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Review of Carbon and Timber Volume Growth Models for the Full Lands Integration Tool (FLINT)

Abstract:

The Full Lands Integration Tool (FLINT) can be used to estimate emissions and removals of greenhouse gases from the land sector spatially and through time. FLINT uses modules that perform specific analyses of carbon flows. Estimating forest biomass underpins all forest-based carbon assessments. There are a wide range of methods for doing this, each with advantages and disadvantages. Our goal was to support the development of a forest module that can be used with the FLINT by identifying suitable existing forest growth and disturbance models. We have reviewed 12 growth models against 48 criteria related to availability, reliability, resolution, input, sensitivity and output. We identified the forest growth and disturbance models of the following model compilations as most promising candidates for a generic FLINT forest module: CO2FIX, FullCAM, 3-PGmix and CENTURY (or derivatives of this model). CO2FIX offers the possibility to initialize growth estimations from a function of the total and maximum aboveground biomass of a forest stand. Using a cohort approach, the model also facilitates simulations of forest transitions (e.g. forest degradation). The Tree Yield Formula of FullCAM allows to factor dynamic environmental conditions into an empirical model. 3-PGmix is based on plant physiological processes and generates timber volumes and common forest stand parameters for pure and mixed species/age stands. This is of interest for simultaneously projecting carbon fluxes and the availability of biomass (relevant in the context of bioeconomy). CENTURY is a generic process model that addresses early-age growth problems explicitly. It is sensible to environmental growth conditions and can simulate a wide range of disturbances and climate change effects. Taking the example of CO2FIX, we show how a growth model could be implemented more specifically within a FLINT forest module.

Acknowledgements

This document was prepared as part of the deliverables of the “Expanding Market Opportunities” contribution agreement between Her Majesty the Queen in Right of Canada, represented by the Minister of Natural Resources and the non-for-profit organization “Climate Advisers Trust” (Project: "moja global - International collaboration on sustainable forest management tools”).

The views expressed in this report do not necessarily reflect the positions of Climate Advisers Trust or the Government of Canada.

We thank Dr Keryn Paul, Associate Professor Cristopher Brack and Dr Stephen Roxburgh for their valuable feedback.

Disclaimer

The presented growth model review was conducted with great care. However, in the scope of the project it was not feasible to run and test the growth models. The provided information relies heavily on user manuals, peer reviewed papers, web sources and third party opinions. Most of the reviewed growth models rely on a wide range of input data and provide numerous outputs. Providing a comprehensive list of all required inputs, interactions and potential outputs for each of the models was not feasible. Instead we display those inputs and outputs we considered as most relevant. Users are responsible for clarifying if a specific model meets their needs and data availability using the original sources. If possible we provided information about legal restrictions and whether or not a model is provided as open source software/code. The legal status of a software or code can be subject to change and some of the available information on this matter is ambiguous. Users are responsible for clarifying the legal status of software/code prior to usage. Under no circumstances will the authors be held responsible or liable in any way for any claims, damages, losses, expenses, costs or liabilities whatsoever (including, without limitation, any direct or indirect damages for loss of profits, business interruption or loss of information) resulting or arising directly or indirectly from your use of this report.

Introduction

Countries recognise the importance of improving decision making and supporting land sector policies to reduce greenhouse gas (GHG) emissions and increase removals (FAO 2016, Griscom et al. 2017). At the same time, there is heightened attention globally on transparency in climate action to support the goals of the Paris Agreement and in supporting transitions to achieve the Sustainable Development Goals (Winkler, Mantlana, & Letete 2017, Pauw et al. 2018). The Full Lands Integration Tool (FLINT) is an open-source platform to estimate emissions and removals of greenhouse gases from the land sector using modules that perform specific analyses of carbon flows.

Estimating forest biomass underpins all forest-based carbon assessments. There are a wide range of methods for doing this, each with advantages and disadvantages (Kurz et al. 2009, Kim et al. 2015). Emissions factors remain a popular method for national scale reporting but have many limitations for Monitoring, Reporting and Verification (MRV) (Eggleston et al. 2006), particularly when used for planning mitigation actions or considering the effects of management and climate. Biomass maps from remote sensing offer some improvements but are often not available in a consistent time-series (Saatchi et al. 2011, Zhang, Liang, & Yang 2019) and cannot be used to support projections. To address these issues, countries will need to start using more advanced forest growth models (Tier 3 models) (Penman et al. 2003).

The issue is that many of the existing models are often perceived as not suitable for use in more complex tropical systems (Vanclay 1994). There are several reasons for this. Firstly, many are developed starting with estimates of stem volume, moving to biomass using expansion factors and wood density values. In many countries these data are not readily available so it is easier to start with biomass obtained from inventories and allometric equations (Shi and Liu 2017). Secondly, many models are based on species and age but in tropical forests the composition is complex, being multi aged and multi-species (Vanclay 1994). However, the core concepts of these models can still be applied in many cases when 'age' is replaced with 'condition' or 'time since disturbance' (Gu et al. 2016). Finally, many existing models do not easily account for the range of silvicultural practices applied (Waterworth and Richards 2008). Fortunately, there are numerous good examples of generic growth models that could be adapted (Landsberg and Waring 1997, Kurz et al 2009, Kim et al. 2015, Schelhaas et al. 2004).

The aim of this project was to support the development of a generic forest module to be used with the FLINT by:

- Developing a set of criteria for reviewing existing models (either carbon or timber volume estimation) for their use in carbon reporting and accounting.
- Reviewing existing empirical and hybrid empirical / process models against these criteria. The review:
    - included analysis of methods of calibration, generic applicability, sensitivity to site and climate factors and ability to consider management effects and

- considered methods and processes for subdividing the aboveground biomass into important components (for example, wood, bark, leaves, branches).
- Documenting how the module can be used on the FLINT, including the data requirements.
- Planning for how to implement one of these models as a FLINT module in the future.

The FLINT

The FLINT is a second-generation tool aimed to facilitate the implementation and operation of land sector emissions estimation systems worldwide.[1] It was developed through cooperation between Kenya, Australia and Canada and incorporates lessons learned from the development of the CBM-CFS3 (Canada) and FullCAM (Australia). Some core features are:

- A full-mass balance framework able to meet all IPCC requirements
- Possibilities for customisation to meet national policy and reporting requirements
- A modular system that allows the use of individual and exchangeable modules
- Ability to operate in a spatially explicit way
- Ability to produce fine resolution time series data
- Ability to report on the past and to generate projections
- Flexibility for representing all land uses
- Providing a framework for continuous improvement
- Open-source software managed by moja global under the Linux Foundation

The FLINT provides a framework to progressively develop MRV-related systems, data and capacities. By this means, countries can start with simple implementations using existing global data sets (Tier 1) and then gradually move to more complex calculation approaches, using national and regional information (Tier 2 or 3) (GFOI 2016, moja global 2020).

The basic role of the FLINT is to coordinate the interaction of data (e.g. spatial data, non-spatial data, carbon pools, variables, fluxes) and modules. It also manages computational outputs. FLINT-compatible modules are discreet software packages that can be attached to the FLINT. It is possible to differentiate between calculation modules and functionality modules. Calculation modules can change the state of variables and pools for pixels over a sequence of steps. Functionality modules do not apply changes to variables or pools but affect the utility of the FLINT by e.g. aggregating data or generating outputs.

A unique configuration of modules attached to the FLINT is referred to as implementation (see Figure 1). Existing FLINT implementations are SLEEK-FLINT, GCBM and FLINTpro. SLEEK-FLINT uses the Chapman-Richards function (Pienaar and Turnbull 1973) as the basis of one of it’s forest growth models. GCBM uses growth-and-yield curves that describe the relationship between stand age and stand volume (Kull et al. 2019).

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[1] Information in this section was also derived from the draft of the SLEEK-FLINT Operators Guide, Version 1.0, December (2019).

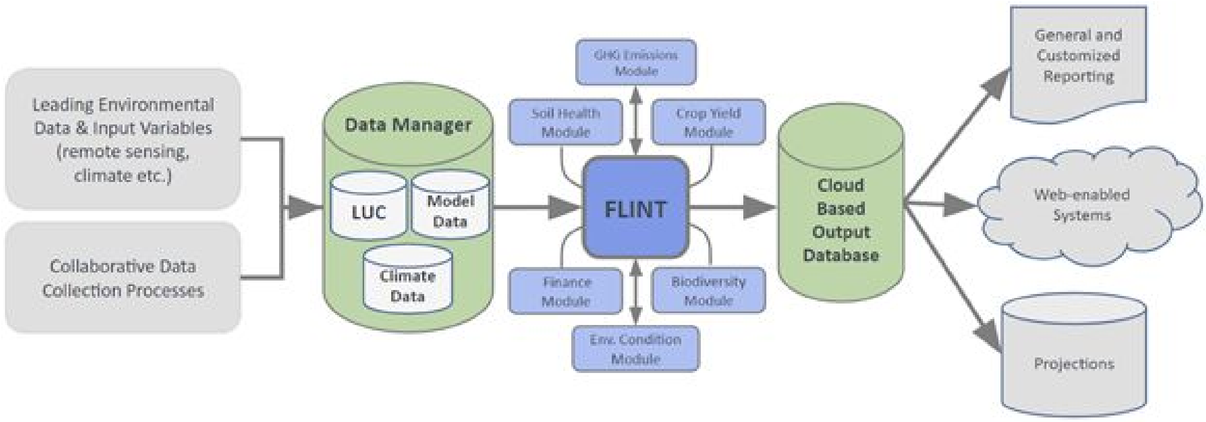

Figure 1: Representation of a complete FLINT implementation (Source: Draft of the SLEEK-FLINT Operators Guide, Version 1.0, December (2019))

Growth Models Overview

Table 1 gives an overview of identified growth models and model compilations that integrate growth models. In the case that a forest growth model was integrated in a model compilation, our review focused on the forest growth model but also included attached models or functions related to disturbances (e.g. harvests, fire) and volume / biomass allocations. Related soil or pasture / crop models were not part of our review.

The far right column of Table 1 indicates which of the models were reviewed in the scope of our project. We tried to incorporate a larger range of forest growth estimation approaches in our review. For example, we included empirical, process and empirical-process hybrid models. We also focused more on models that are already widely used by the scientific community as this could be taken as a first indicator for their generalisability.

Table 1: Identified growth models and model compilations that contain growth models

Abb.	Name long	Revied [2]
3-PG	Physiological Principles in Predicting Growth	Yes
3-PGmix	Physiological Principles in Pred. Growth (mixed species / age)	Yes
3-PGS	Physiological Principles in Predicting Growth with Satellite	No
ALU	Agric. & Land Use National GHG Inv. and Mitig. Anal. Softw. Tool (Emission Factors)	No
BIOMASS	BIOMASS	No
Biome-BGC	Biome-BGC	Yes
BIOS2	Composite model and environment	No
CABALA	CArbon BALAnce	No
CASMOFOR	CArbon Sequestration MOdel for FORestation	Yes
CENTURY	CENTURY	Yes
CenW	Carbon, Energy, Nutrients, Water	No
CO2FIX	CO2FIX	Yes
CO2Land	CO2FIX for landscape level	No
DayCent	DayCent (Daily version of CENTURY)	No
ED Model	Ecosystem Demography Model	No
EFISCEN	European Forest Information Scenario model	Yes
Forest-DNDC	DeNitrification-DeComposition with focus on forest (Based on PnET)	Yes
ForCent	Revision to the DayCent model	No
FullCAM	Full carbon accounting model (Tree Yield Formula, TYF)	Yes
GCBM	Generic Carbon Budget Model / CBM-CFS3 (for comparison)	Yes
IPCC Inv. Softw.	IPCC Inventory Software (Emission Factors)	Yes
LPJ-Guess	Lund-Potsdam-Jena General Ecosystem Simulator	No
PnET	Photosynthesis and EvapoTranspiration	Yes
POP	Populations-Order-Physiology	No
ProMOD	(Predecessor of CABALA)	No
SLEEK-FLINT	System for Land Emission Estimation Kenya - Full Lands Integration Tool	Yes
YTGEN	Forest Yield Table Generator	No

[2] Yes: Reviewed, No: Not reviewed

Reviewing Criteria

We used a set of 48 criteria to evaluate the forest growth models (see Tables A1 to A3 in the Appendix). The criteria can be divided into seven categories:

- Method / Focus
- Availability
- Reliability
- Resolution
- Input Data
- Sensitivity
- Outputs

Method / Focus: This Category is concerned with the focus of the growth model, which can be either carbon or timber volume. Another consideration is whether the model can be regarded as a pure empirical mode, as a pure process model, or whether it is a hybrid model with empirical and process components. The criteria in this category offer a first insight into the context in which the model was developed.

Process-based models incorporate physiological processes (e.g. photosynthesis, transpiration and respiration). They are usually well suited to estimate impacts of climate change on forest growth due to the direct link between growth conditions and stand development. However, calibrating process models can be difficult as they often require many parameters which need to be derived from empirical data (Trasobares et al. 2016). They can also have unexpected and non-linear responses to input variables, sometimes making them difficult to constrain (Wang et al. 2011).

Empirical growth models are generally simpler and the majority of parameters can be derived from forest inventories or long-term trials. A downside of many empirical models is that they integrate only a few parameters related to environmental conditions which are often considered to be static (Trasobares et al. 2016).

Availability: Criteria in this category refer to financial or legal issues that might arise when the model or the related software is utilised. These are namely subscription or purchase/use costs, possibilities to use or change the related code and intellectual property rights.

Reliability: The scope of the project did not allow us to test the models in their prediction performances. Instead, we have based our assessment on four reliability indicators. This included questions of whether a stable and tested version of the model was available and whether the model has been tested on data not used during the model's development. Other indications for the model's reliability were: has it been used to generate data for a national greenhouse gas inventory required by the United Nations Framework Convention on Climate Change (UNFCCC) or to report under the Verified Carbon Standard (VCS)?; and has it been used in a third country which had no part in the original development of the model? This later criterium can also be used to assess the generic nature of the model (see Category Resolution)

We considered a model (or the related software / code) to be stable and tested when the provider offered a version control and a clear indication towards the most recent version available.

Resolution: This category refers to the temporal and spatial resolution with which the model operates. Higher resolutions (e.g. 'daily' / 'project level' instead of 'yearly' / 'national level') make the model more versatile and applicable from Tier 1 through to Tier 3. Data that is available in high resolution can be aggregated to lower resolutions without compromising accuracy. On the other side, interpolating low resolution data to higher resolutions is likely to cause a loss in accuracy. As a downside, high resolution models usually require high resolution input data. Data is not always accessible in the required resolution and quality.

Another criterium related to resolution is the question of whether a model can be considered to be generic. Generic models allow for an application across countries and environmental conditions (upscaling), which increases the comparability of results. Here we classified a model as generic if we could not see any obstacles to its application in the majority of countries without fundamental modifications. Modifications can be considered as non-fundamental if they are simply about applying country or plant-specific variables as input data. We also consider a model to be generic if its setup allows for a country specific parameterisation of the involved functions. In contrast, a model developed for one specific national forest inventory method which cannot readily be applied to other national inventory methods would not be considered generic.

Input data: This category is concerned with the input that has to be provided to run the model. A first set of criteria constitute a rather high level and general assumption of how difficult it is to obtain input data for the model and to calibrate the involved functions.

Some growth models are calibrated on repeatedly measured forest inventory data. If such an inventory has not yet been established it will be difficult to generate the required data in the short term. This is considered with the criteria 'Permanent forest inventory required'.

Another set of criteria refers to input data that specifies the climate, site, soil and forest type. We differentiated between the need for general forest data (forest type, species) and more specific forest or tree data (e.g. stems per ha, leaf C:N ratio).

Two criteria refer to the question of whether the model relates the growth rate directly to tree age or standing volume / biomass. In some cases (especially in the tropics), it can be extremely difficult to collect data on tree age.

The criterion 'Allows input on disturbances' is concerned with possibilities to channel impacts of fire, disease, storm or management operations (e.g. thinning) into the model.

Sensitivity: The category subsumes a range of criteria related to the question of whether the model reflects influences of environmental conditions (climate, soil) and external influences (disturbances, management) on growth. Some of the criteria relate to the growth, others to the mortality of trees. Growth models that are sensitive to climate related variables are of importance for projecting growth in the context of climate change.

Another set of criteria in this category is concerned with the question of whether the model can be applied to forests including trees of different species and/or age and whether it is possible to simulate the effects of selective logging.

Some models fail to simulate the growth of younger trees (DBH < 7-10 cm) accurately. Trees of these sizes are often not measured in forest inventories. Therefore, the criterion ‘Early age issue’ was included.

Output: Criteria related to the output category refer to the model’s ability to generate typical forest stand parameters, to allocate or expand the carbon or timber volume to the various tree components (stem, bark, branches, leaves, roots) and to represent the turnover of material from the living components to dead organic matter (litter, dead organic matter). Two criteria refer to the question of whether the model returns outputs for the harvested and deceased trees.

A further criterion for models with a focus on timber volume is if they provide an additional output for the sequestrated carbon. Some models might have additional beneficial outputs which were not in the focus of this review. This is recorded with the criterion 'additional outputs’.

Comparison of Growth Models

Growth Models currently used with the FLINT

Currently, carbon and timber volume growth models are implemented in the two FLINT implementations SLEEK-FLINT and GCBM. These implementations are here presented and can be used as a base for the growth model comparison (Table 2 and Table 3). The SLEEK-FLINT implementation is described with more detail to familiarise the reader with spatial and modular approaches that are associated with the FLINT.

SLEEK-FLINT

SLEEK-FLINT was developed to be used within the System for Land Emission Estimation Kenya.[3] The implementation includes modules that were developed to match the data availability and management requirements of Kenya. With regards to forest growth, it includes a module for natural forests and for forest plantations. In addition to these growth processes, planting and thinning operations are implemented as events (see Table B1 for additional information).

SLEEK-FLINT applies a Chapman-Richards curve as a growth model for natural forest which estimates total above ground biomass (AGB) based on age. Subsequently, bark, branch, stem, and leaf biomass are partitioned from the total AGB. Below ground biomass is estimated as a ratio of the AGB and then partitioned into coarse and fine roots. Fractions and ratios used for the partitioning and expansion can be defined by the user. Annual turnover rates for leaves, branches and roots can be defined for different forest types. A disturbance probability curve is used to define the initial age of a natural forest pixel. With regards to forest plantations, species specific growth curves were developed and AGB partitioning occurs according to fitted equations. The age of the plantations is recalled from a database.

As a module attached to the FLINT, the Build Land Unit Module (BLUM) defines the rules of developing the sequence of processes (e.g. growth) and events (e.g. planting and thinning). It uses both spatial and non-spatial data. There are two mechanisms that can trigger an event for a simulation unit (pixel) in SLEEK-FLINT: Spatial Triggers and Timing Triggers. For example, a spatial trigger would be where a ‘forest clearing event’ is triggered where a pixel transitions from forest land to non-forest between two points in time in a forest cover dataset. Timing triggers can be defined by the user in a database. For example, it can be defined that a plantation of a particular type is thinned when it reaches four years of age. The system therefore inserts the thinning event into the timeline for the pixel and at 4 years of age, the event ‘Thin the plantation’ is triggered.

[3] Information about SLEEK-FLINT was derived from the draft of the SLEEK-FLINT Operators Guide, Version 1.0, December (2019).

Planting events change the state of a pixel, and initiate the parameters for the forest growth module. That is, the forest growth model is triggered for the pixel and grows biomass on the pixel according to the model type and the parameters that are set for it. Planting events can also be implemented so that they initially move carbon from the atmosphere to the living biomass pools for example to represent the planting of biomass onto the site via seedlings. Thinning events (pruning, thinning or harvest) move biomass from the living biomass pools to product pools or dead organic matter pools. A thinning event that removes all living biomass in the forest can also trigger a transition to a non-forest state. This would end the growth of the forest and the forest growth model would no longer be active for the pixel.

A specific feature of SLEEK-FLINT is the pseudo-randomised definition of stand age for each forest pixel to overcome data related uncertainties in natural forests. Another advantage is the flexibility with which the growth curves are implemented. With its current set up, SLEEK-FLINT's growth module does not explicitly account for competition among trees nor natural mortality. Rather the increment in biomass after losses due to mortality is estimated and turnover due to mortality is treated as a separate turnover term. Disturbances other than harvest / thinning are not included but could be added as additional events.. SLEEK-FLINT does not explicitly account for the age cohorts of multi-aged forests, rather the growth rate of the forest is adjusted based on the biomass that is on site following a disturbance.

Table 2: Evaluation of the reviewed empirical growth models

Criteria		SLEEK FLINT	GCBM	CO2 FIX	CASMO FOR	EFI SCEN	FULL Cam
	Empirical / Process / Hybrid	E	E	E	E	E	H
	Timber volume, Carbon	C	T	C	C	T	C
Availability	Use free of charge (Costs)	?	●	●	●	●	●
	Open source	?	□	□	?	●	●
	No IP issues	?	□	□	?	□	□
Reliab	Stable + tested	□	●	●	□	●	●
	Tested on independent data	□	●	●	?	●	●
	Used in >1 countries	□	●	●	□	●	□
	Used for official reporting	?	●	●	●	?	●
Resolution	Temporal resolution [1]	F	Y	Y	Y	5Y	F
	Spatial resolution [2]	S-N	S-N	S	S-R	C	S-N
	Generic	●	●	●	□	●	●
Input data	Input data availability difficult?	□	●	□	□	□	●
	Calibration difficult?	□	●	□	□	□	●
	Perm. For. Inv. required	□	□	□	□	□	□
	Climate data needed	□	●	□	□	□	●
	Site data needed	□	●	●	●	●	●
	Soil data needed	□	□	□	□	□	●
	General forest data needed	●	●	●	●	●	●
	Specific forest data needed	□	●	●	●	●	●
	Starts with age	□	●	opt	●	●	●
	Starts with volume / biomass	□	●	opt	□	□	□
	Allows input on disturbances	●	●	●	□	□	●
Sensitivity	Climate	□	●	□	□	□	●
	Soil	□	□	□	□	□	●
	Harvest / Thinning	●	●	●	●	●	●
	Density / Competition	□	□	●	□	□	?
	Fire (growth impact)	□	●	□	□	□	●
	Fertilising	□	□	□	□	□	●
	Irrigation	□	□	□	□	□	●
	Mortality / Self-thinning	□	□	●	●	●	●
	Mortality by natural disturbances	□	●	●	●	●	●
	Multi-age forest possible	□	?	●	□	□	□
	Multi-species forest possible	□	●	●	□	●	□
	Selective logging possible	●	?	●	□	□	?
	Early-Age issue	?	?	?	□	?	?
Outputs	Stem number	□	?	□	□	□	?
	Standing Volume	□	●	●	□	●	●
	Height	□	?	□	□	□	?
	Basal Area	□	?	□	□	□	?
	DBH	□	?	□	□	□	?
	Partitioning	●	●	●	●	●	●
	· Stem wood	●	●	●	●	●	●
	· Bark	●	□	□	□	□	●
	· Branches	●	●	●	●	●	●
	· Foliage	●	●	●	●	●	●
	· Roots	●	●	●	●	●	●
	· Coarse / Fine roots	●	●	□	□	●	●
	Harvested stand	●	●	●	●	●	●
	Deceased stand	●	●	□	●	●	●
	Dead Organic Matter	●	●	●	●	?	●
	Litter production	●	●	●	●	□	●
	Carbon	●	●	●	●	●	●
	Additional outputs	□	●	●	□	□	●

● = yes; □ = no; □ = in between; opt. = optional; ? = to be confirmed

[1] A=Annual, M=Month, D=Day, F=Flex.; [2] S= Stand level R=Regional / Landscape Level, N=National Level, C=Continental

GCBM

GCBM is a FLINT implementation of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, Versions 1.2, Kurz et al. 2009).[4] It complies with IPCC carbon estimation methods and uses information which is also required for forest management planning (see Table B2 for additional information).

The model can produce outputs with a comparably high accuracy. It can handle the impacts of disturbances and land-use change and is applicable to small-scale and large-scale forests (Kim et al. 2015).

A major advantage over other models reviewed in this project is that GCBM can return merchantable timber volumes (compare Kim et al. 2015). The biomass is partitioned separately for soft and hardwood into (Kurz et al 2009 cited in Kim et al. 2015):

- Merchantable wood
- Other wood
- Foliage
- Fine roots
- Coarse roots

An important restriction is that growth-and-yield curves are formulated as a relationship between age and volume only. Furthermore, volume has to be converted to biomass. This can be done with high accuracy for Canada based on a study of Boudewyn et al. (2007). However, this study used a large number of samples. Generating a similar set of equations for other countries can be difficult and costly (Kim et al. 2015).

Decay dynamics can be described in a highly flexible way in GCBM. However, density-dependent mortality is not calculated explicitly but seems to be reflected by turnover rates (Kim et al. 2015).

Disturbances like pest related stand mortality, clear cut logging, salvage logging and post-disturbance dynamics can be implemented in a diverse and flexible way across the landscape level (Kim et al. 2015). Post disturbance dynamics can be implemented by applying new modified growth-and-yield curves to a defined proportion of the stand (Kull et al. 2019).

[4] The descriptions of GCBM rely on documentations of CBM-CFS3 as it uses the same science models:
https://github.com/moja-global/About-moja-global/wiki/GCBM-is-runs-CBM-science-models-on-the-FLINT-platform

Alternative Empirical Growth Models

A comparison of alternative empirical growth models is shown in Table 2. A selection of features of these models are described in more detail in this section.

CO2FIX

The aim of CO2FIX (Version 3.2) is to quantify the C stocks and fluxes in the forest using the full carbon accounting approach. Simulations are conducted at the hectare scale with time steps of one year (Schelhaas et al. 2004) (see Table B3 for additional information).

The model applies a cohort approach which can be used to simulate the growth of different successional groups, different species or different stand strata on the same spatial unit (Schelhaas et al. 2004). Compared to GCBM, this facilitates the simulation of a more complex stand dynamic as each cohort grows, competes and dies or if harvested as an individual unit of a stand (Kim et al. 2015).

Another potential advantage of CO2FIX is that the stem growth of each cohort can be defined in two different ways: (a) as a function of tree / stand age and (b) as a function of the total and maximum aboveground biomass of the chort (Schelhaas et al. 2004).

Starting from stem volume growth (in m^3 ha^{-1} yr^{-1}), time-dependent allometric equations are used to derive growth rates for foliage, branches and roots. These growth rates undergo modifications that reflect the interactions of the cohort with itself and with other cohorts. Tree interactions can range from competition, to no effect, to synergistic effects. In addition, growth rates can be influenced by site condition and modifications of related parameters.

The approach used in CO2FIX to calculate the growth of biomass is simpler and does not need as much data as the one applied in GCBM. But Kim et al. (2015) suggest that the model is able to generate reasonable results.

CO2FIX can also account for (Schelhaas et al. 2004):

- Tree mortality due to senescence
- Turnover
- Harvesting
- Natural mortality
- Mortality due to logging (harvesting) damage

The model includes a maximum age for trees and applies the assumption that mortality increases with increasing stand age or biomass. By using the cohort approach, density-dependent mortality might be described more dynamically compared to GCBM. However, CO2FIX assumes that all parts of a tree die at the same time and it does not allow for a more distinctive description of mortality like CASMOFOR or GCBM (Kim et al. 2015).

According to Kim et al. (2015), CO2FIX can implement disturbance types like fire, wind storms, pests and disease and climate change. They also suggest that growth tables could be modified in a way that would simulate damages restricted to foliage and branches. This could be used to simulate the effect of fire and infestations on growth. For the criteria 'Climate', 'Soil' and 'Fire (growth impact)' we have set the value in Table 2 to 'in between'. This is because CO2FIX does not seem to provide an explicit integration of these factors. For the growth model the effects of soil are hidden in site conditions and the impact of fire on growth as well as the impact of climate change requires a manipulation of the growth tables . CO2FIX cannot simulate the underlying processes (Schelhaas et al. 2004).

While the software is freely available, the use of CO2FIX is strongly restricted and closed source. The License Agreement does not allow any commercial exploitation and selling written reports associated with the software requires a special license.

FullCAM

The Full Carbon Accounting Model (FullCAM, Version 2016) is Australia's primary modelling system for land sector greenhouse gas reporting and accounting. It provides fully integrated estimates of carbon pools in forest and agricultural systems and accounts for human-induced changes in emissions and sequestrations. FullCAM operates on a plot (per ha) or pixel level, uses flexible timesteps (day, week, month, year) and can account for forest systems, agricultural systems and mixed systems (forest and agricultural systems) (Australian Government 2013) (see Table B4 for additional information).

FullCAM uses the empirical tree yield formula (TYF) as a growth model. The TYF derives the current annual increment in AGB under the assumption that (Waterworth et al. 2007, Roxburgh et al. 2019):

- the potential AGB varies spatially in accordance with the maximum AGB of relatively undisturbed native vegetation
- growth varies with the spatial-temporal input of an annual Forest Productivity Index (FPI_t) in relation to a mean long-term average annual forest productivity index (FPI_{ave})
- AGB growth can be captured more accurately by shaping and scaling the yield curve with a set of empirically-derived parameters

To generate carbon stocks in above- and below-ground biomass, a number of parameters are then applied to the predicted AGB. This parameter relate to:

- biomass partitioning
- litterfall
- root slough
- decomposition
- carbon fractions and
- management scenarios

FullCAM includes a comprehensive database for forest management practices which differ according to region, species, site productivity, and previous land use. Furthermore, plantation management regimes account for different thinning regimes, site preparation, fertiliser applications and additional parameters (Waterworth and Richards 2008, Roxburgh et al. 2019). Many of these regimes appear to be very specific to Australia.

An advantage of the TYF is that the FPI_t is generated from physiological principles of growth derived from the 3-PG model, accounting for parameters like soil fertility, sunlight, rainfall, vapour pressure deficit, temperature and frost (Kesteven and Landsberg 2004, Roxburgh et al. 2019, Richards 2001). This is of particular interest for modelling growth under changing environmental conditions and to simulate growth under different climate change scenarios. Another advantage of FullCAM compared to other reviewed models is that it is sensitive to fertilisation and irrigation measures.

A downside of using the FPI_t and the additional empirical parameters of the TYF is the need for calibration using a set of sample plots. Similar to GCBM, this impedes an ad hoc application of the model in regions where available data is insufficient for a parameterisation. FullCAM does not provide options for explicitly modelling multi-species and multi-age forests in a way that is as flexible as the cohort approach of CO2FIX.

At the time this document was written, FullCAM was freely available and could be reproduced, modified and adapted as well as used to develop derivative products. The uptodate FullCAM licence agreement needs to be studied carefully to understand current legal implications and obligations that come along with these rights.

CASMOFOR

The CArbon Sequestration MOdel for FOrestation (CASMOFOR) was developed to estimate the amount of carbon fixed in a forest stand in the years or decades after its establishment. The model was developed for Hungary and uses a structure, conditions and parameters that are ideal for Hungary. However, it could be used for countries with similar forestry systems (Somogyi 2002-2019, Somogyi 2019) (see Table B5 for additional information).

The model uses standard yield tables (currently the major species in Hungary) and assumes unmixed even-aged stands. The growth model of CASMOFOR estimates volume as total AGB volume. The total AGB is then partitioned into the tree components by using defined ratios. Expansion factors are not applied (Kim et al. 2015, Somogyi 2002-2019).

The silvicultural model is based on silvicultural model tables. These tables provide information at which age thinnings are to be conducted. Thinning intensities (ratios of thinning and stock volume) were then calculated from the yield tables (Somogyi 2002-2019).

CASMOFOR differentiates between density-dependent and density-independent mortality. Density-dependent mortality is implemented as a long-time average rate. It includes a function to account for time passed after the last thinning and site condition and provides options to include site specific mortality in relation to density (Kim et al. 2015).

Putting a focus on afforestation, the longevity of trees is considered of lower importance and only 120 simulation years can be produced (it is possible to initialize a stand at e.g. 80 years and then run the simulation to a stand age of 200) (Kim et al. 2015).

In comparison to GCBM, Kim et al. (2015) suggest that CASMOFOR applies a simpler growth model but handles density-dependent mortality more effectively. Kim et al. (2015) argue that CO2FIX is more flexible than CASMOFOR in estimating the growth of branches related to tree structure and growth rate.

EFISCEN

The European Forest Information SCENario Model (EFISCEN, Version 4) is a large-scale forest model that can be used to project the development of forest resources over 50 to 60 years on a regional to continental scale. EFISCEN uses forest inventory data as its principal input and is based on a matrix approach (European Forest Institute 2016, European Forest Institute 2019, Sallnäs 1990) (see Table B6 for additional information).

In EFISCEN forest type is defined by species, region, site class and owner and each forest type has a separate matrix. For each forest type basic inputs consist of the area (ha), the average growing stock volume per hectare (m3 ha-1) and the net annual increment per age class (m3 ha-1 yr-1) (Kim et al. 2015, European Forest Institute 2019).

Growth and mortality processes as well as impacts of thinning, final felling and choice of tree species are simulated by transferring the area between matrix cells. Growth dynamics are represented by shifting proportions of the forest area. The shifting between cells occurs in 5-year steps (one age class). Volume increment is informed by growth functions based on inventory data and is simulated by shifting a part of the area to higher volume classes. Natural mortality (defined by the user as percentage of growing stock) is implemented by moving a part of the area one volume class down. Natural mortality is restricted to areas that have not been the subject of recent thinning operations (European Forest Institute 2019). Senescence mortality is a function of forest type (associated with region, owner class, site class and tree species) and age. Thinning is implemented as moving the area one class downwards. Age range for the occurrences of thinning can be specified (Kim et al. 2015).

Biomass estimations for branches, coarse roots, fine roots and foliage are based on stem biomass and require biomass distribution tables by age classes (Schelhaas et al. 2007).

Kim et al. (2015) evaluate EFISCEN as a relatively simple and less precise growth model compared to GCBM, CO2FIX and CASMOFOR. However, they state that the approach might be adequate for large forest areas where the model can describe processes with high efficiency (Kim et al. 2015).

Alternative Process Growth Models

An overview of the comparison of process growth model with reference to the defined criteria is shown in Table 3.

3-PG and 3-PGmix

The Physiological Processes Predicting Growth (3-PG) model is a process model that produces forest stand variables that are familiar to forest managers (stems per ha, standing volume per ha, basal area per ha, average DBH, average tree height). It operates on monthly timesteps (Landsberg and Waring 1997, UBC 2019) (see Table B7 for additional information).

The model estimates the energy which is absorbed by the forest canopies. The absorbed energy is then converted into biomass which is allocated by dynamic equations to leaves, stems and roots. Effects of nutrition, soil drought, water balance, atmospheric vapor pressure deficits and stand age modify the efficiency of the radiation conversion (UBC 2019).

3-PG requires input data related to weather, soil and site characteristics. More than 100 variables are required to parameterize an individual tree species. A simulation is started with an initial stand age (years) and stocking (trees per ha). The model is self-constrained and uses a well-established mortality function (UBC 2019).

A 3-PG version for mixed species forests (3-PG_{mix}) was developed by Forrester and Tang (2016). This 3-PG derivative includes a light absorption sub-model and allows for within-canopy vertical gradients in climate (water balance sub-model). Furthermore, 3-PG was adapted to facilitate simulations of deciduous species and predict diameter distributions (Forrester 2019).

Table 3: Evaluation of the reviewed process growth models

Criteria		CEN TURY	DNDC Forest	PnET	Biome-BGC	3-PG	3-PG mix
	Empirical / Process / Hybrid	P	P	P	P	P	P
	Timber volume, Carbon	C	C	C	C	T	T
Availability	Use free of charge (Costs)	●	●	●	●	●	●
	Open source	□	?	●	□	●	●
	No IP issues	□	?	●	□	□	□
Reliability	Stable + tested	●	●	●	●	□	□
	Tested on independent data	●	●	●	●	●	●
	Used in >1 countries	●	●	●	●	●	●
	Used for official reporting	●	?	?	?	?	?
Resolution	Temporal resolution [1]	M	D	M	D	M	M
	Spatial resolution [2]	S-N	R	S-N	S-N	S-N	S-N
	Generic	●	□	●	●	●	●
Input data	Input data availability difficult?	□	□	□	□	□	□
	Calibration difficult?	●	●	●	●	●	●
	Perm. For. Inv. required	□	□	□	□	□	□
	Climate data needed	●	●	●	●	●	●
	Site data needed	□	●	●	●	●	●
	Soil data needed	●	●	●	●	●	●
	General forest data needed	□	●	●	□	●	●
	Specific forest data needed	●	●	●	●	●	●
	Starts with age	●	●	●	□	●	●
	Starts with volume / biomass	□	□	□	□	□	□
	Allows input on disturbances	●	●	●	●	●	●
Sensitivity	Climate	●	●	●	●	●	●
	Soil	●	●	●	●	●	●
	Harvest / Thinning	●	●	●	●	●	●
	Density / Competition	●	●	●	●	●	●
	Fire (growth impact)	●	●	●	●	●	●
	Fertilising	●	●	●	●	●	●
	Irrigation	●	●	●	●	●	●
	Mortality / Self-thinning	□	●	●	●	●	●
	Mortality by natural disturbances	●	●	●	●	●	●
	Multi-age forest possible	□	□	□	□	□	●
	Multi-species forest possible	□	□	□	□	□	●
	Selective logging possible	●	●	●	●	●	●
	Early-Age issue	□	?	?	?	●	●
Outputs	Stem number	□	□	□	□	●	●
	Standing Volume	●	□	□	●	●	●
	Height	□	□	□	□	●	●
	Basal Area	□	□	□	□	●	●
	DBH	□	□	□	□	●	●
	Partitioning	●	□	□	●	□	□
	· Stem wood	●	□	□	●	●	●
	· Bark	□	□	□	□	□	□
	· Branches	●	□	□	□	□	□
	· Foliage	●	□	□	●	●	●
	· Roots	●	□	□	●	●	●
	· Coarse / Fine roots	●	□	□	□	□	□
	Harvested stand	●	●	●	□	●	●
	Deceased stand	□	●	●	□	●	●
	Dead Organic Matter	●	●	●	●	□	□
	Litter production	●	●	●	●	●	●
	Carbon	●	●	●	●	□	□
	Additional outputs	●	●	●	●	●	●

● = yes; □ = no; □ = in between; opt. = optional; ? = to be confirmed

[1] A=Annual, M=Month, D=Day, F=Flex.; [2] S= Stand level R=Regional / Landscape Level, N=National Level, C=Continental

Coops et al. (1998) developed the spatial version 3-PG with Satellite (3-PGS) which uses Arc/INFO float files and facilitates spatial predictions (UBC 2019).

An advantage of 3-PG is the large amount of output variables that can be produced with the model. The inclusion of physiological processes makes the model sensitive to changes related to growth conditions and climate. 3-PG differs from other process models reviewed in this project by the fact that it produces standard forest stand parameters and that it allows for growth predictions for mixed species stands (in the 3-PG_{mix} version).

3-PG is freely available as an Excel version. This current method of distribution can make version control difficult. Another downside is the large amount of variables necessary for the parameterization of individual species. Problematic is the reliance of 3-PG on soil-characteristics (fertility rating parameter) while the relationships between soil chemical properties and plant growth are not well understood (Landsberg et al. 2003). It is likely that ongoing work on providing species-specific parameters and adjustments to local parameters will further improve the application of the model in future (Bernier et al. 2003).

CENTURY

CENTURY (Version 4.0) is a general model of plant-soil nutrient cycling which computes the flow of carbon, nitrogen, phosphorus and sulfur through the various components. It can be used to simulate carbon dynamics for grasslands, agricultural lands, forest and savannas (NREL 2019, Parton et al. 1983). There exists a Daily Century Model (DayCent, Version 4.5) which uses a similar approach to calculate growth in daily timesteps (Del Grosso et al. 2001). ForCent is a derivative of DayCent with focus on forest growth (Parton et al. 2010) (see Table B8 for additional information).

CENTURY includes submodels related to soil, water, grassland/crop, forest, management and events. It is assumed that moisture, temperature and live leaf-area-index influence the maximum monthly plant production rates. These rates decrease if the nutrient supply is insufficient. The net potential production rate cannot exceed the maximum net production rate of a specific tree. The forest production model differentiates between evergreen and deciduous forests and between juvenile and mature growth phases. Nutrient competition and shading effects can be simulated for savanna and shrubland by combining the grassland/crop submodel with the forest production submodel and additional code. Disturbances like fire and harvest can be simulated with the events scheduling function (Metherell et al. 1993, NREL 2019).

Important parameters for forest growth are the maximum gross and net production rates, the relationship between wood biomass and leaf-area-index, as well as the ratio between leaf-area-index and wood biomass. The model uses a fixed allocation scheme to distribute carbon and nutrients among leaves, fine roots, fine branches, large wood, and coarse roots. Only the sapwood part of a tree is assumed to respire carbon. (Metherell et al. 1993).

CENTURY is able to generate a large range of outputs relevant for carbon accounting. Of particular interest is its ability to simulate interactions of plants in tree-grassland communities. It produces outputs as carbon measurements which do not allow direct conclusion about standing timber volumes or other traditional forest stand data. Only monospecific forest stands can be calculated with CENTURY. CENTURY 4.0 is protected by copyright law and international treaties. The unauthorized reproduction or distribution of the program or any part of it is not permitted.

PnET and DNDC forest

PnET (Photosynthesis and EvapoTranspiration) is a forest physiological model simulating photosynthesis, respiration, C allocation and litter production (Aber et al. 1992, Aber et al. 1996). The model runs on monthly timesteps and focuses on temperate forests. PnET-Daily is also available. A more generic version applicable to all terrestrial ecosystems is currently under development (ESRC 2013) (see Table B9 for additional information).

PnET consists of the three submodels PnET-Day, PnET-II and PnET-CN. PnET-Day is a canopy flux model. PnET-II is responsible for nutrient allocation, water balance, soil respiration and is driven by nitrogen availability. PnET-CN tracks nitrogen and carbon through all compartments and fluxes (ESRC 2013).

PnET is freely available and released on an open source basis. It is available as MATLAB and Visual Basic source code (ESRC 2013).

A derivative of PnET is the Denitrification-Decomposition forest (DNDC forest, Version 9.5) model (Li et al. 1992a, Li et al. 1992b, Stange et al. 2000). DNDC forest evolved from a combination between PnET and DNDC. DNDC forest follows a matrix approach with input requirements kept at a minimum to operate the module from readily available spatial data. The model runs on daily timesteps and the focus is placed on upland and wetland forest ecosystems (GRAMP 2013) (see Table B10 for additional information). Another derivative is PnET-N-DNDC (Li et al. 2000, Stange et al. 2000) which was further developed to Wetland-DNDC (Zhang et al. 2002).

Biome-BGC

Biome-BGC (Version 4.2) is an ecosystem process model for estimating storage and fluxes of energy, water, carbon and nitrogen in daily timesteps. It focuses on the terrestrial ecosystems with their vegetation and soil compartments (Thornton et al. 2002, NTSG 2020) (see Table B11 for additional information).

A key assumption of the model is that vegetation processes are controlled predominantly by weather conditions. The process of growth is dependent on weather dynamics (climate). The algorithms of the model simulate physical and biological processes that control fluxes of energy and mass (NTSG 2020).

Biome-BGC differentiates between woody and non-woody as well as between evergreen and deciduous plants. The growth process on a site with an existing stand can be started with an indication of the initial carbon (kgC/m2) in the coarse woody debris and by indicating the maximum leaf and stem carbon (kgC/m2) in the first year (together with other required input parameter referring to litter, soil, meteorology and climate) (Thornton and Running 2002).

The Biome-BGC code assumes that all years have 365 days. As a consequence, the 29th of February has to be deleted from concerned input data files.

The model provides options to offset max and min temperatures to account for climate change. Biome-BGC can be parameterized for specific species or plant communities by defining the ecophysiological characteristics of the vegetation type. Default parameterization settings for a smaller number of highly aggregated vegetation classes is provided with the model. These values are based on scientific research and can be used as a first approximation. Users should replace these entries with case and site specific parameters if available. However, replacing parameters with more specific local data can be difficult as covariances between variables have to be considered (Thornton and Running 2002).

While the code of Biome-BGC (Version 4.1.2) is freely available online, the code is protected by copyrights. It is not allowed to make copies of any part of the code for distribution. The purpose of this restriction is to keep track of the distributed versions and to inform the user community about updates or notices.

The use of Biome-BGC in research requires a specific acknowledgement with a predefined text provided by the authors. Any significant modifications to the code in a research project should be mentioned in scientific manuscripts (Thornton and Running 2002).

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Emission Factors

Emission factors (EF) are coefficients which quantify the estimated emission or removal per unit activity. For example, where a forest is converted to a cropland, an Emission Factor would be used to quantify the amount of emissions created per unit of forest converted to cropland..

In GHG inventories, EFs are used to account for the change of carbon stock in the carbon pools above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter. Biomass growth (below-ground and above-ground) is counted as gains. Harvests of wood or fuelwood and losses from other disturbances like fire, insects or disease are counted as losses. These losses also result in a reduction of the below-ground biomass which is transformed into dead organic matter (Eggleston et al. 2006).
The Biomass Gain-Loss method is a Tier 1 approach which can be used when country-specific estimates of activity data are not available. It estimates the annual change in biomass carbon stocks based on EFs as follows (Eggleston et al. 2006):

- Estimate annual increase in biomass carbon stock by multiplying the area under each forest subcategory by mean annual increment (t dry matter ha^{-1} yr^{-1}).
- Estimate below-ground biomass as
    - a ratio of the above-ground biomass or by
    - using conversion and expansion factors (BCEFI)
- Estimate the annual biomass loss or decrease in biomass carbon stocks
- Estimate the transfer of biomass to dead organic matter (mortality, slash, below-ground biomass reductions)
- Convert the estimated biomass to carbon values (carbon fraction of dry matter)

The Biomass Gain-Loss method can also be used for a Tier 2 approach. In this case, some of the general information is replaced with country-specific data. For example, species-specific wood densities and forest inventory data can be used (Eggleston et al. 2006).

The Intergovernmental Panel on Climate Change (IPCC) provides the IPCC Inventory Software (Version 2.69). The current version implements Tier 2 methods (Eggleston et al. 2006) for the agriculture categories within the Agriculture, Forestry and Other Land Use (AFOLU) sector. At the time this report was written, no Tier 2 methods were available for the forestry category (IPCC 2020).

The IPCC software is available free-of-charge for non-commercial purposes. The use of the software has to be acknowledged in publications with a standard clause (TFI 2019).

The EF Gain-Loss method is an appropriate approach where country specific data is not available or limited. This might also be the case for areas with diverse forest types and / or relative low biomass change rates (Eggleston et al. 2006).

Selection of Suitable Growth Models

Most of the reviewed growth models would be suitable for implementation as FLINT modules. We suggest that CO2FIX, FullCAM, 3-PGmix and a derivative of CENTURY are of particular interest.

CO2FIX is a highly flexible growth model. A major advantage is the possibility to choose between stand age or a function of the total and maximum aboveground biomass when initializing a growth process. This allows an application of the model in regions where an estimation of stand age is difficult (e.g. tropical regions). Another advantage of CO2FIX is the cohort approach. This allows for a sophisticated representation of growth processes and disturbance events in stands with multiple species or age classes. CO2FIX (Version 3.2) is currently restricted to stand level simulations. Developing a version of the model that can be used as a FLINT module could turn this shortcoming into an advantage. The FLINT would allow a compilation on project, regional, landscape or national level. With a combination of CO2FIX and FLINT it would be possible to simulate changes in forest compositions (e.g. transitions from monocultures to mixed forests, forest degradation) through space and time.

As CO2Fix is not open source, the development of a CO2FIX FLINT module would require the consent of the authors and developers of CO2FIX.

FullCAM's TYF growth model stands out due to its ability to integrate climate and environmental growth conditions into an empirical growth model. Following the current license agreement it seems to be possible to develop derivatives of FullCAM without further restrictions (see FullCAM's license agreement for detail). We recommend identifying the specific areas of application (e.g. only Australia or worldwide) of a potential TYF based FLINT module prior to the development.

3-PGmix stands out as a process model able to generate outputs of interest for carbon accounting and biomass/timber supply simultaneously. This is relevant in the context of an evolving knowledge-based bioeconomy sector. Due to its sensitivity to environmental growth conditions it could be especially suitable for generating future biomass supply and carbon emission scenarios in the context of climate change. Another feature of 3-PGmix is its ability to simulate growth and disturbances for forest stands with multiple species or age classes. We suggest testing 3-PGmix with regards to potential problems in predicting the growth of younger forest stands. Problems related to version control, the impact of the soil factors and species parameterization should be assessed and addressed.

CENTURY is an interesting growth model for various reasons. However, we recommend to review the CENTURY derivatives DayCent and ForCent before a final decision is made. Of particular interest is the generic nature of CENTURY and that it addresses early-age growth problems explicitly. As a process model it is sensible to environmental growth conditions and can simulate a wide range of disturbances. In comparison to the other process models we reviewed, the partitioning of carbon into the different compartments of trees is comparably detailed. Existing legal restrictions have to be considered and addressed before a CENTURY FLINT growth module could be designed.

CASMOFOR could be of interest for estimating afforestation impacts. The practicality of the approach outside Hungary should be evaluated beforehand. EFISCEN was designed as an efficient model for projections from forest inventories over large areas. It projects forest growth in five-year intervals. An integration into a FLINT module should not be a priority at this stage as we cannot see any particular advantages for either FLINT or EFISCEN in combining the two. The current version of PnET focuses on temperate forests and it does not provide options to output results partitioned by tree compartments. The ongoing development of the model into a generic version should be followed up. Derivatives of PnET and DNDC are of particular interest for simulating growth processes in specialised forest ecosystems (e.g. wetlands). Biome-BGC might be of interest for producing dynamic growth condition maps on a daily basis. These could be used for generating detailed hybrid process-empirical models.

Integrating an empirical growth model in the FLINT

As discussed above, the FLINT modelling framework integrates different data types (spatial and aspatial) and modules to calculate GHG emissions and removals for the AFOLU sector. Modules, data, and output processes can be attached to the FLINT framework in a unique configuration known as an “implementation” (e.g., SLEEK-FLINT, GCBM and FLINTpro). Although the science behind all of these implementations builds on 20 years of experience with integration frameworks developed and operated in the land sector, this section explores two aspects that have not been explored in the existing configurations: (a) growth dynamics as a function of maximum stand biomass, and (b) species competition using a cohort-based approach.

Of the 12 models reviewed in this document, the CO2FIX is the only one that allows users to simulate biomass carbon increments as dependent on stand age, as well as on a function of the total and maximum aboveground biomass of a forest stand. Thus, in the following we present a potential implementation design of the later approach of the CO2FIX into FLINT.

For implementation within the FLINT framework, there are three broad categories that must be resolved. Model initialisation (allocating initial biomass), representing processes (growth, turnover, and mortality), and representing events (natural and anthropogenic). Each of these components of a CO2FIX Implementation would be coded as an individual module. An overview of the potential implementation design of is shown in Figure C1.

Growth Model Initialisation

The CO2FIX model tracks carbon stocks and fluxes within the forest biomass component at the hectare scale, in annual time steps. The CO2FIX considers four carbon pools in the biomass compartment: stemwood, branches, foliage and roots (Schelhaas et al. 2004). The user is required to provide information on any biomass carbon initially present on the site at the start of the simulation. This data can be derived from local inventory data, from published literature for similar forests, etc., expressed as tons of carbon per ha. Additional details of CO2FIX are discussed in more detail in the chapter ‘Comparison of Growth Models’ and in Table B3.

Because CO2FIX can simulate biomass dynamics for multiple plant species and age-classes, the user is required to provide an initial carbon value in biomass by “cohorts”. A cohort is a way in which CO2FIX represents a group of individual trees or species types with similar growth characteristics as one single entity (Masera et al. 2003). Examples of cohorts include: (a) successional species in natural forests (e.g., pioneers, intermediate, and climax), dominant species in a mixed forest (e.g., coniferous and broadleaf species), species within each strata in a multi-strata agroforestry system (e.g. understory, middle layer, upper layer).

In FLINT, initial biomass carbon is estimated using spatial and aspatial information provided by the user. For example, information on land-use/land cover, forest type, climatic zones, administrative or project boundaries, ownership, etc. are provided as spatial layers that help define the spatial extent and main characteristics that affect the forest biomass component in a simulation scenario. While aspatial information such as stem volume, wood density, carbon fraction, initial carbon content (when simulations do not start at age zero), and maximum biomass in the stand, can be included within a database that relates to specific forest types or cohorts. For this to be implemented, the combination of spatial inputs would result in a unique identifying number, which relates to a database entry with the relevant forest biomass data.

As an alternative of using the database derived values, would be to use a biomass map to determine the initial conditions. In this sense, the FLINT would look up the relevant initial biomass value for a pixel at the project initiation. There may be challenges in this approach as the method used to derive the initial biomass maps differs from that used to determine the maximum stand value. If the methods are not comparable, it may be that the initial biomass map includes forest areas with an initial biomass higher than the maximum possible biomass. In this circumstance, specific rules would be needed within the system on how these pixels are modelled.

A challenge which is relatively unique to the CO2FIX modelling construct is that the initial biomass made be spread across one or more cohorts of tree species for one pixel. In this circumstance, with either the database, or spatial approach, it would be necessary for the system to allow users to define the proportion of initial biomass associated with each cohort. This would require a database referencing a forest type (or some other spatial identifier) with the initial biomass proportions by cohort.

Representing Processes

Processes continuously occur on every time-step of a simulation once a variable status is met. This includes processes that increase carbon stock in biomass, such as plant growth, as well as processes that decrease carbon stock in biomass, such as decomposition and turnover. When the variable of tree status is set to ‘True’, for example, the tree growth will occur. This is a ‘process’. For the CO2FIX implementation, three processes need to be represented, growth, turnover, and mortality.

Growth component

When the status of the pixel has trees present, the variable for ‘tree’ will be set to true, initiating forest growth. Typically, forest stand growth is modeled as a function of a cohort age (actual or effective age). This is the basis of the existing forest modules that have been incorporated with the FLINT. However, information on true “age” is rarely available or known for many trees in tropical forests. While it is possible to represent these forests using a function of age, simply by calculating the age based on the aboveground biomass, as an alternative approach, the relationship can be reorganised so that forest growth increments can be modeled, for example, using diameter increment functions (Vanclay, 1989). The CO2FIX follows this approach, but uses information of standing biomass. For example, figure 2 depicts annual biomass increments over time for three different cohorts, as a function of the ratio between standing biomass relative to a maximum attainable biomass.

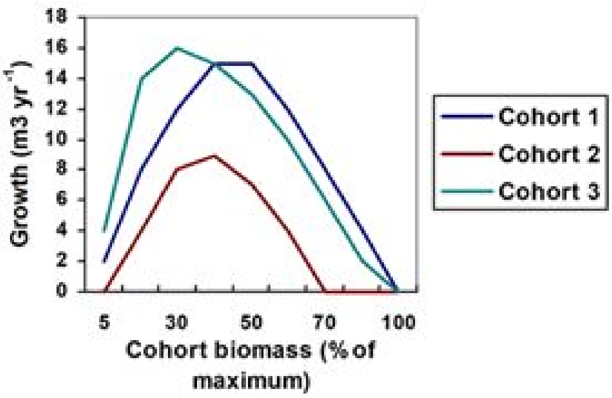

Figure 2: Hypothetical example of the current annual increment (CAI) of three cohorts relative to cohort biomass in a forest stand (from Schelhaas et al. 2004).

To simulate biomass growth, the CO2FIX requires information on the production of stem wood volume per ha, which is then multiplied by wood density and carbon fraction values to estimate carbon flux in the stemwood compartment. In the case of the other biomass components (i.e., foliage, branches, and roots), the model simulates their growth relative to the stemwood production (relative fractions), which are then multiplied by a carbon content value to estimate carbon flux. These relative fractions are additional to the growth rate of stem biomass and can change as a function of the actual biomass over maximum biomass (Figure 3).

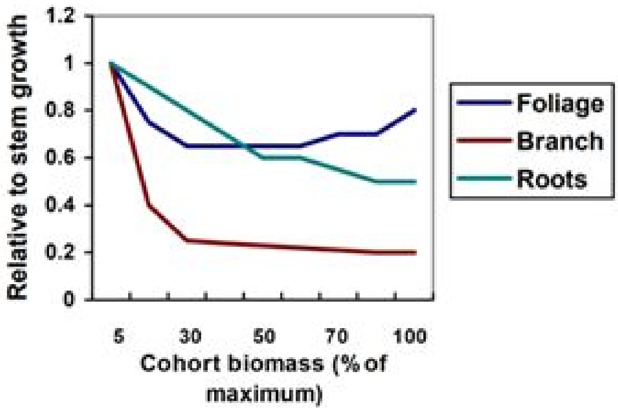

Figure 3: Hypothetical example of the biomass allocation of foliage, branches and roots, relative to stem growth, as a function of cohort biomass in a forest stand (from Schelhaas et al. 2004).

Total biomass growth Bt = Bs + Bf + Bb+ Br

Where

Bt = Growth of total tree biomass

Bs = Growth of stem biomass

Bf = Growth of foliage biomass

Bb = Growth of branch biomass, and

Br = Growth of root biomass

Relative fraction Bi = Fi*Bs

Where:

Bi = growth of biomass (Bf for foliage, Bb for branches, Br for roots)

Fi = relative biomass allocation coefficient (Ff for foliage, Fb for branches, Fr for roots)

Bs = growth of stem biomass

As the FLINT Implementation may have additional modules attached running at a different time-step, the system would scale down the CO2FIX output to the minimum time-step reported. For example, if a monthly crop module was also attached, the output from the CO2FIX growth module would scale down to a 1 month time-step in a linear relationship for the annual value.

Turnover

Turnover refers to the annual rate of mortality and replacement of the biomass in foliage, branches, or roots. For example, a 0.1 turnover rate in foliage would indicate that 10% of the total biomass of this component is converted to litter in the relevant time-period. Depending on the type of cohort (i.e. coniferous or broadleaves species) the model characterizes the quality of the litter turnover to soil (Schelhaas et al., 2004). In the case of roots, CO2FIX does not distinguish between coarse and fine roots. However, the user can modify the rate to represent a higher proportion of coarse versus fine roots. For example, it is expected that in short rotation management systems, there will be a higher proportion of fine roots and thus, the turnover rate will be relatively high (Schelhaas et al. 2004).

In FLINT, the turnover would be incorporated in the same method as applied within CO2FIX, and is applied under the SLEEK FLINT implementation. This would involve the calculation of the proportion of biomass from each tree component to turnover in a time-step and for this component to move from the living pool to the dead organic pool, and associated module.

Natural mortality

CO2FIX represents natural tree mortality within each cohort as a result of senescence and due to density related interactions between cohorts. As described earlier in this document, the user can define how these interactions will affect biomass growth by using a dimensionless growth modifier (Masera et al. 2003). If the growth modifier equals to 1, there is no effect, more than 1 reflects synergistic effects (e.g., mixture of cohorts with complementary functional traits, Pretzsch et al. 2019), less than 1 reflects competition, where 0 implies no biomass growth (Figure 4). Competition is considered the major type of trees interactions, which can be simulated relative to the total biomass in the stand or to each cohort (Schelhaas et al. 2004).

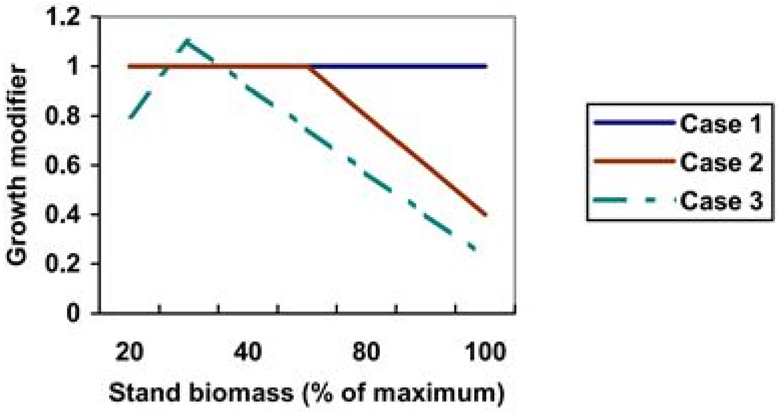

Figure 4: Examples of growth modifiers of total stand biomass (Mg ha^{-1}) representing synergistic interactions, competition and no interaction effect on growth (value = 1) (from Schelhaas et al. 2004).

In any case, natural mortality is incorporated as a fraction of the standing biomass to reflect the impact of changes in tree size (Figure 5). For example, the user can increase the mortality rate to represent dense stages, highly competing cohorts, or standing tree biomass approaching its maximum attainable biomass (Schelhaas et al. 2004).

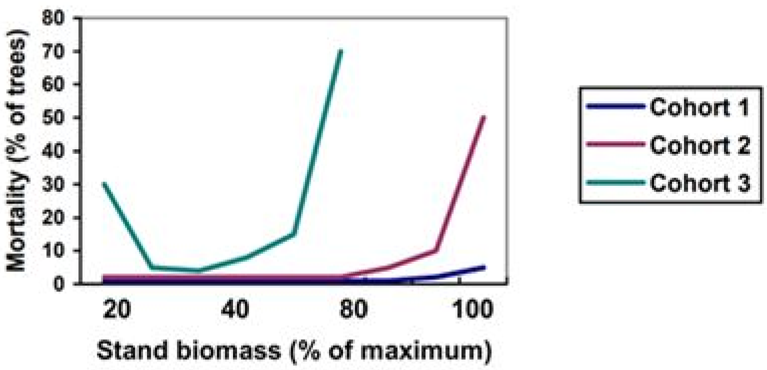

Figure 5: Hypothetical example of natural mortality as a function of the ratio of actual biomass over maximum biomass (from Schelhaas et al. 2004).

In FLINT, mortality would be implemented in a similar format as turnover, with a proportion of biomass converted from living biomass to dead biomass during each timestep. This would be applied to each cohort, with the parameters provided in a relational database that corresponds with a spatial variable (i.e. forest type, see Figure 6). Information on natural mortality can be derived from local measurements of permanent forest inventory plots or from available literature (Camac et al. 2018, Arellano 2019).

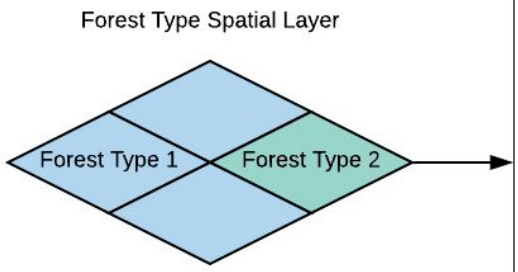

Table within DB

Forest Type	% of Max Biomass	Mortality Rate (%)
Forest Type 1	10	0
	20	5
	50	10
	70	15
	100	20
Forest Type 2	40	5
	80	15

Figure 6: Suggested implementation of mortality within a potential CO2FIX FLINT Module**.** Where there are gaps in the data, for example, % of max biomass is 10% and 20%, the module would interpolate between these values.

Representing Events

At any time-step, CO2FIX biomass module calculates total carbon stored in living trees as a result from the sum of the original biomass, plus biomass growth, minus the turnover of branches, foliage and roots, minus tree mortality due to senescence. In addition, the same module accounts for the effect of events.

An event is an operation that occurs intermittently (rather than for every time step in a simulation) resulting in the movement of carbon from one pool to another. Events include natural and anthropogenic events including fire, harvesting, ploughing, and fertiliser application. For implementation, events are coded for the FLINT as a module, and can be triggered by spatial data, or through event timing.

As with SLEEK-FLINT, a Spatial Trigger is one that is triggered using a spatial product. This is ideal where the event can be identified accurately through remote sensing. For implementing the CO2FIX model, Spatial Triggers may be extended to include the transition of forest composition, as detected by forest type mapping. In this circumstance, where the remote sensing detects changes in the forest composition, for example, a mixed species stand becomes a single species, then a transition event may be applied. Such a design would be novel in comparison with the existing FLINT Implementations, which model forest cover loss (clearfell/clearing) and re-establishment rather than transitions without forest cover loss. Where a transition is detected, a specific management regime can be applied with one or more events. Where there are multiple management regimes associated with a Spatial Trigger, relative frequency can be used to identify one to be applied at the pixel level. This approach can result in neighbouring pixels having different management regimes applied.

Alternatively, a Timing Trigger could be used if the spatial data is not sufficient to detect events. This would include a specific regime for a given spatial variable (i.e. Forest type), where events are triggered based on some measure, such as percent of maximum stand biomass. As FLINT is a spatial modelling system, there must always be some spatial variable that relates to a record in a database. This may be relatively simple, such as only one forest type, or more complex combinations of spatial data, such as forest type and ownership. This record would relate to a management regime within the database, which is then used to build the event queue. Where multiple management regimes may apply for a given spatial variable, relative frequency can be used to assign one.

As CO2FIX models growth of cohorts, events would also need to be designed to interact with a cohort, as opposed to all biomass. This introduces additional complexity, and will impact on the compute requirements for simulations as more cohorts are modelled.

Conclusions

From the selection of reviewed forest growth and disturbance models we consider the following models as most promising candidates for a new generic FLINT forest module: CO2FIX, FullCAM, 3-PGmix and CENTURY (or derivatives of this model). Each of these models have particular advantages and shortcomings and would add new opportunities for projecting forest growth and disturbance within the FLINT framework.

We have described a potential implementation of CO2FIX as FLINT forest module in more detail. CO2FIX offers the possibility to initialize growth estimations from a function of the total and maximum aboveground biomass of a forest stand. Using a cohort approach, the model also facilitates simulations of forests with diverse species and age structures as well as forest-to-forest transitions (e.g. forest degradation). These are important features in the context of e.g. tropical forests which have not been implemented in the FLINT framework yet.

With this report we present a set of review criteria. We hope that our evaluation of existing growth models along these criteria will assist scientists and developers in finding adequate models for their projects. In general, process based models required more data and parameters than empirical models. This sits alongside the general ability of process based models to represent more complexity within systems. This is a tradeoff that needs to be considered by the potential users. For example is there benefit in modelling species growth separately, or can an adequate result be found using a model that aggregates species into a single forest growth function.

In the scope of the project, we were able to review only a selection of forest growth models out of a large pool of existing models. The list of models reviewed with the provided criteria should be extended by including additional models and updated as new versions of the models will be released. It is our intention to update this document over time. This is an open source document. Everybody is welcome to contribute.

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Appendix A

Table A1: Criteria for model evaluation

Category	Criterium	Description
Method / Focus	Empirical / Hybrid	Can the model be considered to be empirical or a hybrid that includes process and empirical components?
	Timber Volume / Carbon	Is the primary purpose of the model to estimate timber volumes or to estimate stored carbon?
Avail-ability	Costs	Can the model be used free of charge? If not: What are the costs of buying (a subscription to) the related software?
	Open source	Is the code of the related software available and is it permissible to make use of and change the code?
	IP issues	Are there any intellectual property issues that would restrict the use or distribution of the model, the related code, or software?
Reliability	Stable + Tested	Is a stable and tested version of the related software available? (considered as ‘yes’ when the provider offered a version control and a clear indication towards the most recent version available.)
	Tested on independent data	Has the model been tested on data independent from the training data?
	Used in >1 countries	Has the model been used in a country that is different from the one where it was originally developed?
	Used for official reporting	Has the model been used to derive data for a UNFCCC national greenhouse gas inventory or to report to VCS?
Resolution	Temporal resolution	What is the temporal resolution of the model? Is it run on annual, monthly, daily or flexible time steps?
	Spatial resolution	What is the spatial resolution of the model? Does it work on a project, regional or national level?
	Generic	Can the model be applied in the majority of countries worldwide? This criterium is still met when country specific parameters have to be used as input.
Input data	Input data availability difficulty	Can it be assumed that the majority of countries will find it difficult to derive the required input data for the model?
	Calibration difficulty	Can it be assumed that the majority of countries will find it difficult to calibrate the model?
	Permanent forest inventory required	Is a permanent (remeasured) forest inventory needed to calibrate the model?
	Climate data needed	Does the model require climate related data such as temperature, day length, solar radiation, precipitation, vapour pressure or frost days?
	Site data needed	Does the model require site-related data such as ecological region, surface efflux, N deposition?
	Soil data needed	Does the model require soil-related data such as soil layer types, depth, fertility, texture, pH?

Table A2: Criteria for model evaluation (continued)

Category	Criterium	Description

Input data (continued)	General forest data needed?	Does the model require general tree or stand-related data such as forest type or species?
	Specific forest data needed?	Does the model require more specific tree- or stand-related data such as stems per ha, basal area, leaf area, wood density, leaf C:N ratio?
	Starts with age	Does the model use tree age or stand age as an essential input parameter?
	Starts with volume or biomass	Does the model use standing volume or biomass as an essential input parameter?
	Allows input on disturbances	Does the model allow settings for potential disturbances (e.g. fire, disease, storm, management)?
Sensitivity	Climate	Is the growth influenced by climate-related variables?
	Soil	Is the growth influenced by soil-related variables?
	Harvest / Thinning	Are the impacts of thinning and harvests on growth reflected in the model?
	Density / Competition	Are the impacts of stand density (e.g. trees per ha) reflected in the growth model?
	Fire (growth impact)	Does the model reflect the impact of fires on growth?
	Fertilising	Are impacts of potential fertilising measures reflected in the model?
	Irrigation	Are impacts of potential irrigation measures reflected in the model?
	Mortality / Self-thinning	Does the model consider mortality due to senescence or competition?
	Mortality by natural disturbance	Does the model consider mortality due to disturbances (e.g. storms, disease, or fire)?
	Multi-age forest possible	Can the growth of multi-aged or structured forests (cohorts) be estimated with the model?
	Multi-species forest possible	Can the growth of stands with more than one tree species be estimated with the model?
	Selective logging possible	Is it possible to estimate the effects of selective logging with the model?
	Early age issue	Does the model misrepresent the growth of young trees (DBH < 7-10 cm)?

Table A3: Criteria for model evaluation (continued)

Category	Criterium	Description
Outputs	Stem number	Does the model return stem number per area (e.g. ha)?
	Standing Volume	Does the model return standing volume per area (e.g. ha)?
	Height	Does the model return tree heights or an average stand height?
	Basal Area	Does the model return basal area per area (e.g. ha)?
	DBH	Does the model return diameter at breast height (DBH) for individual trees or an average stand DBH?
	Partitioning	Does the model incorporate some sort of procedure to partition its major output (carbon or timber volume) into tree components (see below)? This is a summary criterion which is fulfilled in the case that any of the sub-criteria below is answered with 'yes'.
	● Stem wood	Does the model return carbon or timber volumes for stem wood explicitly?
	● Bark	Does the model return carbon or biomass volumes for bark explicitly?
	● Branches	Does the model return carbon or biomass volumes for branches explicitly?
	● Foliage	Does the model return carbon or biomass volumes for branches explicitly?
	● Roots	Does the model return carbon or biomass volumes for roots explicitly?
	Coarse / Fine Roots	Does the model differentiate between coarse and fine roots (usually < 2 mm in diameter) when returning compartment explicit carbon or biomass volumes?
	Harvested stand	Does the model return an estimation of the thinned / harvested stand?
	Deceased stand	Does the model return an estimation of the part of the stand that died for reasons other than harvest or thinning?
	Dead Organic Matter	Does the model return dead organic matter production per area (e.g. ha)?
	Litter production	Does the model return litter production per area?
	Carbon	Does the model return an explicit value for produced and (stored) carbon? This is of particular interest for models that focus primarily on timber volume growth.
	Additional outputs	Does the model return any additional outputs like stored nitrogen?

Appendix B

Table B1: SLEEK-FLINT key information

Model:	**SLEEK-FLINT**
Aim:	National Carbon Accounting System for Kenya
Focus:	System for Land Emission Estimation in Kenya
Modules:	● Forest Module ○ Natural Forests ○ Plantation Forests ○ Forest Debris ○ Harvest Wood Products (not yet completed) ● Crop Module ● Soils (Tier 1) Module ● Build Land Unit Module (BLUM)
Principals:	General ● Use of spatial and aspatial data ● Build Land Unit Module (BLUM) defines the rules of developing the sequence of processes (e.g. growth) and events (e.g. thinning) ● Hierarchy approach to overcome data limitations: ○ Activity Suits ○ Activities ○ Regimes ○ Events ● Application of regimes in relative frequency to overcome uncertainties. For example, to a forest pixel apply ○ 80% of the time: Sawlog regime and ○ 20% of the time: Pulp Log regime Natural forest growth: ● Chapman-Richards growth curve used to define above ground biomass (AGB) for natural forest ● Partitioning of AGB to above ground biomass compartments ● Suspension of AGB to roots (partitioned into fine and coarse roots) ● Disturbance probability curve used to define the initial age for a natural forest pixel Plantation growth: ● Species specific parameterized growth curves ● Partitioning of AGB to above ground biomass compartments ● Initial age according to information in a database Events: ● Events are triggered by Transition Triggers and Timing Triggers

Table B1(continued): SLEEK-FLINT key information

Input:	Natural Forest Growth: ● Species ID ● Name (of the forest system) ● Maximum peak carbon yield (t C ha^{-1}) ● Age of the forest (years) (pseudo-randomly defined) ● k (dimensionless parameter used in modeling tree growth) ● m (dimensionless parameter used in modeling tree growth) ● Root to shoot ratio ● Stemwood fraction ● Bark fraction ● Branch fraction ● Foliage fraction ● Coarse root fraction ● Fine root fraction ● Turnover rates per forest type Plantation Growth / Thinning: ● Growth equations ● Site index ● Forest Age ● Age Index (I) ● Species specific coefficients for growth ● Parameters for biomass partitioning ● Turnover rates per plantation type ● Plantation regimes
Output:	
Web:	
Sources:	SLEEK-FLINT Operators Guide (unpublished), Version 1.0, December (2019).

Table B2: GCBM key information

Model:	**GCBM / CBM-CFS3** (Version 1.2)
Aim:	Simulate the dynamics of all forest carbon stocks required under the United Nations Framework Convention on Climate Change
Focus:	General stand- and landscape-level modelling framework
Modules/ Structure:	Structure: ● Preprocessing ● Composing assumptions and simulations ● Processing ● Post Processing
Principals:	● The atmospheric C is transformed into net growth using the living parts of the forest stand (biomass pool) ● C can transition to a dead organic matter (DOM) pool in the soil forest floor or woody debris ● Uses volume-age curves as empirical growth and yield curves ● Volumes are converted to partitioned biomass following specific equations ● Mixed species forests can be presented with ratios per species ● Biomass-turnover is used to calculate ongoing and partial mortality of which an annual share is transferred to DOM pools ● The longevity of a species is defined by the highest age entry in the growth curve.
Input: **(Not comprehensive. See Kull et al. (2019) for more detail.)**	● Stand or a group of stands with similar attributes ○ Stand identifier ○ Administrative unit, ○ Ecological region, ○ Land Ownership ○ UNFCCC Land Class ○ Delay ● Stand attributes ○ Site Quality (‘Excellent’, ‘Very good’, ‘Good’, ‘Poor’) ○ Area ○ Age ○ Species ○ Forest type ○ Volume ○ HistDist (Historical Disturbance ID) ○ LastDist (Last disturbance ID) ● Volume–age curves (growth-and-yield curves) ○ Classifier value (ID) ○ Species type ○ Merchantable volume ● Disturbance events ○ Source classifier value ID(s) ○ UsingID entry ○ Softwood starting age class ID ○ Softwood ending age class ID ○ Hardwood starting age class ID ○ Hardwood ending age class ID ○ Disturbance ID ○ Post Disturbance classifier value ID(s) ○ Regeneration delay ○ Reset age ○ Percentage

Table B2 (continued): GCBM key information

<table>
<tr><td>Output:

(Not comprehensive. See Kull et al. (2019) for more detail.)</td><td>

Stocks (t C) e.g.

Carbon in the aboveground and belowground biomass pools
Carbon in all aboveground biomass pools
Carbon in all belowground biomass pools (coarse plus fine roots)
Carbon in the merchantable portion of softwood stem wood and stem bark (excluding tops and stumps)
Carbon in the merchantable portion of hardwood stem wood and stem bark (excluding tops and stumps)
Carbon in hardwood foliage
Carbon in hardwood fine roots
Carbon in hardwood coarse roots
Carbon in belowground fast, medium, softwood, and hardwood stem snag, and softwood and hardwood branch snag DOM pools
Stable carbon from incomplete combustion after fire

Stock Changes (t yr^{-1})
Ecosystem Indicators (t yr^{-1}) e.g.

Net biomass increment before losses from disturbances
Sum of litterfall and litter decomposition inputs to DOM pools

Ecosystem Transfers (t yr^{-1})

Total transfer of carbon from the ecosystem pools to the forest product sector
Transfer of carbon from the deadwood stocks pools to the atmosphere
Transfer of carbon from the Softwood Foliage and Hardwood Foliage pools to DOM pools

Emissions (t yr^{-1}) e.g.

Total emissions from all biomass components resulting from fire disturbance
Methane emissions from all biomass pools resulting from fire disturbance

Disturbed Area (ha $yr\text{-}^{1}$)
Age Classes and Age Classes by Timestepe.g.

Area of the forest in a particular age class
Total biomass carbon by age-class for each time step

</td></tr>
<tr><td>Web:</td><td>http://www.nrcan.gc.ca/forests/climate-change/carbon-accounting/13107</td></tr>
<tr><td>Sources:</td><td>Boudewyn, Paul; Song, X.; Magnussen, S.; Gillis, M. D. (2007): Model-based, volume-to-biomass conversion for forested and vegetated land in Canada. In Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Inf. Rep. BC-X-411.

Kim, Hojung; Kim, Young-Hwan; Kim, Rahyun; Park, Hyun (2015): Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. In Forest Science and Technology 11 (4), pp. 212–222. DOI: 10.1080/21580103.2014.987325.

Kull, Stephen J.; Rampley, G. J.; Morken, S.; Metsaranta, J.; Neilson, E. T.; Kurz, W. A. (2019): Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2. USER'S GUIDE. Northern Forestry Centre. Ottawa, Canada.</td></tr>
</table>

Table B3: CO2FIX key information

<table>
<tr><td>Model:</td><td>CO2FIX (Version 3.2)</td></tr>
<tr><td>Aim:</td><td>Ecosystem-level simulation model that quantifies the C stocks and fluxes in the forest using the full carbon accounting approach</td></tr>
<tr><td>Focus:</td><td>General stand-level modelling framework</td></tr>
<tr><td>Modules:</td><td>Biomass module
Soil module
Products module
Bioenergy module
Financial module
Carbon accounting module</td></tr>
<tr><td>Principals:</td><td>General:
Atmospheric carbon becomes part of the biomass module via production and storage (C Stock)
Transfer from biomass to soil module by litterfall or harvest residuals
Transfer from biomass to product module through harvest
Uses time-dependent coefficients and growth rates
The volume in branches, foliage and roots can be calculated based on the growth rate of the stem volume
Biomass model:
Use of a cohort approach
Starts with growth rate of stem volumes (gross annual increment) derived from yield tables
Growth rate of foliage, branches and roots are calculated with time-dependent allocation coefficients
Growth rates are modified to simulate the interaction of a cohort with itself and with other cohorts
Growth rates for good, medium and poor site qualities are take from yield tables
Two approaches for modelling growth:
Function of time: current annual increment
Function as the ratio between actual biomass and maximum attainable biomass</td></tr>
<tr><td>Input:</td><td>General:
Simulation length (yr)
Growth as function of: ‘Age’ <u>or</u> ‘Biomass’
Competition relative to: ‘Total biomass in the stand’ <u>or</u> ‘each cohort’
Manag. mort.: ‘Dep. on which cohort is harv.’ <u>or</u> ‘Dep. only on the total Vol harv.’
Region
Size class
Owner
Forest stand:
Cohort (species) with
Start age (if age as growth function) and
Type (‘broadleaf’ or ‘conifer’)
Site condition (good, medium, poor)
Maximum biomass in the stand (Mg/ha)
Species specific:
Carbon content (MgC/MgDM)
Wood density (MgDM/m^3)
Initial carbon (MgC/ha)
CAI (current annual increment) (m^3/ha/year) per age class
<u>Or</u> CAI (m^3/ha/year) per Biomass/MaxBiomass
<u>(continues ...)</u></td></tr>
</table>

Table B3 (continued): CO2FIX key information

<table>
<tr><td>Input:</td><td>

<li style="list-style-type:circle"><u>(... continued)</u>
<li style="list-style-type:circle">Per Compartment (Foliage, Branches, Roots):

Carbon content (MgC/MgDM)
Initial carbon (MgC/ha)
Growth correction factor
Turnover rate (1/year)
Relative growth per Age group
<u>Or</u> Relative growth per Biomass/MaxBiomass

Mortality per age group
Competition: Growth modifier per Biomass/MaxBiomass group
Management mortality matrix including:

Volume (m³)
Starting mortality
Impact time

Rotation length
Thinning-Harvest matrix including with reference to Age:

Fraction of biomass removed of which shares go to:

StemsLogWood (share of the rem. stem biom.)
StemsPulpPap shares (share of the rem. stem biom.)
StemsSlash shares (share of the rem. stem biom.)
BranchesLogWood (share of the rem. branch biom.)
Branches PulpPap (share of the rem. branch biom.)
BranchesSlash (share of the rem. branch biom.)
FoliageSlash (share of the rem.foliage biom.)
SlashFireWood (share of total rem. slash biom.)
SlashSoil (share of total rem. slash biom.)

Soil module requires additional parameters for Climate, and Soil under Cohorts

Products and Bioenergy modules requires additional parameters
</td></tr>
<tr><td>Output:
(soil module and total GHG emission outputs not included)</td><td>

Growing forest:

Per species per year:

Stems Biomass Carbon (MgC/ha)
Stems Biomass Dry weight (MgDM/ha)
Stems Biomass Volume (m³/ha)
Stems Biomass CAI (m³/ha/yr)
For branches, foliage and roots separately

Biomass Carbon (MgC/ha)
Biomass Dry weight (MgDM/ha)

Total Biomass Carbon (MgC/ha)
Total Biomass Dry weight (MgDM/ha)

Increments and losses (MgC/ha/yr) per species per compartments

Harvested Products / Bioenergy:

Various categories related to Products and Bioenergy

</td></tr>
<tr><td>Web:</td><td>http://dataservices.efi.int/casfor/models.htm</td></tr>
<tr><td>Sources:</td><td>
Kim, Hojung; Kim, Young-Hwan; Kim, Rahyun; Park, Hyun (2015): Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. In Forest Science and Technology 11 (4), pp. 212–222. DOI: 10.1080/21580103.2014.987325.

Masera, Omar R.; Garza-Caligaris, J. F.; Kanninen, Markku; Karjalainen, Timo; Liski, J.; Nabuurs, G. J. et al. (2003): Modeling carbon sequestration in afforestation, agroforestry and forest management projects. the CO2FIX V. 2 approach. In Ecological Modelling 164 (2-3), pp. 177–199.

Schelhaas, M. J.; van Esch, P. W.; Groen, T. A.; Jong, B. H.J. de; Kanninen, M.; Liski, J. et al. (2004): CO2FIX V 3.1. A modelling framework for quantifying carbon sequestration in forest ecosystems. Alterra-rapport 1068. Alterra. Wageningen.
</td></tr>
</table>

Table B4: FullCAM key information

Model:	**FULLCAM** (Version 2016)
Aim:	To provide fully integrated estimates of carbon pools in forest and agricultural systems and account for human-induced changes in emissions and sequestrations
Focus:	Australia's primary modelling system for land sector greenhouse gas reporting and accounting
Modules:	
Principals:	

Input:
 	
(Not comprehensive)
	● Age of oldest trees
	● Av. age of trees
	● % of Maximum Tree Biomass, or masses (dmt/ha), or Volume (m^3/ha) for stems and masses for other components for:
	    ○ Stems
	    ○ Branches
	    ○ Bark
	    ○ Leaves
	    ○ Coarse roots
	    ○ Fine roots
	● Maximum Aboveground biomass (tdm/ha)
	● Mean long-term average annual forest productivity index
	● Annual Forest Productivity Index over a defined period (sum of key site-factors: soil type, fertility and climate)
	● tree age of maximum growth rate (years)
	● species multiplier of maximum above-ground biomass, M

Output: **(Not comprehensive)**	● AGB (Mg DM ha^{-1} $year^{-1}$) ● Carbon stocks in all woody biomass (above- and below-ground) ● Standing dead biomass ● Debris ● Soil ● Wood products ● Fluxes from decomposition ● Soil carbon turnover
Web:	https://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/land-sector
Sources:	Australian Government (2013): Guidance for using FullCAM in Carbon Farming Initiative (CFI) methodologies. Carbon Credits (Carbon Farming Initiative) (Native Forest from Managed Regrowth) Methodology Determination 2013. Version 1.0. Department of Environment. Australian Government (2016): FullCAM Guidelines. Requirements for using the Full Carbon Accounting Model (FullCAM) in the Emissions Reduction Fund (ERF) methodology determination: Carbon Credits (Carbon Farming Initiative) (Reforestation by Environmental or Mallee Plantings—FullCAM) Methodology Determination 2014. Version 2.0. Department of the Environment and Energy. Roxburgh, S.; England, J.; Paul, K. (2019): Recalibration of the Tree Yield Formula in FullCAM for plantations. CSIRO. Australia. Waterworth, R. M.; Richards, G. P. (2008): Implementing Australian forest management practices into a full carbon accounting model. In *Forest Ecology and Management* 255 (7), pp. 2434–2443. DOI: 10.1016/j.foreco.2008.01.004. Waterworth, R. M.; Richards, G. P.; Brack, C. L.; Evans, D.M.W. (2007): A generalised hybrid process-empirical model for predicting plantation forest growth. In *Forest Ecology and Management* 238 (1), pp. 231–243. DOI: 10.1016/j.foreco.2006.10.014.

Table B5: CASMOFOR key information

<table>
<tr><td>Model:</td><td>CASMOFOR (Version 6.1)</td></tr>
<tr><td>Aim:</td><td>Assess the removals and emissions of carbon by afforestations</td></tr>
<tr><td>Focus:</td><td>Carbon balance of afforestations</td></tr>
<tr><td>Modules:</td><td>CASMOFOR consists of worksheets, graphs and accounting functions. These functions are interlinked, and operate with MS Excel formulas.</td></tr>
<tr><td>Principals:</td><td>Process of growth in 5 steps:
1. Estimation of above ground tree volume increment
2. Multiplying volume by biomass expansion factor (BEF)
3. Convert biomass to carbon
4. Calculation of other biomass components from BEF
5. Calculating Net Primary Production (NPP) including all biomass increment</td></tr>
<tr><td>Input:

(decomp. and wood utilization parameters not included)</td><td>● Growth-Yield Curves (Age to Current annual increment in $m^3ha^{-1}yr^{-1}$)
● Annual rate of afforestation
● Duration of afforestation
● Area and above-ground-biomass stocks
● Initial (non above-ground-biomass stocks)
● Soil parameters
● Other parameters
● Growth and disturbance parameters
● For each yield groups (‘good’, ‘medium’, ‘poor’):
○ Species
○ Basic density (t dry wood/m3 fresh wood)
○ Biomass expansion factor (dimensionless)
○ Carbon fraction (tC/tdm)
○ "root-to-shoot" ratio
○ Leaf biomass increment over aboveground woody biomass increment ratio
○ Fraction of leaves of living trees (relative to all leaves) that dies at the end of year
● Thinning intensity
● Mortality intensity</td></tr>
<tr><td>Output:</td><td>● Aggregated carbon fixed (million t)
● Sequestered carbon (tC) in:
○ Above ground biomass
○ Roots
○ Leaves
○ Deadwood
○ Dead roots
○ Litter
○ Wood products
○ Fuelwood
○ Unused wood products</td></tr>
<tr><td>Web:</td><td>http://www.scientia.hu/casmofor/indexE.php</td></tr>
<tr><td>Sources:</td><td>Kim, Hojung; Kim, Young-Hwan; Kim, Rahyun; Park, Hyun (2015): Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. In Forest Science and Technology 11 (4), pp. 212–222. DOI: 10.1080/21580103.2014.987325.

Somogyi, Z. 2019. CASMOFOR version 6.1. Forest Research Institute, Budapest. Website: www.scientia.hu/casmofor

Somogyi, Z. 2010CASMOFOR. In: Somogyi, Z., Hidy, D., Gelybó, Gy., Barcza, Z., Churkina, G., Haszpra, L., Horváth, L., Machon, A., Grosz, B., 2010. Modeling of biosphere-atmosphere exchange of greenhouse gases - Models and their adaptation. In: Atmospheric Greenhouse Gases: The Hungarian Perspective (Ed.: Haszpra, L.), pp. 201-228.</td></tr>
</table>

Table B6: EFISCEN key information

Model:	**EFISCENT** (Version 4)
Aim:	Assesses the availability of wood and projects forest resource development on regional to continental scale
Focus:	Compare different policy and forest management scenarios
Modules:	
Principals:	Matrix approach: ● A forest type is defined by species, region, site class and owner ● Each forest type has a separate matrix ● Includes 6-15 age classes and 10 volume classes Growth: ● Growth is estimated by shifting the proportion of area in the matrix from one cell to the next higher volume class ● Volume class of a cell can increase until the maximum is reached which is then maintained until the time of harvest
Input:	● National Forest Inventory data Minimum required: ● area (ha), including temporarily unstocked areas ● growing stock volume (m^3 ha^{-1} overbark) ● net annual increment (m^3 ha^{-1} yr^{-1} overbark) Structured by: ● age-classes ● tree species ● geographic regions ● ownership classes ● Site-classes In addition: ● Minimum and maximum age at which thinning can take place ● Minimum age for final felling ● Biomass expansion factors
Output:	
Web:	https://www.efi.int/knowledge/models/efiscen/availability
Sources:	European Forest Institute (2016): EFISCEN. European Forest Information SCENario model, version 4. European Forest Institute. Joensuu, Finland. Kim, Hojung; Kim, Young-Hwan; Kim, Rahyun; Park, Hyun (2015): Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. In *Forest Science and Technology* 11 (4), pp. 212–222. DOI: 10.1080/21580103.2014.987325. Sallnäs, O. (1990): A matrix model of the Swedish forest. In *Studia Forestalia Suecica* 183 (23). Schelhaas, M.; Eggers, Jeannette; Lindner, Marcus; Nabuurs, Gert-Jan; Pussinen, A.; Päivinen, Risto et al. (2007): Model documentation for the European Forest Information Scenario model (EFISCEN 3.1).

Table B7: 3-PG key information

Model:	**3-PG (Physiological Principles in Predicting Growth)**
Aim:	Bridge the gap between conventional, mensuration-based growth and yield, and process-based carbon balance models
Focus:	Generic forest growth model
Modules:	
Principals:	● Process-based growth model ● Calculation of the radiant energy absorbed by forest canopies ● Converting the absorbed energy into biomass production ● The efficiency of the radiation conversion is modified by: ○ Effects of nutrition ○ Soil drought (continues calculation of water balance) ○ Atmospheric vapour pressure deficits ○ Stand age ● Dynamic equations allocate the produced carbon to ○ Leaves ○ Stems ○ Roots ● 3-PGmix includes mixed-species / -age forests ● 3-PGS is a spatial version of 3-PG
Input: **(Not comprehensive)**	● Plant physiological data per species ● Stand age (year) ● Initial stocking (trees ha^{-1}) ● average incoming photosynthetically active radiation (MJ m^{-2} day^{-1}) ● mean daytime vapour pressure deficits (mbar) ● temperature extremes (°C) ● Mean monthly precipitation (mm $Month^{-1}$) ● Estimates of soil water storage capacity ● Fertility rating
Output: **(selection)**	● stand volume (excluding branch and bark) (m^3 ha^{-1}) ● Cumulative extracted volume (by thinning) (m^3 ha^{-1}) ● Volume extracted during the most recent thinning event (m^3 ha^{-1}) ● Stand stocking (trees ha^{-1}) ● Average stem diameters (cm) ● Mean height (m) ● Mean grown diameter (m) ● Stand basal area (m^2 ha^{-1}) ● Leaf Area Index (m^2 m^{-2})
Web:	https://3pg.forestry.ubc.ca/ https://sites.google.com/site/davidforresterssite/home/projects/3PGmix
Sources:	Coops, N.C; Waring, R.H; Landsberg, J.J (1998): Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. In *Forest Ecology and Management* 104 (1-3), pp. 113–127. DOI: 10.1016/S0378-1127(97)00248-X. Landsberg, J. J.; Waring, R. H. (1997): A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. In *Forest Ecology and Management* 95 (3), pp. 209–228. DOI: 10.1016/S0378-1127(97)00026-1. Forrester, David I.; Tang, Xiaolu (2016): Analysing the spatial and temporal dynamics of species interactions in mixed-species forests and the effects of stand density using the 3-PG model. In *Ecological Modelling* 319, pp. 233–254. DOI: 10.1016/j.ecolmodel.2015.07.010.

Table B8: CENTURY key information

Model:	**CENTURY** (Version 4.0)
Aim:	General model of plant-soil nutrient cycling
Focus:	Grasslands, agricultural lands, forests, savannas
Modules:	• Soil organic matter and decomposition sub model • Water budget model • Grassland / Crop model • Forest production model • Management and event scheduling function

Principals:	• The flow of carbon, nitrogen, phosphorus, and sulphur through the model's compartments is computed
	• Forest model
	  ○ Simulates the growth of deciduous and evergreen forests
	  ○ Differentiates between juvenile and mature phases
	• To simulate savanna and shrubland the grassland and forest models are used with additional code to simulate nutrient competition and shading effects
	• The Events scheduling function can be used to simulate disturbances by fire, harvest and grazing / cultivation

Input:	Various variables to parameterize tree species Data related to site: • Monthly precipitation in centimetres • Monthly mean minimum temperatures in degrees Celsius • Monthly mean maximum temperatures in degrees Celsius • Site latitude and longitude • Percentage of sand, silt, and clay in top 20 cm layer of mineral soil • Bulk density of the top 20 cm layer of soil (g/cm^3) • Rooting depth and root distribution of the vegetation (in cm) • Best estimate of annual wet and dry N deposition • C in the soil organic matter in the top 20 cm of soil • N in the soil organic matter in the top 20 cm of soil Data related to Vegetation (forest focus): • Productivity of vegetation (gC/m^2 per year or growing season) • C:N ratio for leaves, branches, large wood, fine roots, and coarse roots • Percentage allocation of production to leaves, branches, large wood, fine roots, and coarse roots • lignin content for leaves, branches, large wood, fine roots, and coarse roots
Output:	• sum of C in forest system live components (g/m^2) • C in forest system fine branch component (g/m^2) • C in forest system fine root component (g/m^2) • sum of C in wood components of forest system (g/m^2) • C in wood2 (dead large wood) component of forest system (g/m^2) • C in wood3 (dead coarse roots) component of forest system (g/m^2) • total C in forest system i.e. sum of soil organic matter, trees, dead wood, forest litter
Web:	https://www.nrel.colostate.edu/projects/century/century-obtain.php https://www.nrel.colostate.edu/projects/century/century-documentation.php http://www.cgd.ucar.edu/vemap/abstracts/CENTURY.html
Sources:	Parton, W. J.; Anderson, D. W.; Cole, C. V.; Stewart, J.W.B. (1983): Simulation of soil organic matter formation and mineralization in semiarid agroecosystems. In R. R. Lowrance, R. L. Todd, L. E. Asmussen, R. A. Leonard (Eds.): Nutrient cycling in agricultural ecosystems. Athens, Georgia (Special Publ., 23).

Table B9: PnET key information

Model:	**PnET (Photosynthesis and EvapoTranspiration)**
Aim:	Simulation of carbon, water and nitrogen dynamics in forest ecosystems
Focus:	Temperate Forest Canopy Model
Modules:	PnET day ● Canopy flux module PnET/II ● Produces a monthly time-step carbon and water model ● Driven by nitrogen availability ● Allocates nutrients ● Considers water balance and soil respiration PnET-CN ● Extends the soil dynamics component ● Tracks N and C through all compartments and fluxes and closes the N cycle
Principals:	● Foliar N concentration determines photosynthesis (A_{max}) ● Realized A_{max} at the top of the canopy is driven by solar radiation, temperature, vapour pressure deficit, and mean daily climate variables ● A_{max} declines with canopy depth (lower radiation, lower leaf weight) ● Day and night leaf respiration differ temperature and photosynthesis
Calibrated:	Pine, spruce, hemlock, fir, oak, hardwoods, birch, beech, rainforest
Input: **(Selection)**	● Age ● 45 other plant related variables ● Disturbance and Management
Output: **(Selection)**	● Foliage C (g/m^2) ● Live wood C (g/m^2) ● Dead wood C (g/m^2) ● Wood C (g/m^2) ● Litter C (g/m^2) ● Leaf Area Index (m^2/m^2)
Web:	http://www.pnet.sr.unh.edu/
Sources:	Aber, John D.; Federer, C. Anthony (1992): A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. In Oecologia 92 (4), pp. 463–474. DOI: 10.1007/BF00317837. Aber, John D.; Reich, Peter B.; Goulden, Michael L. (1996): Extrapolating leaf CO2 exchange to the canopy: a generalized model of forest photosynthesis compared with measurements by eddy correlation. In Oecologia 106 (2), pp. 257–265. DOI: 10.1007/BF00328606. Miehle, P.; Livesley, S. J.; Feikema, P. M.; Li, C.; Arndt, S. K. (2006): Assessing productivity and carbon sequestration capacity of Eucalyptus globulus plantations using the process model Forest-DNDC: Calibration and validation. In Ecological Modelling 192 (1-2), pp. 83–94. DOI: 10.1016/j.ecolmodel.2005.07.021.

Table B10: DNDC Forest key information

Model:	**Denitrification-Decomposition (DNDC) forest model** (Version 9.5)
Aim:	Quantify carbon sequestration and emissions from forest ecosystems.
Focus:	Upland and wetland forest ecosystems
Modules:	Process model
Principals:	• Daily timesteps • Matrix approach • Combination of PnET and DNDC

Input:	• Meteorology
	  ○ daily maximum and minimum air temperature
	  ○ Rainfall
	  ○ ambient CO2 concentration
	  ○ N concentration in rainfall
	• forest type
	• forest age
	• soil properties
	  ○ humus layer type
	  ○ litter layer depth
	  ○ litter layer pH
	  ○ bypass flow (surface efflux)
	  ○ mineral soil texture
	  ○ mineral soil pH
	  ○ stone content
	  ○ organic carbon content
	  ○ depth to groundwater level
	• forest management practises.
	• water table information (for wetland applications)
	• latitude
	• management operations (e.g. planting, fertilisation, harvest, thinning, wetland restoration, etc.)

Output:	• estimates of model forest growth
	• net ecosystem C exchange
	• nitrogen (N) leaching from the root zone
	• fluxes of
	  ○ carbon dioxide (CO2)
	  ○ methane (CH4)
	  ○ nitrous oxide (N2O)
	  ○ nitric oxide (NO)
	  ○ nitrogen gas (N2)
	  ○ ammonia (NH3)
	• emissions on a daily and annual basis

Web:	http://gramp.org.uk/models/1
Sources:	Li, Changsheng; Frolking, Steve; Frolking, Tod A. (1992a): A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. In *J. Geophys. Res.* 97 (D9), pp. 9759–9776. DOI: 10.1029/92JD00509. Li, Changsheng; Frolking, Steve; Frolking, Tod A. (1992b): A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. In *J. Geophys. Res.* 97 (D9), pp. 9777–9783. DOI: 10.1029/92JD00510. Stange, Florian; Butterbach-Bahl, Klaus; Papen, Hans; Zechmeister-Boltenstern, Sophie; Li, Changsheng; Aber, John (2000): A process-oriented model of N 2 O and NO emissions from forest soils: 2. Sensitivity analysis and validation. In *J. Geophys. Res.* 105 (D4), pp. 4385–4398. DOI: 10.1029/1999JD900948.

Table B11: Biome-BGC key information

Model:	**Biome-BGC** (Version 4.2)
Aim:	Estimates storage and flux of carbon, nitrogen and water vegetation and soil
Focus:	Process model for terrestrial ecosystems
Modules:	Process model

Principals:	• Vegetation growth depends strongly on weather and climate
	• Physical and biological processes control fluxes of energy and mass like
	    ○ New leaf growth and old leaf litterfall
	    ○ Sunlight interception by leaves, and penetration to the ground
	    ○ Transpiration of soil water through leaf stomata
	    ○ Photosynthetic fixation of carbon from CO2 in the air
	    ○ Uptake of nitrogen from the soil
	    ○ Distribution of carbon and nitrogen to growing plant parts
	    ○ Decomposition of fresh plant litter and old soil organic matter
	    ○ Plant mortality
	    ○ Fire

Input:	Plant parameterization data (optional) Necessary inputs (Best case): • Daily maximum temperature (°C) • Daily minimum temperature (°C) • Daylight average temperature (°C) • Daily total precipitation (cm) • Daylight average partial pressure of water vapor (Pa) • Daylight average shortwave radiant flux density (W/m^2) • Daylength (s) Alternative Inputs: • Radiation and humidity parameters can be estimated from daily maximum and minimum temperatures and the daily total precipitation. • Estimation from nearby weather stations
Output: **(Selection)**	More than 500 possible output variables • Annual vegetation ($gC/m^2/yr$) • Annual litter ($gC/m^2/yr$) • Annual total ($gC/m^2/yr$) • Annual maximum value of projected leaf area index (m^2/m^2) • Annual total evapotranspiration (mm/yr) • Annual total net primary production ($gC/m^2/yr$) Calculated Fluxes: • New leaf growth and old leaf litterfall • Sunlight interception by leaves, and penetration to the ground • Precipitation routing to leaves and soil • Photosynthetic fixation of carbon from CO2 in the air • Distribution of carbon and nitrogen to growing plant parts • Plant mortality • Fire
Web:	https://www.ntsg.umt.edu/project/biome-bgc.php
Sources:	Thornton, P.E; Law, B.E; Gholz, Henry L.; Clark, Kenneth L.; Falge, E.; Ellsworth, D.S et al. (2002): Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. In *Agricultural and Forest Meteorology* 113 (1-4), pp. 185–222. DOI: 10.1016/S0168-1923(02)00108-9.

Appendix C

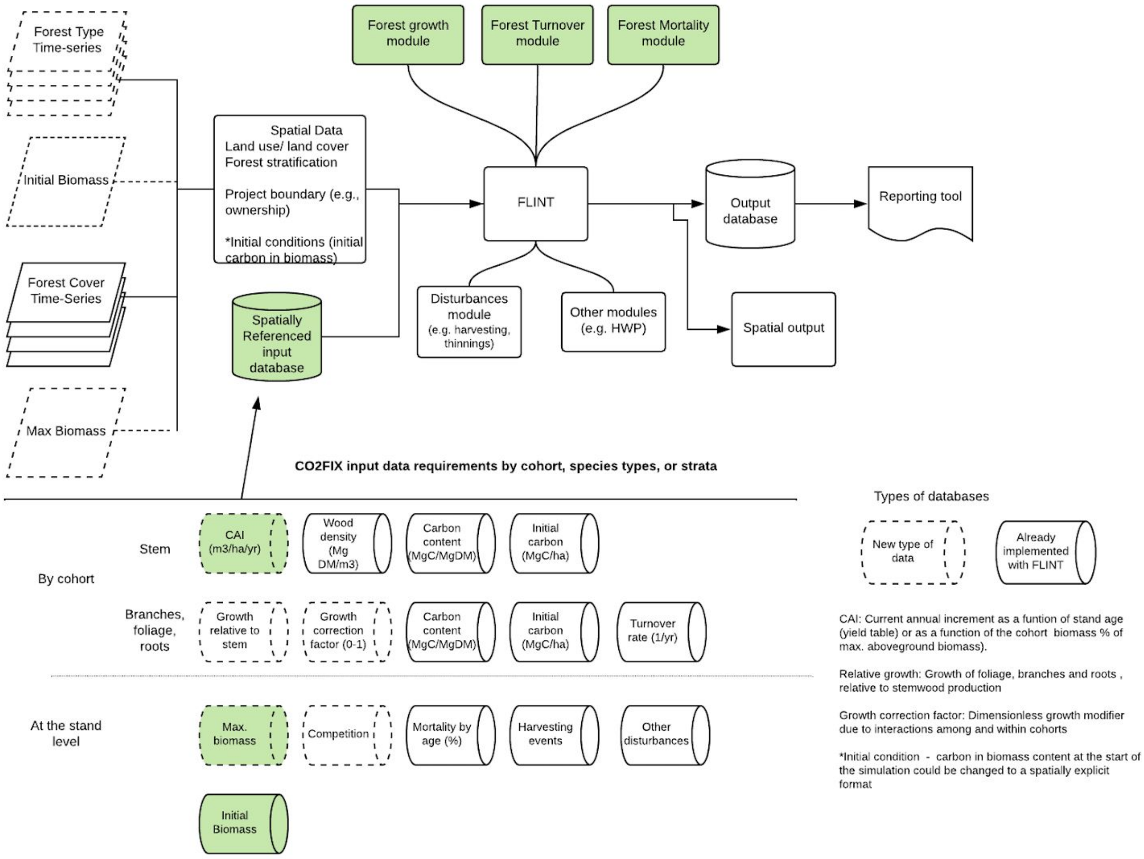

Figure C1: Potential implementation design of the biomass growth module of CO2FIX into FLINT.