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Chapter 6

Maintaining Ecosystem Function by Restoring Forest Biodiversity – Reviewing Decision-Support Tools that link Biology, Hydrology and Geochemistry

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Additional information is available at the end of the chapter

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1. Introduction

Land use change in forest ecosystems is a worldwide problem. In many cases, however, the change is only temporary, and after a period of economic activity, the original forest must be reclaimed back to its original (or as close as possible) estate. A typical case is in open-pit mining. In many juridictions there is a legal requirement for the company to engage in restorative activities designed to bring back biodiversity and function to those areas espoiled by mining.

To reclaim a fully functional forest ecosystem, soil, topographic and hydrological properties must foster the biogeochemical and ecological processes required to support a vigorous vegetative community. While significant advances have been made in this regard, each reclaimed forest ecosystem is unique, and there remains considerable uncertainty as to how these interdependent processes will be manifest in any particular instance. One of the most important interdepencies is between water availability and plant uptake. Our understanding of biodiversity and linkage with surface water availability and distribution is limited because this relationship has not been examined within and across scales. The availability and distribution of water can influence ecosystem structure and function at a range of scales and levels of organization through its influences on various processes and feedbacks that can affect both animals and plants. For example, at a landscape level, the distribution of herbivore home ranges and vegetation communities may be influenced by the mosaic created by water sources. At the ecosystem and community levels, ecosystem processes such as nutrient cycling, predator-prey interactions, and interspecific competition may be influenced by the availablility and location of water sources. At a population level, surface and soil water availability and

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distribution may influence herbivore and vegetation survivorship through processes such as droughts, pests and diseases.

Water scarcity can be produced by seasonal or annual droughts, but also by difficulties in uptake due to salinity or other contaminants. Naturally saline systems within the boreal forest are infrequent but are widespread across western North America [1]. Typical saline sites can be found in partially-closed catchment areas with inflows of groundwater [2]. Levels of salinity in shallow soils generally increase as the elevation declines toward a basin, reflecting the movement of the salts along the topographic gradient.

Reclaimed landscapes must hold enough water for plant growth but have enough downward movement of water to flush any contaminants from the rooting zone. Excessive percolation is also a concern, however, since drainage from toe slopes can carry dissolved contaminates out of a landform [3]. In northern climates, evapotranspiration is the largest annual loss of water [4], and a primary factor in the movement of salts to the surface. Interactions between vegetation productivity, nutrient budgets and evapotranspiration must therefore be assessed simultaneously [5]. There has been little research, however, on how changes in vegetation and climate affect the energy balance and water movement in northern ecosystems [3].

A broad array of decision support tools is available for projecting forest stand development in reclaimed ecosystems. These include forest ecosystem classification and ecosite manuals, stand establishment keys/guides, competition index methodologies, volume tables, site index curves, soil-site equations, stand density management tools, and growth and yield equations/tables/decision systems [6]. Many of these tools are empirically based. This means they have significant limitations in their ability to accurately project productivity because in a strict sense, their application should be restricted to the stand conditions from which their underlying relationships were derived [7]. This can be problematic in mine reclamation for two reasons. First, the soil prescriptions that form the basis for reclamation often lack the historical legacy (propagule bank, organic matter, soil structural and biochemical properties, etc.) common to natural sites [8-11]. Secondly, forests are growing under climatic conditions that differ from the historical climate regime, particularly in more northerly regions. Global circulation model projections indicate continued increases in atmospheric and surface temperatures at least through this century, along with associated changes in the precipitation regime. Historical properties are now no longer tenable as the sole basis for deriving empirical growth relationships.

With the widespread increase in computing power, model sophistication and complexity have seen a rapid increase though this has not necessarily resulted in better and more reliable outcomes [12]. One issue with greater complexity is the increased cost and difficulty of obtaining calibration data sets for specific local ecosystems. From the perspective of reclamation, another issue is that most forest stand decision support tools have little or no representation of hydrological processes. In essence, the implicit assumption underlying these models is that the hydrological regime is in an equilibrium condition such that short-term temporal or spatial fluctuations in available moisture are of little consequence to long-term trends in productivity.

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One way of resolving these limitations is to build a fully integrated vegetation-hydrology tool that combines a detailed representation of all critical processes within a single computing environment. The resulting 'mega-model' would possess the benefits of a fully integrated and interactive system with appropriate feedbacks and system controls. In such models, linkage between the different components of the model would be in real time, with vegetation growth and development in each time step related to the hydrological processes driving available moisture [13].

Seldom it is feasible or desirable, however, to build a model that includes all processes and scales of interest [14]. There are no a single model can be used in every situation that could arise during planning or management. If such a model is constructed, it will probably have one or more issues of being too generalist, having issues to represent processes at different scales, and continuous tuning and modifications to handle new data and issues [15]. Furthermore, ensuring these models are reliable requires substantial investments of time and energy, and their applicability tends to become overly specialized thereby reducing flexibility and portability (applying the model in different locations or circumstances). Other disadvantages include an increased calibration load associated with the myriad feedback and system controls, validation (establishing the veracity of model structure and architecture) and verification (assessing output accuracy). In this respect, more complex models are not 'better' due simply to the fact they incorporate a greater representation of reality because complexity does not necessarily equate to improved accuracy and precision. This leads to the modelling mantra that models should be only as complex as absolutely necessary.

A compromise (and popular) approach is to construct a 'meta-model' wherein the most suitable forest productivity and hydrological models would be coupled as input-output (I/O) systems. This I/O linkage refers to the idea that output from a given model serves as input to another. Fall [14] provided a list of the benefits and costs of the meta-modeling approach. The most important benefits of the meta-modelling approach are that it can use previous knowledge and expertise generated when developed well document models, but at the same time allow for flexibility to match the meta-model to the local conditions, data availability and other user needs. In addition, different teams can work in different processes and sub-models at the same time, improving the use of time and resources. Such advantage is particularly important when individuals are separated geographically. Another advantage is that by linking different models or sub-models, each of them can be analyzed and validated separately. Such advantage is important to increase understanding of complex interactions between different ecosystem components, and to allow comparisons of different model components. Data flow in the meta-modelling approach is also more flexible, and output from one model can be used as input for several other model components. This allows partial verification as intermediate data can be analyzed and stored, something important in adaptive management and monitoring. Finally, in a meta-modelling framework model sensitivity and scenario analyses are facilitated as they can be performed for different model components.

Not all forest models are applicable to a meta-modelling approach. Hence, the objective of the research presented here was to identify and compare the available forest models already being used in research, and to evaluate their suitability for use as decision-support tools in designing

successful restoration plans to bring forest biodiversity and function back to sites disturbed by industrial activities (mining in particular).

2. Review methodology

2.1. Literature review on forest growth models

The review covered papers available at the beginning of 2013 in scientific journals, scientific books, proceedings of scientific workshops and conferences, and technical reports. The literature search was conducted using the term "forest growth model" in combination with each of the following 8 keywords: "climate change, gap model, hydrology, mixedwood, productivity, regeneration, simulation, and succession". 'Hits' were then screened and those pertaining to ecosystems other than temperate and boreal forests were eliminated (tropical and subtropical ecosystems, Mediterranean ecosystems, grasslands, etc.). The data bases consulted were:

- *Canadian Forest Service Bookstore* (list of publication by Canadian authors compiled by the Canadian Forest Service compiled by the Canadian Forest Service)

Available at http://bookstore.cfs.nrcan.gc.ca

- *ISI Web of knowledge* (academic search engine by Thomson Reuters).

Available at http://www.isiwebofknowledge.com

- *Google Scholar* (academic search engine by Google Inc.).

Available at http://scholar.google.ca

- *C.E.M.A. Research library* (collection of reports and publication for the Alberta Oil Sands area compiled by the Cumulative Environmental Management Association)

Available at http://www.cemaonline.ca

- *U.B.C. library* (academic library at the University of British Columbia)
- On-line catalogue available at http://www.library.ubc.ca
- *Register Of Ecological Models* (self-registration tool to compile ecological models by the Kasel University).

Available at http://ecobas.org/www-server/index.html

2.2. Ranking of forest models

Development of a system for ranking models is a challenging and inexact exercise. The criterion used to build the ranking system, for example, as well as the relative weighting attached to each ranking variable are important decisions. First and foremost, we are of the opinion that the scientific peer review process provides the best assurance that model structure and

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application are sound and have been subjected to expert scrutiny, particularly for those models with multiple entries in the scientific literature. Hence, only models cited in three or more peer-reviewed publications were considered in creating a ranking of model suitability. Models with lesser publications were therefore omitted from further analysis because their low publication rates indicate that they have not yet received a proper assessment of their suitability. The objective of the ranking exercise was to identify the best 3 to 5 models according to five criteria. The ranking was created in two steps:

2.2.1. Initial partial score (0 to 8 points)

Each model was scored initially using four criteria that varied in maximum value between 1.5 to 2.5 points. A proportional approach was used to derive a relative ranking for each model within a given criterion: The model with the best mark received the maximum criterion score, and the remainder were scored in direct proportion to how they compared with the top model. The four criteria used to create the rankings were:

- *Number of publications in the database* (for models with ≥ 3 publications; maximum 2.5 points): An index of model application.
- *Time between first and most recent publications in the database* (in years; maximum 1.5 points): An index of model durability.
- *Time to last publication* (in years; maximum 1.5 points): an index of current activity around the model.
- *Number of citations in Web of Science®* (maximum 2.0 points): an index of the utility and relevance of the work done with the model, as perceived by the scientific community.

A final partial score for a given model was calculated by adding up the score for each criterion.

2.2.2. Full score (0 to 10 points) and shortlisting

An additional criterion was defined as the number of countries, ecosystem types and forest types in which each model had been applied. This criterion was considered a measure of model versatility, and was assigned a potential maximum of 2 points. Given the time-consuming nature of gathering data to calculate the values of this criterion, only models with an accumulated score of 5 or above (out of a maximum score of 8) for the previous four criteria were given scores for model versatility. Following the ranking exercise, a total score (out of a maximum of 10 points) was calculated and those models with 6.5 points or more made the shortlist.

All models can be broadly classified into three categories, depending on their structure and how they are parameterized:

- *Empirical models:* use a bioassay method to estimate tree growth. These models are constructed from historical growth patterns of, for example volume-age curves, height-age cures, yield tables, etc.
- *Process-based models:* simulate the physical processes underlying ecological dynamics.

- *Hybrid models:* combine elements of the above two categories. In this approach, empirical data are used to parameterize one or more of the ecophysiological processes driving in tree growth and ecosystem production.

3. Results and discussion

3.1. Literature review

A total of 466 documents were identified through the literature search. Most of the documents were detected using the general modeling-related keywords: "gap model" (83 documents), "productivity" (89 documents), "regeneration" (86 documents), and "simulation" (33 documents). These 291 documents account for 62.3% of the total. Following the pioneering work of Botkin et al. [16] with development of the JABOWA gap model, the number of models addressing forest productivity has increased steadily over the previous four decades (Figure 1). Several factors have likely contributed to this trend. Most models developed prior to the 1990s were designed to simulate timber production. Since then, forest management has moved from an almost exclusive focus on timber towards an emphasis on the sustainable production of multiple ecosystem goods and services [7]. Subsequent model developments have reflected this change.

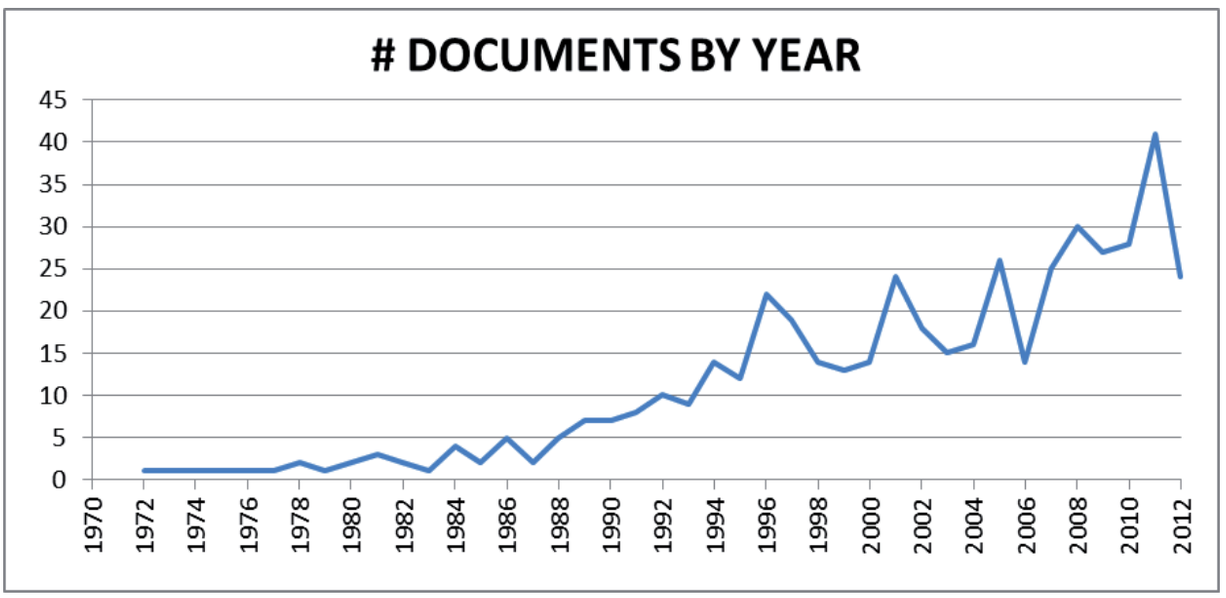


Figure 1. Number of documents published in a given year as derived from the keyword searches.

Climate and climate change have also emerged as a dominant issue in forest management, as government and industry strive to understand its impact on the present and future flow of goods and services. Keywords related to moisture ("climate change", "hydrology") accounted for 96 documents, 20.8% of the total. Of the 96 documents, 33 were related to the "climate change' keyword and 63 under "hydrology". A proportion of the documents under the

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keyword "hydrology" were also related to how climate change might alter the hydrological cycle. To avoid duplication, those documents were not accounted under the results for "climate change". Hence, under the "climate change" keyword only documents that deal with climate change and anything other than hydrological process are accounted for (mostly temperature-related research).

Tian et al. [17] argue that current forest growth models are seldom "well balanced" in terms of equivalence in the detail with which water, C, and N cycles are represented (see also [18, 19]). For instance, G'DAY [20], PnET-CN [21], and Biome-BGC [22] simulate forest growth and/or biogeochemical processes in detail but are much less rigorous in their approach to representing forest hydrology. Unbalanced model design is likely to limit the ability of a given model to accurately predict the hydrology and biogeochemistry of forest ecosystems in response to changes in climate, land use, and/or management practices [19, 23].

In recent years, there have been several attempts to better link forest growth with hydrology. Chen and Driscoll [24] demonstrated that incorporating a more detailed hydrologic cycle into the Biome-BGC model improved predictions of seasonal effluent nitrate concentrations. Seely et al. [25] developed a stand-alone hydrology model for forest management applications (ForWaDy), with the explicit objective of minimizing data requirements. This model has been incorporated into the forest ecosystem simulation model, FORECAST [7]. Evidence suggests it provides a robust representation of moisture availability on tree growth, based on the balance between inputs from precipitation and seepage, and outputs by canopy interception, evapotranspiration, plant uptake, percolation and runoff [26].

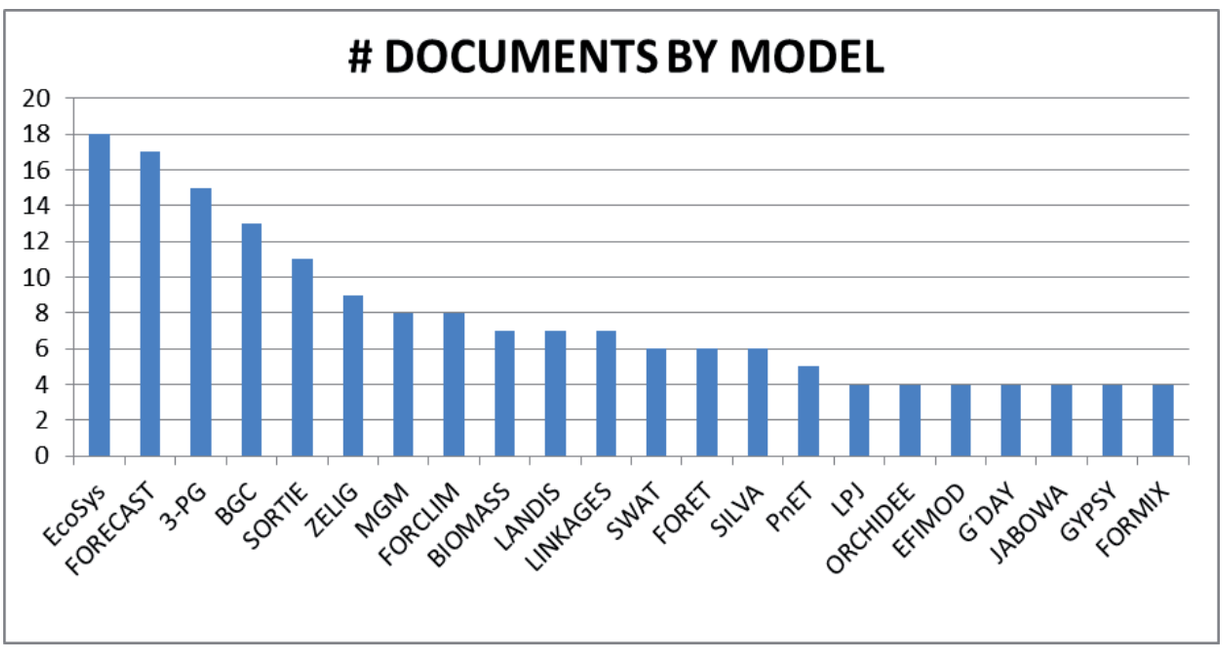


Figure 2. Number of document per model, for models with four or more documents in the database.

Despite the large number of models identified from the initial search, only 22 had 3 or more references (Figure 2). This suggests that many models are developed as one-time tools to

explore issues of scientific importance, rather than as decision-support tool in support of management. This can limit the ease with which a model can be applied to situations different from that for which it was originally designed (i.e., the model's portability). It might also constrain the flexibility in model architecture, making it difficult to add management capabilities at a later date [7].

3.2. Model shortlisting

Only five models had more than 10 references: ECOSYS (18), FORECAST (17), 3-PG (15), BGC (13), and SORTIE (11; including both of its versions, SORTIE-ND, SORTIE-BC). It should be noted that the count for BGC is inflated by the fact it has three different variants (TREE-BGC, FOREST-BGC, and BIOME-BGC) which were grouped together for purposes of analysis. Arguably, it may be more appropriate to consider each separately since they are applicable to widely different scales (tree, stand, and biome, respectively). In that case, the ranking for each separate model would be much lower. The models LINKAGES, BIOMASS and CENTURY had relatively few publications but they ranked fairly well in the remaining criteria (Table 1). In the case of ECOSYS, 14 of the 18 references listed the developer (Grant) as the primary author. This is an unusually high number despite the fact the model was first published 14 years ago (Table 1). Publications of the remaining top models in the review encompassed a broad range of authors. This could be an indication that ECOSYS has not received broad acceptance, which could at least partly explain its low citation rate (see below). The common features of the top seven models (in green and yellow colours in Table 1) are that they are subject to ongoing development (≥ 14 years), have been broadly applied in temperate and boreal ecosystems, and been cited within the last 2 years. The one exception is BIOMASS, which has not been cited in the previous 4 years. The top models were also heavily cited, with more 80 citations; ECOSYS was the clear exception, with only 25 citations (Table 1).

On its own, a high citation rate alone does not necessarily mean that a model is indeed being used extensively or is pertinent to the needs of Total. For example, a model that has been cited extensively is CENTURY. This model was originally developed for grasslands and so references to CENTURY were relatively frequent in the agricultural literature. In its current version, the model possesses a crude ability to represent forest growth. Its focus, however, is still mainly on soil processes even though this may be within the context of forest management. To an extent our ranking system was designed to take these factors into account by assigning the publication rate a higher weighting than the citation rate (a maximum score of 2.5 versus 2, respectively).

An important aspect of model suitability to oil sands reclamation is its portability. Portability refers to the ease with which a model can be calibrated, and its algorithms applied to, an ecosystem different from that in which it was originally developed. This is because no tool has been developed specifically for the conditions that characterize oil sands materials. Hence, the higher the number of countries and ecosystems where the model has been successfully applied, the higher its portability. The portability criterion was the final key factor that discriminated among the "shortlisted" models (BGC, FORECAST, 3-PG, and ECOSYS) and the remainder (Figure 2). These four models had more than 10 documents in the database, meaning they have

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been used in more than 10 different countries and/or ecosystem types, indicating a high portability potential.

3.2.1. ECOSYS

ECOSYS is a process-based, ecosystem-level model. It was originally developed as a soil model for agricultural ecosystems, but since then it has evolved into a complex simulator of the plant-atmosphere-soil system [27]. ECOSYS has a time step of one hour. It has representation of multi-layered canopies and soils. In this model, flows and transformation of growth resources (radiation, water, C, N, and P) are simulated for populations of plants and microorganisms. The model is constructed in order to link at different spatial and biological scales ecological processes that determine the ecophysiology of linked plant and microbial populations.

The model can represent ecosystems scales from homogeneous stands to heterogeneous landscapes, including natural and human-made disturbances. The model estimates ecosystem productivity through an energy balance approach.

Energy flows are simulated between the atmosphere and ground surfaces (snow, soil, litter). For plants, energy flows are simulated between the atmosphere and leaf or stem surfaces [29]. To calculate total exchange energy, energy exchanges between all plant and ground surfaces are added up. Hydrological processes (surface runoff, infiltration macro- and micro-pore flow) are then coupled with surface energy exchange and soil heat transfer [28].

ECOSYS calculates energy exchange in the canopy at an hourly basis, using a two-stage convergence solution to estimate heat and water transfers for the soil-root-canopy system for several plant populations and layers of soil and canopy. In the first stage, a canopy temperature value is calculated for each plant population by closing the canopy energy balance (sensible heat, latent heat flux, net radiation, and change in stored heat).These fluxes are controlled by aerodynamic and canopy stomatal resistances [29].

The simulation of water status effects on energy exchange is based on coupling the uptake of water from the soil through the root to the canopy, with the evaporation of water from the canopy to the atmosphere. This coupling determines the water status of the canopy and hence its conductance to water vapor [27].

Leaf C fixation is determined by carboxylation, which is controlled by irradiance, temperature, and leaf CO_2 concentration, and by diffusion, which is controlled by the atmosphere-leaf CO_2 concentration gradient and leaf conductance. The coupling of carboxylation and diffusion in ECOSYS allows the calculation of a leaf C fixation rate, which is then aggregated to the canopy level. Net C exchange between plants and the atmosphere is the difference between the two. Losses of leaf C are accelerated by reducing C fixation compared to maintenance respiration by reduced availability of growth resources (N, heat, or water). Net CO_2 fixation is calculated for each branch as the difference between gross fixation and the sum of respiration through maintenance, growth, and reproduction [27].

Model	Model	References		Time elapsed		Time since last reference		Citations in Web of Science		PARTIAL	Forest types applied				FINAL
	Type	#	score	years	score	years	score	#	Score	SCORE	# C	# E	Total	score	SCORE
BGC	process	[13]	1.81	23	1.33	2	1.89	178	1.67	6.70	6	14	20	1.48	8.18
FORECAST	hybrid	[17]	2.36	17	0.98	1	2.00	81	0.76	6.10	6	21	27	2.00	8.10
3-PG	process	[15]	2.08	14	0.81	2	1.89	118	1.11	5.89	7	10	17	1.26	7.15
ECOSYS	process	[18]	2.50	14	0.81	1	2.00	25	0.23	5.54	2	11	13	0.96	6.51
LINKAGES	process	[7]	0.97	26	1.50	2	1.89	110	1.03	5.40	3	7	10	0.74	6.14
BIOMASS	process	[7]	0.97	20	1.15	4	1.68	149	1.40	5.21	4	7	11	0.81	6.02
CENTURY	process	[3]	0.42	18	1.04	2	1.89	213	2.00	5.35	4	3	7	0.52	5.87
LANDIS	process	[7]	0.97	12	0.69	1	2.00	132	1.24	4.90	N / A				4.90
ZELIG	process	[9]	1.25	24	1.38	1	2.00	27	0.25	4.89	N / A				4.89
SORTIE	process	[11]	1.53	18	1.04	2	1.89	44	0.41	4.87	N / A				4.87
MGM	hybrid	[8]	1.11	17	0.98	1	2.00	37	0.35	4.44	N / A				4.44
SILVA	process	[6]	0.83	24	1.38	5	1.58	45	0.42	4.22	N / A				4.22
FORCLIM	process	[8]	1.11	18	1.04	4	1.68	35	0.33	4.16	N / A				4.16
SWAT	process	[6]	0.83	6	0.35	2	1.89	105	0.99	4.06	N / A				4.06
PnET	process	[5]	0.69	17	0.98	4	1.68	29	0.27	3.63	N / A				3.63
G´DAY	process	[4]	0.56	17	0.98	3	1.79	28	0.26	3.59	N / A				3.59
LPJ	process	[4]	0.56	11	0.63	1	2.00	18	0.17	3.36	N / A				3.36
EFIMOD	hybrid	[4]	0.56	12	0.69	2	1.89	10	0.09	3.24	N / A				3.24
FORWADY	hybrid	[3]	0.42	14	0.81	2	1.89	4	0.04	3.16	N / A				3.16
PICUS	process	[3]	0.42	12	0.69	3	1.79	20	0.19	3.09	N / A				3.09
ORCHIDEE	process	[4]	0.56	4	0.23	3	1.79	39	0.37	2.94	N / A				2.94
TRIPLEX	hybrid	[3]	0.42	8	0.46	3	1.79	11	0.10	2.77	N / A				2.77
GYPSY	empirical	[4]	0.56	5	0.29	4	1.68	9	0.08	2.61	N / A				2.61
PROGNOSIS	hybrid	[3]	0.42	8	0.46	8	1.26	31	0.29	2.43	N / A				2.43
JABOWA	process	[4]	0.56	22	1.27	19	0.11	25	0.23	2.16	N / A				2.16
CLASS	process	[3]	0.42	4	0.23	9	1.16	9	0.08	1.89	N / A				1.89
FORMIX	process	[4]	0.56	9	0.52	13	0.74	3	0.03	1.84	N / A				1.84
FORET	process	[3]	0.42	17	0.98	19	0.11	32	0.30	1.80	N / A				1.80
FORGRO	process	[3]	0.42	5	0.29	12	0.84	11	0.10	1.65	N / A				1.65
FORECE	process	[3]	0.42	7	0.40	17	0.32	5	0.05	1.18	N / A				1.18

C: Number of different countries where the model has been applied.

E: Number of different ecosystems where the model has been applied.

N / A: Non applicable, for models that did not pass the cut-off score of 5.0, the number of countries and ecosystems was not assessed.

Table 1. Ranking and scores of the models included in the comparative study (with 3 or more documents in the database).

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The simulation of nutrient status effects on energy exchange is based on coupling nutrient (N and P) uptake from the soil through the root to the canopy, with nutrient assimilation in the root and canopy. This coupling determines nutrient concentrations in the leaf, which in turn determines leaf carboxylation rates and hence leaf conductance.

Growth respiration is linked to expansive growth of vegetative and reproductive organs at different nodes of each shoot branch, using data on biochemistry of growth and yield to estimate coefficients to partition mobilized C, N and P. Such coefficients also depend on phenological stages. Estimated growth is then allocated to different stem internodes, leaves, and sheaths, changing their lengths, areas and volumes [30, 31]. Then, leaf and stem surfaces (heights and areas) are estimated and used to calculate irradiance interception and aerodynamic conductance. Root and mycrorrizhal axes (both primary and secondary) extensions are driven by growth respiration, mobilizing stored C, N and P [32].

Microbial activity in ECOSYS is represented as a parallel set of substrate-microbe complexes, which includes the rhizosphere, plant residues and animal manure, and native organic matter [32-34]. To simulate microbial growth (facultative and obligated aerobic and anaerobic heterotrophs) at an hourly step, the temperature and water contents of the litter and soil layers are used [34-36]. Temperature and moisture are derived from the energy balance calculations described above.

ECOSYS is a highly complex model with substantial calibration requirements. The strength of its approach is its flexibility, provided by a detailed representation of ecophysiological processes that allow the exploration of the ecological consequences of modifying many different environmental factors. The main weakness of this approach is that validating the accuracy of its simulation algorithms and verifying output are significant challenges, due to the difficulty of finding independent values of many ecophysiological values. In addition, its management capabilities appear limited suggesting that the model is best catagorized as a research tool.

3.2.2. 3-PG

3-PG (the acronym represents Physiological Principles in Predicting Growth) was originally developed to simulate homogeneous, fast-growing plantations such as Eucalyptus [37], but has since been calibrated for other forest types [38]. 3-PG is a monthly time-step model working at stand and population levels. It is a model that includes general ecological processes and therefore needs to be calibrated for each individual species. It is designed for homogeneous forests, particularly even-aged or planted stands.

The model is built around the basic principles that drive ecosystem production. These same principles underlie earlier models such as FOREST-BGC [39] and BIOMASS [40]. The structure of 3-PG is based on two linked sets of calculations [41]: one set estimates biomass and growth values, whereas the other set estimates biomass allocation among different tree components. 3-PG is a conservation-of-mass model.

The model, like most process-based approaches, calculates rates of photosynthesis, transpiration, growth allocation and litter production. 3-PG derives estimates of radiation interception,

gross primary production (GPP), net primary production (NPP) and allocation of the resultant carbohydrate pool to component parts of the trees. NPP is calculated as a fixed fraction of gross photosynthesis [42]. GPP is derived by applying a canopy quantum efficiency value to the amount of photosynthetically active radiation absorbed by a stand.

Quantum efficiency (the potential rate of photosynthesis) is a constant fraction of absorbed photosynthetically active radiation, and is constrained by atmospheric vapour pressure deficit. The latter is a function of stomatal conductance, which is influenced by air temperature, frost, water balance and nutrition. Canopy conductance is estimated as a function of leaf area index. The ratio of actual/potential photosynthesis is assumed to decrease in response to a suite of limiting environmental factors. It decreases with reduced availability of water and nutrients, which triggers a higher proportion of photosynthate allocated belowground.

Soil nutritional status (the availability of nutrients such as N and P) is represented by an index, the *fertility rating*, which can assume a value between 0 and 1 [38]. The fraction of production not allocated to roots is partitioned among foliage, stem and branches based on species-specific allometric equations.

3-PG can be used as a stand-level tool, or ground-based forest inventory data can be incorporated into a Geographical Information System (GIS) to simulate forest growth over large areas. 3-PG has a wide range of predicted stand properties that are directly compatible with conventional inventory measurements, including stem density, DBH, basal area, total volume, current and mean annual increment. In addition, the model outputs information pertaining to the underlying biophysical relationships. This means that growth patterns can be linked to specific controls, such as resource deficiencies and climate.

From the perspective of reclamation, a strength of 3-PG is that it appears suitable for predicting tree growth in areas currently devoid of tree cover and has relatively low calibration requirements [38]. Whether it could be reliably calibrated for oil sands materials, however, is unknown. 3-PG can be used to evaluate different management effects of stand density, thinning and fertilization (within the limitations of the fertility rating approach used for simulating nutrient availability).Arguably, the main weakness of 3-PG is its relative simplicity. It does not accommodate stands with complex structure (either in space or in terms of multiple aged trees), multiple species, and it has no understory representation. In addition, representation of soil nutritional status is overly simplified and is considered a static site property (it cannot vary through time). This significantly limits its application to oil sands materials and how soil properties might be expected to change over time.

3.2.3. BGC

BGC is a family of models, designed to accommodate different biological scales (TREE-BGC, FOREST-BGC, and BIOME-BGC). The original model was FOREST-BGC [39], an individual-entity, distance-independent model [42]. The term “entity” is used because STAND-BGC (a derivative of FOREST-BGC; [43]) grows shrubs and grass in addition to trees. Shrubs and grasses are described as per unit area entities, while trees have unique dimensions. All the models have the same core architecture and work on a daily time step, with results typically

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summarized annually. BIOME-BGC is a biome/ecosystem model, with spatial scales from stand to region.

BGC simulates fluxes and storage of water, carbon, and nitrogen [44-46]. BGC simulates fluxes and storage of water, carbon, and nitrogen [44-46]. The model has been designed to study the interactions between management, disturbances, climate and vegetation ecophysiological features, and their influences in water, nitrogen and carbon flows.

Net primary productivity is calculated as the difference between gross primary productivity (GPP) and autotrophic respiration, where GPP is a function of air temperature, water vapour pressure deficit, soil moisture, CO_2 concentration, LAI, and solar radiation at the top of the canopy. N concentrations in root and leaf, combined with temperature, are used to estimate respiration [47]. Canopy is simulated as one layer with sunlit and shaded foliage. The Farquhar equation is used to calculate photosynthesis [48]. Atmospheric CO_2 and humidity, leaf water and N contents, radiation and air temperature are used to calculate leaf conductance. Then, based on LAI values at leaf level, canopy C and water fluxes are calculated.

BGC is fundamentally driven by daily weather data. Therefore, ecophysiological descriptors of site vegetation, daily weather records and site physical properties are used by the model to simulate plant, soil, and litter variables, as well as water, carbon and nitrogen fluxes between the soil, the vegetation and the atmosphere. Unlike earlier models in the BGC model family (e.g. Forest-BGC, [39]), in Biome-BGC LAI is predicted as a function of the amount of leaf carbon, one of multiple vegetation state variables that are updated daily within the model [22]. Vegetation type is a user-defined, constant set of ecophysiological parameters. However, the model simulates changes in vegetation structure as consequence of disturbance, climate and ecophysiological characteristics of each vegetation type simulated.

The main strength of the model is its application in a broad range of ecosystem types. BGC´s structure makes the model a suitable research tool to predict the impact of climate change. Forest-BGC, for example, has been widely used to predict climate change effects on natural disturbance and carbon dynamics [49]. In addition, BIOME-BGC offers a link between input data and GIS databases, which is useful for application of data collected from regional studies. A shortcoming of BGC is that the canopy is homogeneous. Therefore, although leaf area index is proportional to canopy depth, this may not be sufficient to capture water and carbon budgets accurately [39]. Its main drawback is the lack of a management interface, which makes it difficult to consider BGC as a decision-support tool for forest management and land reclamation.

3.2.4. FORECAST

FORECAST is a management-oriented, stand-level forest growth and ecosystem dynamics simulator [50]. The model was originally designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect on forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. FORECAST-Climate version (see below) calculates climate modifiers on forest productivity on a daily basis. The modifiers are then accumulated across the year to estimate annual biomass production. FORECAST performs many calculations at the stand level but it also disaggregates stand-level

productivity across individual stems in relation to age-specific stem size distributions. Top height and DBH are calculated for each stem and used in a taper function to calculate total and individual gross and merchantable volumes, and biomass.

Stand growth and ecosystem dynamics are based on a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources. FORECAST calculates biomass productivity (NPP) based on estimates of inherent productivity derived from historical bioassay data (see below) constrained by site-specific nutrient and water availability determined from within the model. The rates of the key ecological processes driving tree and plant growth are calculated from the bioassay data and inputted values for ecosystem variables (decomposition rates, photosynthetic saturation curves, for example) and their relation to nutrient uptake, the capture of light energy, and net primary production. Using this 'internal calibration' (hybrid simulation) approach, the model generates a suite of growth properties for each tree and plant species [50]. These growth properties are retained within the model and used to model subsequent growth as a function of resource availability and competition.

FORECAST's reliance on historical bioassay data serves to reduce calibration requirements while ensuring its projections of productivity are reasonable. Calibration data are assembled that describe the accumulation of biomass (above and below-ground components) in trees and minor vegetation for three chronosequences of stands, representing three different nutritional qualities. Tree biomass and stand self-thinning data can be derived from height, diameter at breast height, and stand density output generated by traditional growth and yield models in conjunction with species-specific biomass allometric equations [51]. To calibrate the nutritional aspects of the model, data describing the concentration of nutrients in the various biomass components are required. FORECAST also requires data on the degree of shading produced by different quantities of foliage and the photosynthetic response of foliage to different light levels. A comparable but simpler set of data for minor vegetation must be provided if the user wishes to represent this ecosystem component (see, for example, [52]). Lastly, data describing the rates of decomposition of various litter types and soil organic matter are required for the model to simulate nutrient cycling. The second aspect of calibration requires running the model in "spin-up" mode to establish initial site conditions. This component is a key feature in the ability of the model to simulate the site conditions characteristic of oil sands reclamation. For a broader discussion on this topic, see [7, 53, 54]).

Stand hydrology and water limitation for tree growth (see [25]) are simulated within the FORECAST-Climate model [55], which on a daily time step provides a mechanistic representation of above and belowground hydrological interactions in forest stands with multiple soil and canopy layers. This facilitates a representation of competition between trees in different canopy layers and minor vegetation for available soil water. In addition, the hydrological model also estimates the influence of drought on litter decomposition rates, and therefore on nutrient mineralization and its availability for vegetation [56]. Hence, as noted above the model tracks the balance between inputs from precipitation and seepage, and outputs by canopy interception, evapotranspiration, plant uptake, percolation and runoff.

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FORECAST has been calibrated for the Ft. McMurray region. It has been applied to oil sands reclamation for over almost 15 years, in large part to compare current and alternative reclamation practices and their relationship to indicators of ecosystem function and the achievement of end land-use objectives. In this regard, FORECAST output was used to derive multipliers and nutrient regime classes for the Landscape Capability Classification System [57]; to explore issues associated with peat decomposition rates; the depth and type of the capping material; nitrogen deposition; subsoil organic matter content; species mixes, planting densities, understory dynamics, and dead organic matter dynamics (specifically snags), all within the context of growth and yield [58 – 60]. Recently, FORECAST-Climate was used in a risk analysis of the potential development of water stress in young reclamation plantations consisting of white spruce, trembling aspen, and jack pine established on different ecosites, as a function of soil texture and slope position [61]. In the second phase of this work, the principal objective was an evaluation of the impact of climate and climate change on reclamation success, as compared to the base case analysis (no climate-related impacts) [62]. The potential effect of different climate change scenarios on growth and mortality in reclamation areas was therefore projected using the FORECAST Climate model and associated modelling tools to evaluate their combined impacts on overall ecosystem development in a risk assessment context. A final component of this work consisted of: (1) Model projections of tree regeneration under climate change on actual oil sands reclamation materials, and (2) A comprehensive model analysis of the risks to ecosystem productivity from climate change as a consequence of the impact of moisture stress on tree mortality [55]. Recently, funding was approved for a project to:

a. Improve the applicability of two established models that have been used to support adaptation decision-making within the context of oil sands reclamation, a state-and-transition simulation model (STSM; [63], and the process based forest ecosystem model, FORECAST-Climate [55, 62].

b. Develop a decision support tool (DST) by linking the STSM and FORECAST-Climate.

c. Use the DST to evaluate reclamation best management practices in the oil sands sector in terms of climate-related risk exposure and then inform adaptation and management planning within the context of climate change at both the stand and landscape scale.

Produce a guidance document on how to implement the tools, interpret output, and assess the implications for reclamation principles and practices as reflective of an adaptive decision framework.

4. Conclusions

Over the last four decades, a large number of ecological models that can simulate tree growth and forest hydrology have been developed for temperate and boreal ecosystems. The models best suited for simulating forest growth and hydrology in reclamation are likely to be at the scale of the stand level and in the daily to yearly time scale, as these scales provide sufficient detail to account for the key processes involved in tree growth but can also use operational

data from forest management for calibration. In addition, a variety of tools have been developed to assist biodiversity planning in forest management. Among these are statistical models that utilize correlations between forest attributes and the presence of a particular wildlife or plant species or guild to determine habitat suitability [64]. These models have gained popularity because habitat descriptors can be derived from variables commonly available in forestry databases tor through modeling (for example, timber volume, forest age, dominant tree height, and species composition) [65-68]. When properly applied, they can also be used to predict the response of selected species to forest reclamation and to evaluate the efficacy of alternative practices [6, 69, 70].

Few models achieve recognition and use much beyond their development team, and even less have used within an operational setting [7]. Even among the four shortlisted models (ECOSYS, BGC, 3PG, and FORECAST) there is considerable variation in their ultility as decision support tools, particularly within the context of reclamation.

ECOSYS [28] is a complex model, with a strong representation of plant ecophysiological processes. It is a research tool to explore energy and matter fluxes in forest ecosystems. Its calibration requirements are substantial. BGC, particularly its most recent variant BIOME-BGC, is designed to represent the state and fluxes of carbon (C), nitrogen (N), and water (H_2O). The model has been applied to several forest and non-forest ecosystems around the world. The latest versions of the model include options for alternative forest management activities (see Table 4). BGC, however, is mainly a research tool designed to start from equilibrium conditions in a well-established ecosystem [71]. Hence, it is questionable whether the model is suitable for representing the biophysical characteristics of a reclaimed site. BGC also has fairly extensive and elaborate calibration requirements, though not as data-intensive as ECOSYS.

3-PG is a relatively popular forest growth model. It has been used as a research tool in a variety of forest ecosystems around the world. The model has been applied mostly in plantations, especially fast-growing species such as Eucalyptus and subtropical pines. 3-PG has been streamlined in recent years to facilitate its calibration with remote sensing data, therefore making it easy to apply to new sites and over large spatial scales [72]. One conceptual limitation of the model in terms of its application to reclamation is that site quality is represented as a fixed property [49]. This is problematic for two reasons. First, site quality must be known beforehand. This is generally not an issue in established natural forests (though it can be) but it has much greater uncertainty in a peat-based reclaimed system. Secondly, a reclaimed site is expected to transition from nutrient cycling based on the peat/mineral mix to that derived from the dead organic matter deposited by the developing plant community. It is unclear whether this transition will accompany a change in site quality. 3-PG also has no understory representation. Shrubs and herbs can be a key determinant of ecosystem development and productivity [52, 73].

FORECAST is model with a long history of development, but with a strong focus on management applications [50]. With the inclusion of a hydrology submodel (ForWaDy; see [25]), FORECAST now has the capability to simulate climate and climate impacts, and its impact on moisture availability, and C and N fluxes. The calibration requirements of FORECAST are

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moderate (but they are not trivial) though many parameters can be calibrated with standard inventory data and/or growth and yield tables. Some parameter values are universal and exhibit little variation; for others, the model is relatively insensitive to their variability (see [74], for a sensitivity analysis). Although FORECAST is a stand-alone model, it has been used for landscape-level analysis by linking it to GIS systems that classify the area under study into different ecosystem types [75, 76]. One advantage with FORECAST is that it has already been used extensively in oil sands reclamation (12, and references therein), and so datasets have already been constructed for the dominant tree and understory species. In this respect, FORECAST can be used to simulate complex mixtures of tree and understory species [77].

"A model should be as simple as possible, but no simpler". This is the principle put forward by Albert Einstein (in reference to scientific theories) and is applicable to model construction. Complex models are often required in ecology when the interactions between different ecological factors, both biotic and abiotic, need to be explicitly represented and understood [12]. This is especially important for ecosystems in which there are often no natural analogues, such as reclaimed landscapes [78]. The four shortlisted models provide a good representation of the range of complexity and approaches used to estimate biomass production, nutrient and water cycling. These differences are also reflected in the calibration requirements and calibration load associated with a given model. For example, ECOSYS is fundamentally a 'bottom-up' model in that it integrates ecophysiological processes starting at leaf scale to generate values of biomass production and water consumption at the stand level. BGC, in contrast, is more of a top-down model. FORECAST and 3-PG are somewhere 'in-between', estimating stand productivity with some simplification of the ecophysiological processes that occur at the cellular or leaf levels. The range in modeling approaches is also a reflection of the different origins of each model; FORECAST and 3-PG are forest management models, ECOSYS began as a crop research model, and BGC a forest ecology research model.

Determining the appropriateness of a given model to support biodiversity restoration within the context of reclamation depends on the balance between the accuracy required from the model output, the calibration effort and data available for calibration, model complexity, model flexibility, model robustness, and the capability to assess model performance [51]. Highly complex models such as ECOSYS simulate a large array of ecophysiological processes at fine temporal and spatial scales. Consequently, they require a considerable effort to assemble the data required for calibration. Often, it is necessary to make educated guesses for parameter values that are difficult to measure or which may not exist for the particular circumstances to which the model is to be applied. For obvious reasons, uncertainty in the input data reduces confidence in model output, an issue that becomes more problematic as the calibration requirements increase. Relatively simple models such as 3-PG have low calibration needs which allows for easier portability of the model to new ecosystem types. An overly simplified structure, however, also reduces model applicability (and flexibility) to complex systems and to account for interactions among all the ecosystem compartments. Conversely, robustness refers to a model's capability to produce acceptable estimates of the target variables in the required application. Robustness is not an inherent property of model complexity, and both complex and simple models can

be robust, provided that calibration parameters are estimated with low uncertainty, especially for those key parameters for which the model is more sensitive [7].

Recovery of biodiversity in reclaimed sites depends on the timing of reclamation events, the type of forest system reclaimed, and how progressive reclamation impacts the vegetation (understory and stem distribution) relative to what would have been present had the landscape not been mined. Reclamation practices could be targeted toward the habitat requirements of particular wildlife or vegetation species by preferentially reclaiming more favourable ecological sites. Conversely, a broad range of ecological sites is necessary to promote suitable habitats for a diverse range of species on the reclaimed landscape. Such planning needs decision support tools that incorporate the best scientific knowledge available.

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