each of the 3 commitment periods (2010–2040; 2041–2070; 2071–2100) either manually or via the auto-populate functionality for 3 pre-selected locales (i.e., northwestern Ontario (Dryden), central Ontario (Thunder Bay) and northeastern Ontario (Kirkland Lake)). All such input requirements are inputted by the end-user directly into the input GUI dialog screen as exemplified in Figure 2a for the unthinned (Regime 1) and thinned (Regimes 2 and 3: PCT of −750 stems/ha at 15 yr and a CT of −15% basal area removal at 65 yr; and PCT of −750 stems/ha at 15 yr plus a CT of −30% basal area removal at 65 yr; respectively) crop plans for natural-origin jack pine stands that established at high initial densities (3500 stems/ha) on medium-to-good site qualities (site index 18) and managed over 80 year rotation lengths. Note, Table 1 also provides a non-GUI tabular account of all the required input parameter settings pertaining to this specific example.



(a)

Figure 2. *Cont.*



(**b**)

Figure 2. (**a**) Exemplification of the generic input GUI dialog structure of the CP_{DSS} when used to simulate 3 potential crop plans for natural-origin jack pine stands established at high densities (3500 stems/ha) on medium-to-good site qualities (site index 18 [65]). In this example, Regimes 1, 2 and 3 denote the 3 specific crop plans simulated over an 80 year rotation length: (1) unthinned control stand (Regime 1); (2) thinned stand consisting of a PCT treatment implemented at an age of 15 yr in which 750 stems/ha were removed followed by a CT treatment at an age of 65 yr in which 15% of the basal area was removed (Regime 2); and (3) thinned stand consisting of a PCT treatment implemented at an age of 15 yr in which 750 stems/ha were removed followed by a CT treatment at an age of 65 yr in which 30% of the basal area was removed (Regime 3). As shown, the required input included the operability criteria, economic parameters, model defaults in terms of merchantability specifications, and regime-specific details regarding initial density, rotation age, operational adjustment and product degrade factors, variable cost estimates at harvest and the magnitude of the thinning response expected. For each thinning treatment, the age of intervention, type (PCT or CT), intensity (number of trees or basal area removed) and cost estimates, are also specified. (**b**) Exemplification of an abridge selection of graphic and tabular outputs derived from the CP_{DSS} when used to simulate the 3 potential crop plans as defined in (**a**). As shown, the resultant crop plans are presented within traditional SDMD graphic (upper left-hand side) along with abridge tabular yield summaries for each crop plan (lower left-hand side), illustration of the graphical reporting options (right-hand side) with the specific presentation of the temporal diameter frequency distributions for each crop plan throughout the rotation (right-hand side). Note, abbreviations Vol, Merch, Rel Den, Ht Diam and LCR refer to volume, merchantable, relative density, height and diameter, and live crown ratio, respectively. Refer to Summary Report SM1 (Supplementary Material) for a complete account of the output produced for this crop plan set.

In relation to commonalities of the output generated, for each rotational year within a given regime, the program generates annual estimates of mean tree mensurational and wood quality related metrics including mean dominant height, quadratic mean diameter, live crown ratio, height-diameter ratio, whole-stem mean wood density, maximum mean branch diameter within 1st-order 5 m sawlog, and stand-level estimates related to stocking (basal area), volumetric yields (merchantable and total volumes) and site occupancy (absolute and relative densities). From a set of these generated mensurational variables, the program recovers the grouped-diameter frequency distribution for each year and extracts for each diameter class the following estimates: total height, number of pulp and saw logs and residual tip volumes, merchantable and total volumes, biomass and carbon mass equivalents for each above-ground component (bark, stem, branch, foliage and total), sawmill-specific (stud and random length) recoverable chip and lumber volumes and associated inflation-adjusted monetary worth equivalents. The diameter class estimates are accumulated to yield additional stand-level estimates which are then used to generate a comprehensive set of rotational performance indices including a suite of end-product-based fibre attributes metrics (e.g., see Table A1; Appendix A). This attribute suite included stand-level basal-area-weighted mean breast-height (1.3 m) estimates of wood density, microfibril angle, modulus of elasticity, fibre coarseness, tracheid wall thickness, tracheid radial and tangential diameters and specific surface area. All output is presented in tabular and (or) graphical formats inclusive of the traditional SDMD graphic as exemplified in Figure 2b. Static and real-time dynamic stand structural silhouettes are also generated for each regime and can be presented in concert with the temporal size-density trajectories as they are displayed in the traditional SDMD graphic.

Table 1. Input parameters for the example CP_{DSS} simulations for natural-origin jack pine stands situated on medium-to-good quality sites subjected to PCT and CT treatments (Figure 2a).

Parameter (Units) [a]	Regime 1 (Unthinned)	Crop Plan [b] Regime 2 (PCT + CT(L))	Regime 3 (PCT + CT(H))
Simulation year	2021	2021	2021
Rotation length (yr)	80	80	80
Initial planting density (seedlings/ha)	3500	3500	3500
PCT: stand age (yr)/number of trees thinned (stems/ha)	-	15/750	15/750
PCT: response model assumption	-	maximum	maximum
CT: stand age (yr)/basal area removal (%)	-	65/15	65/30
Operational adjustment factor (%/yr)	0.01	0.01	0.01
Merchantable Specifications			
Pulp log length (m)/minimum diameter (inside bark; cm)	2.59/10	2.59/10	2.59/10
Saw log length (m)/minimum diameter (inside-bark; cm)	5.03/14	5.03/14	5.03/14
Merchantable top diameter (inside-bark; cm)	10	10	10
Product degrade (%)	10	10	10
Minimum Operability Targets			
Piece-size (merchantable sized stems/merchantable volume; stems/m^3)	10	10	10
Merchantable volume stand yield (m^3/ha)	150	150	150
Economic Parameters			
Interest rate (%)	2	2	2
Discount rate (%)	4	4	4
Regeneration assessment cost (CAN$K/ha)	0.8	0.8	0.8
PCT: fixed cost (CAN$K/ha)	-	0.75	0.75
CT: fixed (CAN$K/ha)/variable costs (CAN$/$m^3$ of merchantable volume removed)	-	0.5/65	0.5/65
Rotational harvesting+stumpage+renewal+transportation+manufacturing variable costs (CAN$/$m^3$ of merchantable volume harvested)	75	55	55

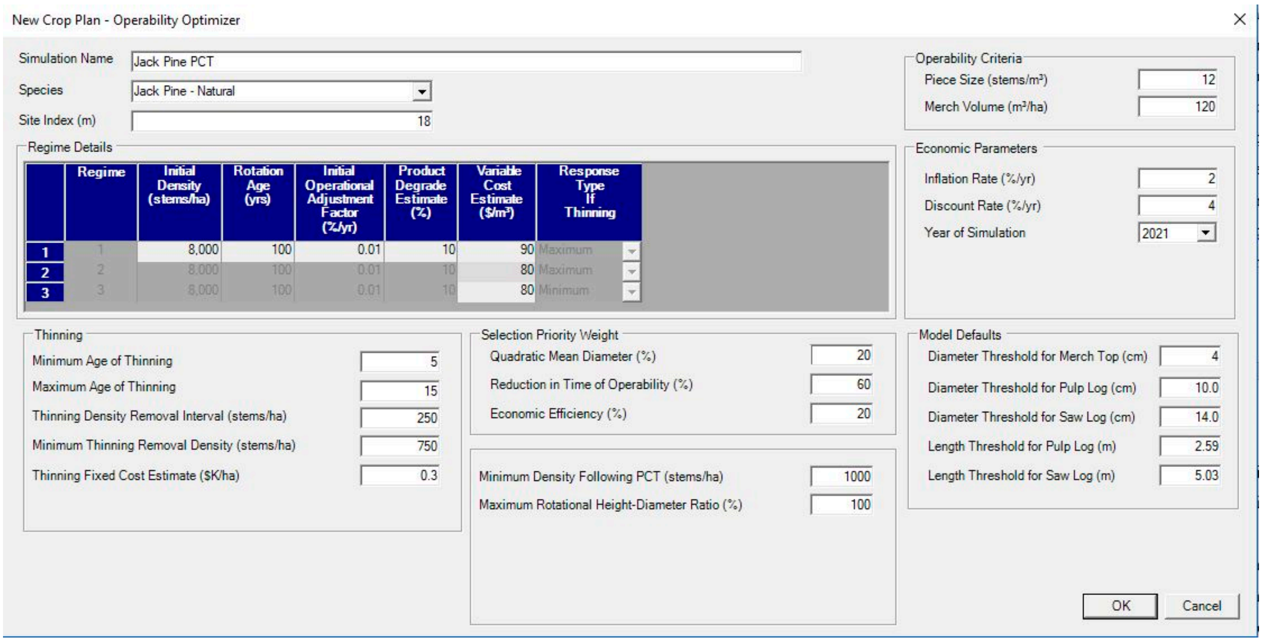
Notes: (1) medium-to-good site quality is defined as having a mean dominant height of 18 m at a breast-height age of 50 yr [65]; and (2) economic rate assumptions, and fixed and variable cost values, are informed approximations (sensu [76]). [a] Operational adjustment factor is the annual mortality rate attributed to non-density-dependent abiotic and biotic causes (e.g., wind throw and pathogens, respectively). Product degrade is an end-user specified allowance for correcting for potential over-estimation arising from the use of product prediction functions derived from virtual sawmill-based simulation studies (sensu [77]). Variable costs for thinning treatments include all on-site equipment-related operating costs and associated stumpage payments, renewal fees, transportation expenses and manufacturing costs, cumulatively expressed as a function of merchantable volume extracted during thinning. Fixed costs for PCT and CT included forest management, operational costs (PCT) and equipment-related transportation fees (CT). Rotational variable costs for final harvesting include all on-site equipment-related operating costs and associated stumpage payments, renewal fees, transportation expenses, and manufacturing costs, cumulatively expressed as a function of merchantable volume harvested. [b] CT(L) and CT(H) are used to nominally differentiate between the regimes in terms of CT treatment intensities: light CT and heavy CT treatments, respectively.

Table 2 also provides a non-GUI tabular summary of the rotational stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product wood quality measures, and productivity and economic indices, considered key decision-support metrics for evaluating and selecting the most appropriate crop plan. In this specific example, the performance metrics indicated that the more intensive CT treatment within the PCT treated stand (Regime 3) was superior to the other regimes (Regime 3 > Regime 2 > Regime 1) in terms of attaining larger rotational mean tree sizes, volumetric productivity, carbon sequestration potential, producing greater volumes of recoverable products (wood chips and dimensional lumber), and maintaining optimal site occupancy levels for a greater temporal duration. In accord with expectation, the heaver CT treatments also elicited increases in the percentage of the above-ground rotational biomass allocated to the crown components (branch and foliage biomass; 23% for Regime 3 versus 14% for Regime 1). Although marginal negative differences were evident for mean maximum branch diameter within the 1st-order sawlog for the CT stands (5%

larger), there were negligible differences in the Silviscan-based wood quality indicators. For a full account of the CP_{DSS} output for this example set of crop plan simulations, refer to the document entitled, Summary Report SM1 in the Supplementary Material section. This MS Excel formatted report is generated from the CP_{DSS} upon request and consists of the (1) master file (regime-specific input summaries), (2) SDMD graphic, (3) crop plan cumulative summaries, (4) annual regime-specific yield details, (5) end-user-selected regime comparisons if specified, and the (6) summary of the key performance indices.

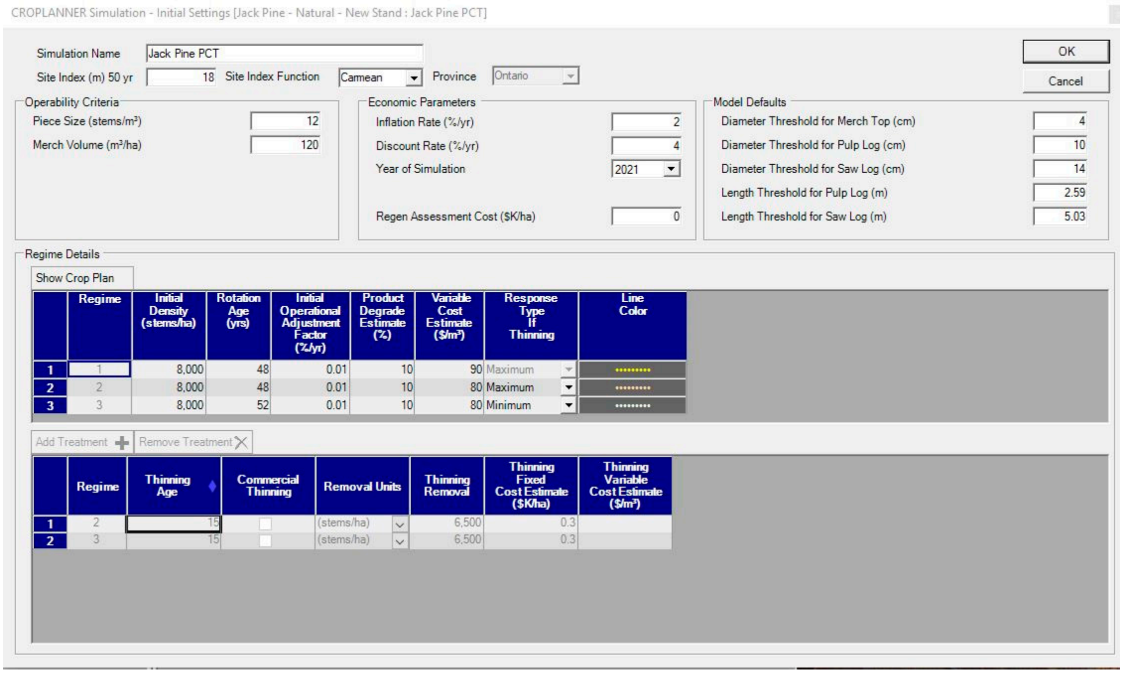
3.2. Exemplification of the Automated Crop Plan Selection Capability of the CP_{DSS}: The PCT Operability Optimizer

Firstly, within the setup screen of the CP_{DSS}, the end-user is required to select from among 3 optimizers which are placed under the File/Optimizer tab, followed by the provision of the necessary input parameter ranges inclusive of the threshold constraint values via the input GUI dialog screen. For example, Figure 3a illustrates the GUI input screen when using the PCT operability optimizer for natural-origin jack pine stands. More specifically, the regimes are specified as follows: Regime 1 is the unthinned control stand; Regime 2 is the PCT stand deploying the maximum thinning growth response modelling assumption [51]; and Regime 3 is the PCT stand deploying the minimum thinning growth response modelling assumption (1/4 of the maximum rate; [51]). Secondly, following execution, the optimizer then returns a set of optimal regimes and automatically populates the CP_{DSS} input screen Figure 3b.

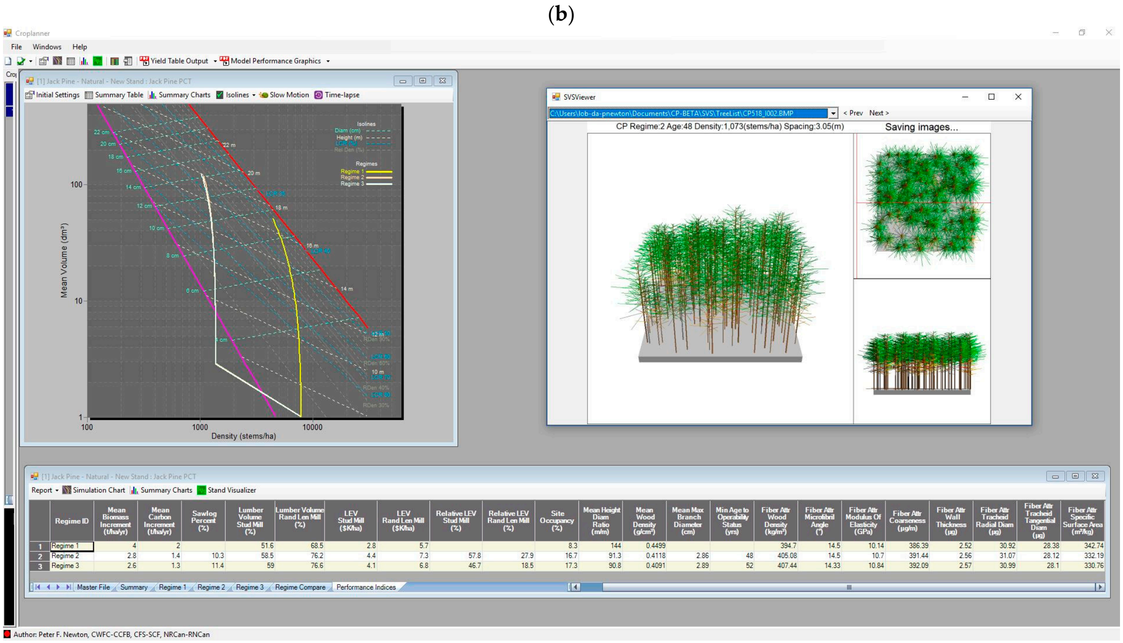


(**a**)

Figure 3. *Cont.*



(**b**)



(**c**)

Figure 3. Exemplifying the automated crop plan selection capability of the CP$_{DSS}$ in regard to determining the optimal PCT regime within natural-origin stand-types (jack pine) via the deployment of the operability optimizer: (**a**) input GUI dialog panel inclusive of end-user required input which consisted of the specification of (i) stand-type, simulation identifier (name), site index and associated function, initial density, maximum rotation age, operational adjustment factor, product degrade, variable cost, thinning response model type, merchantable limits, and operability targets, (ii) treatment specifics and constraints (range of treatment ages, thinning density searching interval (algorithmic-based), minimum removal densities (operational-based), fixed treatment cost, minimum post-thinning residual density; maximum height/diameter ratio), and (iii) multivariate selection priority weights (tree size, operability and economic efficiency); (**b**) auto-populated input GUI dialog panel returned from the optimizer with the selected optimal PCT-based crop plan inclusive of regime-specific revised rotation ages corresponding to the minimum age at which the specified operability status is attained, thinning response model utilized, and the selected optimal time of treatment and associated thinning removal density; and (**c**) resultant optimal crop plans presented within traditional SDMD graphic, tabular summary of rotational performance metrics, and an example stand visualization graphic at rotation (Regime 2). Refer to Summary Report SM2 (Supplementary Material) for a complete account of the output produced for this set of crop plans.

Table 2. Crop-plan-specific rotational (80 yr) outcomes: stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product-related wood quality metrics, and productivity and economic indices, for natural-origin jack pine stands established at high initial densities (3500 stems/ha) growing on medium-to-good quality sites (site index of 18 [65]) which were left unthinned (Regime 1) or subjected to density control treatments (PCT of 750 stems/ha at 15 yr and a CT of 15% basal area removal at 65 yr (Regime 2); and PCT of 750 stems/ha at 15 yr followed by a CT of 30% basal area removal at 65 yr (Regime 3)).

Index [a,b] (Unit)	Crop Plan [c]				
	Regime 1 (Unthinned)	Regime 2 (PCT + CT(L))	(%Δ)	Regime 3 (PCT + CT(H))	(%Δ)
Structural measures					
N (stems/ha)	1011	758	−25	580	−43
H_d (m)	21.5	21.6	0	21.6	0
$\overline{V}$ (dm^3)	255.74	297.46	16	336.09	31
D_q (cm)	18.85	20.33	8	21.66	15
G (m^2/ha)	28.23	24.61	−13	21.37	−24
V_t (m^3/ha)	258.7	259.6	0	262.7	2
V_m (m^3/ha)	222.7	226.6	2	229.2	3
P_r (%/100)	0.738	0.6265	−15	0.5301	−28
L_{cr} (%)	34.55	35.89	4	37.44	8
N_m (stems/ha)	1001	1054	5	1150	15
Biomass and carbon outcomes					
M_p (t/ha)	12.71	15.44	21	17.93	41
M_s (t/ha)	155.54	167.92	8	178.93	15
M_b (t/ha)	17.59	26.82	52	38.69	120
M_f (t/ha)	9.14	13.99	53	20.31	122
M_t (t/ha)	194.98	224.17	15	255.86	31
C_t (t/ha)	97.49	112.09	15	127.93	31
Log product distribution					
$N_{l(s)}$ (logs/ha)	867	894	3	890	3
$N_{l(p)}$ (logs/ha)	2686	2562	−5	2458	−8
Sawmill-specific recoverable product volumes					
$V_{l(s)}$ (m^3/ha)	140.22	150.52	7	158.05	13
$V_{c(s)}$ (m^3/ha)	69.8	69.98	0	71.16	2
$V_{l(r)}$ (m^3/ha)	163.65	173.94	6	183.77	12
$V_{c(r)}$ (m^3/ha)	47.08	45.02	−4	44.91	−5
Rotational performance metrics					
R_{MAI} (m^3/ha/yr)	2.8	2.8	0	2.9	4
R_{BAI} (t/ha/yr)	2.4	2.8	17	3.2	33
R_{CAI} (t/ha/yr)	1.2	1.4	17	1.6	33
R_{SL} (%)	24.4	25.9	6	26.6	9
$R_{LV(s)}$ (%)	66.8	68.3	2	69	3
$R_{LV(r)}$ (%)	77.7	79.4	2	80.4	3
$E_{(s)}$ ($K/ha)	4.4	5.8	32	6.5	48
$E_{(r)}$ ($K/ha)	6.3	7.8	24	8.6	37
S_O (%)	8.8	10	14	11.2	27
S_s (m/m)	110.1	102.6	−7	100.2	−9
O_T (yr)	61	61	0	61	0
$\overline{W}_D$ (g/cm^3)	0.4531	0.4479	−1	0.4452	−2
$\overline{B}_D$ (cm)	2.38	2.49	5	2.49	5
$\overline{W}_d$ (kg/m^3)	407.54	410.76	1	413.52	1
$\overline{M}_a$ (°)	14.2	14.26	0	14.26	0
$\overline{M}_e$ (GPa)	10.98	11.16	2	11.33	3
$\overline{C}_o$ (μg/m)	381.73	386.13	1	389.55	2
$\overline{W}_t$ (μm)	2.55	2.57	1	2.59	2
$\overline{D}_r$ (μm)	30.91	30.94	0	30.94	0
$\overline{D}_t$ (μm)	27.49	27.6	0	27.68	1
$\overline{S}_a$ (m^2/kg)	334.74	331.43	−1	329.01	−2

[a] Predicted rotational values. Denotations: N is total stand density; H_d is mean dominant height; $\overline{V}$ is mean stem volume; D_q is quadratic mean diameter; G is stand basal area; V_t and V_m are total stand volume and total stand merchantable volume inclusive of thinning yields, respectively; P_r is relative density index; L_{cr} is live crown ratio; N_m is total stand merchantable density inclusive of thinning yields; M_p, M_s, M_b, M_f and M_t are periderm (bark), stem, branch, foliage and total stand oven-dried biomass inclusive of thinning yields, respectively; C_t is total stand carbon biomass-equivalent mass inclusive of thinning yields; $N_{l(p)}$ and $N_{l(s)}$ are the total number of pulp logs and saw logs per stand inclusive of thinning yields, respectively; $V_{c(s)}$ and $V_{l(s)}$ are the recoverable wood chip and lumber volumes inclusive of thinning yields extracted under a stud sawmill processing protocol; and $V_{c(r)}$ and $V_{l(r)}$ are the recoverable wood chip and lumber volumes inclusive of thinning yields extracted under a random-length sawmill processing protocol. [b] Performance indices: R_{MAI}, R_{BAI} and R_{CAI} is the mean annual merchantable volume, biomass (total aboveground) and carbon (total aboveground biomass-based equivalent) increments, respectively; R_{SL} is the percentage of saw logs produced inclusive of thinning yields; $R_{LV(s)}$ and $R_{LV(r)}$ are the percentage of lumber volume recovered via stud and randomized length sawmill processing protocol inclusive of thinning yields, respectively; $E_{(s)}$ and $E_{(r)}$ are the land expectation values for a stud and randomized length sawmill processing protocol, respectively; S_o is the percentage of the rotation in which the regime was maintained within the optimal relative density management window after initial attainment of crown closure status; S_s is the mean height/diameter ratio; O_T is the time to operability status as defined by the specified piece-size and merchantability thresholds; $\overline{W}_D$ is mean whole-stem cross-sectional-area weighted density; $\overline{B}_D$ is the mean maximum branch diameter within the 1st-order sawlog; $\overline{W}_d$, $\overline{M}_a$, $\overline{M}_e$, $\overline{C}_o$, $\overline{W}_t$, $\overline{D}_r$, $\overline{S}_a$ and are the mean basal-area weighted fibre attribute values at breast-height for wood density, microfibial angle, modulus of elasticity, fibre-coarseness, tracheid wall thickness, tracheid radial diameter, tracheid tangential diameter and specific surface area, respectively. Refer to Table A1 for a detailed description of the computations used. [c] Percentage differences (Δ) are relative to the control regime (Regime 1).

For this example, according to the specified 20–60–20 mean size-operability-economic selection priority weighting, thinning restrictions (5–15 yr treatment age range; minimum of 750 stems/ha removed; and minimum post-PCT density of 1000 stems/ha), stand structural goal (maximum height/diameter ratio of 100), and economic parameter settings (inflation and discount rates, rotational variable costs), for natural-origin jack pine stands with an establishment density of 8000 trees/ha growing on a site of medium-to-good quality (site index of 18 m [66]), the optimal crop plan in terms of reaching the operability target (12 stems/m^3 and 120 m^3/ha) in shortest amount of time would be: (1) PCT at age 15 yr and removing 6500 stems/ha thus yielding a harvestable stand at 48 yr when deploying the maximum PCT growth response assumption (Regime 2); and similarly (2) PCT at age 15 yr and removing 6500 stems/ha thus yielding a harvestable stand at 52 yr when deploying the minimum PCT growth response assumption (Regime 3). These crop plans were the most optimal among all the other regimes considered that were in compliance with the imposed constraints and included within the specified search space. Essentially, for this specific example, the search consisted of the evaluation of a total of 308 crop plans for each of the PCT growth response modelling assumptions: i.e., 11 potential PCT treatment ages (5–15 yr) and a maximum of 28 PCT removal intensities for each treatment year (initial establishment density (8000 stems/ha) minus the minimum residual stand density (1000 stems/ha) divided by the density searching interval value (250 stems/ha) gives a total of 28 intensities), yields a total of 308 simulations (11 × 28). Note, Table 3 provides a non-GUI tabular account of all the input parameter settings required for this specific example.

Table 3. Summarization of the input parameters deployed in the CP_{DSS} demonstration of the Operability Optimizer for dense natural-origin jack pine stands, as extracted from Figure 3b.

Parameter (Units) [a]	Crop Plan [b] Regime 1 (Unthinned)	Regime 2 (PCT-Maximum)	Regime 3 (PCT-Minimum)
Simulation year	2021	2021	2021
Rotation length (yr)	48	48	52
Initial density (seedlings/ha)	8000	8000	8000
PCT: stand age (yr)/number of trees thinned (stems/ha)	-	15/6500	15/6500
PCT: response model assumption	-	maximum	minimum
Operational adjustment factor (%/yr)	0.01	0.01	0.01
Merchantable Specifications			
Pulp log length (m)/minimum diameter (inside bark; cm)	2.59/10	2.59/10	2.59/10
Saw log length (m)/minimum diameter (inside-bark; cm)	5.03/14	5.03/14	5.03/14
Merchantable top diameter (inside-bark; cm)	4	4	4
Product degrade (%)	10	10	10
Minimum Operability Targets			
Piece-size (merchantable-sized stems/merchantable volume; stems/m^3)	12	12	12
Merchantable volumetric stand yield (m^3/ha)	120	120	120
Economic Parameters			
Interest rate (%)	2	2	2
Discount rate (%)	4	4	4
Regeneration assessment cost (CAN$K/ha)	0	0	0
PCT: fixed cost (CAN$K/ha)	-	0.3	0.3
Rotational harvesting + stumpage+renewal + transportation + manufacturing variable costs (CAN$/$m^3$ of merchantable volume harvested)	90	80	80

Notes: (1) medium-to-good site quality is defined as having a mean dominant height of 18 m at a breast-height age of 50 yr [66]; and (2) economic rate assumptions, and fixed and variable cost values, are informed approximations (sensu [76]). [a] Operational adjustment factor is the annual mortality rate attributed to non-density-dependent abiotic and biotic causes (e.g., wind throw and pathogens, respectively). Product degrade is an end-user specified allowance for correcting for the potential over-estimation arising from the use of product prediction functions derived from virtual sawmill-based simulation studies (sensu [77]). [b] Fixed costs for PCT included forest management and employment expenses. Rotational variable costs for final harvesting include all on-site equipment-related operating costs and associated stumpage payments, renewal fees, transportation expenses, and manufacturing costs, cumulatively expressed as a function of merchantable volume harvested.

Thirdly, using this information, the CP_{DSS} then executes the computational sequence as shown in Figure 1, which generates a full range of graphical and tabular output for the selected optimal regimes along with the comparable unthinned control stand. These include for example, (1) size-density trajectories for the selected crop plans within the context of the traditional SDMD graphic Figure 3c, (2) stand structural visualizations at rotation, e.g., Figure 3c, and (3) site-dependent annual and rotational diameter-class and stand-level estimates in terms of volumetric yields, log distributions, biomass and carbon yields, recoverable product volumes and associated values by sawmill-type, cost profiles and fibre attributes, for each of the 3 regimes along with a set of performance indices, e.g., Figure 3c. For this example, these metrics indicated that the optimal PCT-based regimes (Regimes 2 and 3) relative to the unthinned control stand were capable of producing more sawlog-sized trees, greater dimensional lumber recovery volumes with slightly better wood quality attributes (e.g., higher elasticity (stiffness)), higher economic worth, greater optimal site occupancy utilization, more structurally stable stands, and operable stands in a shorter rotational time frame. For a more complete account of the results specific to this example, refer to: (1) Summary Report SM2 in the Supplementary Material section for a complete account of the CP_{DSS} output (MS Excel formatted file inclusive of the (i) master file (regime input specifics), (ii) SDMD graphic, (iii) crop plan cumulative summaries, (iv) annual regime-specific yield details, (v) end-user-selected regime comparisons, and the (vi) summary of the key performance indices); and (2) Table 4 for an abridge tabular summary of the rotational stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product wood quality measures, and productivity and economic indices, considered key decision-support metrics for evaluating and selecting the most appropriate crop plan.

Table 4. Operability optimizer (automated crop plan selection): crop-plan-specific rotational (48, 48 and 52 yr for Regimes 1, 2 and 3, respectively) stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product-related wood quality metrics, and productivity and economic indices, for natural-origin jack pine stands established at very high initial densities (8000 stems/ha) growing on medium-to-good quality sites (site index 18 m) which were left unthinned (Regime 1) or subjected to density control treatments (PCT of 6500 stems/ha at 15 yr deploying the maximum thinning response model setting (Regime 2); and PCT of 6500 stems/ha at 15 yr deploying the minimum thinning response model setting (Regime 3)).

Index [a,b] (Unit)	**Crop Plan [c]**				
	Regime 1 (Unthinned)	**Regime 2 (PCT)**	**(%Δ)**	**Regime 3 (PCT)**	**(%Δ)**
		Structural measures			
N (stems/ha)	4422	1073	−76	1026	−77
H_d (m)	17.04	17.92	5	18.04	6
$\overline{V}$ (dm^3)	51.26	119.91	134	125.69	145
D_q (cm)	9.37	14.13	51	14.43	54
G (m^2/ha)	30.47	16.83	−45	16.78	−45
V_t (m^3/ha)	226.8	133.5	−41	133.8	−41
V_m (m^3/ha)	168.0	120.0	−29	120.8	−28
P_r (%/100)	0.8586	0.4193	−51	0.417	−51
L_{cr} (%)	39.26	45.41	16	45.26	15
N_m (stems/ha)	2324	974	−58	943	−59
		Biomass and carbon outcomes			
M_p (t/ha)	15.36	10.87	−29	10.91	−29
M_s (t/ha)	162.63	94.85	−42	95	−42
M_b (t/ha)	9.3	17.95	93	18.66	101
M_f (t/ha)	5.41	10.65	97	11.04	104
M_t (t/ha)	192.7	134.33	−30	135.6	−30
C_t (t/ha)	96.35	67.17	−30	67.8	−30
		Log product distribution			
$N_{l(s)}$ (logs/ha)	0	222	-	244	-
$N_{l(p)}$ (logs/ha)	2468	1923	−22	1888	−24
		Sawmill-specific recoverable product volumes			
$V_{l(s)}$ (m^3/ha)	81.97	70.19	−14	71.26	−13
$V_{c(s)}$ (m^3/ha)	76.94	49.82	−35	49.49	−36

Table 4. *Cont.*

Index [a,b] (Unit)	Crop Plan [c] Regime 1 (Unthinned)	Regime 2 (PCT)	(%Δ)	Regime 3 (PCT)	(%Δ)
$V_{l(r)}$ (m^3/ha)	112.04	91.49	−18	92.46	−17
$V_{c(r)}$ (m^3/ha)	51.59	28.52	−45	28.29	−45
		Rotational performance metrics			
R_{MAI} (m^3/ha/yr)	3.5	2.5	−29	2.3	−34
R_{BAI} (t/ha/yr)	4	2.8	−30	2.6	−-35
R_{CAI} (t/ha/yr)	2	1.4	−30	1.3	−35
R_{SL} (%)	0	10.3	–	11.4	–
$R_{LV(s)}$ (%)	51.6	58.5	13	59	14
$R_{LV(r)}$ (%)	68.5	76.2	11	76.6	12
$E_{(s)}$ ($K/ha)	2.8	4.4	57	4.1	46
$E_{(r)}$ ($K/ha)	5.7	7.3	28	6.8	19
S_O(%)	8.3	16.7	101	17.3	108
S_s (m/m)	144	91.3	−37	90.8	−37
O_T (yr)	>52	48	-	52	–
$\overline{W}_D$ (g/cm^3)	0.4499	0.4118	−8	0.4091	−9
$\overline{B}_D$ (cm)	0	2.86	–	2.89	–
$\overline{W}_d$ (kg/m^3)	394.7	405.08	3	407.44	3
$\overline{M}_a$ (°)	14.5	14.5	0	14.33	−1
$\overline{M}_e$ (GPa)	10.14	10.7	6	10.84	7
$\overline{C}_o$ (μg/m)	386.39	391.44	1	392.09	1
$\overline{W}_t$ (μm)	2.52	2.56	2	2.57	2
$\overline{D}_r$ (μm)	30.92	31.07	0	30.99	0
$\overline{D}_t$ (μm)	28.38	28.12	−1	28.1	−1
$\overline{S}_a$ (m^2/kg)	342.74	332.19	−3	330.76	−3

[a,b,c] As defined in Table 2.

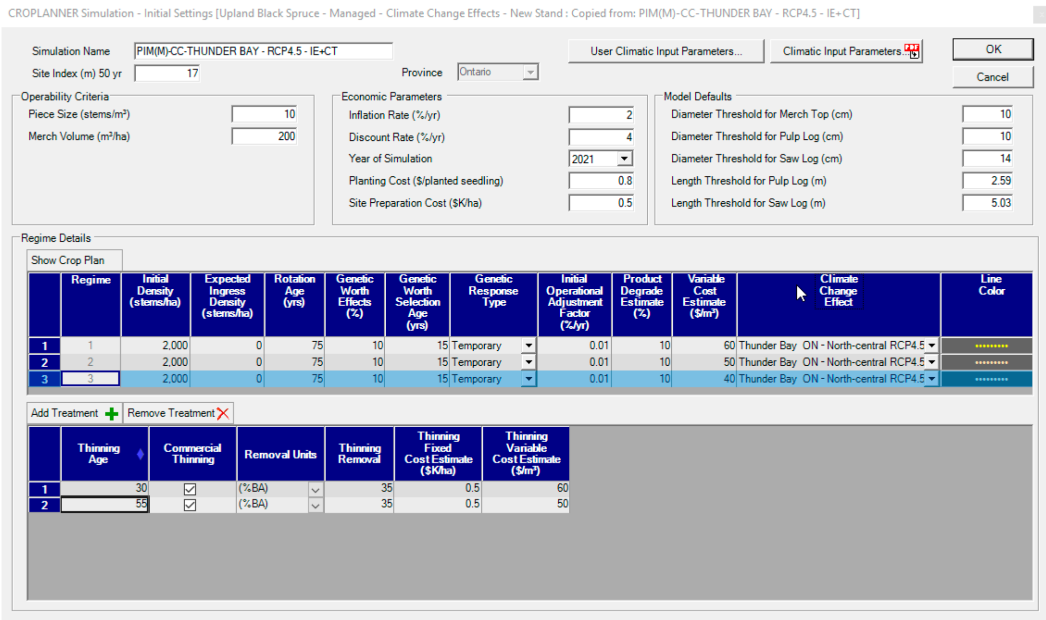
3.3. Exemplification of the CP_{DSS} in Plantation Management under Climate Change: Upland Black Spruce IE + CT Crop Plans for a RCP4.5 Climate Change Scenario

The climate-sensitive structural SDMD variant for the black spruce plantation stand-type is used to exemplify the iterative utility of the CP_{DSS} in boreal crop planning. Briefly, the climate-sensitive SSDMD variants were developed through the incorporation of a biophysical site-specific height-age model within Module A-Dynamic SDMD (sensu Figure 1; [36]). This biophysical model includes precipitation (mean total precipitation (mm) during the growing season) and temperature (mean temperature (°C) during the growing season) as predictor variables in order to explicitly account for localized effects of climate-change on forest productivity [64]. The actual predicted future values of these climate-based variables for a given geographic location (longitude and latitude coordinates), climate change scenario (1970–2000 climate normals and representative concentration pathways (e.g., RCP2.6, RCP4.5 or RCP8.5 [78])), and commitment period (2010–2040, 2041–2070, and 2071–2100), are extracted from a set of external models (i.e., the second generation Canadian Earth System Model (CanESM2 [79]) in combination with a geo-referencing regional spatial climatic model [80]). The scope of this exemplification consisted of simulating IE+CT crop plans for upland black spruce plantations situated in north-central Ontario (Thunder Bay) growing under a RCP4.5 climate change scenario over the 2021–2096 period.

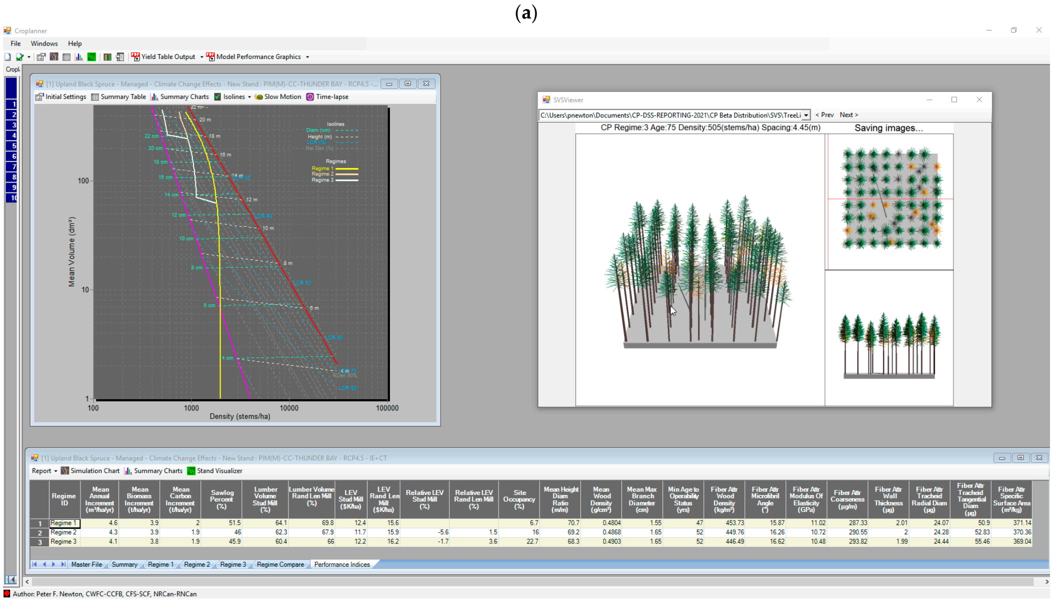
Procedurally, within the setup screen of the CP_{DSS}, the end-user is required to first select the applicable stand-type (e.g., Upland Black Spruce–Managed–Climate Change Effects) under the File/New tab. The crop plan input setup screen is displayed once the stand-type is selected (Figure 4a). Secondly, the end-user populates the input dialogs according to their chosen set of crop plans (N = 3 where Regime 1 is the unthinned control stand which is used to measure the performance of Regimes 2 and 3 against). This includes the following global parameters which are applicable to all 3 crop plans, and individual values that are unique to each specific crop plan (Figure 4a): (1) global input requirements include the specification of site index (17 m), operability criteria (piece size (10 trees/m^3) and merchantable volume (200 m^3/ha) targets), economic parameters (annual inflation (2%) and discount (4%) rates, simulation year (2021), planting and site preparation costs), and model defaults in terms of merchantability specifications; and (2) crop-plan-specific input requirements for each regime including their (i) initial density (2000 stems/ha), (ii) expected ingress density, (iii) rotation age (75 yr), (iv) genetic worth effects, selection age and response model (e.g., 10% increase in dominant height growth initiating at a selection age of 15 yr and carried forward until rotation [50]), (v) annual expected density-independent mortality rate (0.01%/yr), (vi) product degrade (i.e., accounting for the potential overestimation of sawmill-specific product recovery equations (sensu [76])), (vii) variable costs at the time of harvest inclusive of stumpage fees, renewal costs and harvesting, transportation and manufacturing expenses, expressed on a per cubic meter of merchantable volume harvested basis (sensu [77]), (viii) climate change effect which requires locale-specific growing season precipitation and temperature input values by commitment period and climate change scenario, entered via the accompanying input GUI dialog screen (Figure 4b); note, these can be auto-populated using the on-board examples provided for the pre-selected locales and scenarios, and (ix) treatments specifics with respect to Regimes 2 and 3 in terms of the time of thinning (age), type of thinning (CT), removal units (stems/ha or % of pre-treatment standing basal area), thinning intensity (magnitude of removal expressed in the chosen unit), fixed thinning costs (equipment transportation) and variable thinning costs (applicable stumpage and renewal fees and harvesting, transportation and manufacturing expenses, expressed on a per cubic meter of merchantable volume removed basis (sensu [76])). Note, Table 5 provides a non-GUI tabular account of all the input parameter settings required for this specific example.

Thirdly, deploying this input configuration, the CP_{DSS} then executes the computational sequence as detailed in Figure 1, which then generates a full range of graphical and tabular output for each of the proposed crop plans. These include for example, the (1) size-density trajectories for the selected crop plans displayed within the context of the traditional SDMD graphic (e.g., Figure 4b), (2) stand structural visualizations at rotation (e.g., Figure 4b), and (3) 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 along with a set of performance indices (e.g., Figure 4b) for each of the 3 regimes (note, Figure 4c provides an abridge summary of the annual mean tree and stand level estimates for Regime 3).

For this specific example, the performance metrics indicated that the set of CT treatments implemented at stand ages of 30 yr and 55 yr (Regime 3), relative to both the unthinned (Regime 1) and the single CT (Regime 2) plantations, was optimal in terms of economic worth and site occupancy. However, marginal negative differences were evident in terms of volumetric, biomass and carbon productivity levels, lumber production and the fibre determinates underlying end-product-potential. The duration of optimal site occupancy was considerably greater for the twice-thinned plantation suggesting enhanced carbon sequestration potential (i.e., greater proportion of years in which the size-density trajectory was within the optimal density management window, as delineated by relative densities between 0.32 and 0.45, reflecting a higher biotic/abiotic mass production relative to size-density trajectories outside of this window; Figure 4b (sensu [35])). A more in-depth numeric account of the annual progression of each size-density trajectory in terms of all volumetric yield, end-product and ecological-related outcomes is exemplified in Figure 4c for Regime 3. It is evident that the CT treatments complied with regulatory guidelines [73]: pre-treatment stand-level basal areas of $\geq$25 m^2/ha and mean live crown ratio $\geq$ 35%. Furthermore, estimates of the extracted thinning yields are also provided in this tabular example: e.g., number of trees removed (684 and 348 stems/ha) their mean sizes (quadratic mean diameters of 12.6 cm and 20.7 cm), volumes extracted (23 and 69 m^3/ha of merchantable wood), and recoverable sawmill products (e.g., 12 and 7 m^3/ha (1st thinning) and 25 and 33 m^3/ha (2nd thinning) of wood chips and lumber products potentially exactable under a random length sawmill processing protocol, respectively). Although not shown for the unthinned plantation, the number of merchantable sized trees that were lost to mortality during the 45 yr post-thinning period was 708 stems/ha versus only 214 stems/ha in the twice-thinned plantation. For a more complete account of the results specific to this example, refer to: (1) Summary Report SM3 in the Supplementary Material for a summary of the CP_{DSS} output (MS Excel formatted file inclusive of the (i) master file (regime input specifics), (ii) SDMD graphic, (iii) crop plan cumulative summaries, (iv) annual regime-specific yield details, (v) end-user-selected regime comparisons, and the (vi) summary of the key performance indices); and (2) Table 6 for an abridge tabular summary of the rotational stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product wood quality measures, and productivity and economic indices, considered key decision-support metrics for evaluating and selecting the most appropriate crop plan.

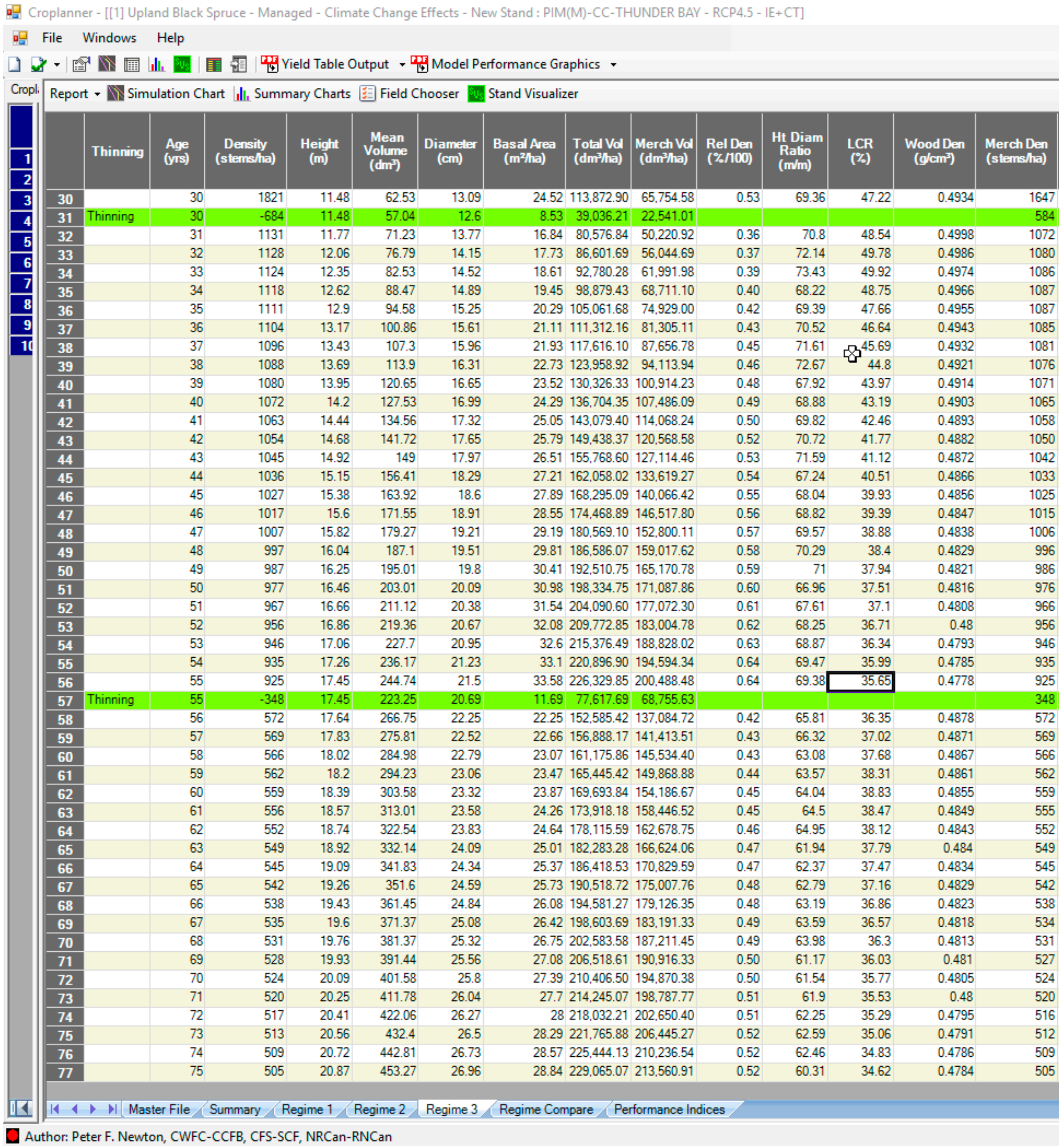


(a)



(b)

Figure 4. *Cont.*



	Thinning	Age (yrs)	Density (stems/ha)	Height (m)	Mean Volume (dm³)	Diameter (cm)	Basal Area (m²/ha)	Total Vol (dm³/ha)	Merch Vol (dm³/ha)	Rel Den (%/100)	Ht Diam Ratio (m/m)	LCR (%)	Wood Den (g/cm³)	Merch Den (stems/ha)
30		30	1821	11.48	62.53	13.09	24.52	113,872.90	65,754.58	0.53	69.36	47.22	0.4934	1647
31	Thinning	30	-684	11.48	57.04	12.6	8.53	39,036.21	22,541.01					584
32		31	1131	11.77	71.23	13.77	16.84	80,576.84	50,220.92	0.36	70.8	48.54	0.4998	1072
33		32	1128	12.06	76.79	14.15	17.73	86,601.69	56,044.69	0.37	72.14	49.78	0.4986	1080
34		33	1124	12.35	82.53	14.52	18.61	92,780.28	61,991.98	0.39	73.43	49.92	0.4974	1086
35		34	1118	12.62	88.47	14.89	19.45	98,879.43	68,711.10	0.40	68.22	48.75	0.4966	1087
36		35	1111	12.9	94.58	15.25	20.29	105,061.68	74,929.00	0.42	69.39	47.66	0.4955	1087
37		36	1104	13.17	100.86	15.61	21.11	111,312.16	81,305.11	0.43	70.52	46.64	0.4943	1085
38		37	1096	13.43	107.3	15.96	21.93	117,616.10	87,656.78	0.45	71.61	45.69	0.4932	1081
39		38	1088	13.69	113.9	16.31	22.73	123,958.92	94,113.94	0.46	72.67	44.8	0.4921	1076
40		39	1080	13.95	120.65	16.65	23.52	130,326.33	100,914.23	0.48	67.92	43.97	0.4914	1071
41		40	1072	14.2	127.53	16.99	24.29	136,704.35	107,486.09	0.49	68.88	43.19	0.4903	1065
42		41	1063	14.44	134.56	17.32	25.05	143,079.40	114,068.24	0.50	69.82	42.46	0.4893	1058
43		42	1054	14.68	141.72	17.65	25.79	149,438.37	120,568.58	0.52	70.72	41.77	0.4882	1050
44		43	1045	14.92	149	17.97	26.51	155,768.60	127,114.46	0.53	71.59	41.12	0.4872	1042
45		44	1036	15.15	156.41	18.29	27.21	162,058.02	133,619.27	0.54	67.24	40.51	0.4866	1033
46		45	1027	15.38	163.92	18.6	27.89	168,295.09	140,066.42	0.55	68.04	39.93	0.4856	1025
47		46	1017	15.6	171.55	18.91	28.55	174,468.89	146,517.80	0.56	68.82	39.39	0.4847	1015
48		47	1007	15.82	179.27	19.21	29.19	180,569.10	152,800.11	0.57	69.57	38.88	0.4838	1006
49		48	997	16.04	187.1	19.51	29.81	186,586.07	159,017.62	0.58	70.29	38.4	0.4829	996
50		49	987	16.25	195.01	19.8	30.41	192,510.75	165,170.78	0.59	71	37.94	0.4821	986
51		50	977	16.46	203.01	20.09	30.98	198,334.75	171,087.86	0.60	66.96	37.51	0.4816	976
52		51	967	16.66	211.12	20.38	31.54	204,090.60	177,072.30	0.61	67.61	37.1	0.4808	966
53		52	956	16.86	219.36	20.67	32.08	209,772.85	183,004.78	0.62	68.25	36.71	0.48	956
54		53	946	17.06	227.7	20.95	32.6	215,376.49	188,828.02	0.63	68.87	36.34	0.4793	946
55		54	935	17.26	236.17	21.23	33.1	220,896.90	194,594.34	0.64	69.47	35.99	0.4785	935
56		55	925	17.45	244.74	21.5	33.58	226,329.85	200,488.48	0.64	69.38	35.65	0.4778	925
57	Thinning	55	-348	17.45	223.25	20.69	11.69	77,617.69	68,755.63					348
58		56	572	17.64	266.75	22.25	22.25	152,585.42	137,084.72	0.42	65.81	36.35	0.4878	572
59		57	569	17.83	275.81	22.52	22.66	156,888.17	141,413.51	0.43	66.32	37.02	0.4871	569
60		58	566	18.02	284.98	22.79	23.07	161,175.86	145,534.40	0.43	63.08	37.68	0.4867	566
61		59	562	18.2	294.23	23.06	23.47	165,445.42	149,868.88	0.44	63.57	38.31	0.4861	562
62		60	559	18.39	303.58	23.32	23.87	169,693.84	154,186.67	0.45	64.04	38.83	0.4855	559
63		61	556	18.57	313.01	23.58	24.26	173,918.18	158,446.52	0.45	64.5	38.47	0.4849	555
64		62	552	18.74	322.54	23.83	24.64	178,115.59	162,678.75	0.46	64.95	38.12	0.4843	552
65		63	549	18.92	332.14	24.09	25.01	182,283.28	166,624.06	0.47	61.94	37.79	0.484	549
66		64	545	19.09	341.83	24.34	25.37	186,418.53	170,829.59	0.47	62.37	37.47	0.4834	545
67		65	542	19.26	351.6	24.59	25.73	190,518.72	175,007.76	0.48	62.79	37.16	0.4829	542
68		66	538	19.43	361.45	24.84	26.08	194,581.27	179,126.35	0.48	63.19	36.86	0.4823	538
69		67	535	19.6	371.37	25.08	26.42	198,603.69	183,191.33	0.49	63.59	36.57	0.4818	534
70		68	531	19.76	381.37	25.32	26.75	202,583.58	187,211.45	0.49	63.98	36.3	0.4813	531
71		69	528	19.93	391.44	25.56	27.08	206,518.61	190,916.33	0.50	61.17	36.03	0.481	527
72		70	524	20.09	401.58	25.8	27.39	210,406.50	194,870.38	0.50	61.54	35.77	0.4805	524
73		71	520	20.25	411.78	26.04	27.7	214,245.07	198,787.77	0.51	61.9	35.53	0.48	520
74		72	517	20.41	422.06	26.27	28	218,032.21	202,650.40	0.51	62.25	35.29	0.4795	516
75		73	513	20.56	432.4	26.5	28.29	221,765.88	206,445.27	0.52	62.59	35.06	0.4791	512
76		74	509	20.72	442.81	26.73	28.57	225,444.13	210,236.54	0.52	62.46	34.83	0.4786	509
77		75	505	20.87	453.27	26.96	28.84	229,065.07	213,560.91	0.52	60.31	34.62	0.4784	505

(**c**)

Figure 4. Exemplifying the iterative crop plan selection ability of the CP_{DSS}; specifically within the context of comparing two CT-based regimes and an unthinned control regime for managed stand-types (black spruce plantations) while simultaneously accounting for localized climate change effects: (**a**) input GUI dialog with end-user required input consisting of the (i) simulation identifier (name), site index, operability criteria, economic parameters, and model defaults (merchantability specifications), (ii) regime-specific (crop plan) specifics in terms of initial density, expected ingress, rotation age, genetic worth, selection age and response model type, operational adjustment and product degrade factors, variable cost estimate at harvest, and climatic change scenario inclusive of locale-specific temperature and precipitation values by commitment period (n., values can be either auto-populated for representative locales and climate change scenarios or manually inputted by the end-user), and (iii) thinning treatment specifics for Regimes 2 and 3 (age and type of each thinning, removal units and thinning intensity, and fixed and variable thinning cost estimates); (**b**) resultant crop plans presented within traditional SDMD graphic, tabular summaries of rotational performance metrics, and example stand visualization graphic at rotation (Regime 3); and (**c**) example regime-specific (Regime 3) annual tabular output for selected variables inclusive of CT yield estimates. Refer to Summary Report SM3 (Supplementary Material) for a complete account of the output produced for this specific set of crop plans.

Table 5. Crop planning simulation input parameters for the climate sensitive variant: specific to upland black spruce plantations situated on medium-to-good quality sites in north-central (Thunder Bay) Ontario, established at a common initial espacement (IE) level, with and without subsequent commercial thinning (CT) treatments, and growing under a RCP4.5 climate change scenario over 75 yr rotations (2021–2096).

Parameter (Units) [a]	Thunder Bay: Constant IE Treatment/Variable CT Treatments/Constant Climate Change Scenario		
	Regime 1 (Unthinned)	Regime 2 (1 CT)	Regime 3 (2 CTs)
Scenario-specific climate change setting			
Climate change scenario	RCP4.5	RCP4.5	RCP4.5
Mean growing season temperature (°C): 2010–2040	14.2	14.2	14.2
Mean growing season temperature (°C): 2041–2070	14.7	14.7	14.7
Mean growing season temperature (°C): 2071–2100	15.4	15.4	15.4
Growing season precipitation (mm): 2010–2040	485	485	485
Growing season precipitation (mm): 2041–2070	550	550	550
Growing season precipitation (mm): 2070–2100	544	544	544
Crop plan specifics			
Planting year	2021	2021	2021
Rotation length (yr)	75	75	75
Simulation years	2021–2096	2021–2096	2021–2096
Initial planting density (seedlings/ha)	2000	2000	2500
1st CT: stand age (yr)/basal area removal (%)	-	30/35	30/35
2nd CT: stand age (yr)/basal area removal (%)	-	-	55/35
Genetic worth (%)/selection age (yr)/response model	10/15/temporary	10/15/temporary	10/15/temporary
Operational adjustment factor (%/yr)	0.01	0.01	0.01
Merchantable Specifications			
Pulp log length (m)/minimum diameter (inside bark; cm)	2.59/10	2.59/10	2.59/10
Saw log length (m)/minimum diameter (inside-bark; cm)	5.03/14	5.03/14	5.03/14
Merchantable top diameter (inside-bark; cm)	10	10	10
Product degrade (%)	10	10	10
Minimum Operability Targets			
Piece-size (merchantable-sized stems/merchantable volume; stems/m^3)	10	10	10
Merchantable volumetric stand yield (m^3/ha)	200	200	200
Economic Parameters			
Interest rate (%)	2	2	2
Discount rate (%)	4	4	4
Mechanical site preparation (CAN$/ha)	500	500	500
Planting (CAN$/seedling)	0.8	0.8	0.8
1st CT: variable costs (CAN$/$m^3$ of merchantable volume removed)/fixed costs (CAN$/ha)	-	60	60
2nd CT: variable costs (CAN$/$m^3$ of merchantable volume removed)/fixed costs (CAN$/ha)	-	-	50
Rotational harvesting + stumpage + renewal + transportation + manufacturing variable costs (CAN$/$m^3$ of merchantable volume harvested)	60	50	40

Notes: (1) medium-to-good site quality is defined as having a mean dominant height of 17 m at a breast-height age of 50 yr [65]; and (2) economic rate assumptions, and fixed and variable cost values, are informed approximations (sensu [77]). [a] Climate change scenario: Representative Concentration Pathways 4.5 (RCP4.5) [78]. All forecasted climate variables were derived from the second generation Canadian Earth System Model (CanESM2) which consists of a physical atmosphere-ocean model (CanCM4) coupled to a terrestrial carbon model (CTEM) and an oceanic carbon model (CMOC) [79]; specific estimates for Thunder Bay were derived from a customized spatial climatic model [80] geo-referenced by its longitude and latitude coordinate positions (i.e., in decimal degrees, of −89.2500 and 48.3833, respectively). Genetic worth is the maximum percentage increase in dominant height growth expected to occur at the specified selection age (see [50] for specifics). The operational adjustment factor is the annual mortality rate attributed to non-density-dependent abiotic and biotic causes (e.g., wind throw and pathogens, respectively). Product degrade is an end-user specified allowance for correcting for the potential over-estimation arising from the use of product prediction functions derived from virtual sawmill-based simulation studies (sensu [76]). Variable costs for commercial thinning (CT) treatments include all on-site equipment-related operating costs and associated stumpage payments, renewal fees, transportation expenses and manufacturing costs, cumulatively expressed as a function of merchantable volume extracted during thinning. Fixed costs for CT included forest management and equipment-related transportation fees. Rotational variable costs for final harvesting include all on-site equipment-related operating costs and associated stumpage payments, renewal fees, transportation expenses, and manufacturing costs, cumulatively expressed as a function of merchantable volume harvested.

Table 6. Iterative crop plan selection under climate change (RCP4.5): crop-plan-specific rotational (75 yr; 2021–2096) stand structure attributes, volumetric yields, log assortments, biomass and carbon outcomes, product volumes, end-product-related wood quality metrics, and productivity and economic indices, for upland black spruce plantations established in north-central Ontario at IE densities of (2500 stems/ha) growing on medium-to-good quality sites (nominal site index of 17 m) which were left unthinned (Regime 1) or subjected to density control treatments (CT of 35% basal area removal at 30 yr (Regime 2); and 2 CTs of 35% basal area reductions at 30 yr and 55 yr (Regime 3)).

Index [a,b] (Unit)	Crop Plan [c]				
	Regime 1 (Unthinned)	Regime 2 (CT)	(%Δ)	Regime 3 (2 CTs)	(%Δ)
Structural measures					
N (stems/ha)	879	754	−14	505	−43
H_d (m)	20.9	20.9	0	20.9	0
$\overline{V}$ (dm^3)	426.7	433.9	2	453.3	6
D_q (cm)	26.3	26.5	1	27.0	3
G (m^2/ha)	47.7	41.5	−13	28.8	−40
V_t (m^3/ha)	375.0	366.2	−2	345.7	−8
V_m (m^3/ha)	347.2	325.9	−6	304.9	−12
P_r (%/100)	0.88	0.76	−14	0.52	−41
L_{cr} (%)	29.5	30.9	5	34.6	17
N_m (stems/ha)	879	1338	52	1437	63
Biomass and carbon outcomes					
M_p (t/ha)	25.2	23.0	−9	18.6	−26
M_s (t/ha)	249.4	219.6	−12	161.9	−35
M_b (t/ha)	7.2	6.9	-4	6.4	−11
M_f (t/ha)	12.1	13.1	8	15.7	30
M_t (t/ha)	293.8	262.7	−11	202.6	−31
C_t (t/ha)	146.9	131.3	−11	101.3	−31
Log product distribution					
$N_{l(p)}$ (logs/ha)	1303	1453	12	1361	5
$N_{l(s)}$ (logs/ha)	1383	1240	−10	1156	−16
Sawmill-specific recoverable product volumes					
$V_{l(s)}$ (m^3/ha)	222.5	200.9	−10	175.1	−21
$V_{c(s)}$ (m^3/ha)	124.7	121.6	−3	115.0	−8
$V_{l(r)}$ (m^3/ha)	242.4	219.1	−10	191.6	−21
$V_{c(r)}$ (m^3/ha)	104.9	103.4	−1	98.6	−6
Rotational performance metrics					
R_{MAI} (m^3/ha/yr)	4.6	4.3	18	4.1	6
R_{BAI} (t/ha/yr)	3.9	3.9	22	3.8	19
R_{CAI} (t/ha/yr)	2.0	1.9	14	1.9	14
R_{SL} (%)	51.5	46.0	-6	45.9	−5
$R_{LV(s)}$ (%)	64.1	62.3	3	60.4	−1
$R_{LV(r)}$ (%)	69.8	62.5	2	60.3	−1
$E_{(s)}$ ($K/ha)	5.6	7.8	39	7.6	36
$E_{(r)}$ ($K/ha)	8.1	10.7	32	10.5	30
S_O(%)	6.7	16.0	139	22.7	239
S_s (m/m)	70.7	69.2	-2	68.3	−3
O_T (yr)	47	52.0	11	52.0	11
$\overline{W}_D$(g/cm^3)	0.4804	0.4868	1	0.4903	2
$\overline{B}_D$(cm)	1.55	1.7	7	1.7	7
$\overline{W}_d$ (kg/m^3)	453.73	449.8	−1	446.5	−2
$\overline{M}_a$ (°)	15.87	16.3	3	16.6	5
$\overline{M}_e$ (GPa)	11.02	10.7	−3	10.5	−5
$\overline{C}_o$ (μg/m)	287.33	290.6	1	293.8	2
$\overline{W}_t$ (μm)	2.01	2.0	−1	2.0	−1
$\overline{D}_r$ (μm)	24.07	24.3	1	24.4	2
$\overline{D}_t$ (μm)	50.9	52.8	4	55.5	9
$\overline{S}_a$ (m^2/kg)	371.14	370.4	0	369.0	0

[a,b,c] As defined in Table 2.

Notably, with respect to climate change impacts, the rotational differences between the no change and RCP4.5 scenarios for identical crop plans for this stand-type at this locale (not shown), suggested that such impacts were marginally positive across most of the performance metrics. However, comparing the performance metrics generated for jack pine plantations established at this same locale and managed deploying the same crop plans for the identical scenario (not shown), revealed consequential negative impacts arising from climate change. For example, declines in rotational mean tree sizes attained, merchantable volume productivity and economic viability where evident for such RCP4.5-based crop plans (e.g., −18% in quadratic mean diameter, −35% in mean annual merchantable volume increment and −40% in land expectation value, respectively, for a crop plan identical to that specific for Regime 3 but for jack pine). These results are in accord with expectation with respect to earlier analyses where model-based inferences were used to interpret potential climate change effects on stand-level productivity (e.g., (1) jack pine > black spruce irrespective of locale with jack pine exhibiting a systematic east-to-west latitudinal-based productivity decline across boreal-Ontario; and (2) black spruce exhibited consequential productivity declines in north-western and north-eastern boreal-Ontario however not so in north-central Ontario; [36]). Collectively, these boreal-Ontario SSDMD simulation results indicated that stand-level productivity under a changing climate will vary by species, site quality, geographic locale, and emission scenario, potentially resulting in a landscape-level mosaic of both negative and positive productivity impacts in the case of black spruce, and mostly negative impacts in the case of jack pine. Although the results were not explicitly presented for these comparisons, the resultant inferences however, re-emphasizes the importance of the potential utility of CP_{DSS} in stand-level management planning under anthropogenic climate change.

3.4. Consequential Considerations When Deploying the CP_{DSS}: Ecological Soundness, Predictive Accuracy and Operational Utility

The results derived from a previous biological-based examination of the concordance of the predicted patterns of stand development and yield dynamics derived from the SSDMDs with respect to the underlying ecological assumptions utilized, confirmed the ecological integrity of these model variants [64]. More precisely, based on the evaluation of the resultant patterns generated from 1980 simulations via the deployment of modified Bakuzis-based graphical matrices, all 6 of the stand-type-specific SSDMDs assessed, performed well in terms of their biological reasonableness. The resultant predictions and developmental trends were in agreement with known even-aged stand dynamic axioms. These included mean dominant height–age trajectories that were in compliance with the response modelling assumptions and site productivity expectations: e.g., accelerate rates of development for PCT treated stands (positive thinning growth response) and plantations established with genetically improved stock (positive genetic worth growth responses). Similarly, site form predictions were in accord with expectation, i.e., dominant height increased with increased quadratic mean diameter converging into a single common relationship across site classes for a given initial density, rotation length, and genetic worth and thinning response effect. The expected Sukatsckew effect in which the temporal rate of density-dependent mortality or self-thinning increases with site fertility, was observed across all stand-types irrespective of initial density or rotation length. Similarly, the majority of the yield–height relationships predicted by Eichhorn's rule were also observed. The temporal production patterns in stand-level yields and their interrelationships were likewise consistent with expectation. The only consequential departure from expectation was the acknowledgement of a potential site productivity effect on the asymptotic size-density relationships (self-thinning rule): i.e., maximal tree size attained at a given asymptotic density-stress level varied directly with site index. Such an inference suggest that stands growing on more fertile sites are able to withstand a greater degree of site occupancy before incurring the consequences of density-stress relative to comparable stands growing on less fertile sites.

In terms of the empirical predictive ability of the underlying SSDMDs, a previous evaluation of the principal drivers underlying volumetric yield predictions (i.e., Module A; Figure 1) which are explicitly or implicitly linked to the majority of the downstream relationships (Modules B–F; Figure 1), indicated that the models where approaching or had attained accuracy thresholds proposed for operational growth and yield models [38]. Specifically, deploying a combination of dependent, partially dependent and independent Ontario-centric permanent sample plots and experimental datasets inclusive of stands that were subjected to IE, PCT and CT treatments, the mean percentage prediction error for mean dominant height, quadratic mean diameter, basal area, total volume, density and relative density, were realizing or approaching the $\pm$20% acceptance threshold suggested by Huang [81]. However, it is worthy to note that given the comprehensiveness of the output metrics produced from the downstream modules (e.g., Modules B–F; Figure 1), particularly estimates associated with biomass and carbon yields, recoverable products and their predicted fiscal worth, and end-product-related fibre attributes, the likelihood of acquiring adequate testing data sets from traditional inventory-based permanent plot systems or stand density field experiments that would enable a whole-model evaluation of error propagation patterns across all the modules, is minimal. As a consequence, such uncertainty should be acknowledged by the end-user when interpreting such output metrics.

In reference to the climate-change variants, the consequences arising from uncertainty pertaining to climate change effects on future growing environments are among the most concerning to both modellers and resource management decision-makers. Specifically, identifying which climate change scenario is the most plausible over the long term, is inherently difficult given unknowns with respect to future regional, national and global mitigation efforts. Furthermore, the biophysical site index functions attempt to address the overall effect of localized changes in precipitation and temperature arising from climate change only on dominant height development (i.e., forest productivity). Although dominant height development is a principal determinate governing overall stand dynamics within the SSDMD analytical framework (e.g., Module A; Figure 1), other climate-change-induced within-stand effects, such as those on density-dependent and density-independent mortality processes, frequency of episodic moisture deficit events, occurrence and severity of insect and disease outbreaks, and increased abiotic risks (wind-throw and stem breakage risk), are not addressed. Hence, given the uncertainty with regard to climate change effects, it is advisable for stand density management decision-makers to access their preferred crop plan across a plausible range of climate change scenarios, and exercise caution when interpreting future predictions. Directing future research efforts on addressing these outstanding knowledge gaps, could yield consequential advancements in the applicability and predictive precision of the climate-sensitive variants.

Analytically, the CP_{DSS} was primarily designed to be an iterative gaming-like crop planning tool: i.e., evaluating rotational outcomes and performance metrics for end-user-specified crop plans and subsequently determining the most applicable one in terms of its ability to achieve specified stand-level volumetric yield, end-product and ecological based objectives. A secondary consideration was the inclusion a computer-intensive automated crop plan selection option so that the iterative selection burden of potentially evaluating a large number of plausible crop plans, could be reduced for both experienced and novel end-users: i.e., enabling an automated regime selection capability in which an end-user-specified multivariate selection criteria and associated constraints are used to search and identify the optimal crop plan(s). Thus this study included an exemplification of each approach in order to partially demonstrate the potential utility of the CP_{DSS} in operational forest management: (1) demonstrating the computer-intensive approach within the context of determining the optimal PCT-based crop plan for jack pine natural-stands without consideration of climate change effects or locale; and (2) illustrating the iterative approach within the context of evaluating 3 black spruce plantation-based crop plans involving IE and CT treatments and growing under a RCP4.5 climate change scenario at a specified locale (Thunder Bay, Ontario). Notably, however, these examples only represent a very abbreviated illustration of the full application scope and potential utility of the CP_{DSS} is stand-level management planning.

The evolving societal requirement for enhanced ecosystem services while achieving greater levels of economic output through end-product diversification and improved fibre quality, combined with the historical volumetric yield maximization proposition, has largely negated consideration of a solely univariate objective when crop planning within the Canadian boreal forest region. Resultantly, crop plans are increasingly being formulated in general concordance with these three overarching management determinates. The diversity of output and performance metrics provided by the CP_{DSS} enables such a wide spectrum of forest management objectives to be assessed simultaneously. For example, the stand-level yield-table-like variables such as total density, basal area, merchantable and total volume, mean volume, quadratic mean diameter, relative density index, height-diameter ratio, and merchantable density, that are reported on an annual, periodic and cumulative basis, can be readily utilized to evaluate traditional volumetric-based objectives (e.g., merchantable volume production, mean tree yield outcomes, stand operability and structural stability). The provision of rotational estimates of the principal fibre attributes that underlie end-product potential augmented by estimates of external morphological tree characteristics which affect grade determinations of extracted end-products (e.g., projections of the size of embedded knots as inferred from branch characteristics), affords an ability to assess wood quality management objectives when evaluating and contrasting crop planning outcomes. Furthermore, including consideration of product volumes (e.g., sawmill-specific recoverable wood chip and lumber volumes) adds an ability to assess the long-term carbon storage potential of a given crop plan. Likewise, the stand-level output variables that are reported on an annual and periodic basis at the diameter-class and stand-levels, such as component biomasses and associated carbon equivalents, combined with measures regarding the degree of optimal site occupancy attained (e.g., duration of rotation within the optimal relative density zone during which net production and hence carbon dioxide sequestration potential is maximized), provides the foundation to also evaluate crop plans on their carbon sequestration potential. Thus the provision of a decision-support system and associated software suite that enables the determination of most appropriate crop plan while simultaneously considering all three of these objectives, with or without consideration for potential anthropogenic climate change effects, represents a consequential advancement for facilitating this paradigm shift towards multi-objective stand-level management planning. Specifically, as exemplified in this study, the scope of the output produced by the CP_{DSS} provides the computational foundation for generating a key set of performance assessment indicators reflective of the realization of volumetric fibre production, end-product potential and ecosystem service based objectives. Essentially, the CP_{DSS} comprehensive output applicable across diverse management domains, collectively provides the analytical foundation for any given boreal-based crop plan set to be contemporaneously evaluated from a multitude of resource management perspectives.

3.5. Concluding Notes

The evolutionary pathway of the SDMD modelling approach has been characterized by increased analytical complexity as the platform has been systematically expanded in order to address an increasing range of volumetric yield, end-product and ecological stand-level objectives [38]: 2-dimensional (size-density) static SDMDs [25,39,40] $\rightarrow$ 3-dimensional (size-density-time) dynamic SDMDs [20,41] $\rightarrow$ n-dimensional (size-density-time-distributional) structural SDMDs [27–30,42]. The associated computational complexity that accompanies this analytical pathway requires the development of algorithmic analogues that are compatible with existing computer hardware and software environments. Furthermore, if intended for operational deployment within forest management planning systems, such algorithms must also attain regulatory and end-user acceptance. The CP_{DSS} presented in this study along with the participatory approach utilized in its development, represents an aspirational attempt to realize these expectations for a collection of third generation SSDMDs developed for black spruce and jack pine stand-types.

Regionally applicable to commercially important boreal-Ontario stand-types and potentially to similar stand-types in other boreal regions, the CP_{DSS} suite should find considerable currency in stand-level management planning and silvicultural decision-making. Specifically, as presented and demonstrated, the CP_{DSS} can be deployed as an iterative crop planning tool where end-users simultaneously contrast density management regimes using detailed annual volumetric yield, end-product and ecological related measures, and (or) abbreviated set of rotational-based performance metrics, from which they can objectively select the most applicable crop plan required for attaining their specified stand-level objective(s). Additionally, the CP_{DSS} can be used as an automated crop planning search tool in which computer-intensive methods are enabled to determine the most appropriate crop plan according to an end-user-specified selection criteria (e.g., operability status, merchantable volume productivity, and economic viability) and associated set of operational constraints (e.g., threshold ranges for thinning intensities and residual occupancy levels). Although space limitations negated specific exemplifications of the Value Management CT and Value Management–IE + CT Optimizers, an example of each is nevertheless provided within Appendices B and C, respectively (i.e., inclusive of required input GUI dialogs, resultant optimal regime sets and outcome summaries). Furthermore, in regards to the optimizers, it is worthwhile to provide an additional perspective on their scope, potential deployment and future development. Specifically, the first two applications are largely applicable to experienced crop planners whereas the last application is more applicable to those who are somewhat new to density management and prefer initial guidance on designing plantation-based crop plans. Currently, only a single thinning event is included within the 3 applications given that current management intensities within the boreal forest are largely limited to such. Conceptually, additional density management optimizers could also be constructed including those that consider wood quality related objectives (e.g., modifying the multivariate selection criteria to include end-product-related attribute-based performance metrics). However, the available fibre attribute sub-models are limited to rotational breast-height predictions and generally lack the ability to explicitly reflect density manipulation treatment effects. Provision of whole-stem attribute prediction models that explicitly account for population effects (e.g., site occupancy) would be an aspirational prerequisite to constructing such optimizers. Of note, the current SSDMD analytical framework does implicitly account for density treatment effects on end-product-based fibre determinates through the predicted stand structural responses arising from density management inputs (e.g., IE, PCT and CT treatment-induced increases in negative skewness within the underlying diameter distributions) combined with the deployment of the size-dependent tree-level attribute prediction models).

The executable variant of the CP_{DSS} requires no additional software programs other than the Windows® 7 SP1 (Microsoft Corporation, Redmond, WA, USA) or newer operating system and Microsoft's.NET Framework 4.6 (Microsoft Corporation, Redmond, WA, USA) to run. All the other executable software required for the GUIs, graphical and tabular reporting tools, and optimizer applications, are embedded. In terms of potentially acquiring the executable version for use in stand-level forest management, silvicultural decision-making, wood quality management or advanced educational instruction, interested end-users are encouraged to contact the author (peter.newton@canada.ca) regarding its potential acquisition. In terms of continued innovation of this modeling platform and its deployment in operational crop planning decision-making, current research efforts are focused on the development of a climate-sensitive red pine (*Pinus resinosa* Ait.) variant applicable to plantation management within the Great Lakes–St. Lawrence Forest Region and the Boreal Forest Region of central and eastern North America.

The CP_{DSS} joins a growing list of user-friendly software tools available for designing optimal crop plans for given stand-level management objectives (e.g., TIPSY [18] and MGM [19]) and more generally to the family of comprehensive forest management decision-support models developed for commercially important species throughout the temperate and boreal forest biomes (e.g., DSSDMD [42], SILVA [82], MOTTI [83], FORSAT [84]). Although validation exercises are still pending in regard to assessing the (1) predictive ability of the CP_{DSS} across the vast array of the output variables produced, (2) interprovincial portability of the suite, and (3) precision of forecasted climate change assumptions and scenarios, confirmation of the ecological integrity and demonstrated predictive ability of the core relationships within the underlying models, provides a consequential measure of validity to the SDMD-based modelling approach in general and to these stand-type-specific SSDMDs in particular. Furthermore, the participatory approach, computational structure and software platform used in the formulation of the CP_{DSS} along with its exemplified utility demonstrated in this study, collectively provides the prerequisite foundation for its operational deployment in boreal crop planning.

Supplementary Materials: The following is available online at https://www.mdpi.com/article/10.3390/f12040448/s1. Material S1: SM-S1.ZIP. CP_{DSS} output summaries for natural-origin jack pine stands established at high densities on medium-to-good site qualities subjected to PCT and CT treatments (Summary Report SM1.xls). Material S2: SM-S2.ZIP. CP_{DSS} output summaries for automated determined crop plans via the operability optimizer for natural-origin jack pine stands established at high densities on medium-to-good site qualities subjected to PCT (Summary Report SM2.xls). Material S3: SM-S3.ZIP. CP_{DSS} output summaries for iterative determined crop plans for upland black spruce plantations growing under a RCP4.5 climate change scenario (Summary Report SM3.xls). Material S2: SM-S4.ZIP. Example CP_{DSS} output summaries for automated determined crop plans via the value management CT optimizer (Summary Report SM4.xls; Appendix B); Material S5: SM-S5.ZIP. Example CP_{DSS} output summaries for automated determined crop plans via the value management IE+CT optimizer (Summary Report SM5.xls; Appendix C). Note, all output summary reports (i.e., Summary Reports SM1, SM2, SM3, SM4 and SM5) are in Microsoft Excel format and include the following: (i) master file (regime input specifics), (ii) SDMD graphic, (iii) crop plan cumulative summaries, (iv) annual regime-specific details, (v) end-user-selected regime comparisons, and (vi) summary of the key performance indices.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A. Performance Metrics

Table A1. Stand-level performance indices: denotations and computations (sensu [30]).

Index (unit)	Computation
Mean annual merchantable volume increment: R_{MAI} (m^3/ha/yr)	$R_{MAI} = \left(V_m + \sum_{k=1}^{K} V_{m(k)}\right)/A_{(T)}$ where V_m is the standing merchantable volume (m^3/ha) at rotation ($A_{(T)}$; yr) and $V_{m(k)}$ is the merchantable volume removed during the kth thinning entry (k = 1, … ,K; K = total number of thinnings).
Mean annual biomass increment: R_{BMI} (t/ha/yr)	$R_{BMI} = \left(M_t + \sum_{k=1}^{K} M_{t(k)}\right)/A_{(T)}$ 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, … ,K).
Mean annual carbon increment: R_{CAI} (t/ha/yr)	$R_{CAI} = \left(C_t + \sum_{k=1}^{K} C_{t(k)}\right)/A_{(T)}$ 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, … ,K).
Percentage of sawlogs produced: R_{SL} (%)	$R_{SL} = 100\left[\left(N_{ls} + \sum_{k=1}^{K} N_{ls(k)}\right)/\left(\left(N_{ls} + \sum_{k=1}^{K} N_{ls(k)}\right) + \left(N_{lp} + \sum_{k=1}^{K} N_{lp(k)}\right)\right)\right]$ 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, … ,K), respectively.
Percentage of lumber volume recovered: $R_{LV(m)}$ (%)	$R_{LV(m)} = 100\left[\left(V_{l(m)} + \sum_{k=1}^{K} V_{l(k,m)}\right)/\left(\left(V_{l(m)} + \sum_{k=1}^{K} V_{l(k,m)}\right) + \left(V_{c(m)} + \sum_{k=1}^{K} V_{c(k,m)}\right)\right)\right]$ 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, … ,K), respectively.
Relative land expectation value: $E_{(m)}$ (%)	$E_{(m)} = 100 \cdot \left(\frac{L^T_{E(m)} - L^C_{E(m)}}{L^C_{E(m)}}\right)$ where $L^T_{E(m)} = \frac{\left(P^T_{t(m)}(1+I_r)^{A(T)} + \sum_{k=1}^{K}\left(P^T_{t(k,m)}(1+I_r)^{A(k)}\right)(1+I_r)^{A(T)-A(k)}\right) - \left(C^E_F(1+I_r)^{A(T)} + C^T_{V-P}(1+I_r)^{A(T)} + \sum_{k=1}^{K} C^T_{F-T(k)}(1+I_r)^{A(T)-A(k)} + \sum_{k=1}^{K} C^T_{V-T(k)}(1+I_r)^{A(T)-A(k)} + C^T_{V-H}\right)}{(1+D_r)^{A(T)}-1}$ $\begin{cases} P^T_{t(m)} = P_{t(m)} \\ P^T_{t(k,m)} = P_{t(k,m)} \\ C^T_{F-T(k)} = c^T_{F-T(k)}(1+I_r)^{A(k)} \\ C^T_{V-P} = 0 \text{ for the natural stand} - \text{type} \\ C^T_{V-P} = c_s N^T_I \text{ for the managed stand} - \text{type} \\ C^T_{V-T(k)} = \left(c^T_{V-T(k)}(1+I_r)^{A(k)}\right)V_{m(k)} \\ C^T_{V-H} = \left(c^T_{V-H}(1+I_r)^{A(T)}\right)V_{m(T)} \end{cases}$ $L^C_{E(m)} = \frac{P^C_{t(m)}(1+I_r)^{A(T)} - \left(C^E_F(1+I_r)^{A(T)} + C^C_{V-P}(1+I_r)^{A(T)} + C^C_{V-H}\right)}{(1+D_r)^{A(T)}-1}$ $\begin{cases} P^C_{t(m)} = P_{t(m)} \\ C^C_{V-H} = \left(c^C_{V-H}(1+I_r)^{A(T)}\right)\hat{V}_{m(T)} \\ C^C_{V-P} = 0 \text{ for the natural stand} - \text{type} \\ C^C_{V-P} = c_s N^C_I \text{ for the managed stand} - \text{type} \end{cases}$

Table A1. *Cont.*

Index (unit)	Computation
	$L^T_{E(m)}$ and $L^C_{E(m)}$ are the land expectation values at rotation attained employing the *m*th sawmill processing protocol within the density manipulated and control stands, respectively, $P^T_{t(m)}$ and $P^C_{t(m)}$ are the inflation-adjusted (to the time of simulation; Y_s) total product values (\$/ha) recovered employing the *m*th sawmill processing protocol from the merchantable-sized trees within the density manipulated and control stands at rotation, respectively, $P^T_{t(k,m)}$ is the inflation-adjusted total product value (\$/ha) recovered employing the *m*th sawmill processing protocol from the merchantable-sized trees removed during the *k*th thinning entry ($k = 1, \ldots, K$), C^E_F is the fixed costs (\$/ha) incurred at the time of stand establishment (e.g., regeneration assessment or vegetation management expenses), C^T_{V-P} and C^C_{V-P} are the variable costs for planting for the treated and control stand, respectively, and are equivalent to the number of seedlings planted (N^C_I or N^T_I initial planting density (stems/ha) within the control and treated stand, respectively) multiplied by the cost per planted seedling (c_s; \$/seedling), $C^T_{F-T(k)}$ is the inflation-adjusted fixed costs (\$/ha) incurred during the *k*th thinning entry (e.g., precommercial thinning cost or logistical costs such as those associated with transporting thinning equipment to CT sites), c^C_{V-H} and C^C_{V-H} 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) and harvesting, transportation, processing and manufacturing costs, at the time harvest within the control stand, c^T_{V-H} and C^T_{V-H} are the inflation unadjusted and adjusted variable costs (\$/m^3), respectively, at the time of harvest within the treated stand, $c^T_{V-T(k)}$ and $C^T_{V-T(k)}$ are the inflation unadjusted and adjusted variable costs (\$/m^3), respectively, at the time of the *k*th 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 *k*th 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 the rotation that the size-density trajectory was within the conceptual optimal relative density management zone ($0.32 \leq P_r < 0.45$), Y_O is the number of years in which the size-density trajectory was within this zone (post attainment of initial crown closure status), 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 $\begin{cases} T_A = \text{ stand age at the time of the last treatment, otherwise zero} \\ \hat{D}_{80(t)} = \hat{b}_{(i)_{(t)}}\left[-\log_e(0.20)\right]^{\hat{c}^{-1}_{(i)(t)}} \end{cases}$ where $\hat{D}_{80(t)}$ is the 80th percentile of the recovered diameter frequency distribution at time *t* as calculated from the Weibull [54] scale and shape parameters [85], $H_{(t,j)}$ is the height (m) of the mid-point-sized tree within the *j*th diameter-class at time *t*, $D_{(t,j)}$ is the breast-height diameter (cm) of the mid-point-sized tree within the *j*th diameter-class at time *t*, $N_{(t,j)}$ is the cumulative number of trees within the *j*th diameter-class (stems/ha) at time *t*, and *T* is the rotation age (i.e., $A_{(T)}$).
Time to operability status: O_T (yr)	$O_T = t \text{ when } \begin{cases} O_{1(t)} \leq O_{1-T} \text{ where } O_{1(t)} = N_{m(t)}/V_{m(t)} \\ and \\ O_{2(t)} \geq O_{2-T} \text{ where } O_{2(t)} = V_{m(t)} \end{cases}$ where O_T is the minimum number of years (*t*) that a stand requires to reach a target piece size, $O_{1\text{-}T}$ (number of merchantable stems per cubic metre of merchantable volume), and merchantable yield threshold, $O_{2\text{-}T}$ (merchantable volume per unit area), $O_{1(t)}$ and $O_{2(t)}$ are the piece size and merchantable yield estimate of the stand at time *t*, respectively, $N_{m(t)}$ is the total number of merchantable size trees $\left(D_{(t,j)} \geq 10\right)$ per unit area (stems/ha) at time *t*, and $V_{m(t)}$ is cumulative merchantable volume per unit area (m^3/ha) of merchantable size trees $\left(D_{(t,j)} \geq 10\right)$ at time *t*.
Whole-stem 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 whole-stem mean wood density (g/cm^3) at time *t* of trees within the *j*th merchantable size diameter class $\left(D_{(t,j)} \geq 10\right)$, and $N_{(t,j)}$ is the cumulative number of trees (stems/ha) within the *j*th merchantable-size diameter-class at time *t*.
Mean maximum branch diameter: $\overline{B}_D$ (cm)	$\overline{B}_D = \frac{1}{T}\sum_{t=i}^{T}\left(\frac{\sum_{j=8}^{J}\overline{b}_{D(t,j)}N_{(t,j)}}{\sum_{j=8}^{J}N_{(t,j)}}\right)$ where $\overline{b}_{D(t,j)}$ is the mean maximum branch diameter (cm) within the first 5 m sawlog at time *t* within the *j*th sawlog-sized diameter-class $\left(D_{(t,j)} \geq 16\right)$, and $N_{(t,j)}$ is the cumulative number of trees (stems/ha) within the *j*th sawlog-size diameter-class at time *t*.
Mean wood density: $\overline{W}_d$ (kg/m^3)	Mean breast-height basal-area-weighted wood density of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation: $\overline{W}_d = \sum_{j=5}^{J} W_{d(T,j)}G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $W_{d(T,j)}$ is the breast-height Silviscan-based wood density estimate (kg/m^3) for the mid-point-sized tree within the *j*th merchantable-size diameter-class (*j* = 5; 10 cm diameter-class) at rotation (*T*), and $G_{(T,j)}$ is the cumulative basal area of all the trees (m^2/ha) within the *j*th merchantable-size diameter-class at rotation (*T*).
Mean microfibial angle: $\overline{M}_a$ (°)	Mean breast-height basal-area-weighted microfibial angle of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation: $\overline{M}_a = \sum_{j=5}^{J} M_{a(T,j)}G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $M_{a(T,j)}$ is the breast-height Silviscan-based microfibial angle (°) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation (*T*).
Mean modulus of elasticity: $\overline{M}_e$ (GPa)	Mean breast-height basal-area-weighted modulus of elasticity of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation: $\overline{M}_e = \sum_{j=5}^{J} M_{e(T,j)}G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $M_{e(T,j)}$ is the breast-height Silviscan-based modulus of elasticity (GPa) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation (*T*).

Table A1. *Cont.*

Index (unit)	Computation
Mean fibre-coarseness: $\overline{C}_o$ (μg/m)	Mean breast-height basal-area-weighted fibre-coarseness of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation $\overline{C}_o = \sum_{j=5}^{J} C_{o(T,j)} G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $C_{o(T,j)}$ is the breast-height Silviscan-based fibre-coarseness (μg/m) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation (T).
Mean tracheid wall thickness: $\overline{W}_t$ (μm)	Mean breast-height basal-area-weighted tracheid wall thickness of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation $\overline{W}_t = \sum_{j=5}^{J} W_{t(T,j)} G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $W_{t(T,j)}$ is the breast-height Silviscan-based tracheid wall thickness (μm) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation.
Mean tracheid radial diameter: $\overline{D}_r$ (μm)	Mean breast-height basal-area-weighted tracheid radial diameter of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation $\overline{D}_r = \sum_{j=5}^{J} D_{r(T,j)} G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $D_{r(T,j)}$ is the breast-height Silviscan-based tracheid radial diameter (μm) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation.
Mean tracheid tangential diameter: $\overline{D}_t$ (μm)	Mean breast-height basal-area-weighted tracheid tangential diameter of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation $\overline{D}_t = \sum_{j=5}^{J} D_{t(T,j)} G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $D_{r(T,j)}$ is the breast-height Silviscan-based tracheid tangential diameter (μm) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation.
Mean specific surface area: $\overline{S}_a$ (m^2/kg)	Mean breast-height basal-area-weighted specific surface area of merchantable-sized trees $\left(D_{(t,j)} \geq 10\right)$ at rotation $\overline{S}_a = \sum_{j=5}^{J} S_{a(T,j)} G_{(T,j)} / \sum_{j=5}^{J} G_{(T,j)}$ where $S_{a(T,j)}$ is the breast-height Silviscan-based specific surface area (m^2/kg) estimate for the mid-point-sized tree within the *j*th merchantable-size diameter-class at rotation.

Appendix B. Exemplification of the Value Management CT Optimizer: Inputs, Outputs and Resultant Summaries

Procedurally, within the initial setup screen of the CP_{DSS}, the end-user is required to first select from among 3 optimizers from under the File/Optimizer tab, and provide the necessary input parameter ranges including constraints (threshold values) via the optimizer-specific input GUI dialog panel. For example, Figure A1 illustrates the GUI input dialog panel when using the Value Management Optimizer–CT for black spruce plantation-based crop planning. More specifically, the initial regimes are specified as follows: Regime 1 is the unthinned control plantation established at an initial density of 2500 stems/ha deploying the temporary genetic worth response (10% genetic worth effect initializing at a selection age of 10 yr and carried forward to rotation age (75 yr); [50]); Regime 2 is the CT plantation established at an initial density of 2500 stems/ha deploying the temporary genetic worth response (10% genetic worth effect initializing at a selection age of 10 yr and carried forward to rotation age (75 yr); [50]); and Regime 3 is the CT plantation also established at an initial density of 2500 stems/ha but deploying the permanent genetic worth response effect (10% genetic worth effect at a selection age of 10 yr that initializes at plantation establishment and is carried forward to rotation age (75 yr); [50]). All 3 regimes deploy the same operational adjustment factor (0.01%/yr) to account for density-independent mortality and the same product degrade estimate (10%). Regime 1 has a slightly higher rotational variable cost estimate than Regimes 2 and 3 given the greater stand structural uniformity and hence potentially lower extraction costs at rotation arising from CT (i.e., \$80 vs. \$70 per cubic metre of merchantable volume harvested, respectively). The timing of the CT treatments, density removal (search-based) interval, intensity of the CT treatment, and fixed and variable thinning cost estimates are defined (i.e., 30–60 year CT treatment window, 250 stems/ha thinning removal searching interval, minimum of 500 tree/ha thinned, and \$0.5 K and 80 \$/m^3 fixed and variable CT cost estimates, respectively). The selection priority relative weightings for mean tree size, merchantable productivity (MAI) and economic efficiency are also specified. Treatment limits on the minimum residual crop density following CT, the maximum rotational height-diameter ratio allowed and the minimum merchantable volume yield required from the CT, are similarly specified. Operability limits (targets), economic parameters and merchantability specification, as shown, must also be defined.

Secondly, following execution, the optimizer then returns a set of optimal regimes and automatically populates the CP_{DSS} input screen Figure A2. In this example, according to the specified 60–20–20 mean size-volumetric-economic selection priority weighting, thinning restrictions (30–60 yr treatment age range; minimum of 500 stems/ha removed; minimum CT yield of 30 m^3/ha; minimum post-CT stand density of 500 stems/ha), stand structural goal (maximum height/diameter ratio of 100), and economic parameters (inflation and discount rates, rotational variable costs) for upland black spruce plantations established at a density of 2500 trees/ha growing on a site of medium-to-good quality (site index 18 m [68]), the optimal crop plan would be to CT at (1) age 35 yr and remove 500 stems/ha when assuming a temporary genetic growth response effect, or (2) age 31 yr and remove 1000 stems/ha when assuming a permanent genetic growth response effect.

Thirdly, using this information, CP_{DSS} executes the computational sequence as described in Figure 1, which then generates a full range of graphical and tabular output for the selected optimal regimes along with the comparable unthinned control plantation. These include for example, (1) size-density trajectories for the selected crop plans within the context of the traditional SDMD graphic, (2) stand structural visualizations at rotation, (3) 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 the 3 regimes and a set of performance indices for each regime. A complete summary report of these crop plans is included in an accompanying MS Excel report: Master file (regime input specifics), crop plan cumulative summaries, annual regime-specific details, results from the end-user regime comparisons when specified, and the summary of the overall performance metrics and associated comparisons (e.g., Summary Report SM4; Supplementary Material).

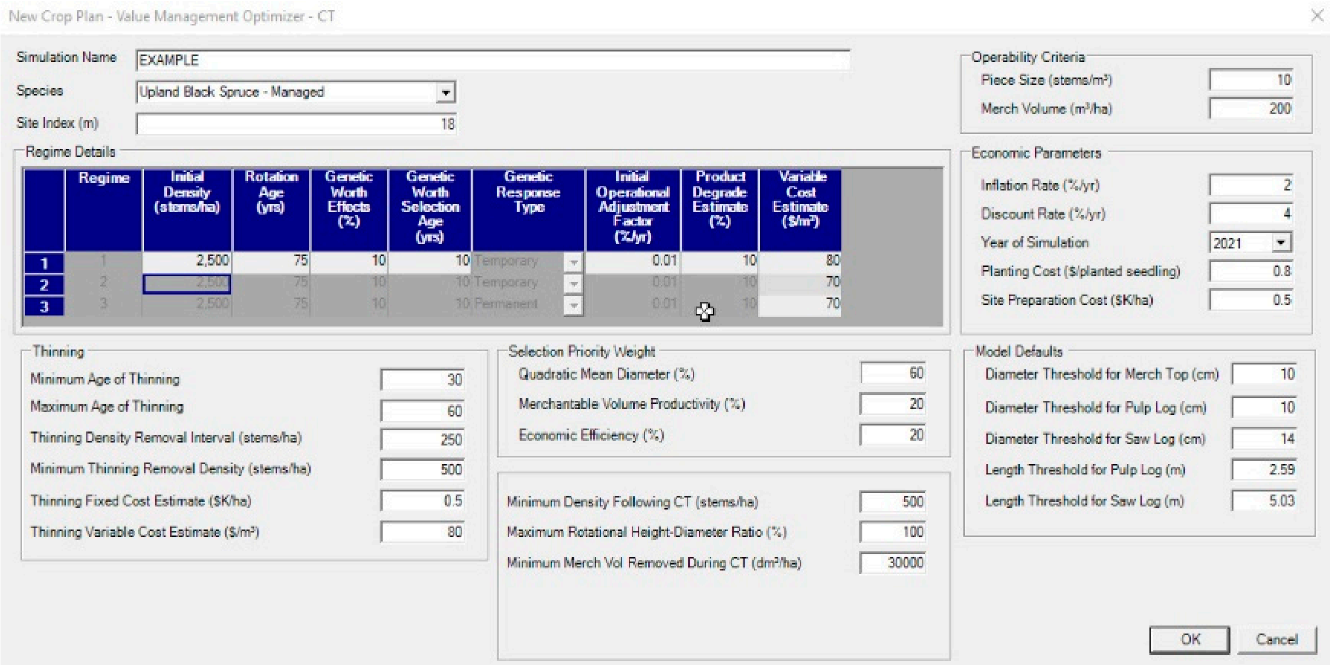

Figure A1. Exemplifying the automated crop plan selection capability of the CP_{DSS} in regard to determining the optimal CT regime within upland black spruce plantations via the deployment of the Value Management Optimizer–CT. Specifically, the input GUI dialog inclusive of end-user required input consisting of the (1) simulation name, stand-type specification (species), site index, regime-specific specification of initial density, rotation age, genetic worth effect, selection age and response model, operational adjustment and product degrade factors, and variable cost estimate, and overall operability targets, economic assumptions and merchantable specifications applicable to all 3 regimes, (2) treatment specifics and constraints inclusive of the range of CT treatment ages (events), removal density searching interval (algorithmic requirement), minimum number of trees thinned (operational requirement), fixed and variable treatment costs, minimum post-thinning residual stand density, maximum height/diameter ratio tolerable and minimum recoverable merchantable volume required from the CT (operational requirement), and (3) multivariate selection priority weights (size, merchantable volume productivity and economic efficiency).

Upon reviewing this example report, it is evident that either of the 2 optimal regimes, that is, Regime 2 consisting of an CT at age 35 yr in which 500 stems/ha are removed when assuming a temporary genetic growth response, or Regime 3 consisting of an CT at age 31 yr during which 1000 stems/ha are removed when assuming a permanent genetic growth response, would yield greater mean diameter sized trees, merchantable volumes, and economic efficiency relative to the unthinned plantation (Regime 1). Although programmed to only select final optimal regimes that comply with the pre-treatment stocking and live crown ratio regulatory requirements (i.e., minimum pre-treatment basal area of 25 m^2/ha and live crown ratio of 35% thresholds [73]), it is also evident within the regime-specific annual outputs, that both selected CT regimes were in such compliance (e.g., 37.1 m^2/ha and 41% at age 31 for Regime 3). Additionally, the CT treatments occurred approximately at the time in each plantation's trajectory when the number of merchantable sized stems maximized. Thus the CT treatments were able to capture a large portion of the merchantable sized stems that would be expected to incur mortality if not thinned (e.g., 43%; mortality in the merchantable size classes for the control regime from age 36 yr to 75 yr (rotation) was 1103 versus 697 stems/ha for Regime 2). Although not shown, these regimes were also the most optimal among all the other regimes considered and were in compliance with all of the imposed constraints. Essentially, the search consisted of evaluating a total of

31 potential CT event years (from age 30 yr to 60 yr) in which 8 CT removable intensities were assessed for each year (removing 250, 500, 750, . . . to a maximum of 2000 stems/ha); hence a potential maximum of 248 regimes for each genetic growth response setting were compared with the comparable unthinned control plantation (8 CT treatments/IE level × 31 CT event years/CT removal level).

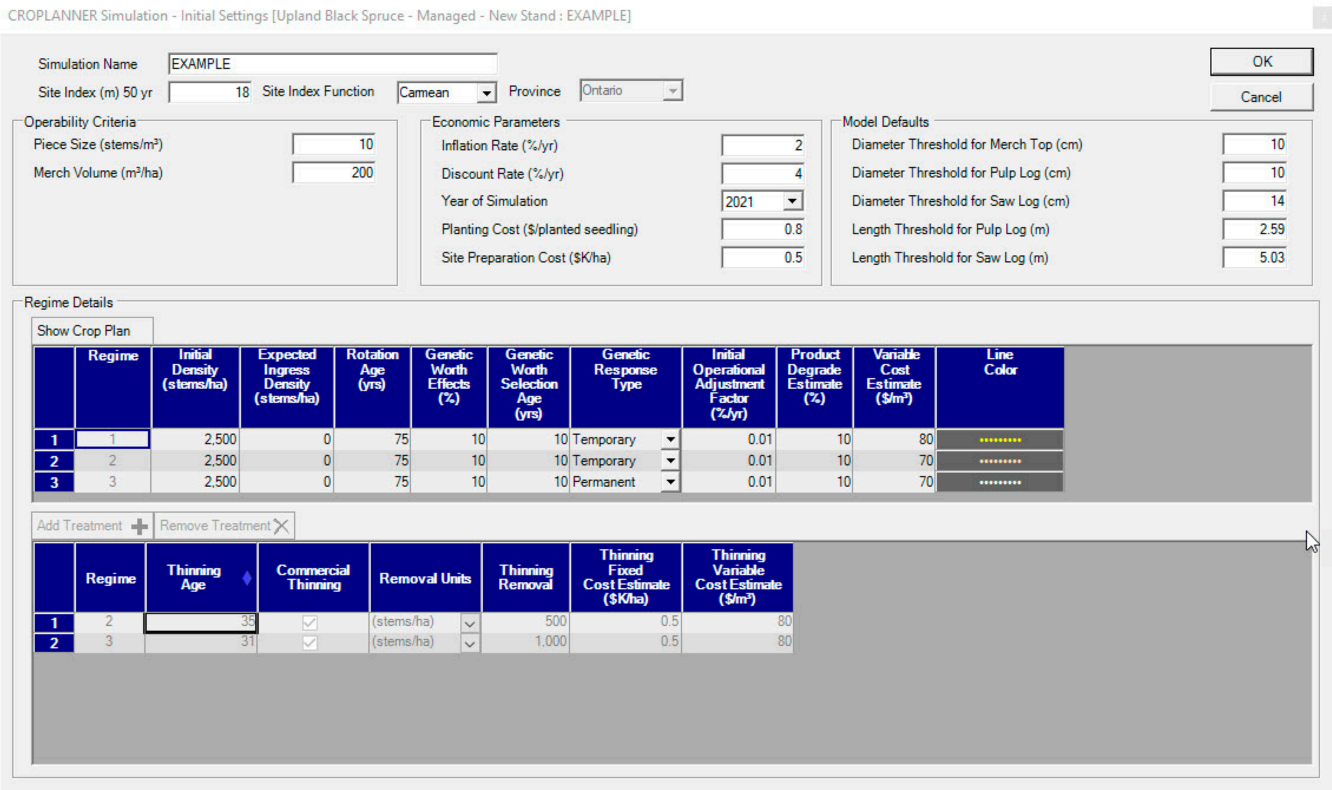

Figure A2. Exemplifying the automated crop plan selection capability of the CP_{DSS} in regard to determining the optimal CT regime within upland black spruce plantations via the deployment of the Value Management Optimizer–CT. Specifically, the auto-populated input GUI dialog screen generated from the optimizer consisting of the selected optimal CT-based crop plan set inclusive of required regime-specific input along with the carried forward operability criteria, economic parameter settings and model (merchantability limits) default values.

Appendix C. Exemplification of the Value Management IE+CT Optimizer: Inputs, Outputs and Resultant Summaries

Procedurally, similar to the other optimizers, the end-user is required to first select from among the 3 optimizer offerings under the File/Optimizer tab and provide the necessary input parameter ranges including constraints (threshold values) via the input GUI dialog panel. For example, Figure A3 illustrates the GUI input screen when using the Value Management IE + CT Optimizer to design crop plans for upland black spruce plantations. More specifically, the initial regimes are specified as follows: Regime 1 is the unthinned control plantation of a yet unknown establishment density which deploys the temporary genetic worth growth response function (10% genetic worth effect initializing at a selection age of 10 yr and carried forward to rotation age (75 yr); [50]); Regime 2 is the CT plantation of a yet unknown establishment density which assumes a temporary genetic worth growth response (10% genetic worth effect initializing at a selection age of 10 yr and carried forward to rotation age (75 yr); [50]); and Regime 3 is the CT plantation of a yet unknown establishment density which assumes a permanent genetic worth growth response (10% genetic worth effect at a selection age of 10 yr initializing at establishment and carried forward to rotation age (75 yr); [50]). All 3 regimes assume the same operational adjustment factor (0.01%/y) to account for density-independent mortality and deploy the same product degrade estimate (10%). Regime 1 has a slightly higher rotational variable cost estimate than Regimes 2 and 3 given the greater structural uniformity of the thinned stands and hence potentially lower extraction costs at rotation ($80 versus $70 per cubic metre of merchantable volume harvested). As with the Value Management CT Optimizer, the (1) timing of the CT treatments, density removal interval, intensity of the CT treatment, and fixed and variable thinning cost estimates (i.e., 30–60 year CT treatment window, 250 stems/ha thinning removal searching interval, minimum of 500 trees/ha thinned, and $0.5 K and 80 $/m^3 fixed and variable cost estimates, respectively), (2) selection priority relative weightings for mean tree size, merchantable productivity (MAI) and economic efficiency, (3) treatment threshold with respect to the residual crop density on site following CT, the maximum rotational height-diameter ratio allowed, and the minimum merchantable volume yield required from the CT, and (4) operability limits (targets), economic parameters and merchantability specification, all need to be specified. However, in addition, input is also required for the scope of the IE search range in terms of the density interval to consider (e.g., 100 seedlings/ha) along with the maximum planting density limit (e.g., 3000 stems/ha).

Secondly, following execution, the optimizer then returns a set of optimal regimes and automatically populates the CP_{DSS} input screen Figure A4. In this example, according to the specified 60–20–20 mean size-volumetric-economic selection priority weighting, initial planting limits (i.e., 1000 to 3000 seedlings/ha by 100 seedling/ha intervals), thinning restrictions (30–60 yr treatment age range; minimum of 500 stems/ha removed; minimum CT yield of 30 m^3/ha; minimum post-CT density of 500 stems/ha), stand structural goal (maximum height/diameter ratio of 100), and economic parameters (inflation and discount rates, rotational variable costs) for upland black spruce plantations growing on a site of medium-to-good quality (site index 18 m [68]), the optimal crop plan would be to established the plantation at an initial density of (1) 2200 trees/ha followed by a CT at age 35 yr and removing 500 stems/ha when assuming a temporary genetic growth response, or (2) 2500 trees/ha followed by a CT at age 31 and removing 1000 stems/ha when assuming a permanent genetic growth response.

Thirdly, as similarly stated for the CT-only value management optimizer, the CP_{DSS} then executes the computational sequence as described in Figure 1, deploying the selected crop plans, and subsequently generates the graphical and tabular output for all of the regimes. Similarly, a complete summary report of the resultant crop plans is also included in an accompanying MS Excel report including a master file (regime input specifics), SDMD graphic, crop plan cumulative summaries, annual regime-specific details, results from the end-user regime comparisons when specified, and the summary of the overall performance metrics and associated comparisons (e.g., Summary Report SM5; Supplementary Material).

In reviewing this example report, it is evident that either of the 2 optimal regimes, that is, Regime 2 consisting an establishment density of 2200 seedlings/ha followed by a CT at age 35 yr in which 500 stems/ha are removed when assuming a temporary genetic growth response, or Regime 3 consisting an establishment density of 2500 seedlings/ha followed by a CT at age 31 yr during which 1000 stems/ha were removed when assuming a permanent genetic growth response, would yield greater sized trees, merchantable volumes, and economic efficiencies relative to the unthinned plantation (Regime 1). Similar to the CT-only value management optimizer, as predetermined, the selected final optimal regimes were in compliance with the regulatory-defined pre-treatment stocking and live crown ratio requirements (i.e., minimum pre-treatment basal area of 25 m^2/ha and live crown ratio of 35% thresholds [73]): e.g., 37.1 m^2/ha and 38% at age 35 yr for Regime 2. Additionally, the CT treatments occurred approximately at the time in each plantation's trajectory when the number of merchantable sized stems maximized and thus the CT treatments were able to capture a large portion of the merchantable sized stems that would be expected to incur mortality if not thinned (e.g., 87%; mortality in the merchantable size classes for the control regime from age 32 yr to 75 yr (rotation) was 1035 versus 386 stems/ha for Regime 3). Although not shown, these regimes were also the most optimal among all the other regimes considered and were in compliance with the constraints imposed. Essentially, the search consisted of evaluating a total of 21 initial espacement levels (1000 to 3000 by 100 seedlings/ha increments) and potentially 10 CT removable intensities (removing 250, 500, 750, . . . to a maximum of 2500 stems/ha) for each CT event year (from age 30 yr to 60 yr) for each IE level; hence a potential maximum of 6510 regimes for each genetic growth response model were compared with the comparable unthinned control plantations (21 IE levels × 10 CT removal levels/IE level × 31 CT event years/CT removal level).

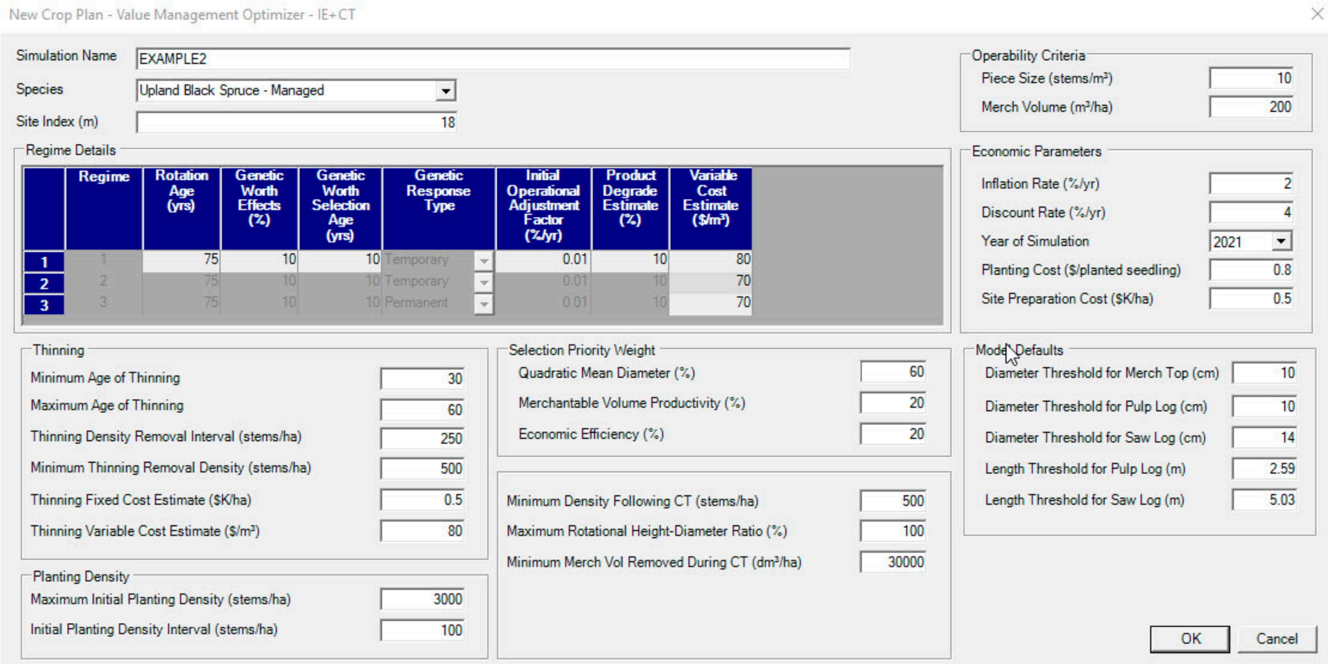

Figure A3. Exemplifying the automated crop plan selection capability of the CP_{DSS} in regard to determining the optimal IE + CT regime within upland black spruce plantations via the deployment of the Value Management Optimizer–IE+CT. Specifically, the input GUI dialog panel inclusive of end-user required input consisting of (1) simulation identifier (name), stand-type selection (species), site index, regime-specific specification of rotation age, genetic worth effect, selection age and response model, operational adjustment and product degrade factors, and variable cost estimates, and overall operability targets, economic assumptions and merchantable specifications applicable across regimes, (2) treatment specifics and constraints inclusive of the maximum IE level and IE simulation searching interval, range of CT treatment ages (events), removal density searching interval (algorithm based), minimum number of trees thinned (operational based), fixed and variable treatment costs, minimum post-thinning residual density, maximum height/diameter ratio tolerable and minimum recoverable merchantable volume from CT required (operational based), and (3) multivariate selection priority weights (size, merchantable volume productivity and economic efficiency).

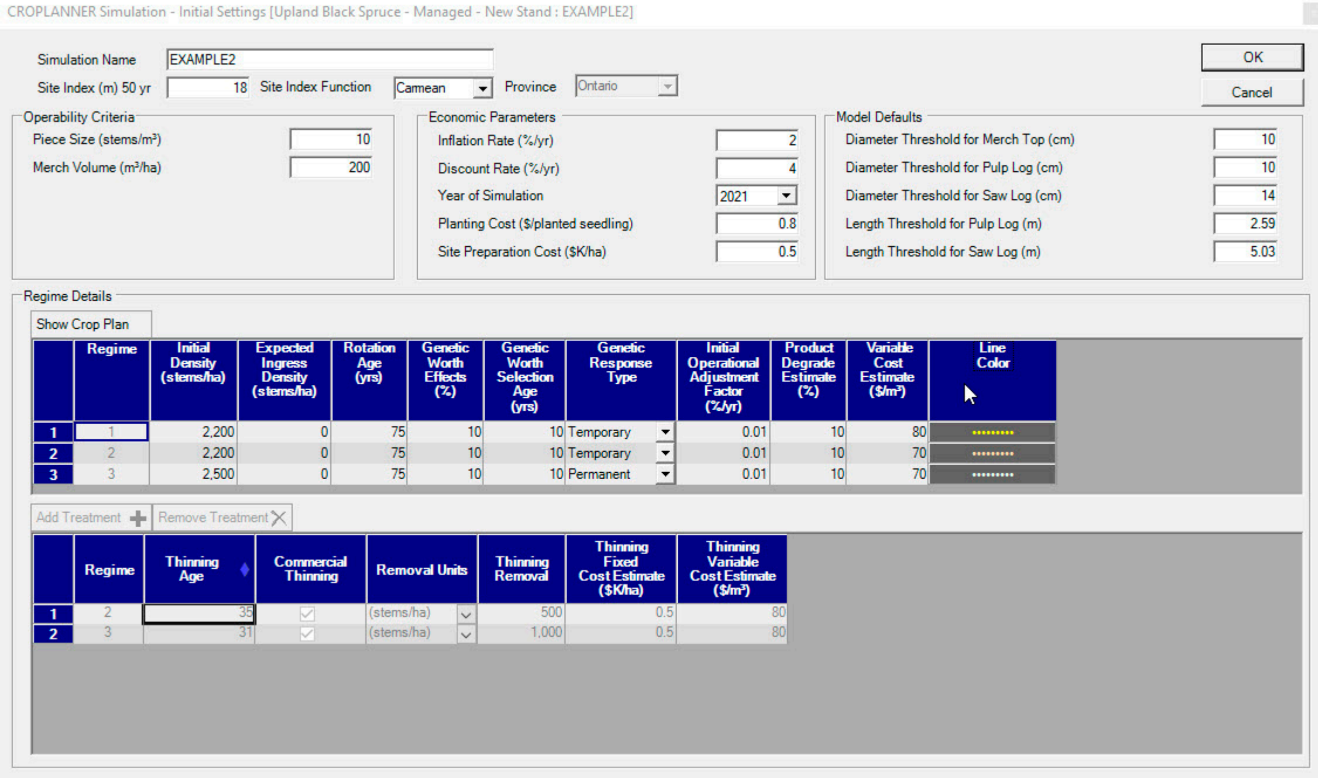

Figure A4. Exemplifying the automated crop plan selection capability of the CP_{DSS} in regard to determining the optimal IE + CT regime within upland black spruce plantations via the deployment of the Value Management Optimizer–IE+CT. Specifically, the auto-populated input GUI dialog is informed from the optimizer's output and includes the optimal IE + CT-based crop plan set along with the required regime-specific input and the carried forward operability targets, economic parameter settings and model (merchantability limit) defaults.

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