Needs of stakeholders and state-of-the-art in tree and forest growth simulation

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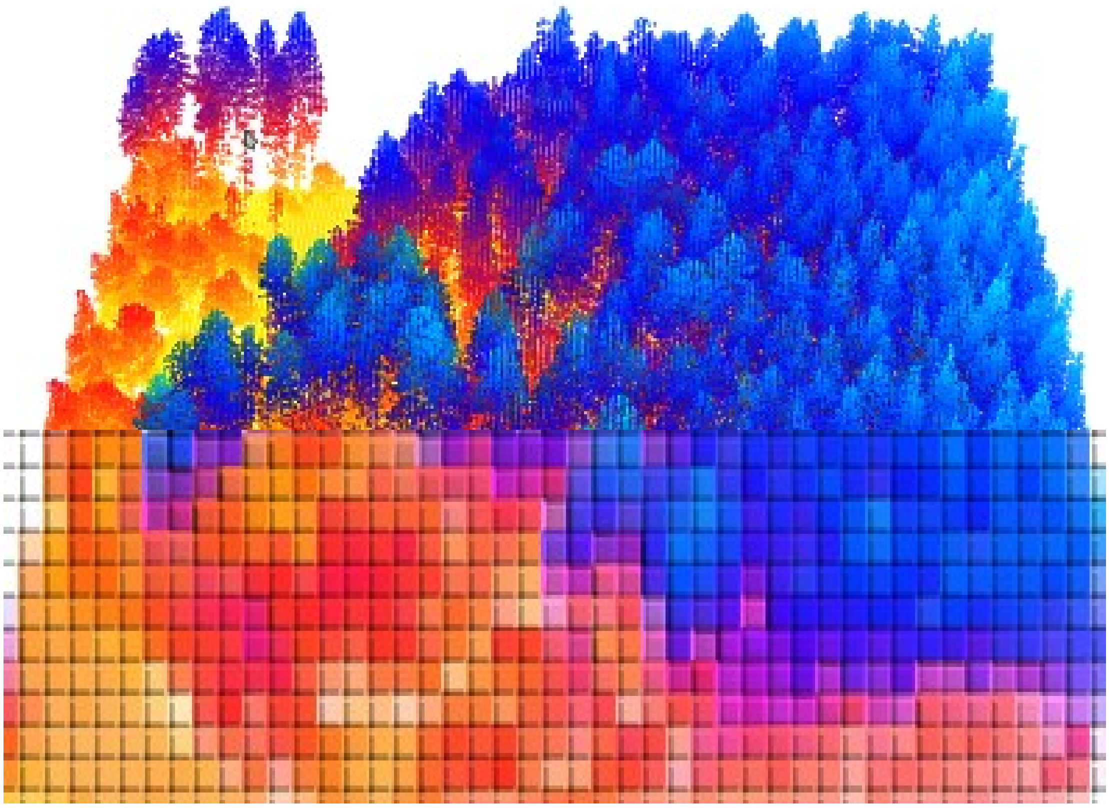
Date: March 2020

Report No: RPF-T002



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Executive summary

The problem

The objective of this report was to provide scope to a development plan for producing the next generation of tree and stand growth simulators. These simulators will be used to answer questions around the effects of factors such as genetic diversity, nutrition management, disease and available growing space on stand development, yields, uniformity and wood properties.

This project

To provide scope and identify requirements for the next generation of tree and forest growth simulators this project used two contrasting approaches:

1) Workshops with stakeholders to identify their needs and requirements
2) Knowledge assimilation in the state of the art in tree and forest growth models/simulators.

For the former approach, stakeholders from differing areas within the forestry sector, were invited to attend workshops at Scion. The aim of the workshops was to gain an understanding of the main topics or issues of importance to stakeholders. For the latter approach, a literature review was conducted.

Key results

Following workshop discussions between Scion staff and stakeholders, key topics, issues, and variables, were identified, rankings of importance assigned, and ideas for potential development directions of tree and growth simulators proposed. Some issues, such as software development platforms, were not resolved in their entirety, however there was a slight preference for the R statistical package. Current and new technologies were both desired as data sources for simulator input – i.e. the use of forest inventory data, as well as the use of remote technologies for data collection, such as LiDAR.

The literature review highlighted different modelling approaches that could be taken along with trade-offs between generalisations and higher spec resolutions, and resultant accuracy (or bias) of forecasted productivity, yield, and other outputs.

Implications of results for the client

The results from two workshops, and information gleaned from the literature, will be used to inform the direction of research for the sub research area "Understand the impacts of inter-tree competition on tree growth and stand uniformity" of Resilient Forest project and the delivery of key outcomes for stakeholders.

Further work

We envisage that the planning and development phases will be iterative, with further discussions with stakeholders, and are pleased to report that the workshop participants indicated that they would be keen to participate in future research gatherings, project outcomes, and workshops for knowledge transfer.

The next phase will see the development of a prototype individual-tree growth simulator capable of modelling growth and competitive interactions among trees with different levels of stem and crown size inequality. The development of this simulator will based on fundamental ecological principles and informed by stem and crown information captured through Light Detection and Ranging (LiDAR), while also incorporating the climatic and management considerations identified as important factors at the workshops.

Introduction

To date, the New Zealand forest sector has relied on empirical biophysical models based on analytical and statistical methods focussed on dominant trees within stands, to address forestry decision making processes. However, this empirical modelling approach has several limitations: trees are considered to be identical in shape and form; are assumed to be of the same species and of the same age; and plantations are assumed to comprise regularly spaced trees. Due to these limitations, amongst others, the current tree and forest growth modelling approach may not be suitable for 21st Century forest estate modelling in New Zealand and may not meet the extra demands of precision forestry.

Precision forestry, the practice of adapting and using advanced technologies in the forestry sector, is gaining increased importance to forest operators as a means of driving improvements in the forestry sector, improving forest management practices, and results of such practices, and reducing costs. Advanced technologies and techniques include the selective breeding of cloned seedlings, remote sensing and digital forest inventories via drones and/or lidar (Kellner et al., 2019), fully mechanised harvesting (Visser, Raymond, & Harrill, 2014), and integrated supply-chain planning (Scholz et al., 2018). Further gains may be possible through use of remote technologies in a combined approach with genetics and genomics, to accurately enable phenotyping of individual trees and even whole forests (Dungey et al., 2018).

At same time, new modelling approaches, such as spatially-explicit individual-tree-based modelling and physiological process-based modelling (Shifley et al., 2017), machine learning (Ou, Lei, & Shen, 2019), and hybrid modelling (Seely, Welham, & Scoullar, 2015) enable for fine-scale and individual-tree modelling. These new techniques and modelling approaches may help with a greater scope of forestry processes including: forest hydrological processes, ecosystem services, abiotic and biotic risks, and climate change adaptation, and will form the foundation of precision forestry in New Zealand.

The development of next generation forest growth and yield models/simulators requires a roadmap which will (1) address the requirements of forest growers and stakeholders and (2) represent the state of the art in forest growth simulators. Hence, we hosted two "Next generation forest modelling" workshops at Scion, Rotorua on the 12th December 2019 and 24th January 2020, and conducted a literature review.

The first workshop, facilitated by David Pont and co-facilitated by Yue Lin, elicited opinions from stakeholders of forestry companies and organisations on their needs, limitations and potential options with new techniques and modelling approaches in current New Zealand forestry. The second workshop, directed by Dean Meason, included a presentation from Michael Battaglia (CSIRO) on "Introduction to Process-based Modelling" and a presentation from Professor Euan Mason (School of Forestry, University of Canterbury) on his own work "Introduction to Hybrid Modelling". This second workshop mainly addressed process-based modelling and its application for precision forestry and included a talk by Dean Meason on the "21st century data collection and applications to modelling". Both workshops were designed to be as interactive as possible to allow stakeholders the freedom to debate the topic, contribute their ideas and draw on their knowledge to achieve the outcomes of the workshops. The full list of participants in the two workshops is shown in Appendix A.

Concurrent with the workshops, the rapidly evolving and continuously developing state of knowledge for forest growth models/simulators was reviewed. To this end, a literature review was conducted, and summarised in this report.

The overall objective presented here was to describe the needs and requirements of different stakeholders and the state of the art in tree and forest growth models/simulators, respectively. In addition, we briefly discuss the potential roadmap for the development of next generation growth and yield simulators, which take into account the state of the art, combining available datasets and new survey techniques, to meet the needs and requirements of stakeholder in New Zealand.

Workshops and literature reviews

The first workshop

The first “Next generation forest modelling” workshop was held at Scion Rotorua campus on 12th December 2019. The workshop opened at 10:00am with a welcome and goals for the day outlined by Peter Clinton. An overview and introduction were presented by David Pont, co-facilitated by Yue Lin. Subsequently, the workshop participants facilitated group discussions related to following key questions:

- Are our current modelling approaches still fit for industry needs?
- What are our forest modelling needs for now and for the future?
- What are the key limitations and barriers?
- How can we overcome those difficulties?
- At what scales shall we focus on (individual-stand-landscape)?
- How do we ensure model interoperability and usability?

Once the topics, issues and needs were identified, and following discussion and debate, a voting or ranking of importance (Low/Medium/High) on each of the topics/issues was made by participants.

The second workshop

After the first workshop, participants were keen to have a second workshop for a further discussion on process-based models and future data collection. Therefore, the second “Next generation forest modelling” workshop, “Understanding Process-Based Modelling and its Application for Precision Forestry”, was held at Scion Rotorua campus on 24th January 2020. The workshop opened at 9:00am with a welcome and goals for the day outlined by Peter Clinton. A review of the first workshop was presented by David Pont. Michael Battaglia from CSIRO gave a talk on “Introduction to process-based modelling”. Euan Mason from University of Canterbury gave a talk on his own work of “Hybrid Modelling”. Dean Meason gave a talk on the “21st century data collection and applications to modelling”. Then the workshop participants facilitated group discussions and debates related to challenges for estate modelling in a changing world and transforming industry, and how our full suite of tools can rise to the tasks.

Literature review

A literature review was conducted to examine, compare, and contrast tree growth simulators. The literature search extended from tree through stand and forest growth simulators and decision support systems. We focused on the simulators that were developed to answer questions around the effects of factors such as genetic diversity, nutrition management, disease and available growing space on stand development, yields, uniformity and wood properties.

Results and discussion

The workshops

There were a series of key topics/issues discussed by the workshop participants, and among those topics/issues there were ten identified as the most important for next generation forest modelling (Table 1). The rankings given to each topic/issue were voted by participants using high (blue), medium (orange), and low (grey) categories (Figure 1).

Table 1: Ten key topics or issues that participants addressed in workshop 1

Rank	Topic/Issue
1	Not just growth functions – mortality, breakage, taper and volume as well
2	Distance-dependent individual tree models
3	Silvicultural planning
4	Flexible framework – i.e. can add in carbon wood and properties etc. later
5	Rethink PSPs and model building now we are collecting tree measurements in a different way, e.g. LiDAR
6	Use of models for valuations and estate modelling and day to day production planning
7	Managing variation of a genetic origin within and between species
8	Statistical basis of measurement and modelling
9	What are the variables we want to collect besides stem variables?
10	What platform do you build and distribute the models on?

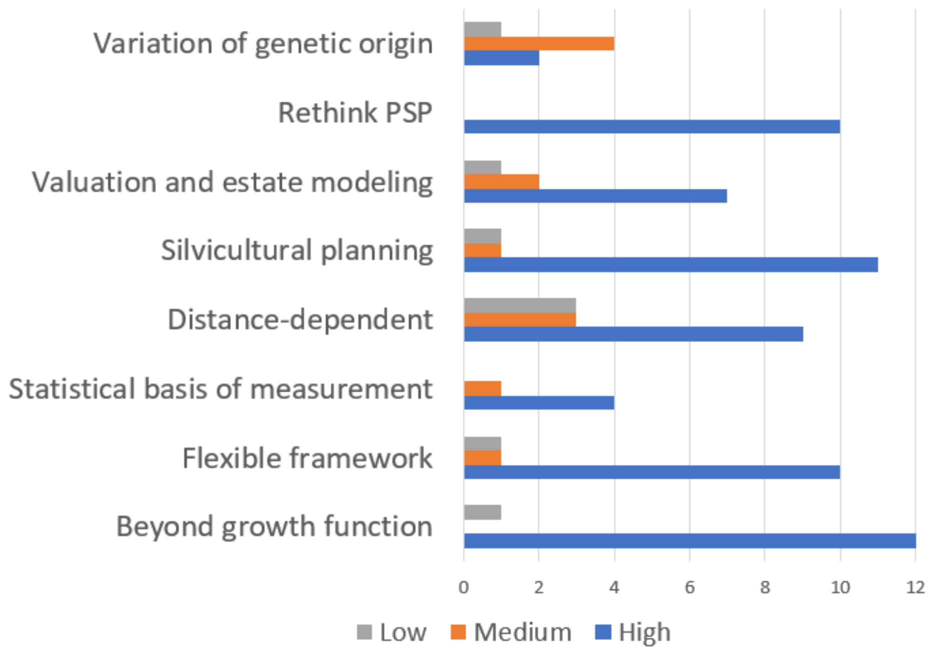

Figure 1: Importance rank of key topics/issues voted by participants

For topic/issue 9 and 10, workshop participants were asked to give specific answers to each. Figure 2 shows their answers to topic/issue 9 – the variables they want to collect besides stem variables. Figure 3 shows their answers to topic/issue 10 – the platform on which they prefer to build and distribute models.

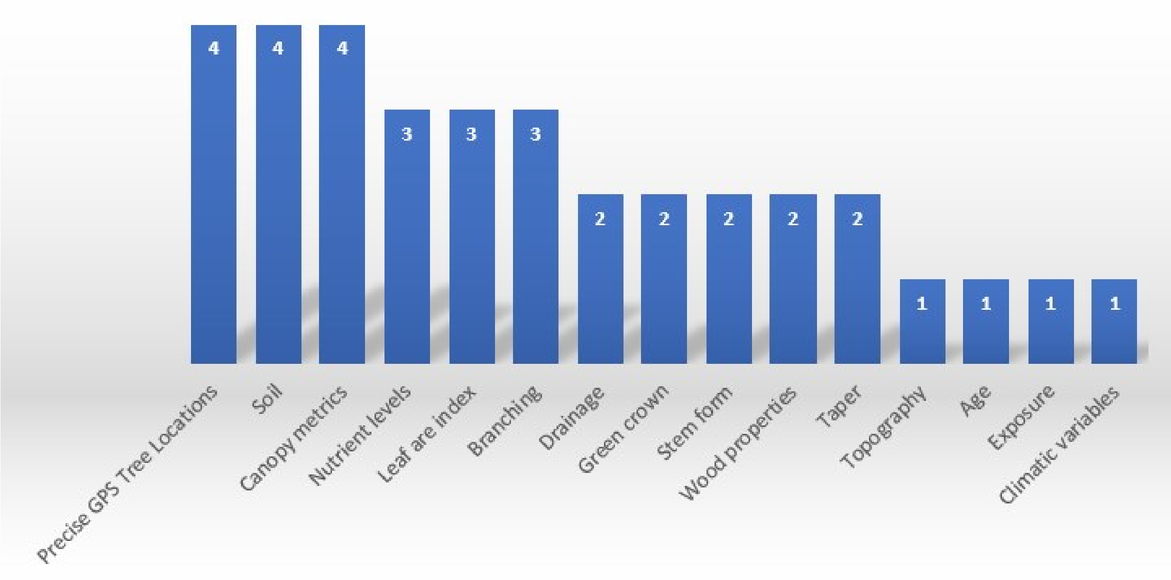

Figure 2: Important variables to collect besides stem variables

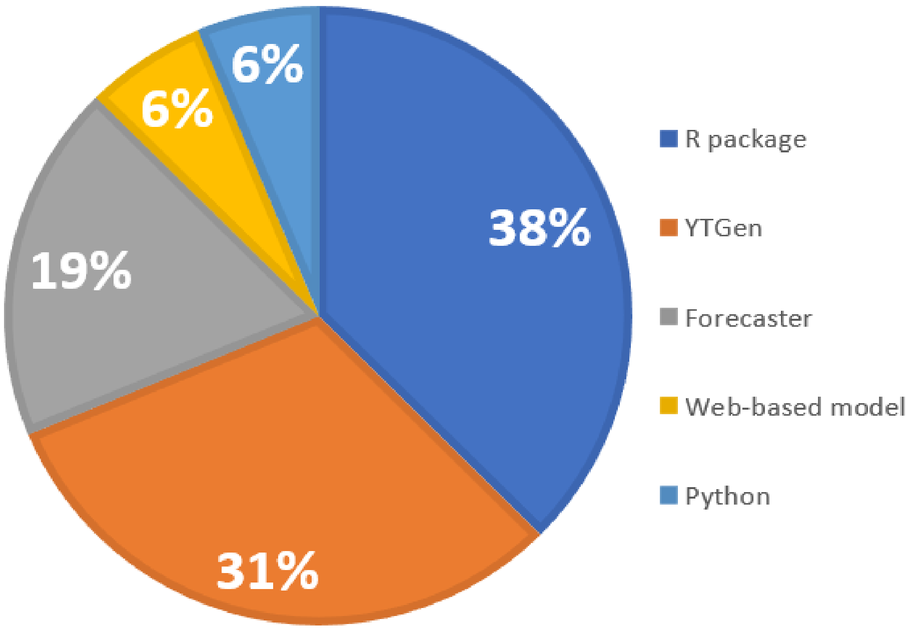

Figure 3: Platforms to build and distribute models

The potential directions of next generation forest growth models and simulators were discussed intensively and diversely. Generally, the discussions can be classified into three aspects.

a) Functions and uses of new forest growth models and simulators:
   - New models should include finer scales, such as soil strata, forest patch or individual tree growth model. This could be driven by analysing of LiDAR (RGB) data; focusing on mid-rotation onwards; and optionally to guide with existing known models.
   - Uses of the new models and simulators should be suitable for yield projection (log grade), silvicultural planning, and regime analysis.
   - The new models and simulators should be able to be applied to different genetics and/or species of trees and can be used for mixed-genetics/species uneven-aged forest structures.
   - Wood properties and their variations within a stand / across nearby stands can be predicted in connection with growing conditions. Tree growth models should support links to wood quality models.
   - Distance dependent models can explain between- and within-tree variations in growth, branching, and wood properties, by using locations of each individual tree and tree-tree interactions.
   - Different modelling purposes, e.g. production and ETS Carbon, had been mentioned which may lead to different structures or sub-models of the models.

b) Connections to other models, PSPs and new data collection methods:
   - Re-fit existing models as needed. Utilizations of both existing models and new models are necessary.
   - Environmental inputs (e.g., soils and climate) and silvicultural and management information (e.g., fertilising, pruning, and thinning) are important, especially in response to global climate change.
   - It is necessary to update the PSP system with new variables, new plots and restructure the database, so as to reflect these issues and to meet requirements for developing new models and simulators.
   - Connecting LiDAR and other 21st Century data collection methods with current PSPs (and additional databases such as MPI, FMA and MfE LUCAS datasets) and existing forest growth models (e.g. 300-Index).

c) Implement of new forest growth models and simulators:
   - Implement framework as an R package (most preferred).
   - Connections and links to existing model systems (e.g., YTGen and Forecaster).
   - Underlying functions in C++ as needed for speed.
   - Flexible platforms, can be linked or extended to include other functions and models (e.g., wood properties, weeds management, pests and disease modelling, windthrow, and forest fire)
   - Type of the models. The pros and cons of different types of models: Process-based models (e.g. 3-PG model), growth and yield models (and hybrid growth and yield model), spatially-explicit individual-tree-based models (also known as forest gap models), and non-

parametric statistical models (machine learning models). A synthetic model or simulator which combines merits of different types of models is highly desired.

- User friendly interface and ease of access.

The overall feedback from the workshop itself was highly positive about the needs and opportunities for new models.

Literature review

We reviewed more than 25 tree and forest growth simulators. Those selected models and simulators from the literature review were summarised:

a) By word maps of Keywords and Abstract contents (Figure 4)
b) In Table 2, which provids details of specific models, their main references, pertinent species, key inputs and outputs, and sub-models
c) In Table 3, which gives details of individual-based, multispecies forest models with spatial considerations taken directly from Busing and Mailly (2004)
d) Through various figures, retrieved from the literature, of selected model overviews of processes and data flows (Appendix B)

Figure 4: Word maps derived from keywords (left) and abstracts (right) of literature reviewed in Table 2 below.

Most of the simulators identified in the literature were derived, and parameterised, for common European species (e.g. BWinPro, FBSM, MOSES, PrognAus) or North American species (e.g. FVS). However, only two simulators had been adapted and tested with NZ native species (i.e. Sortie/NZ, a gap model, and 3PG, a process-based model). Many of the simulators were based on individual tree-growth models while a discussion of possibilities and limitations of individual tree-growth models is provided by Vospernik (2017). For most gap models, the fundamental spatial unit, or patch, comprised an area of 100 – 100 m^2. However, with Sortie much larger tracts of land are considered, and within this area the position of each tree is tracked to enable accurate calculation of light conditions (Bugmann 2001). A review of process-based models is provided by Battaglia and Sands (1998).

Tree diameter was a key driver for all growth models and was generally measured at breast height (1.3 m), except for Sortie where diameter was measured at 10 cm above ground, therefore accommodating growth of seedlings and saplings.

The majority of tree growth simulators comprised modules for determining growth increments, regeneration, recruitment, mortality, thinning, and harvesting. Some also comprised modules for light availability, substrates, competition, and disturbances. Growth increments tended to comprise diameter and height and/or basal area, and were based on yield tables, or more commonly, regressions. The regeneration and recruitment modules represent distinct processes, with the former predicting the development of trees from seeds or seedlings, whereas the latter predicts the number and species of trees reaching some specified size limit (e.g. breast height) (Vanclay 1994). Regeneration is simulated as a stochastic process constrained by species-specific environmental ranges (e.g. temperature, soil moisture, frost) within gap and patch models, whereas within mechanistic or process-oriented models, regeneration is usually simulated by assuming a certain minimum carbon content in the stem and leaf fraction (Miina et al. 2006). Mortality modules generally included natural mortality due to competition, and/or age-related mortality, and less frequently, mortality due to disturbances. Bugmann et al. (2019) concluded that mortality is one of the most uncertain processes when it comes to assessing forest response to climate change, and that more data and a better process understanding of tree mortality are needed to improve the robustness of simulated future forest dynamics. Forest management and silvicultural practices such as thinning, and harvesting were typically included as sub-models. However, self-thinning, and modes of competition that alter self-thinning trajectories (Lin et al. 2013), appeared to be less well represented in simulators. Competition between trees and competition for light appeared to be the more prominent drivers of competition within simulators.

While stand growth and yield are common outputs of most simulators, and biomass/ carbon stock also represented in many, information relating to wood properties is lacking. Prediction of wood yield and volume still appears to be a major focus of modelling in forest management rather than wood quality. Unfortunately, the two traits (i.e. wood volume and wood quality) are, in general, only weakly correlated.

Table 2: Selected examples from the literature of tree-growth and forest simulators.

Model (References)	Individual trees	Species	Competition For	Disturbances	Type	Inputs	Sub-models	Outputs
3D-CMCC-CNR (Collalti et al. 2014, Collalti et al. 2017)			Light, water		Spatially explicit, process-based with provision for functional-structural tree models	Species, DBH class, age, meteorological data, light use, LAI, DBH-crown ratio	Monthly carbon/water fluxes	Forest growth patterns, yield processes; annual increments, MAI, BA, above-ground NPP, GPP, LAI
3PG (Dye 2001, Bernier et al. 2003, Gupta & Sharma 2019)	No	Rimu + others	Crown competition		Process-based model	Observed/ inventory data, remote sensing, GIS	C balance, biomass, thinning, mortality, soil-water balances, management	Stem mass, volume, growth rates, MAI, no. trees.
BWinPro (Nagel & Schmidt 2006) http://www.iefc.net/bdd/models/modeles_affiche.php?Id=101	Yes	Spruce, D-fir, pine, beech, oak	Index (C66) representing social position of a tree	No	Spatial, not age dependent	Inventory data	BA/H increment. Mortality (density- & age-related), crown, regeneration. SI at 100 yrs	Forest growth & yield, timber harvesting revenues
CARBWARE (Black 2015)	Yes	Sitka spruce, lodgepole pine			Age- and distance-independent	Inventory data	Mortality, thinning. Increment, biomass	Carbon stock
ED (Moorcroft et al. 2001)	Yes		Terrestrial biosphere (land vegetation, soil), Water		Spatial			Fluxes of C & water between ecosystem & atmosphere from climate & soil properties
FBSM (Lemm 1991)	Yes	Species in Switzerland		Needle/ foliage loss & effect on growth	Distance independent	Inventory data, SI, forest management., logging practices, assortment qualities, costs	Growth functions based on yield-table data	Economic revenue, volume, assortment
ForClim (Bugmann 1996)	Yes	Species in European Alps	light		Gap model	DBH, annual precipitation, C budget used to	Environment, plants, soil	Above-ground biomass

						derive D increment		
FORECAST (Kimmins et al. 1999)	No		light, nutrients	fire	Process-based	Tree, plant, soil data	hydrology, mortality, soil, biomass	NPP
FVS (Crookston & Dixon 2005)	Yes	Species in US	Crown competition factor – for small trees	Simulated by user specs; insect damage, disease, fire effects	Distance-independent; + spatial variability within stands	Inventory data – tree level + plot/stand level (including slope, aspect, elevation)	Growth, mortality, regeneration, crown	
iLand (Seidl et al. 2012) http://iland.boku.ac.at	Yes	Any?	resources	Fire, wind, bark beetle	Individual-based forest landscape & disturbance model	DBH, x, y cords, species, age, BA, soil properties, climate data, ….	Ecosystem dynamics & processes (above & belowground cycling of C, N, & H_2O), growth, mortality, regeneration	Productivity, mortality patterns
JABOWA (Bugmann 2001, Bugmann et al. 2019)	Yes		Primarily light + water/nutrients 'crowding-dependent' – but competition between trees/shrubs/grasses is ignored		Spatially discretized into patches – Gap model	DBH	Establishment, Growth, light availability, climate, mortality	Impacts of global change on long-term dynamics of forest structure, biomass, competition
MASSIMO (Stadelmann et al. 2019)	Yes	Swiss forests		Storms		Inventory data		Timber harvesting potentials, carbon budgets
MOSES (Thurnher et al. 2017)	Yes	beech, oak, spruce, pine, fir.	Overstocking impacts expressed by competition index	Windthrow, snow breakage based on h/d ratio	Distance dependent, age dependent	Inventory data, SI at 100 yrs	Thinning, harvesting, D/H growth, climate, crown, mortality, regeneration	Growth & yield prediction, economic assortments – NPV, profitability, biomass & C analyses
MOTTI (Hynynen et al. 2005)	Yes	Major species in Finland	Within-stand competition			Inventory	Growth & yield, individual-tree survival, self-thinning	Financial & C analyses
PICUS (Lexer & Hönninger 2001)	No	Main species in Switzerland	Inter-tree competition, consideration of light		3D spatially explicit patch model	DBH, H, height to live crown, leaf area	Radiation, soil moisture, thinning treatments,	

							mortality, recruitment	
PrognAus (Ledermann 2006)	Yes	Main species in Austria	Described by BA of larger trees/ha & crown competition factor	Calamity model for windthrow, wind/snow breakage, beetle infestation	Distance-independent, not age dependent	Inventory data, H/D increment models expanded to include climatic variables	H/D increment, BA increment, crown ratio, mortality	Economic assortments
RegWise – replaces the HUGIN simulator (Wikström et al. 2011, Lundström A. 2017)	Possible, but plot-based models recommended	Scots pine, Norway spruce, birch, oak, beech, aspen+	?	Fire, pests, diseases, storms	spatial	Inventory data	Wood demand, land-use change, soil C & N, regeneration, silviculture, costs & revenues, ecosystem processes	Volumes of growing stock, tree species distributions, biomass, C stocks, economic & environmental indicators
sIMfLOR (Faias et al. 2012)	No	Eucalyptus, maritime pine, cork oak		Forest fire Proposal to include pests & diseases	Stand + regional simulator for forests in Portugal	Inventory data	Growth models, drivers for land use change, hazards (fire), wood consumption	Growing stock, harvested area & volume, burnt area, social, economic. environmental indicators
SiWaWa www.siwawa.org www.planfor.ch/de/content/tools/siwawa	No	Beech, spruce, ash				Inventory data, G, N, H_{dom}	Mortality due to competition	stem BHD distributions to 30 yrs, log distributions top ht & d, productivity index
SILVA (Pretzsch et al. 2002, Pretzsch et al. 2017)	Yes	Norway spruce, silver fir, Scots pine, common beech, sessile oak		Estimate of windthrow/snow breakage based on H/D ratio	Distance-dependent, not age dependent	DBH; stand hg, dg, no., BA, vol per ha, climate, NO_2, atmospheric CO_2, harvesting costs	3D competition, H/D increments, crown models, mortality, thinning	Growth, yield; no., BA, MAI, monetory values, habitat suitability, social forest fns, timber harvesting revenue, silvicultural treatment strategies
Sortie (Pacala & Hurtt 1993,	Yes	Beech, eastern	Light	X	S & M, stochastic	D_{10}, species, x-y co-ords	Height, growth rate,	Radial growth

Pacala & Levin 1997, Messier et al. 1999)		hemlock, sugar maple, re maple, yellow birch, white pine, red oak, black cherry, white ash					Mortality, recruitment	
Sortie/NZ (Kunstler et al. 2011, Kunstler et al. 2013)	Yes	Rimu, mountain beech, silver beech, Hall's totara, Miro, Kamahi, southern rata	Light	Earthquakes		D_{10}	recruitment, growth, mortality, light, disturbance, harvesting, substrate behaviours	Radial growth Height, crown height
STAND (Pukkala & Miina 2006)	?	Even-aged stands in Finland		Windthrow risk		Inventory data		Stand-level decision support system
TREEDYN3 (Bossel 1996)		Spruce, acacia + other		Pollution damage	Process model		Drivers include radiation, light attenuation in canopy	Tree growth, C, N dynamics
TROLL (Chave 1999)	Yes	Tropical rain forests	Light	drought	spatial			Tree growth, C + N, tree species diversity

BA = basal area
C = carbon
dg = stand diameter corresponding to the stem of average basal area
D_{10} = diameter at 10 cm above ground
DBH = diameter at breast height (typically measured at 1.3 m)
GPP = gross primary productivity
hg = stand height corresponding to the stem of average basal area
H = tree height
H_{dom} = dominant height
LAI = leaf area index
MAI = mean annual increment
no. = no. of stems,
N = nitrogen
NPP = net primary productivity

Table 3. Selected examples of individual-based, multispecies forest models with spatial considerations. Source: (Busing and Mailly 2004)

Model	Year*	Angle(s) of insolation	Tree crown dimensions	Tree coordinates	Horizontal space resolution	Patch interactions**	Horizontal seed dispersal	References
JABOWA	1972	Vertical	Height	None	None	None	None***	Botkin et al. (1972)
FOREST	1974	None****	Height, depth & width	Cartesian plane	Individual tree	Competition & dispersal	Non-random	Ek & Monserud (1974)
FORET	1977	Vertical	Height	None	None	None	None***	Shugart & West (1977)
ZELIG	1988	Vertical	Height	None	Patch	Competition	None***	Smith & Urban (1988)
FORSKA	1990	Vertical	Height & depth	None	None	None	None***	Prentice & Leemans (1990)
SPACE	1991	Vertical	Height	Cartesian plane	Individual tree	Competition	Random	Busing (1991)
SORTIE	1993	Multiple	Height, depth & width	Cartesian plane	Individual tree	Competition & dispersal	Non-random	Pacala et al. (1993)
FIRE-BGC	1996	Vertical	Height, depth & width	None	Patch	Dispersal	Non-random	Keane et al. (1996)
FORMOSAIC	1998	None	None	Cartesian plane	Individual tree	Dispersal	Non-random	Liu & Ashton (1998)
TROLL	1999	Multiple	Height, depth & width	Cartesian plane	Individual tree	Competition, dispersal & mortality	Non-random	Chave (1999)
DRYADES	2000	Vertical	Height & depth	Cartesian plane	Individual tree	Competition & dispersal	Non-random	Mailly et al. (2000)
PICUS	2001	Multiple	Height & depth	None	Patch	Competition & dispersal	Non-random	Lexer & Honninger (2001)

* = Approximate year of initial description is provided; model characteristics may have evolved since then.
** = Types of interactions among neighbouring patches of trees are listed.
*** = Ubiquitous availability of seeds of all species is assumed. Seedling species eligibility for ingrowth is based on patch conditions. In certain models (e.g. FORET), seedlings are randomly selected from the pool of eligible species.
**** = Competition effects are based largely on horizontal overlap among tree crowns.

Recommendations and Conclusions

In summary, the two workshops satisfied and achieved the goals and objectives with needs and thoughts of different stakeholders on new forest growth models and simulators were received. All participants voiced their interest in being involved in regular updates, project outcomes, and in future workshops or meetings for the modelling project.

Industry noted that current models perform quite well across their estates, and at that broad level errors are not large and are understood. They also noted that errors are larger for individual stands and at the tree/piece level. The ability to better characterise variability at these finer levels is seen as an opportunity offered by emerging data sources such as remote sensing, and new individual-tree based modelling approaches.

The relatively recent appearance of remote sensing sources such as LiDAR is contrasted with the length of forest growth cycle. This means there is a lack of important time series data for these new data sources which might be a challenge for modelling in the short term. This also raises the challenge of ensuring data from operational data collections, as well as growth monitoring networks (such as PSP and LUCAS) is pro-actively future proofed, to ensure these important time series data can be captured now through to the future. New models can also impact the inventory methods that will be used to capture model input data.

Therefore, the design of new models must consider: the key applications; available and future inputs; trial, inventory, and monitoring plot designs. Demands for implementation include the use of an accessible programming language/platform; the ability to account for genetics, other species, and even mixed species – including weeds; mortality; the ability to link to other models – existing and new. It is an important technical detail to note that model linkage should be possible not just at model start (input) and end (output) but at key points within the simulation time step, i.e. sub-models. This will provide the opportunity for tight integration of models such as climate and wood properties. This mechanism will also allow the use of existing well known empirical models such as PPM88 to be used a 'guide curves' for new models.

A suggested strategy is to meet current and near term modelling needs by re-fitting existing models with updated data sets as needed while designing and implementing the next generation of models in parallel.

Acknowledgements

The authors of this report would like to acknowledge all participants of the two workshops and contributing their time and knowledge towards the delivery of the outcomes of the workshop. Funding for this research came from Scion and the Forest Growers Levy Trust, with the support of the NZ Forest Owners Association (FOA) and the NZ Farm Forestry Association (FFA).

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Appendix A

Workshops participants

	Attendee	Organisation
Workshop 1	Alex Tolan	Rayonier
	Alan Tan	Scion
	Alison Slade	Scion
	Brian Rawley	Silmetra
	Dave Pont	Scion
	Dean Meason	Scion
	Euan Mason	UC
	Fred Schipper	Timberlands
	Grace Villamore	Scion
	Jessica Worboys	Timberlands
	John Moore	Timberlands
	Paul Silcock	Ernslaw
	Peter Clinton	Scion
	Ross Jones	Hancock
	Russell Dale	FGR
	Sean Husheer	Scion
	Simon Papps	Hancock
	Yue Lin	Scion
Workshop 2	Aaron Gunn	Port Blakely
	Angelo Belmar	Hancocks
	Ashley Wade	Scion
	Brian Rawley	Silmetra
	Craig Brown	Nelson Forests
	David Palmer	Scion
	David Pont	Scion
	Dean Meason	Scion
	Euan Mason	UC
	Fred Schipper	Timberlands
	Grace Villamor	Scion
	Harry Li	Rayonier
	Ian Hinton	Timberlands
	Justin Morgenroth	UoC
	Michael Battaglia	CSIRO
	Mitchell Cook	Port Blakely
	Paul Adams	Rayonier
	Paul Silcock	Ernslaw
	Peter Clinton	Scion
	Ross Jones	Hancocks
	Sean Husser	Scion
	Serajis Salekin	UC
	Simon Papps	Hankcocks
	Vega Xu	UC
	Yue Lin	Scion

Appendix B

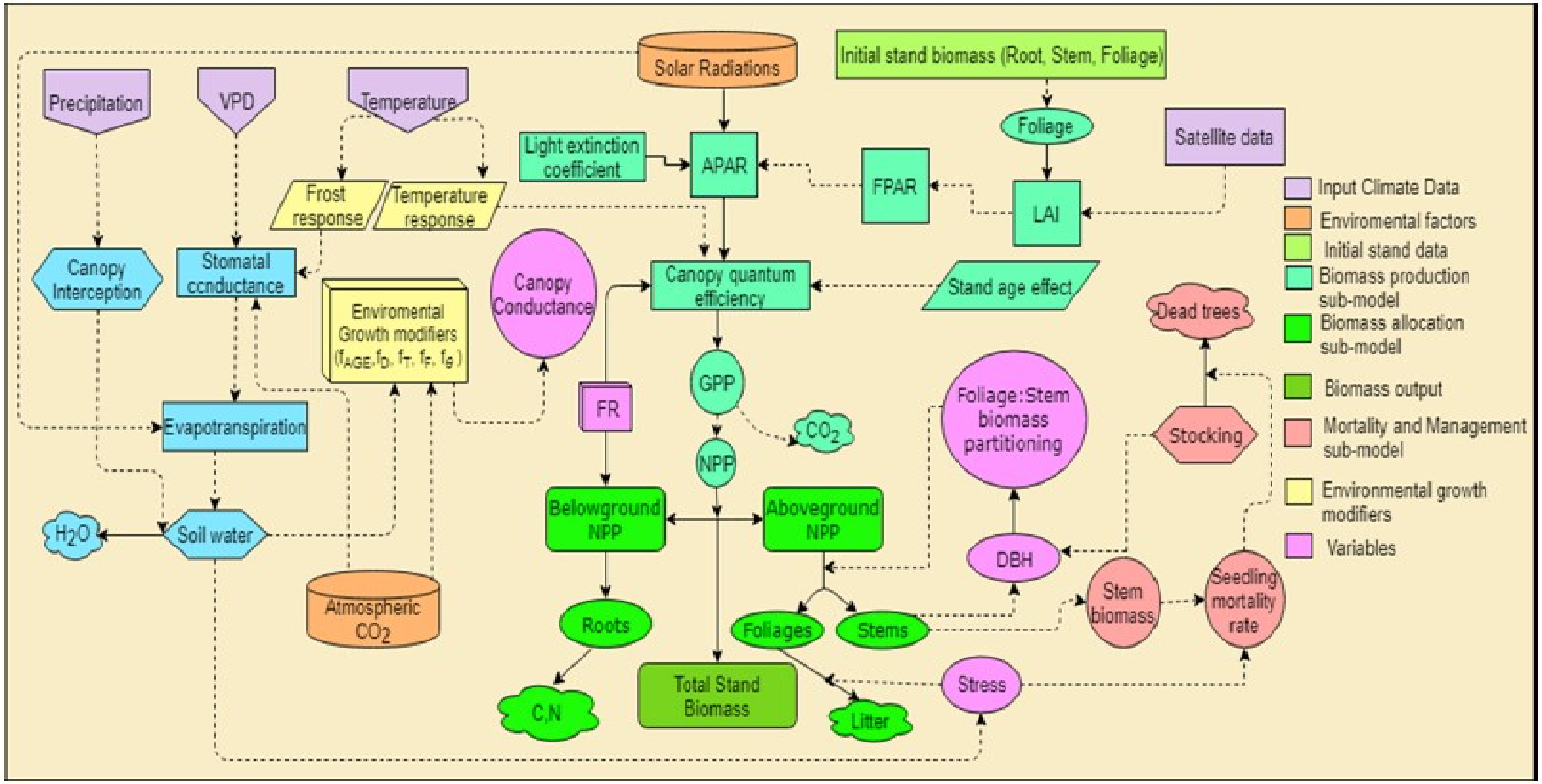

Figure A1: Primary structure of 3-PG process-based model. https://doi.org/10.1016/j.ecolmodel.2019.01.007

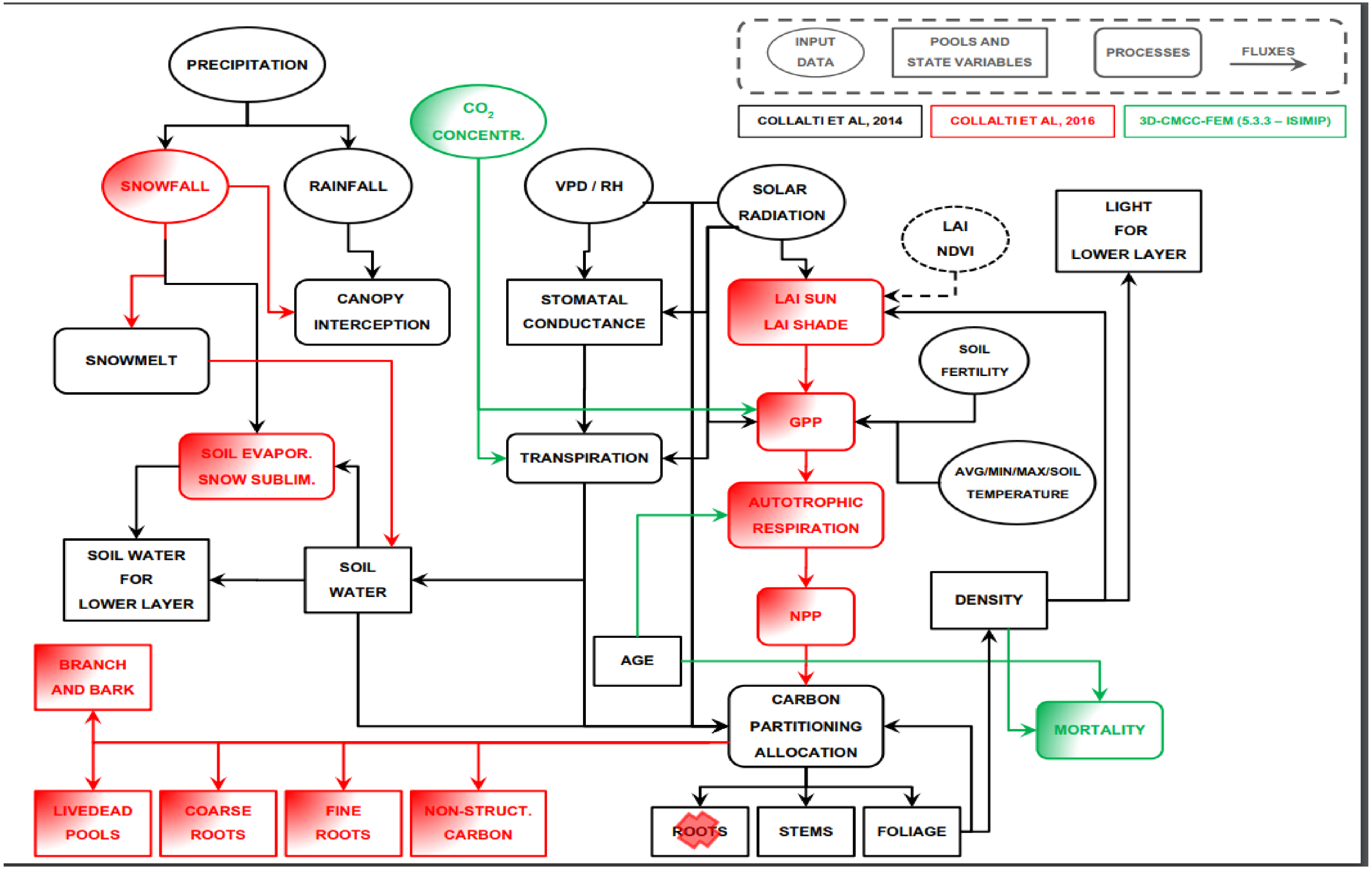

Figure A2: 3D-CMCC-CNR flow chart https://www.3d-cmcc-fem.com/model-flowchart

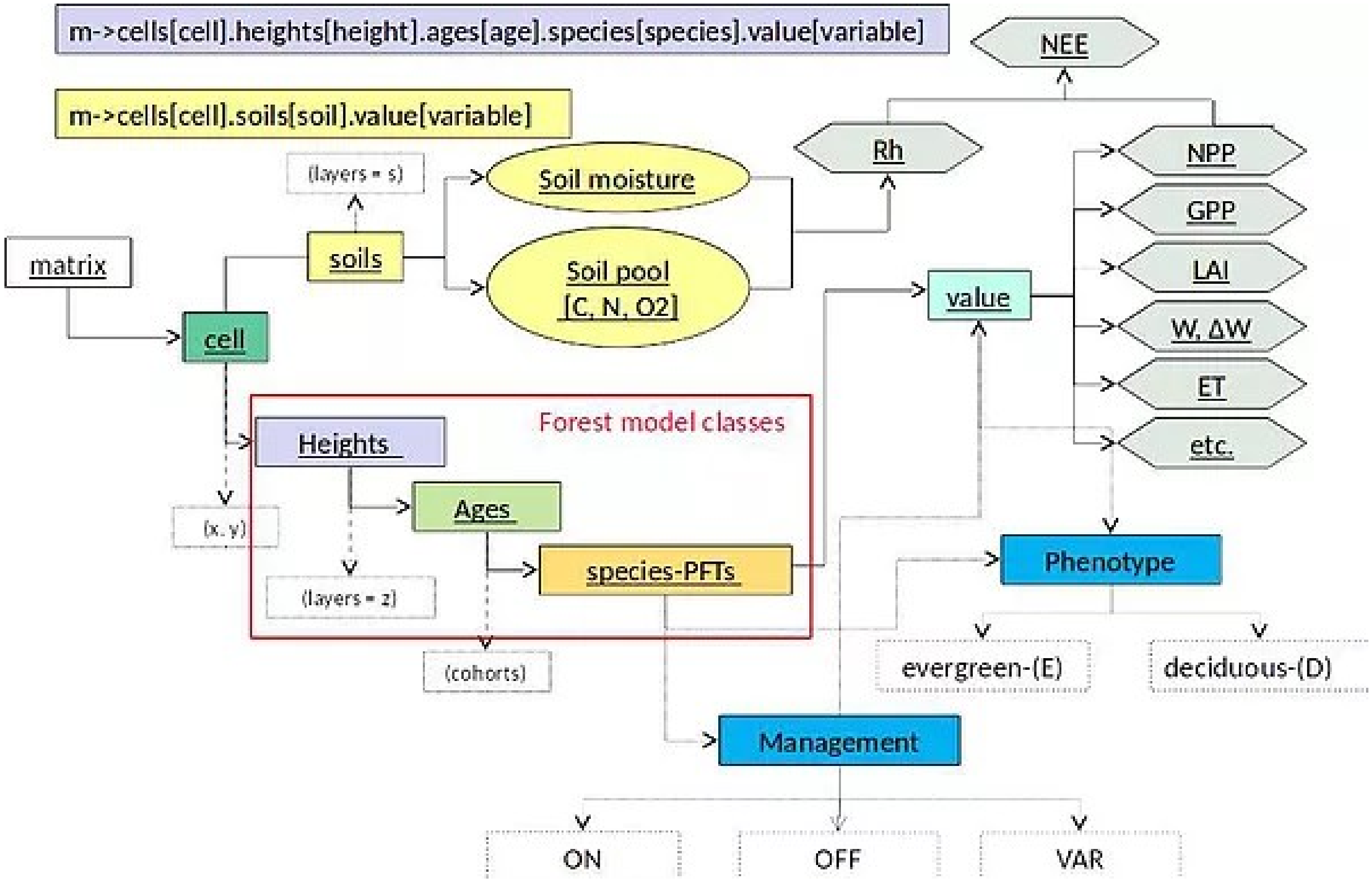

Figure A3: 3D-CMCC-CNR model https://www.3d-cmcc-fem.com/logical-structure

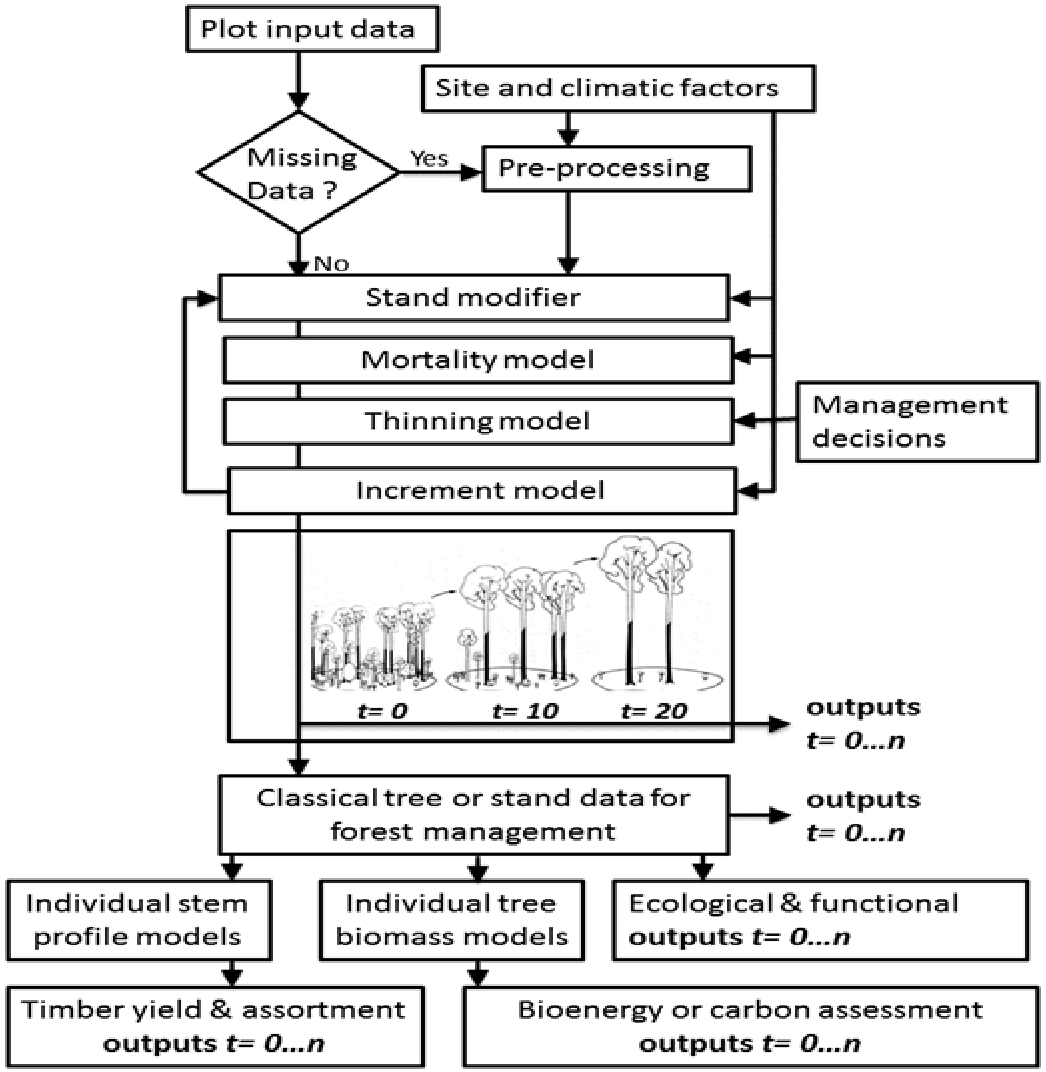

Figure A4: CARBWARE model inputs, functionality, and outputs over time (t) for any given year (n). https://academic.oup.com/forestry/article/89/1/55/2465659

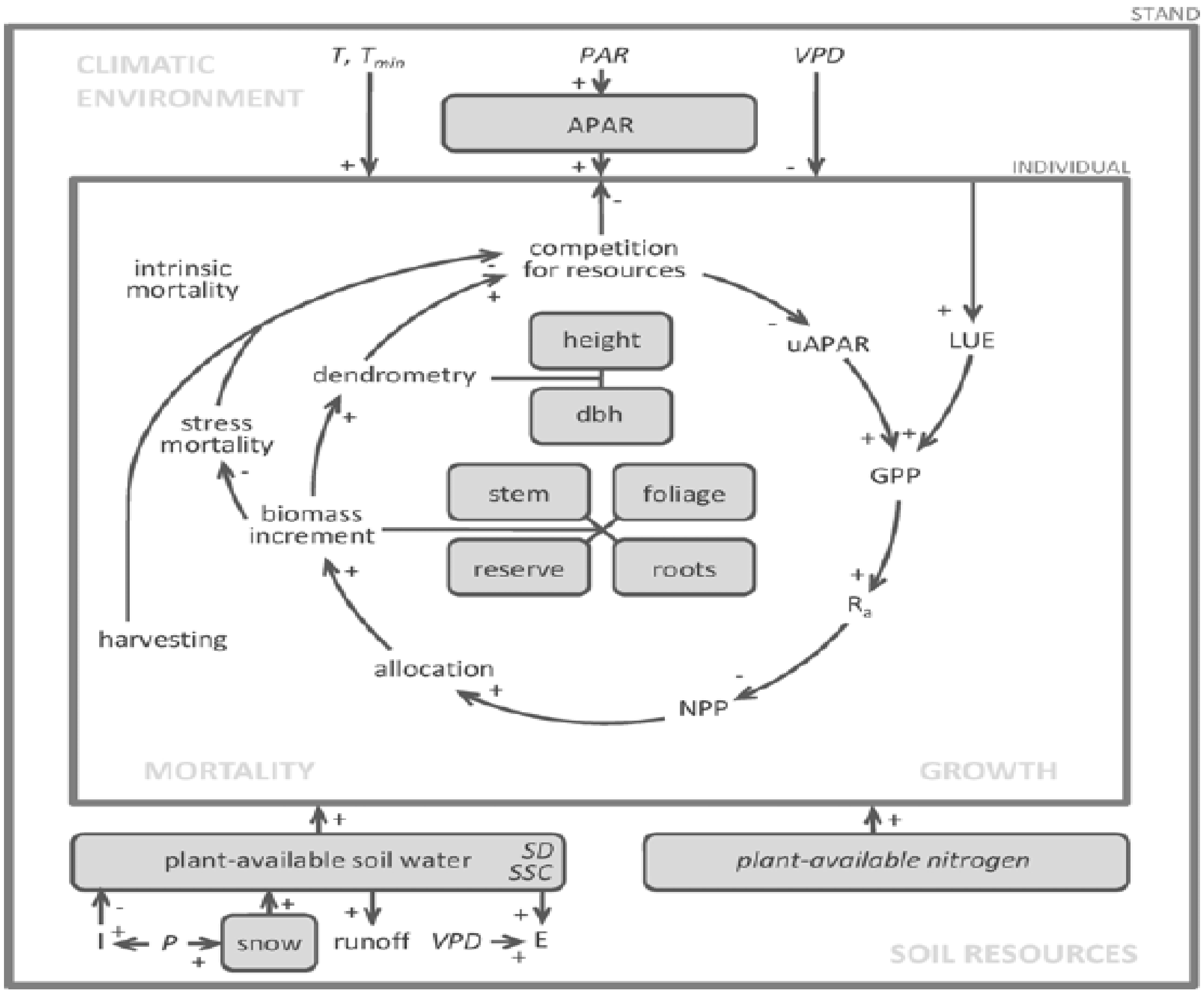

Figure A5: Physiological processes and causal influences in iLand. https://doi.org/10.1016/j.ecolmodel.2012.02.015

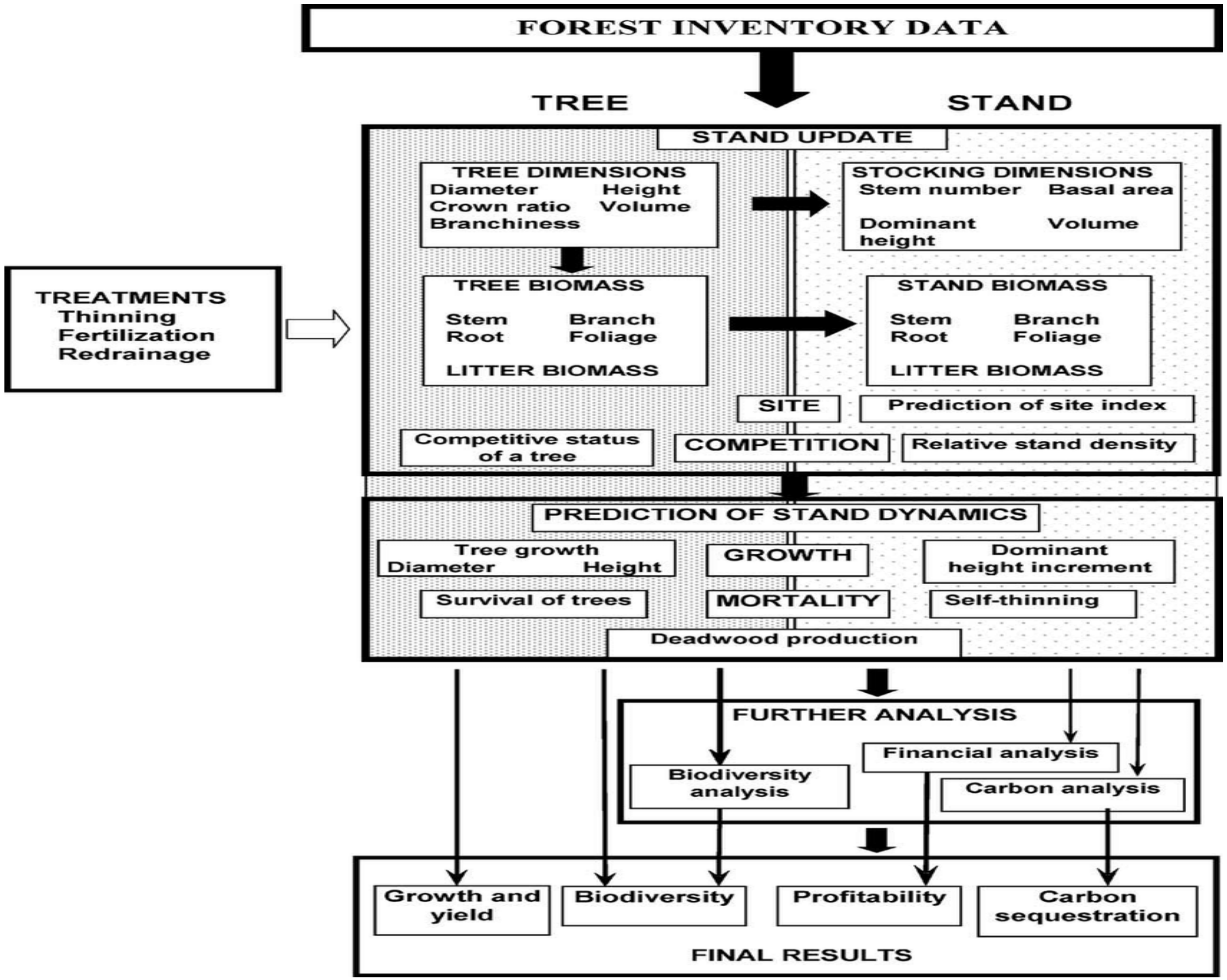

Figure A6: MOTTI stand simulator. https://www.researchgate.net/figure/Overview-of-the-simulation-and-analysis-of-the-MOTTI-stand-simulator_fig1_223026491

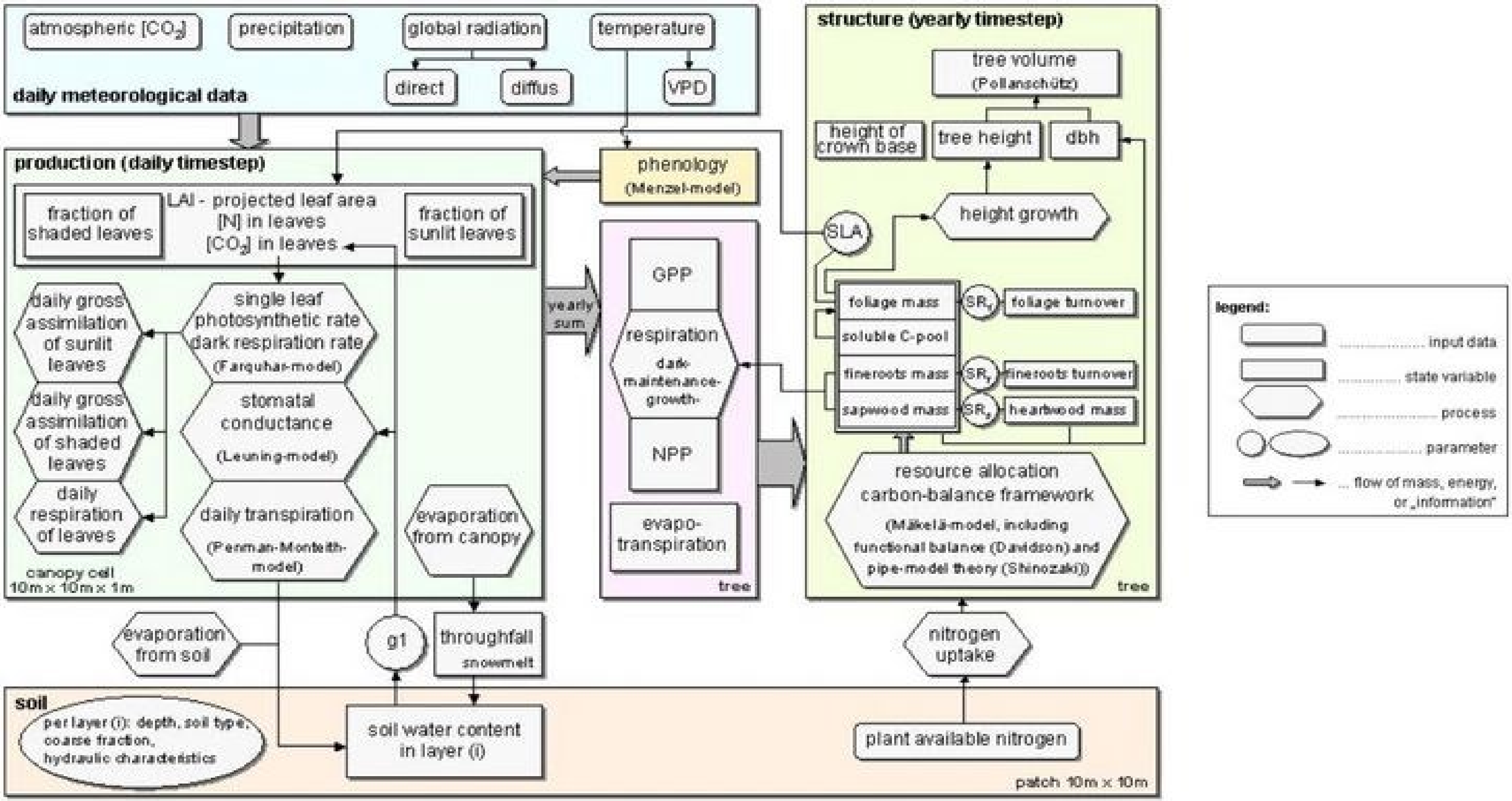

Figure A7: STAND Decision support system. doi: 10.1007/3-540-31304-4_8