Forest Research

CARBINE-R Technical Guide

Version 1.3

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The Research Agency of the
Forestry Commission

Forest Research is the Research Agency of the Forestry Commission and is the leading UK organisation engaged in forestry and tree related research.

The Agency aims to support and enhance forestry and its role in sustainable development by providing innovative, high quality scientific research, data, technical support and consultancy services.

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1. Model specification

1.1. Model description

CARBINE is a forest carbon accounting model. Its basic calculations are made at the scale of a single stand of trees, where a stand represents an area of trees with the same species, yield class and management. Results for individual stands can then be combined to represent whole forests. The model was developed for large-scale (i.e., national) analyses of forest carbon, and, therefore, the minimum scale used is the forest stand level and not the individual tree level. The model represents the exchanges of carbon between forest pools (trees, deadwood, litter, and soil) as well as related pools of non-forest land uses and harvested wood products. These carbon exchanges are derived by considering the balance of carbon flows related to the rate of carbon accumulation resulting from forest tree growth, and the rates of mortality and decay of trees, and losses related to tree harvesting rates.

The model has been in development since 1988 (Thompson & Matthews, 1989), when it was first developed in response to the recognised importance of forests for carbon balances in the first meeting of the Intergovernmental Panel on Climate Change (IPCC). Its ongoing development has continued with respect to IPCC guidance, with its first use in reporting forest greenhouse gas (GHG) emissions in 2014. The CARBINE model corresponds to a Tier 3 method of reporting forest emissions, which is the most detailed level of approach as defined by the IPCC. Model development has also been influenced by the need to address policy questions about the carbon balance of forestry systems.

The CARBINE model has been developed specifically for, and applied extensively in, the United Kingdom (UK). Its development has been reliant on forest yield tables developed in the 1960s for production forests. These yield tables underpin the M1 growth model, which is used by CARBINE to estimate the stem volume in tree stands over time under different management conditions. The set of species and management conditions modelled within CARBINE are, therefore, limited to those parameterised within M1. The M1 growth model itself is an area of active development within Forest Research, being updated with new stand growth relationships based on the latest data from a network of forest sample plots across the UK.

1.2. Model diagram

The main inputs include: i) a config file ‘0_carbin_config.xlsx’ where run type, parameters and output options are selected; ii) a stand prescription file (known as the 'spplist'); iii) one or more area files which delineate afforestation years and planting areas; and iv) multiple parameter files. These inputs first enter the regional scale modules which include the start-up scripts which prepare and format parameter and stand prescriptions for use in the M1 growth model. The output of this is one or more formatted stand prescriptions, which are entered into the stand level modules. These modules start with the M1 growth model and estimate carbon stocks for that tree stand. The one or more carbon stock results for each stand are then returned to the regional scale modules, where results are aggregated and formatted for output. The outputs include this main aggregated carbon stock file, as well as optional stand level results and graphs.

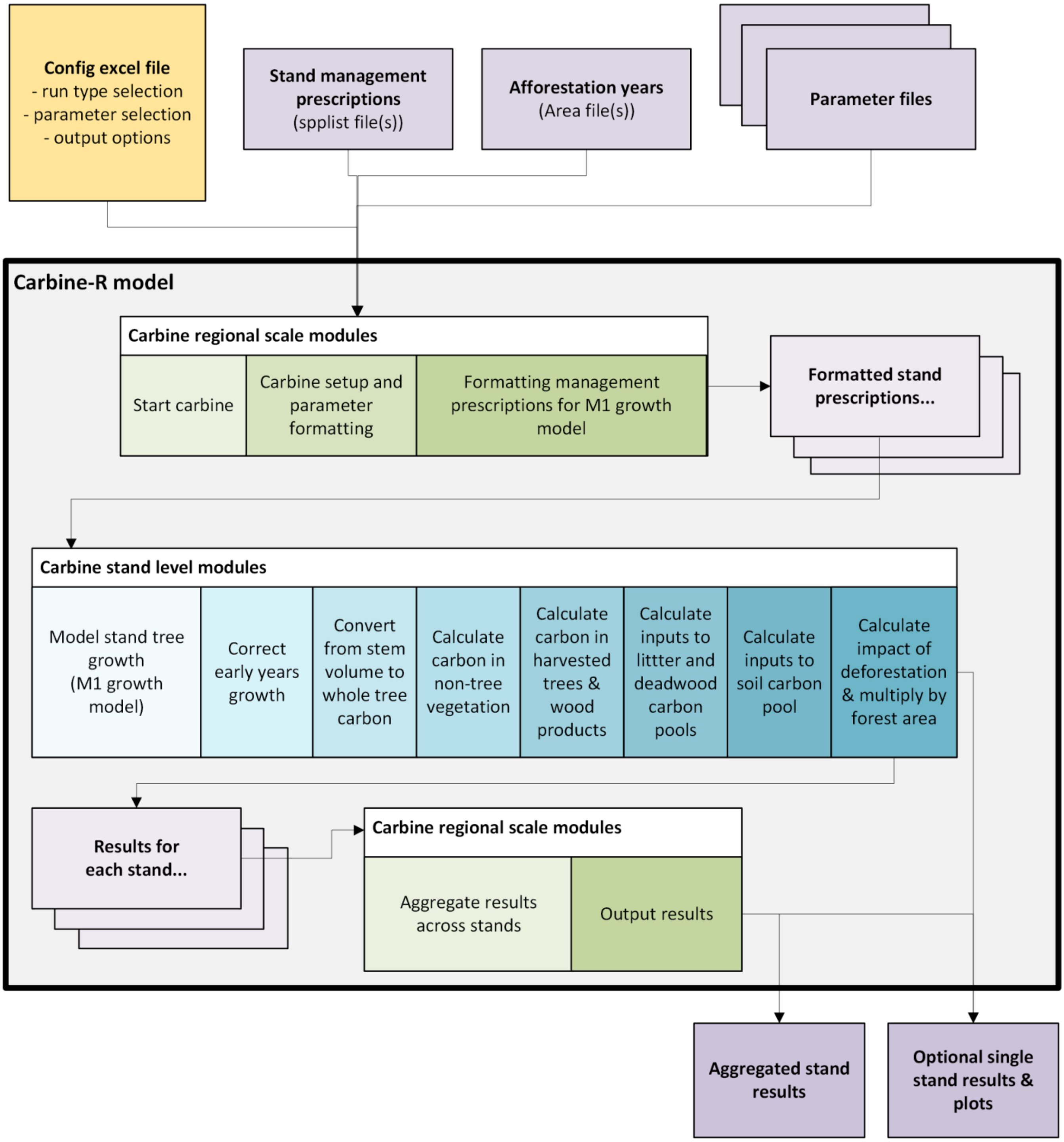

Figure 1. A visualisation of the simplified CARBINE-R model structure.

1.3. Model application and run types

CARBINE-R is set up to allow different run types of the model, which are described in turn in the following sections

1.3.1. Test case run

- A test case run involves running pre-prepared stand prescriptions. See Table 1 for test case descriptions. These test cases include both single stand runs (cases 1 to 12), and multi-stand runs (cases 13 to 21).
- These stand prescriptions and their corresponding area files are saved in input/management_prescription/test_case_files/[test case file number 1 to 21]/CARB0/

  A test case run can be selected from the 'project info' sheet in the config file ('0_carbine_config.xlsx') by selecting the 'Test case' option from the drop-down list in cell C4. A new option will appear to select a specific test case number to select (cell C8). The weather data file (cells C11 & C12) and projection start and end years (cells C15:16) should also be selected.
- Alternatively, all test cases can be run from the **'R/run_test_cases.R'** script where the numbers of the test cases to be run simultaneously can be selected by changing the values set by the 'test_case_numbers' command (line 32). Note that this approach will run regardless of the run_type selected in the config file.
- Test case results will be saved in 'output/test_case_[test_case_number] folders.

1.3.2. GHG inventory

- The GHG inventory run is the run type which will be used by Forest Research to deliver the carbon estimates for the Forest component of the GHG inventory.

- This run type is separated to run for each nation and each tree type (broadleaf and conifer). It takes stand prescription and area files generated from preparatory calculations via the Forest Research software 'Reconcile' which is not publicly released. ("input/management_prescription/reconcile_files/[nation]/[tree_type]/CARB0/").
- This run type can be selected in the 'project_info' sheet of the config file (cell C4), in which a corresponding project id (cell C2) and weather data file (cells C11 & C12) should be selected.
- The output of this run type will be saved in a folder using the project id given in the config file, i.e., "output/[project id]".

1.3.3. Manual spplist

This run type allows users to specify their own stand prescription for both single stand and multi-stand runs. The steps to generating a user-defined stand prescription are:

- Edit the config file
    - Add a name for your project for the 'project_ID' row (cell C2). Please do not include any spaces in the name
    - For the row 'run_type' select 'Manual_spplist' from the drop-down box (cell C4)
    - Enter a folder name for the 'manual_spplist_sub_folder' row (cell C9). Please do not use any spaces in the file name. Create a folder with this name within the 'input/management_prescription/user_defined_files' folder
    - Select the desired weather data for the run from the drop-down lists (cell C11 & C12)

- Create the spplist file
  - A template for this file structure, called 'Spplist_template.xlsm', is provided in the 'input/management_prescription/user_defined_files/Templates' folder
  - This file contains instructions and guides for data entry for this file. Multiple stand prescriptions can be added to this file and should be identified by different area_codes in column 'A' (see the file for more instructions). The desired settings for the spplist file can be written here and then copied into a separate .csv file, saved in the 'manual_spplist_sub_folder' specified above, and saved with the name 'spplist.csv'. For this the first row of the template, which contains data entry instructions for each column, should not be copied over. The column headings in row 2 should not be changed.
  - Example spplist files are given in the two scenarios supplied in the 'user_defined_files' folder. Scenario 1 illustrates a simple scenario with one stand prescription and one afforestation year. Scenario 2 illustrates a scenario with two stand prescriptions, where stand 'AREAAAAA' has two afforestation years.
- Create the area file
  - An area file is required for each stand prescription (identified by different area codes) in the spplist file generated above.
  - Example area files are given in the two scenarios supplied in the 'user_defined_files' folder.
- Create a deforestation file
  - The deforestation file should be named 'deforestation_pc.csv' and saved in the 'manual_spplist_sub_folder' specified in the config file.
  - The deforestation file contains two columns:

    - Reporting_year: the calendar year in which deforestation occurs
    - Deforestation_pc: the percentage of deforestation occurring in that year. Note that deforestation is cumulative and so cannot add up to more than 100% across all years.
    - Column names should remain unchanged.
    - Example deforestation files are given in the two scenarios supplied in the 'user_defined_files' folder.
- Edit deforestation start and end years in config file
    - CARBINE-R can allow for deforestation to occur only during certain time periods. The default for the GHG inventory is to only allow deforestation to first occur in 1990 and to end in 2150. These values should be edited in the 'default_param_options' sheet of the config file to meet user requirements.
- Run CARBINE-R with generated inputs using the 'carbine_start' script and selecting the relevant config file.
- The output of this run type will be saved in a folder using the project id given in the config file, i.e., "output/[project id]".

1.3.4. Yield table

Not yet implemented

- This method will allow carbon stocks to be calculated for tree volumes supplied from external files, and so may be calculated outside of M1.

Table 1. Description of test cases provided with CARBINE-R.

Test case number	Single- or multi-stand	Description
1	Single-stand	A stand prescription with 8 management transitions, starting with Scots pine for the first five management periods under varying thin or no thin management types and varying rotation lengths, to oak under varying thin and no thin management types and varying rotation lengths. Single afforestation year of 1500, area of 1 ha and England weather data used.
2	Single-stand	A stand prescription with 4 management transitions. All management transitions are oak stands, but with varying management (thin, fell; to LISS; to no thin, fell; to LISS again). Single afforestation year of 1500, area of 1 ha and England weather data used.
3	Single-stand	A stand prescription with one management transition, from a Sitka spruce stand with no thinning for 80 year rotation to a Sitka spruce stand with no thinning for a 100 year rotation. Single afforestation year of 1500, area of 1 ha and England weather data used.
4	Single-stand	The same stand prescription and area as test case 1, but with deforestation occurring
5	Single-stand	The same stand prescription and area as test case 2, but with deforestation occurring
6	Single-stand	The same stand prescription and area as test case 3, but with deforestation occurring
7	Single-stand	The same stand prescription as test case 1, but with an afforested area of 500 ha and deforestation occurring

Test case number	Single- or multi-stand	Description
8	Single-stand	The same prescription as test case 1, but with deforestation occurring, an area of 500 ha and an afforestation year of 1600
9	Single-stand	The same stand prescription as test case 1, but with an afforestation year of 1600
10	Single-stand	A stand prescription with no transitions in management occurring. The tree species is Scots pine under an unchanging management of no thinning, fell regime and 100 year rotation length. A single afforestation year of 1600, area of 1 ha and England weather data used.
11	Single-stand	A stand prescription with no transitions in management occurring. The tree species is beech under an unchanging management prescription of no thinning, fell regime and a 273 year rotation length. A single afforestation year of 1600, area of 1 ha and England weather data used.
12	Single-stand	A stand prescription with no transitions in management p occurring. The tree species is poplar under an unchanging management regime of no thinning, fell regime and a 25 year rotation length. A single afforestation year of 1600, area of 1 ha a different weather data used.

Test case number	Single- or multi-stand	Description
13	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each stand prescription is composed of different tree species and different yield class and with varying rotation lengths, but all are managed under no thinning, fell regimes. Prescriptions may have different afforestation years and planting areas.
14	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of a different tree species and different yield class and with varying rotation lengths, but all are managed under no thinning, fell regimes. Prescriptions may have different afforestation years and planting areas.
15	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes and with varying rotation lengths, but all are managed under thin, fell regimes. Prescriptions may have different afforestation years and planting areas.
16	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes and with varying rotation lengths, but all are managed under thin, fell regimes. Prescriptions may have different afforestation years and planting areas.

Test case number	Single- or multi-stand	Description
17	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription stand is composed of different species of different yield classes and with varying rotation lengths. All are managed under an edge case management setup of thin, no fell. Prescriptions may have different afforestation years and planting areas.
18	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes and with varying rotation lengths. All are managed under an edge case management setup of thin, no fell. Prescriptions may have different afforestation years and planting areas.
19	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes, but all are managed under LISS regimes. Prescriptions may have different afforestation years and planting areas.
20	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes, but all are managed under LISS regimes. Prescriptions may have different afforestation years and planting areas.

Test case number	Single- or multi-stand	Description
21	Multi-stand	Multiple stand prescriptions with no transitions in management in any prescription. Each prescription is composed of different species of different yield classes, but all are managed under LISS regimes. Prescriptions may have different afforestation years and planting areas.

1.4. Key data & model theory descriptions

1.4.1. Species

The model is currently parameterised for 19 tree species, which were selected as representing the most commonly planted commercial tree species in the UK. A list of these 19 species and their characteristics are provided in Table 2.

Table 2. Categorisation of tree species in the CARBINE model.

Species code	Species name	Leaf type	Tree type	Wood type
AH	Ash	broadleaf	deciduous	hardwood
BE	Beech	broadleaf	deciduous	hardwood
BI	Birch	broadleaf	deciduous	hardwood
OK	Oak	broadleaf	deciduous	hardwood
PO	Poplar	broadleaf	deciduous	hardwood
RON	Nothofagus	broadleaf	deciduous	hardwood
SY	Sycamore	broadleaf	deciduous	hardwood
CP	Corsican pine	conifer	evergreen	softwood
DF	Douglas fir	conifer	evergreen	softwood
EL	European larch	conifer	deciduous	softwood
GF	Grand fir	conifer	evergreen	softwood
JL	Japanese larch	conifer	deciduous	softwood
LP	Lodgepole pine	conifer	evergreen	softwood
NF	Noble fir	conifer	evergreen	softwood
NS	Norway spruce	conifer	evergreen	softwood
SP	Scots pine	conifer	evergreen	softwood
SS	Sitka spruce	conifer	evergreen	softwood
WH	Western hemlock	conifer	evergreen	softwood
WRC	Western red cedar	conifer	evergreen	softwood

Typically, a forest stand, as represented in CARBINE, is assumed to be composed of a single tree species; however, forest stands can also be made up of more complicated mixtures of tree species. These types of stands are represented in CARBINE by partitioning the specified stand area of the mixed forest into hypothetical single-species units. If a forest stand with an area of 20 ha consists of an intimate mixture of Sitka spruce (60% crown occupancy) and Scots pine (40% crown occupancy), CARBINE will base its calculations for this stand on 12 ha of Sitka spruce and 8 ha of Scots pine with no interactions represented.

1.4.2. Management

There are four management options modelled within CARBINE. These four options are a combination of three different thinning types and a clearfelling option. CARBINE-R mostly uses the management code, although there are some instances where the thinning code is used instead, such as in M1.

Table 3. Description of management types used in the model.

Management code	Name	Thin code	Clearfell	Description
1	No thin, fell	1	Yes	No thinning takes place and all trees are clearfelled at the end of the rotation
2	Thin, fell	2	Yes	Standard thinning (thinning reduces over time for mature stands, to maintain MAI). Trees are clearfelled at the end of the specified rotation length.

Management code	Name	Thin code	Clearfell	Description
2	Thin, no fell	2	No	A rare case, so management code remains as '2' even though the stand is never clearfelled. To prevent clearfell occurring the rotation length is extended to 999 years long.
3	LISS	3	No	Low Impact Silvicultural Systems (LISS), represented in CARBINE by systems where trees are thinned continuously, removing the same volume at each thinning, until the initial stand is removed while being replaced by regenerating trees growing underneath the tree canopy. This allows rotations to overlap and form continuous canopy silviculture.
4	No management	1	No	No thinning or felling

In addition to these management options, the following parameters can be varied:

- Fallow period: The number of years before replanting a stand after clearfelling occurs.
- LISS overlap period: The number of years of overlap between two LISS rotations.
- No go period: The number of years before a clearfelling event during which thinning is avoided

- Thin cycle: The number of years between thinnings.

Default values for these parameters are set in the 'default_param_options' sheet of the config file. These can be overwritten in this sheet.

2. Module descriptions

The CARBINE model can be categorised into two main components: a regional-scale section and a stand-scale section. The regional-scale section carries out actions which are ubiquitous across all stand configurations that are possible to be run in the model. Specifically, it reviews and prepares the list of stand prescriptions to be run through the stand-level module; prepares shared functions and equations used for stand calculations; and aggregates and outputs the results of the stand-level module.

The stand-level section calculates carbon in each stand based on the output prescription from the regional-level module. Based on those sets of inputs, the stand-level module estimates tree growth and carbon exchange between trees and litter, deadwood, soil, and harvested wood product pools. The model is set up in this way to allow efficiencies to be made in running loops of stand-level functions for all listed stand prescriptions.

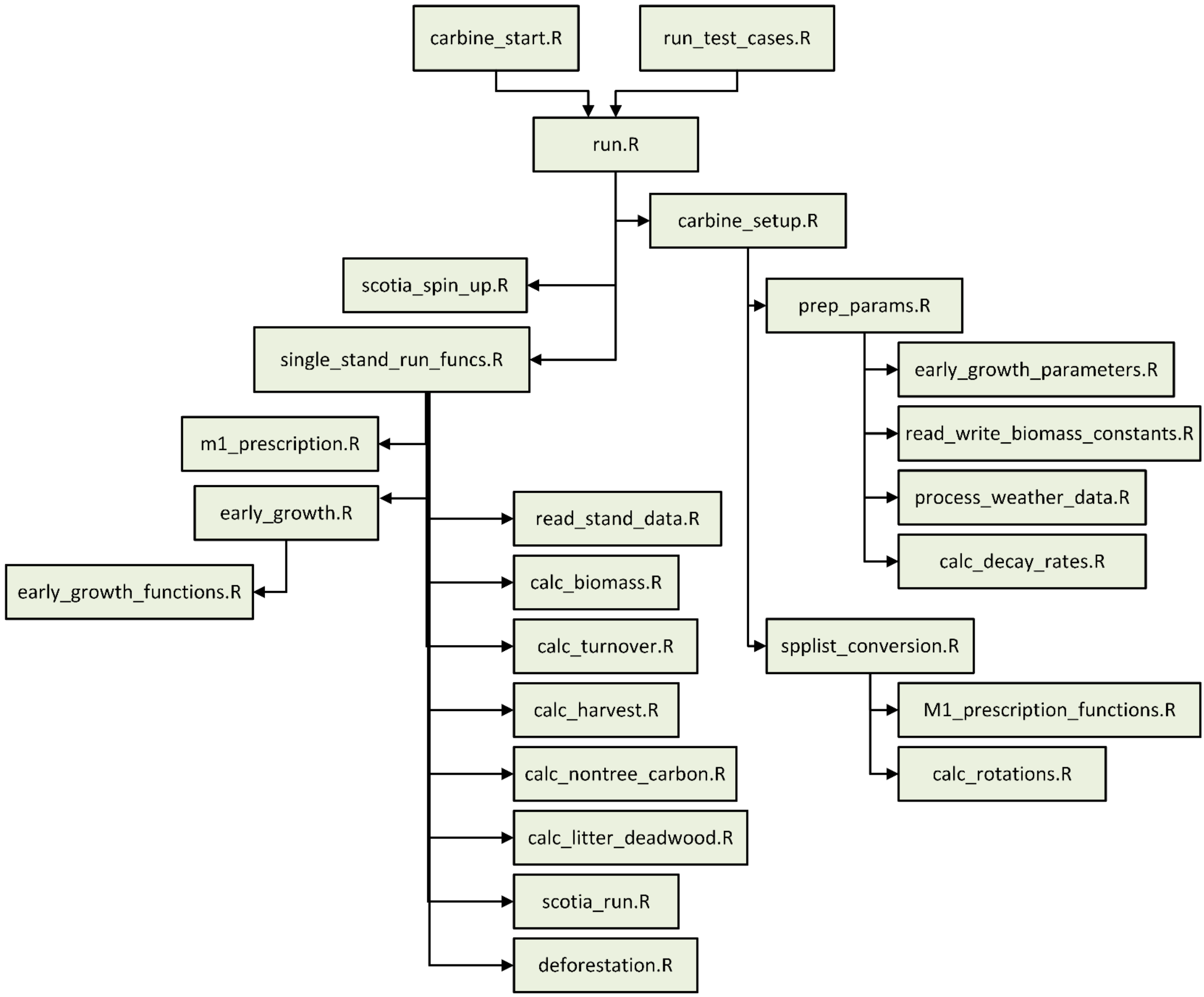

Figure 2. Running order of CARBINE-R scripts.

2.1. Regional scale level CARBINE description

2.1.1. Start & setup

Script: carbine_start.R

The **'carbine_start.R'** script is where the CARBINE-R model can be run. This is the only script with which the user needs to interact, unless the user is modifying code. The script can be run, thereby activating the whole CARBINE-R model to run, using the 'Source' button in the top right-hand corner of the script pane in RStudio.

The script then prompts the user to select a config file. This is first used to assign the run type for the model, which defines the file paths for the stand prescription.

The script then initiates the CARBINE setup scripts and loads the single-stand functions. It then sets up the 'run_carbine' function, which it applies to the list of generated spplists. Results for each stand are listed in the 'results' dataframe.

Script: Run.R

Actions stand level scripts

The 'run.R' script first calls the 'carbine_setup.R' and calls the 'single_stand_run.R' so its main function (called 'run') which enacts the single stand modules is ready for the next step. This script then sets up the 'run_carbine' function which enables the 'run' function to be looped through each stand prescription. The output of this is called 'stand_results' which is a list holding each stand's individual results.

Aggregation step

For multi-stand runs, the values across stands are aggregated into a single dataset. Each stand's values are aggregated where they share the same afforestation year, and values are summed across each reporting year.

For stands which are afforested after the projection start year (e.g., projection starts in 1500, and stand is afforested in 1700), the years before the stand is afforested are supplied with the pre-afforestation soil carbon calculated via the SCOTIA spin-up. This prevents any unusual jumps in stock change in afforestation years.

Output

The final step of this script is to write the outputs. The main outputs are:

- **ghg_inventory_output**: This is the output format used by the GHG inventory which summarises carbon stocks by afforestation year and reporting year. See Table 36 for full details of what this contains.
- **Annual carbon stocks:** Carbon stocks summarised by reporting year only.
- **Annual carbon stocks single stand:** An output for single-stand runs only; it attaches the run metadata, including species, rotation number, and management type, to the results.

Script: carbine_setup.R

The CARBINE setup script actions the loading and formatting of parameters by calling the **'prep_params.R'** script. It then actions the preparation of spplist files into the correct format for use in the M1 growth model by calling the **'spplist_conversion.R'** script. This script is kept in the M1 folder as it mostly interacts with the M1 growth model to inform how spplists should be reformatted.

Script: prep_params.R

This script first sets out to define the selected output options from the config file. The script identifies for which modules, if any, data or graph outputs have been selected and saves those in 'data_output_extract' and 'plot_output_extract' dataframes. These dataframes are then inspected in if statements for each graph to determine whether the graph should be produced and exported.

This script then sets up parameters for the following modules:

- Early growth module
  - The script calls the **'early_growth_parameters.R'** script to prepare parameters for this module.
- Biomass module
  - The script calls the '**read_write_biomass_constants.R'** script which reads in and reformats the expansion factor, wood density, and carbon content values used in the biomass module.
- Litter and Deadwood module
  - The script loads and formats the selected weather data file, as selected from the config file, and processes the data for use in the litter and deadwood module via the **'process_weather_data.R'** script.
  - The script then loads and formats the decay rates used in this module via the **'calc_decay_rates.R'** script.

Finally, the **'prep_param.R'** script reads in the default parameters which aren't held in parameter files from the 'default_param_options' sheet in the config file.

2.1.2. Model run modules

Script: Single_stand_run_funcs.R

This script is the source for calls of all the single-stand level modules, which is actioned by the 'run' function from the **'carbine_start.R'** script. The script also contains functions to generate the output folder file structure and to save the console log to a saved 'log.Rout' file.

Once the stand-level modules have been run, the 'aggregate_tree_carbon' function is used to combine standing tree crop and turnover results to generate a 'before thin' representation of the stand, which is required for GHG inventory outputs. This represents the state of trees at the 'start' of the year, when it is assumed that no decay (turnover) or thinning has occurred. Therefore, the estimated turnover values are added to the standing crop values (crop, mort, and thin/fell stages).

This script then also adds in the reporting year, i.e., the calendar year to which the stand results correspond. Finally, the **'calc_deforestation.R'** script is run to calculate the total carbon stocks in forested areas accounting for deforestation rates.

Script: Spplist_conversion.R

This script takes the spplist output from Reconcile. The spplist details the management to be applied to the stand. The spplist comes as a .dat file. The spplist may describe one or more management periods for the same stand. Each management period is specified in its own set of columns (wide format). An example is shown below for a stand prescription for stand "NDBN" with four management periods (each period is identified by alternating bold and normal font):

NDBN **SY SY 12 2 201 T 1814** SY SY 12 2 100 T 0 1955 **SS SS 18 1 999 F 5 2014** CP SP 16 2 150 T 0

This would indicate that AREANDBN.dat file would contain areas associated with the stand prescription above:

Management period 1 (**SY SY 12 2 201 T 1814**) specifies management of planting sycamore, yield class 12, standard thinning (2) applied, for a 201-year rotation length, with clearfelling and transitioning to a new management in the year 1814. No fallow periods are specified in the first management period.

Management period 2 (SY SY 12 2 100 T 0 1955) specifies a sycamore rotation, yield class 12, with standard thinning (2) over a 100-year rotation, clear fell at the end, a zero-year fallow period, running up until the next transition year of 1955.

Management period 3 (**SS SS 18 1 999 F 5 2014**) specifies a Sitka spruce rotation, yield class 18, under a no thin regime (1), with a rotation length of 999 years and no clear fell occurring (i.e., no management regime). A fallow period of 5 years is applied at the start of every rotation. This management continues up until the transition year of 2014.

Management period 4 (CP SP 16 2 150 T 0) specifies a Corsican pine planting which is mapped to Scots pine for the wood product utilisation process. The trees are yield class 16, with standard thinning (2) applied and a rotation length of 150 years, clearfelled at the end of the rotation and with a zero-year fallow period. No transition year is given for the final management period in a spplist.

The **'spplist_conversion.R'** script converts this into a usable format for R and the **'M1_prescription.R'** script. The main steps are:

1. Read in stand settings
    - Sets the key parameters of when the model projection starts (afforestation / planting year) and for how long the projection is to run.
2. Extract spplist into R-friendly format
    - For GHG inventory and test case runs, the spplist is generated as a .dat file, which is presented as a headerless, single row with data for each management transition specified in additional columns (a wide format).
    - The 'convert_spplist' function reformats this into an R-friendly 'long' format, adding in the correct column name. The correct allocation of columns into rows (each row representing one period of management) is worked out based on the pattern of column lengths, as this changes depending on the number of transitions and whether it is a first or last transition.
    - This section is skipped for manual spplist runs, as the formatting undertaken in the 'convert_spplist' function occurs during the manual generation of the spplist in excel instead.

3. Add management detail

- The spplist provides only the essential information on the management. This section adds in further detail and description for each management setting.

4. Extract stand year

- This code chunk extracts the planting year from the 'AREA' file; this is matched to the spplist by using the area code. This is done with the 'get_planting_year' function.
- Up to this point, the spplist is presented in calendar year for both planting and transition years. This code chunk adds a 'stand year' which begins at year zero when the stand is first afforested. Transition years are then converted to the relevant 'stand_year'. For example, for a planting year of 1500, the transition year would be converted from calendar year 1700 to a stand year of 200.
- Note that, in this section, the projection start year (read in from the config file) is overwritten with the planting date in the area file.

5. Check transitions relevant

- This code chunk runs through checks on management periods using the 'check_transitions' function to ensure that they do not occur outside of the projection period (before the stand is planted or after the end of projection).

6. Estimate LISS rotation lengths

- Although a rotation length is given for LISS management periods in spplists, these may not reflect the true rotation length, which needs to be calculated using the M1 growth model.
- First, the stand prescription is split into LISS management periods and non-LISS management periods. The LISS management periods are run through

the ‘calc_liss_length’ function to run a rotation under that management specification through M1 and extract the rotation length. A lot of dummy values are fed to M1 at this point, such as rotation number and age etc., to allow the LISS rotation to run to its full end (all trees thinned) without interruption. The corrected rotation length is then inserted into the stand prescription which are then joined back with the non-LISS rotations.

7. Calculate rotation start and end years

- This code chunk estimates the start and end year of each rotation, representing each rotation in one or more rows in the dataframe. Where transitions occur during a rotation (which do not require a tree change, i.e. a restock to different species or yieldclass), each period of the rotation under the different management conditions is specified in a different row. The different start and end dates of these transition periods within rotations are also calculated here.
- This is carried out using the ‘calc_rotations’ function which is specified, along with supporting subsidiary functions, in the **‘calc_rotations.R’** script. See full description of that function here: Script: Calc_rotations.

8. Add in clearfell age

- Clearfell age is a required input value to M1. It is required even for rotations which are not clearfelled, for which it instead represents the value when that rotation ends. It is calculated using the ‘add_clearfell_age’ function, as the total rotation length (‘entire_rotation_length’). This variable is calculated within the ‘calc_rotations’ function and accounts for length of rotations over multiple transitions within the same rotation.

9. Expand short rotations

- The early growth fix module requires at least four years of tree data to run. Any rotations less than four years in length must be artificially extended so that their early growth can be correctly calculated in the early growth module. The artificially added rotation length is removed in the **'read_stand_data.R'** script.

10. Output

- The formatted M1 prescriptions are then output as .csv files.

Explainer 1. Understanding rotation lengths

The assumption in CARBINE is that the rotation length is the age at which the stand of trees will be felled. If there is no fallow period, the next rotation is assumed be planted in the same year that the last rotation was felled (i.e., so that a growing season is not missed). This is illustrated in Table 4.

Table 4. Example rotations of varying lengths and fallow periods.

Rotation number	Start year	Fallow period	Rotation length	End year	Tree age at start	Tree age at end
1	0	0	100	100	0	100
2	100	0	125	225	0	125
3	230	5	100	330	0	100
4	335	5	100	435	0	100

Note that M1 only models growth from tree age 1 onwards as the trees are assumed to not contribute any carbon to the various carbon pools in the year of planting.

Note: Full rotation length is classified in the R code to help calculate subsequent start years. It is also calculated to include fallow period. For example, if the rotation length was 100 years and it had a fallow period of 10 years, the full rotation length would be 110.

Rotation start dates and transition years

If a transition is occurring at the end of rotation (either coincidentally or because transition was delayed to allow rotation to finish so the new transition can start with new trees), then:

> next transition start year equals the previous transition end year, which equals the transition year, i.e., the rotation is felled and the next rotation planted in the same year.

If a transition is occurring during a rotation, where there isn’t restocking occurring, then the previous transition must end the year before the transition year. This is to prevent double-counting of two standing crops in one year.

Explainer 2. Understanding fallow periods

Fallow periods are considered to occur at the beginning of the rotation (as opposed to being added on the end of a rotation).

A fallow period is technically only considered to cover the growing season (summer). Due to this, a 1-year fallow period doesn't require its own 'year' to be completed. Instead, it can occur in the same year the previous rotation is felled, allowing the next rotation to occur in the following year. See Table 5 and Table 6 for a comparison between a scenario assuming no fallow and an equivalent scenario assuming a 1 year fallow period.

Table 5. Description of an example scenario in which a 1-year fallow period is assumed. The end year for the first rotation is year 200. The start year for the next rotation, after 1 year fallow, is year 201.

Year	Period	Activity
200	Spring	fell
200	Summer (growth)	fallow
200	Winter	fallow
201	Spring	plant – age 0
201	Summer (growth)	age 0
201	Winter	age 0

Table 6. Description of an example scenario in which no fallow period is assumed. The end year for the first rotation is year 200. The start year for the next rotation, with no fallow, is also year 200.

Year	Period	Activity
200	Spring	fell Plant (age 0)
200	Summer (growth)	age 0

Year	Period	Activity
200	Winter	age 0
201	Spring	age 1
201	Summer (growth)	age 1
201	Winter	age 1

Fallow periods cannot occur in the very first rotation, as the first rotation always starts in the year in which trees are planted.

Fallow periods also cannot occur between consecutive LISS rotations as, by definition, these involve continuous canopy cover without gaps in tree cover.

Script: Calc_rotations.R

This script iteratively calculates the start and end date of each rotation and each management 'phase' within each rotation. It is important that this is done iteratively, because rotation lengths cannot always be pre-calculated as they depend on the timing of transitions, especially where there are transitions to LISS regimes. The iteration ensures that each rotation correctly follows on from the end date of the previous rotation. The script loops through each management period, calculating all rotations within that period, whether that period occurs for just one part of a rotation or covers multiple rotations.

The key rules for creating rotations are:

- The next rotation is planted in the same year the previous rotation is felled (if fallow period is zero). Therefore, if rotation 1 is felled at year 100 at age 100, rotation 2 is planted in year 100 at age 0.
- When a transition takes place within a rotation, which doesn't require a tree change, then the next rotation starts in the transition year, and the previous rotation ends the year before.
- When a transition takes places during a rotation, which does require a tree change, then the current rotation must complete before the transition to the new management regime can take place. The new rotation with the new management will be planted the same year the previous rotation is felled.

'Calc_rotations.R' steps:

This script creates a new 'rotations' dataframe to which to iteratively add each phase of rotation. This is initially created with a dummy 'pre-start' rotation. As the logic in much of this function calls on what occurs in the previous row, this first dummy row allows the same logic to be applied to the first true rotation.

The script then enters a for loop, which runs for each transition period (i.e., each row) in the input spplist. For each management period:

  - The management settings for this management period are extracted and placed into a holding 'new_rotation' dataframe.
  - The next step varies as to whether the last rotation couldn't be completed (i.e., whether a transition has occurred mid-way in the rotation). This is outlined below.

If yes (previous rotation was not completed):

- Work out if there's any remaining fallow period. Transitions may occur during the fallow period, which may need to completed if new management period has the same or longer fallow periods, or immediately ended if the new management period has no or a smaller fallow period. The remaining fallow period is calculated based on this information, and the rotation start year (when trees are planted) is adjusted accordingly. A new 'remaining rotation length' value is calculated reflects when the current rotation should end based on how long it has existed under the previous management period and the current management period's fallow period length and new rotation length.
  - If transitioning to LISS, need to re-work out the LISS rotation length as it will depend when it begins from where previous part of the rotation ended. This new rotation length is then used to update the 'remaining rotation length' value.
    - If this mid-progress rotation can be completed (based on the remaining rotation length) before the next transition year:
      - If yes:
        - Finish the mid-progress rotation under the new management settings
        - If can add a full rotation before the next transition year, then add it and keep adding full rotations until cannot. This uses a while loop which repeatedly calls a

'add_full_rotations' function until a full rotation cannot be added before the next transition year occurs. calc_step tag = "add full rotation". Apply LISS overlaps at this point if in a LISS management period

- Once a full rotation can't be added, check if the next rotation requires a tree change or not.
- If it does require a tree change (and checking this tree change does not occur in a fallow period), then allow a full rotation to be added, altering the transition year to the year this full rotation ends. Then return to the start of the for-loop to begin again with the next management period. Calc_step tag = "1. Mid-rotation transition delayed due to tree change"
- If it doesn't require a tree change, then the management transition can occur mid-rotation. The first part of this rotation under the current management is added, ending the year before the next transition starts. A flag is added to identify this as a 'mid-progress rotation'. Then return to the start of the for-loop to begin again with the next management period. Calc_step tag = "1. Mid rotation transition without tree change".

- If no, cannot complete a mid-way rotation, then need to a 'middle' section to the rotation. Again, need to check if there's a tree change or not.
  - If it does require a tree change. calc_step tag = "2. Mid-rotation transition delayed due to tree change"
  - If it does not require a tree change. "2. Mid rotation transition without tree change"

If no (previous rotation was completed):

- If a full rotation can be completed before the next transition year, then add it and keep adding full rotations until cannot. This uses a while loop which repeatedly calls a 'add_full_rotations' function until a full rotation cannot be added before the next transition year occurs. calc_step tag = "add full rotation".
  - Once a full rotation can't be added, check if the next rotation requires a tree change or not.
    - If it does require a tree change, then allow a full rotation to be added, altering the transition year to the year this full rotation ends. Then return to the start of the for-loop to begin again with the next management period. Calc_step tag = "3. Transition delayed due to tree change".
    - If it does not require a tree change, then the management transition can occur mid-rotation. The first part of this rotation under the current management is added, ending the year before the next transition starts. A flag is added to identify this as a 'mid-progress rotation'. Then return to the start of the for-loop to begin again with the next management period. Calc_step tag = "3. First rotation phase before transition without tree change".

2.2. Stand level CARBINE description

2.2.1. M1 Tree Growth model

The CARBINE model obtains information on the growth of stemwood volume in different stands of trees from the M1 growth model (Arcangeli and Matthews, unpublished model), which is a dynamic representation of the standard UK forest yield tables (Matthews et al., 2016). These yield tables have been constructed based on field measurements of forest growth from a network of permanent forest mensuration sample plots in Great Britain, covering a relatively large number of tree species and rates of growth.

The M1 model predicts the annual stem volume in a specified stand of trees, defined by three main factors:

- Tree species
- Stand growth rate
- Management regime.

Some examples of outputs of the M1 model are shown in Figure 3. The figure shows the development of standing tree stem volume with stand age, as predicted by the M1 model for two example stands of Scots pine. The stands are assumed to have a potential maximum growth rate (yield class) of 6 m^3 ha^{-1} yr^{-1} and the trees are established with an assumed initial density of about 5,000 trees per ha.

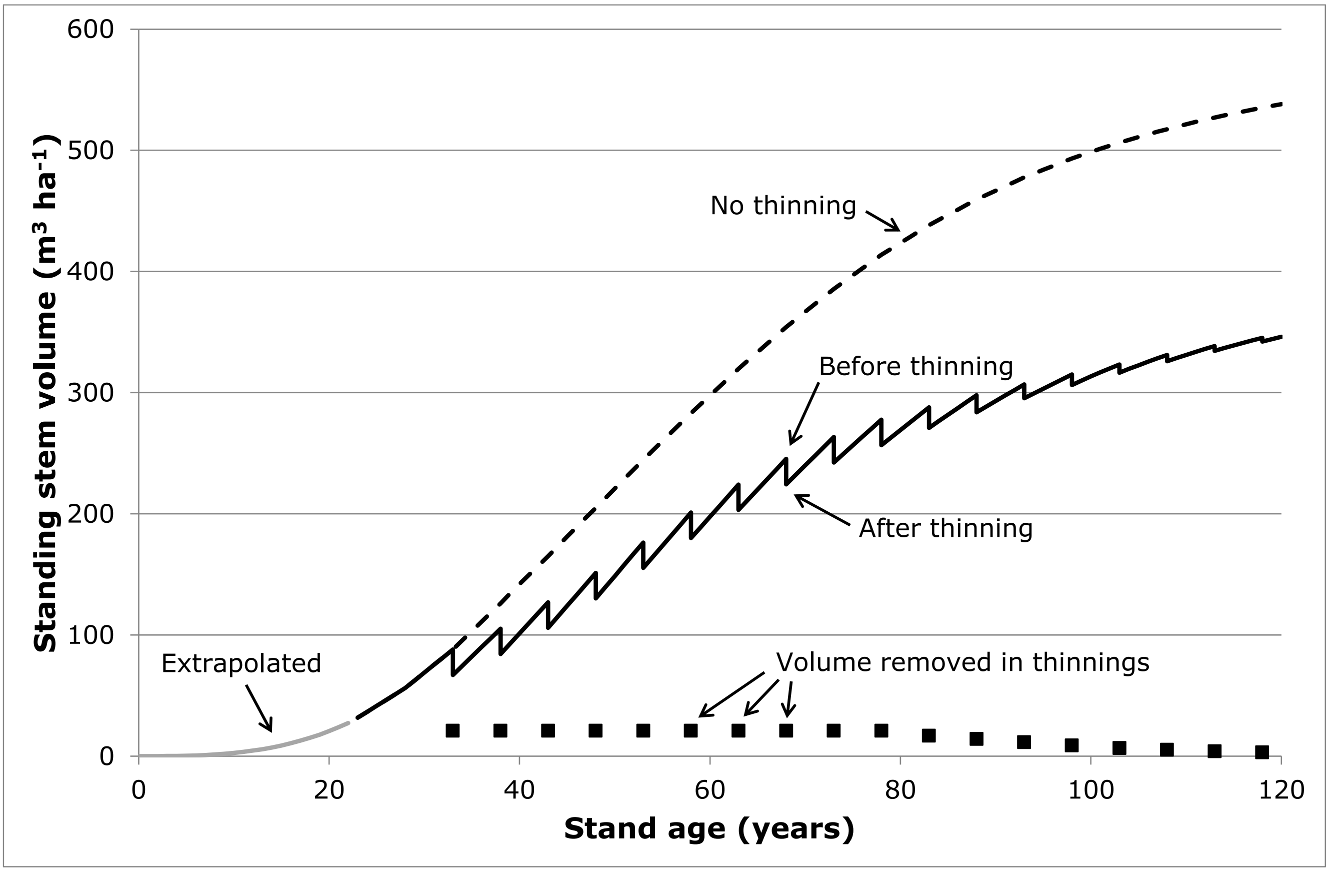

Figure 3. Development of stem volume with age as predicted by the M1 model for stands of Scots pine with a maximum stem volume production potential of 6 m^3 ha^{-1} yr^{-1}, showing the impacts on predictions of assuming either no disturbance or thinning of the stand of trees (dashed black line) compared with regular thinning of the stand (solid black line).

The M1 outputs are reported at a stand level, i.e., at a scale of 1 ha, and include results for dominant height, numbers of trees, mean stem diameter, and stem volume per ha. Individual tree growth is not represented either in the M1 model or in CARBINE and is not required at the scale at which CARBINE is generally intended to be applied, i.e., national or regional simulations encompassing thousands or millions of ha of forest. Complete forests are represented in CARBINE as a collection of individual forest stands, each with a specified area, tree species, growth rate, tree age, and management regime.

Script: M1_prescription.R

This script takes a spplist file which details the management to be prescribed to each stand. The prescription provides instructions for the management of each stand over its entire timeline. This module prepares this prescription for input into the M1-R model, which uses the prescription to graph tree growth and volume estimates.

For the simplest form of prescription, the stand has the same management and species planted throughout its entire timeline. Other stands, however, may have one or more management transitions, where the form of management is changed. Each period of management transition is given its own row in the prescription dataframe.

Transition periods can occur at any time, i.e., a Scots pine stand under a thin and fell regime could be changed to a LISS regime 100 years after planting. Note that changes in species and yield class can only occur at the end of rotations.

The prescription structure is shown in Table 7.

Table 7. Structure of the stand prescription which is used by the M1 model to estimate tree volume growth.

Column name	Description
Stand_ID	ID of each stand
Area_code	Code which matches to an area file which lists the areas planted in each year with this stand prescription
Species	Species planted code (note that species codes can only change when a rotation ends)
Yieldclass	Yield class code

Column name	Description
Species_wp_utilisation	The matched species code to model the wood product (wp) utilisation under in the harvest module
Liss_overlap	The number of years of which two consecutive LISS rotations overlap by (default = 30?)
Rotation_length	The length of rotations (years) – i.e. length of time trees in ground (fallow periods are not considered to be 'within' the rotation
Years_since_stand_afforested	The years this management period first starts in (i.e. 0 for the first management period, and then year 200 for the second management period if the rotation length is 200 years).
Transition_present	Y/N code as to whether or not any transitions are present for this stand
Num_transition	The number of transitions present across this stand's timeline
Fallow_period	The number of years of fallow before a new rotation is planted. Fallow periods are applied to the start of new rotations. Fallow periods are not considered for the first rotation.
Transition_period	A numeric indicating if it's the first, second, third etc transition period in the stand's timeline
Transition_year	The year (based on the stand timeline) when the change in management takes place
Management_code	The management code to be applied for this management period

Column name	Description
No_go_period	The number of years which before the stand is felled in which no thinning takes place (default = 6 years)
Thin_cycle	The number of years between each thin event (default = 5 years)
Rotation_order	A string value indicating if this rotation is the first, middle or last rotation in the stand's timeline. This could be useful to do checks, such as preventing fallow periods being calculated for the first rotation.

A challenge with the stand prescription is that it needs to be as 'anonymous' as possible so that it can be applied to stands being planted in different years. As such, the timings of changes in management etc. are all calculated based on 'time since stand afforested' (in other words on the 'stand timeline'). This way, a single prescription can be applied to a stand first planted in 1800 and one planted in 1870.

This script has the following steps:

- Reads in the stand prescription
- Extracts the afforestation year
- Checks stand prescription is appropriate – there are some combinations of management which M1 cannot model, so we need to alter the prescription if this is present. These include:
  - Checking there are no transitions away from LISS to a thin regime:

    We do not have yield tables to estimate how trees will grow after being in a period of LISS or how to estimate thinnings from this. Therefore, if a

LISS period (code 3) is changed to any other code, we need to change the code to 1 (no thin, clearfell).

- Remove unused fallow periods

- Set management conditions for each management regime (see Table 8)

Table 8. Management details mapped to prescriptions required for M1 runs. The column name 'Is_mt_thin_regime' indicates whether management regime matches a management table (mt). The column name 'Is_floffs' indicates if there is a "fall off" on thinning as stands age – for thins in code 2, thins get smaller as more and more trees are removed. In LISS regime (code 3) as the stand is thinned in extinction, thinnings do not get smaller in subsequent cycles.

Management_code	Management_description	Is_clearfelled	Thin_code	Thin_description	Is_thinned	Is_mt_thin_regime	Is_floffs
1	No thinning, clearfell	clearfelled	1	No thinning	FALSE	NA	TRUE
2	Thinning, clearfell	clearfelled	2	Thinning	TRUE	NA	TRUE
3	LISS	Not clearfelled	3	LISS - thinning	TRUE	NA	FALSE
4	No management (no thinning or clearfell)	Not clearfelled	1	No thinning	FALSE	NA	TRUE

- Run M1
  - This section works through each rotation in the stand prescription and:
    - Checks if there is a transition present:

        - If ‘N’ then go straight to running M1 with the prescription with minimal prep using the ‘prep_standard_run’ function.
        - If ‘Y’ then there is a transition present and we need to work out the bespoke thinning regime for the rotation with the transition present. This has several steps coded as functions:
            - ‘get_bespoke_thin_regime’
            - ‘prep_m1_bespoke_run’
        - Once both standard and bespoke M1 runs prepared, then M1 can be run using ‘run_m1’ function (see ‘m1_prescription_functions’ script description below for details of these functions).
    - Once all rotations have been run, the results are then joined together.
- Extract tree metadata

The output from this script is a dataset called ‘stand_results’ which contains a list of each rotation. Each rotation item contains:

- Crop_extra_results
- Input_params
- Tree_results
- Errors
- Has_errors

The main dataset used from this is ‘tree_results’, so these are extracted for each rotation and joined into a single dataset: ‘stand_tree_results’.

Script: M1_prescription_functions.R

This script contains functions which are called in the ‘m1_prescription.R’ script.

Prep_standard_run

This function extracts the values needed from the prescription into the format for M1 to use it. This largely means adding the data into two 'S4' data class objects: StandManagement and StandInformation.

Run_m1

This is the main function to call M1 to extract outputs to use in CARBINE-R. The function requires StandInfo and StandManagement inputs generated by prep_standard_run or prep_bespoke_run.

M1 outputs tree volumes in three forms:

- Bmbt (before mortality, before thinning)
- Ambt (after mortality, after thinning)
- Amat (after mortality, after thinning).

The amat dataset is used as the main crop dataset.

The data just for dead trees (termed 'mort' stage) are extracted as the difference between the ambt and bmbt datasets. The values for dead trees are calculated as:

$\text{Volume}_{\text{mort}} = \text{volume}_{\text{bmbt}} - \text{volume}_{\text{ambt}}$

$\text{Basal area}_{\text{mort}} = \text{basal area}_{\text{bmbt}} - \text{basal area}_{\text{ambt}}$

$\text{Number of trees}_{\text{mort}} = \text{number of trees}_{\text{bmbt}} - \text{number of trees}_{\text{ambt}}$

Diameter at breast height (DBH) and mean volume are average values for each tree in the stand and are therefore calculated as:

$$Mean\ dbh_{mort} = 200 \times \sqrt{\frac{basal\ area_{mort}}{\pi \times number\ of\ trees_{mort}}}$$

$$Mean\ vol_{mort} = \frac{volume_{mort}}{number\ of\ trees_{mort}}$$

The data for thinned trees can be extracted in a similar way using the difference between ambt and amat, or else using a built-in function to M1 of 'GetThinnings'.

The three stages of data (crop, mort, and thin) are combined together into the main 'tree_results' dataset (see Table 9 for structure of this dataset).

Table 9. M1 outputs for 'tree results'.

Type	Column	Description
Default M1 output	tree_age	Age of trees
Default M1 output	num_trees	Number of trees
Default M1 output	basal_area	Mean basal area across all trees
Default M1 output	dbh	Mean DBH across all trees (recalculated for mort trees)
Default M1 output	Mean_vol	Mean volume across all trees (recalculated for mort trees)
Default M1 output	vol	Total volume
Added column	stage	Assigned "crop", "thin" or "mort" stage. All values above are provided for each stage.
Added column	Rotation_age	Age of rotation in years
Added column	stand_year	Year since stand first afforested

Local yield adjustments are applied to this combined dataset if necessary. Local yield adjustments are applied when tree species and yield class combinations are not parameterised within M1. Therefore, they have been run under a different species and yield class combination and the local yield adjustment value converts this output into one more expected to match the output for the input species and yield class. See section 3.7.10 for further description of local yield adjustments)

Any errors in the M1 run are also extracted and reported for each rotation's run.

The outputs are then returned from this function, those being:

- Crop extra results: a dataframe similar to the 'crop' stage but with further tree details. These are not currently used later at any point in CARBINE but are extracted to enable any future use
- Input parameters: a list of all the input values used for this CARBINE run
- Tree results: the main dataset of crop, thin and mortality data containing the volume estimates from M1.
- Errors: A list of any errors encountered during the M1 run
- Has_errors: a true/false value indicating if any errors were encountered during the M1 run.

2.2.2. Early Growth

The early stage of stand growth (typically up to around age 20 years) is not explicitly represented in the M1 model. The early development of stem volume is, therefore, inferred from the extrapolation of the M1 predictions for later ages back to earlier ages, assuming that stem volume is zero at age zero. From these early growth stand volume estimations, DBH, basal area, and mean volume can then be calculated to complete the early growth data.

Script: Early_growth.R

This script applies these calculations using functions and parameters defined in early_growth_functions.R and early_growth_parameters.R. The operation of these early growth volume and subsequent DBH, basal area, and mean volume calculations can be toggled on or off by changing the parameters feg_toggle and feg_toggle_dbh to either TRUE or FALSE.

Main steps:

1. Read in functions
    - Reads in several functions from early_growth_functions.R.

2. Check for valid toggle state combinations
   - This snippet gives a warning message if early growth volume fix is disabled whilst early growth dbh/basal area/mean vol fix is enabled, stating that no early growth fixes will be performed.
3. Check toggle states and fix early growth
   - This code chunk checks the toggle states for enabling early growth volume calculations and early growth dbh, basal area, and mean volume calculations. If both toggles are disabled, no changes to the m1_prescription.R output 'stand_tree_results' are made. The early growth volume fix may be enabled without first enabling the early growth dbh/basal area/mean volume fix. However, the early growth DBH, basal area and mean volume fix requires extrapolated results from early growth volume predictions and so may only be enabled if early growth volume fix is also enabled.
   - The parameter 'max_trees' (the maximum number of trees per ha) from is joined onto the 'stand_tree_results' output from m1_prescription.R for use in DBH, basal area and mean volume calculations.
   - The stand data is split by rotation number and early growth volume calculations defined in the function 'apply_early_growth' are mapped across each.
   - early growth DBH, basal area and mean volume calculations defined in the function 'apply_calc_basal_area_dbh' are then mapped across each, before list elements are bound back together.

Script: Early_growth_functions.R

This script contains functions for calculating early growth stand volume and subsequent DBH, basal area, and mean volume calculations.

Main steps:

1. Split stand rotation list by species and yield class
   - The function ‘apply_early_growth’ takes stand data split by rotation number and further splits into lists grouped by species and yield class. The function ‘fix_early_growth’ is then applied to each species and yield class combination in the list, before binding the rows back together.
2. Calculate age1 and parameters
   - When called, the function ‘fix_early_growth’ extracts the species, yield class, rotation number, and first thinning age of the group. The calculations for age1 then begin first setting it to the tree_age maximum+1. The code then loops by index over tree_age, setting age1 to tree_age the first instance when thin volume is greater than 10 before exiting the loop, thereby automatically calculating first thinning age.
   - If first thinning age for the group is greater than 0, age1 is then set as the minimum between age1+4 and first thinning age −2. If no adjustments are made to age1, i.e. age1 remains to be the maximum tree_age+1, then age1 is set as the tree_age maximum.
   - Overall, age1 is usually set to first thinning age −2.
   - Stand volumes at age1 and age1+1 are then extracted to be used as parameters for calc_spline.

Calc_spline

- The function ‘calc_spline’ is then called. This function serves to calculate the parameters for the exponential and linear functions used to fit the early growth splines. Beta and alpha are parameters for the exponential spline component; slope and const are parameters for the linear spline component and; xspline is a parameter that defines the joining point between the exponential spline and the linear spline. Xspline is calculated using the x = f(x) approach to a numerical solution, where the solved value for xspline gives the same value and slope at the join point for the initial curve and the backwards-extrapolated points.

- An initial estimate of xspline is made, equal to 90% the distance between the x-intercept (or 0.1, whichever is larger) and age1. A While loop is then used to converge on the true xspline value, utilising Aitken's delta-squared process to accelerate convergence.
- The returned parameters from calc_spline are then used to apply an exponential spline from age zero to xspline, and a linear spline from xspline+1 to first_thin_age-1.

Script: Early_growth_parameters.R

This script is called from the 0_prep_params.R script and format the main input parameters for the early growth fix. The parameters read in are:

- max_no_trees – contains species, yield class, and corresponding maximum number of trees plants
- early_growth_parameters – contains:
    - feg_toggle – an on/off toggle for running early growth stand volume calculations
    - feg_toggle – an on/off toggle for running early growth DBH, basal area, and mean volume calculations
    - beta_val – the scaling factor for the exponential function for calculating early growth stand volume

2.2.3. Biomass module

Script: Read_stand_data.R

The purpose of this script is to format the outputs of the M1 growth model (via the early growth module) for use in the later modules. The main steps in this are:

- Clean the data
  - Removing any unnecessary columns and adding full species names etc
- Remove dummy rotation extensions
  - In the M1 prescription module, some very short rotations were artificially extended so early growth could be appropriately modelled in the early growth model. This is because the early growth module requires at least 4 years of tree data to run. This code chunk therefore identifies the artificially extended years using a tag 'rotaton_length_extended' and removes these years from the dataset.
- Remove years after projection end date
- Extend values after maximum age.
  - For a rare management type (thin, but no fell), rotations can occur beyond the maximum age which the growth model M1 can model (500 years). In this situation, to prevent rotations being thinned to extinction, the 500 year stem volume and other tree size values are fixed to the value at age 500 for all ages over 500.
- Find clearfell age
  - Clearfell years (unlike thinnings) are not automatically output from the M1 model. They therefore need identified from the 'crop' stage data in the final year in a rotation.
- Fill fallow periods
  - The M1 model only outputs values for when live trees are present. This section of the code adds in the years which represent fallow periods (where there are no trees in between two rotations) into the dataset.
- Graphs
  - Optional graphs are output to show the stem volume by stage

Script: Read_write_biomass_constants.R

This script is called from the prep_params.R script in the setup stage of the model. It loads and prepares the three main parameters used in the biodiversity module:

- Expansion factors
  - These factors are used to extrapolate volume in tree crown (branches + foliage), foliage, coarse roots, and fine roots.
- Wood density
  - These factors are used to convert from volume to biomass.
- Carbon content
  - These factors are used to convert from biomass to carbon.

Script: Calc_biomass.R

Conversion from stem volume to whole tree volume

The M1 model outputs the stem volume estimate for tree stands. The biomass module first converts the stem volume outputs from M1 model into volume for each tree component (crown, foliage, coarse roots and fine roots). The volume of components are set up in a matrix column. Volumes in branches are calculated as the difference between crown and foliage values.

Conversion from volume to biomass

The volume data is then converted to biomass using wood density parameters.

The biomass of fineroots is constrained to 4 tonnes C ha^{-1}. This value is applied to prevent fineroot values expanding to what is assumed to be unrealistically large values. It is also assumed that dead trees (mort stage) have no biomass in fineroots or foliage components.

Conversion from biomass to carbon

Biomass is then converted to carbon using wood carbon content factors. A single standard carbon content value of 0.5 tC odt^{-1} is assumed.

Dead trees are assumed to have no foliage or fineroots, so all volume, biomass and carbon values for these components for dead trees are changed to zero.

Disaggregation of dataset

Once carbon stocks in all trees are calculated, this dataset is split up to allow certain tree data to be funnelled into the correct next module. The main output datasets are:

Crop: This dataset contains the live standing trees after any harvesting. No further changes are made to this dataset and it is output in the final results at this point. It is also used in the turnover and non-tree vegetation modules.

Mort: This dataset contains the standing dead trees, minus any that are harvested in thin or fell years. This dataset is passed through to the litter and deadwood module.

Harvested: This dataset contains the trees which are thinned or felled. It also includes any dead trees which are assumed to be harvested in thin or fell years. This dataset is passed through to the harvest module.

Fallow: Any years where there are no trees on site (i.e. years in between rotations known as fallow periods) are extracted for later use in the non-tree vegetation module

Output data:

Output data is split into different datasets which are then sent to different subsequent modules for stage specific calculations:

- Crop stand data
    - Values for live standing trees in the ‘crop’ stage
- Harvested trees

- ○ Thin and fell stages, plus any mortality which occurs in thin or fell years

- Mort stand data

    - ○ Standing dead trees, minus those harvested in thin or fell years

Output graph:

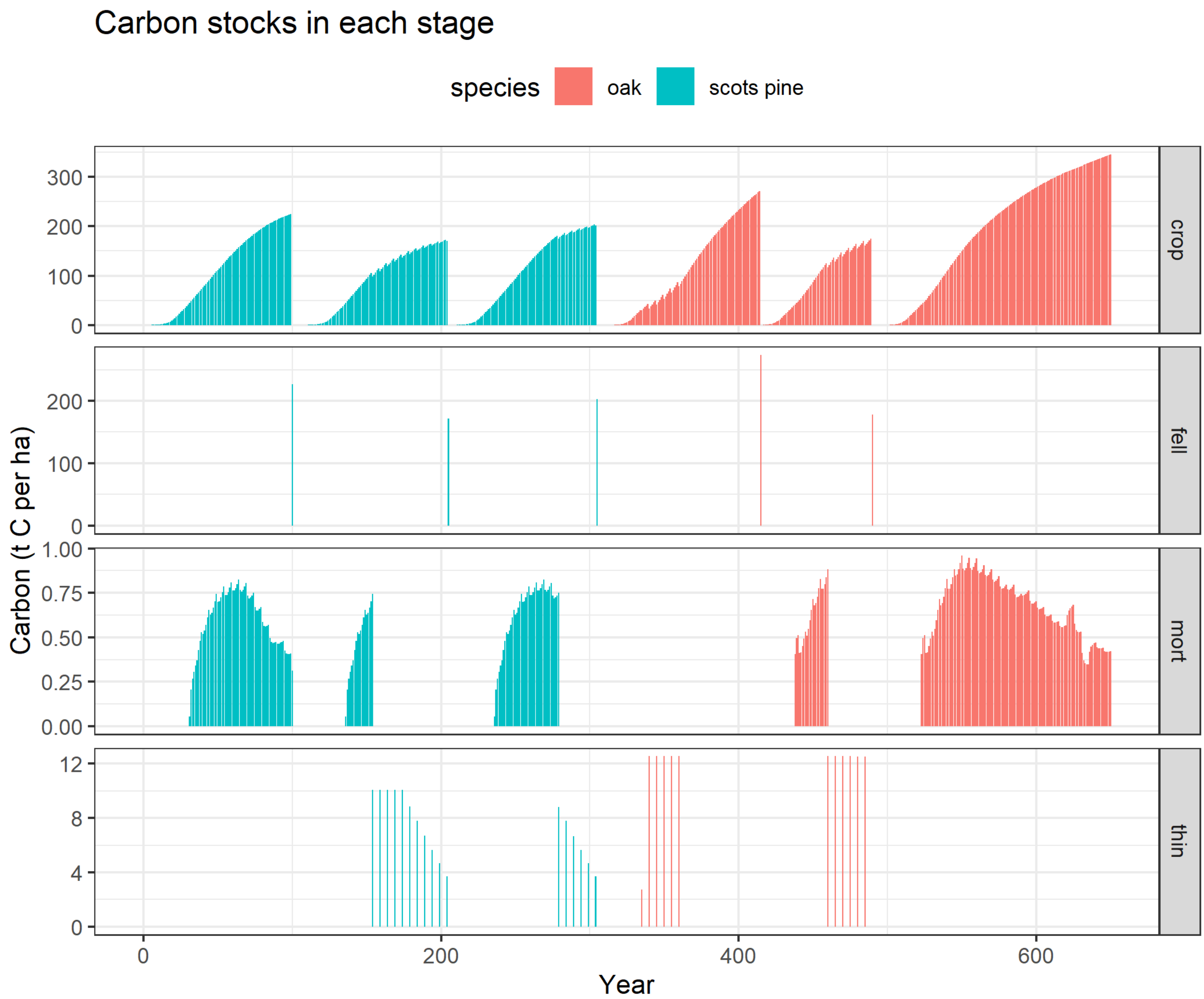

Figure 4. Output graph from the biomass module showing carbon stocks per ha for a stand with four rotations, starting with Scots pine for two rotations and then oak for two rotations. The top row of the graph shows the carbon in live standing trees (crop), the middle graph shows standing dead trees (mort) and the bottom graph

shows the carbon stocks in thinned and felled trees (thin). Note the y-axis has different scales for each graph.

2.2.4. Turnover module

Script: Calc_turnover.R

The turnover module calculates the amount of carbon that is lost from live standing trees as part of senescence, or natural decay of live trees, such as occasionally dropping branches or deciduous trees dropping leaves in winter. Turnover is assumed to occur before thinning occurs, so turnover for both crop and thin/fell stages is calculated.

Turnover rates vary as to whether they are specific to a species, tree type (deciduous or evergreen) specific or general across all species. Turnover rates for branches and coarse roots are constant across all species. Turnover rates for foliage and fine roots are not always species specific. There is assumed to be zero turnover from the stem component.

The carbon calculated in live trees in the biomass module is already exclusive of these carbon losses (and therefore these turnover carbon stocks do not need to be subtracted from the tree carbon stock). The carbon from tree turnover is then input into the deadwood, litter and soil carbon pools.

Input data:

- Stand data 'crop' stage from biomass module
- Stand data 'thin' and 'fell' stages from biomass module

Output data:

- Turnover data: this is passed through to the litter and deadwood module to be used to calculate litter, deadwood and soil carbon pools

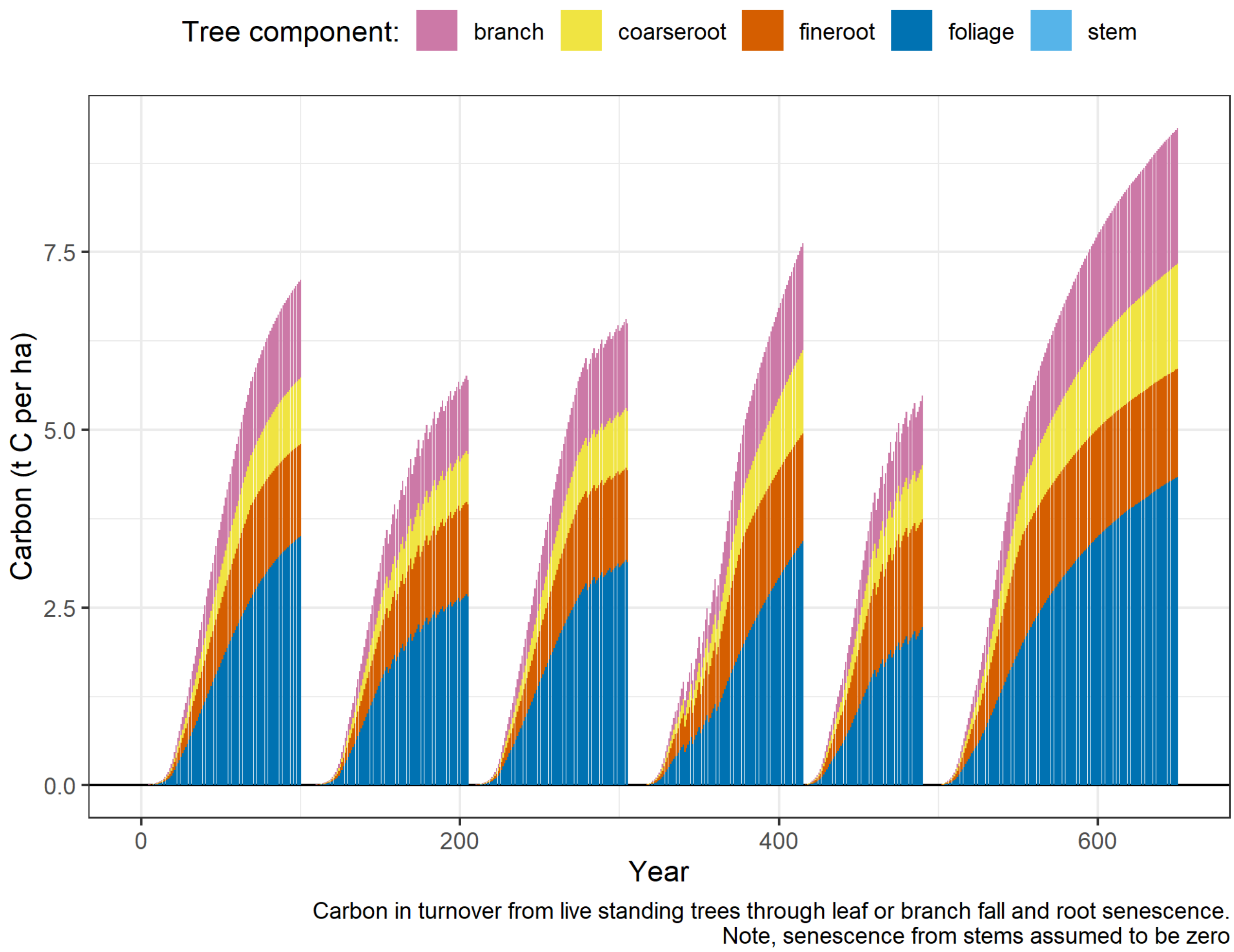

Figure 5. Output of the turnover module showing carbon in 'turnover' which is destined for either litter or deadwood pools. The graph shows turnover production over four rotations and its source from different components of the tree.

2.2.5. Harvest and wood products module

Script: Calc_harvest.R

The harvest module calculates the carbon in trees felled and removed from the stand site, carbon lost through felling and processing trees, and the input to carbon pools from any parts of the tree left at the site (such as coarse roots, i.e. the stump). The harvest module takes inputs from both the 'thin' and 'harvest' stage datasets. It also assumes that trees that die in the same year as thin and fells are also harvested (note that this allocation of dead trees to harvested trees dataframe takes place in the biomass module).

There is one main function in the calc_harvest script: calc_harvest_func. This function calculates both the total volume and carbon of extracted wood and assigns extracted volume to wood products. The function is called for both the forested and deforested tree volume inputs.

Extraction from harvests

The module first assumes that harvesting takes place in winter. Therefore, any volume or carbon in the foliage of deciduous trees is assumed to be zero.

The next step is for conversion loss to be calculated Conversion loss is the proportion of volume in trees which is lost during the felling process. Conversion loss is currently assumed to be 10% for the stem only.

Harvest proportion factors are then applied to tree volumes and carbon after conversion loss has been removed. Harvest proportions determine the proportion of each tree component is extracted from the site, or otherwise left on site. Currently only stems are assumed to be harvested.

In future, we will add flexibility so that harvest proportions can vary depending on whether stage is thin or fell. The carbon left at the site that has not been removed or lost from conversion are combined into 'harvest residues', when then become an input into the litter and deadwood module.

The 10% of conversion loss and any proportions of components which aren't harvested are assumed to be left on site. These are termed 'harvest residues' and are later processed in the litter and deadwood module.

At this stage, any harvested volume from dead trees are added to values for thin and fell stages where they occur in the same year. This requires the mean DBH of trees to be recalculated for the change in tree number.

The harvested proportions are further processed in the harvest module to estimate the use of harvested volume into wood products.

Wood product allocation

Wood product allocations are species-specific parameters which determine how harvested tree biomass is allocated to fuel, wood products or left on site. Product allocation values were not available for all species, and so some species are mapped to other species (Table 10).

It is assumed that wood product allocation is the same in both thin and fell years. The first step is to split the extracted volume / carbon and split into three 'raw' product categories of:

- Bark
- Small roundwood
- Sawlogs

The allocation is dependent on the size and shape of harvested trees (Table 11). The relative percent of underbark volume (from the total volume) and sawlog volume (from the underbark volume) are held in two parameter input files: bark_factors and sawlog_factors. The values in these files are sourced from standard tables given in Matthews and Mackie (2006) and Edwards and Christie (1981). These give species and DBH (7 – 50 cm) specific values for bark factors and leaf type (broadleaf or conifer), management and DBH (7 – 50 cm) specific values for saw log partitions. DBH values between 0 and 7 are assumed to be 0 and DBH values above 50 are assumed to have the same value as that at DBH 50.

The bark and sawlog factors are supplied on an integer DBH basis. The values are interpolated in estimate the specific values for non-integer DBH values.

The calculations are ordered as:

- Total underbark volume = total volume * bark_partition_coefficient
- Bark volume = total volume – total underbark volume

- Saw log volume = total underbark volume * sawlog partition coefficient
- Round wood volume = total underbark volume – saw log volume

This gives relative volume for bark, roundwood and sawlogs as shown in **Figure 6**.

Table 10. Mapping of species to wood product utilisation code. Highlighted rows indicate where wood product utilisation values are not available for that species and so are mapped to another species.

Modelled species name	Modelled species code	Wood product utilisation species name	Wood product utilisation species code
Norway spruce	NS	Sitka spruce	SS
Sitka spruce	SS	Sitka spruce	SS
Scots pine	SP	Scots pine	SP
Corsican pine	CP	Scots pine	SP
Lodgepole pine	LP	Scots pine	SP
European larch	EL	Japanese larch	JL
Japanese larch	JL	Japanese larch	JL
Douglas fir	DF	Douglas fir	DF
Grand fir	GF	Grand fir	GF
Noble fir	NF	Grand fir	GF
Western red cedar	WRC	Western red cedar	WRC
Western hemlock	WH	Western hemlock	WH
Oak	OK	Oak	OK
Beech	BE	Beech	BE
Sycamore	SY	Sycamore	SY
Ash	AH	Ash	AH
Birch	BI	Birch	BI
Nothofagus	RON	Beech	BE
Poplar	PO	Poplar	PO

Table 11. Definition of sawlogs and small roundwood.

Raw product	Tree type	Definition
Sawlogs	Coniferous (softwood)	Individually or collectively taking up the maximum available length in stemwood up to a minimum top diameter of 18cm over bark, but with a minimum length constraint of 1.3 m.
Sawlogs	Broadleaf (hardwood)	Individually or collectively taking up the maximum available length in stemwood, up to a minimum top diameter of 24 cm over bark, but with a minimum length constraint of 1.3m.
Small roundwood	Broadleaf or coniferous	The remaining portion of stem material after sawlog allocation to a minimum top diameter of 7 cm overbark.

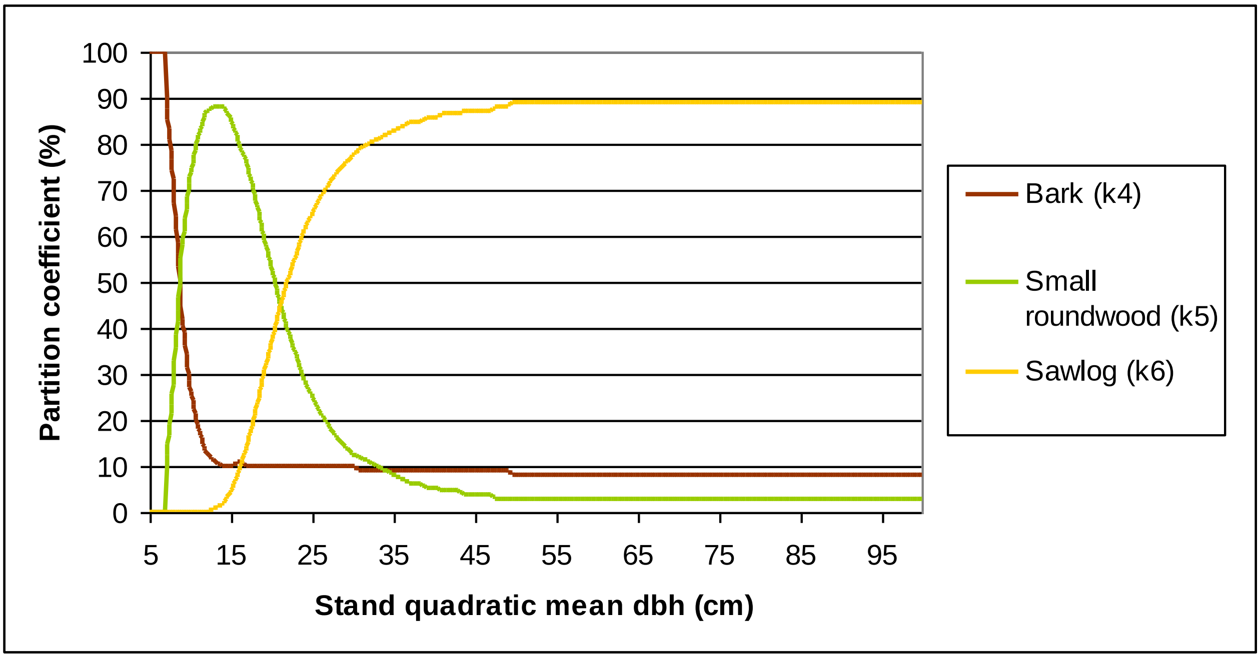

Figure 6. Percentage of stem wood allocated to the 'raw' products of bark, small roundwood and sawlogs as determined by the quadratic mean DBH of the

harvested trees. The example shown is for Sitka spruce which has been subjected to thinning.

Next, semifinished wood product allocation is calculated from the raw products. The semifinished product categories are defined by the IPCC and are Fuel, Pallets & Fencing, Paper, Particle board and sawn wood. The conversion of raw to semifinished products is shown in Table 12. The proportional allocation from raw product to semifinished products is held in a parameter file 'product_allocation'. This gives species specific values, where an allocation value of 1 means 100% of carbon in that product pool is allocated to that semifinished product pool.

Table 12. Allocation of raw products to intermediate, finished and IPCC products.

Raw product	Intermediate product	Semifinished products	Semifinished product allocation value	IPCC products
Branch	LeftInForest	Added to harvest residues		
	HarvestForFuel	Woodfuel	1	Fuel
Bark	LeftInForest	Added to harvest residues		
	ToFuel	Woodfuel	1	Fuel
	ToNonFuel	Unextracted material	1	
Small Roundwood	LeftInForest	Added to harvest residues		
	ToNonFuel	Unextracted material	1	
	ToFuel	Woodfuel	1	Fuel

Raw product	Intermediate product	Semifinished products	Semifinished product allocation value	IPCC products
	ToPalletsAndFencing	Pallet wood/ fencing	1	Sawn wood
	ToPaper	Paper 1	1	Paper
		Paper 2	0	Paper
		Paper 3	0	Paper
	ParticleboardEtc	Particleboard-long-lived	1	Wood-based panels
		Particleboard – short-lived	0	Wood-based panels
Sawlogs	LeftInForest	Added to harvest residues		
	ToNonFuel	Unextracted material	1	
	ToFuel	Woodfuel	1	Fuel
	PalletsAndFencing	Pallet wood/ fencing	1	Sawn wood
	ParticleboardEtc	Particleboard-long-lived	1	Wood-based panels

Raw product	Intermediate product	Semifinished products	Semifinished product allocation value	IPCC products
		Particleboard – short-lived	0	Wood-based panels
	StructuralTimber	Structural	1	Sawn wood

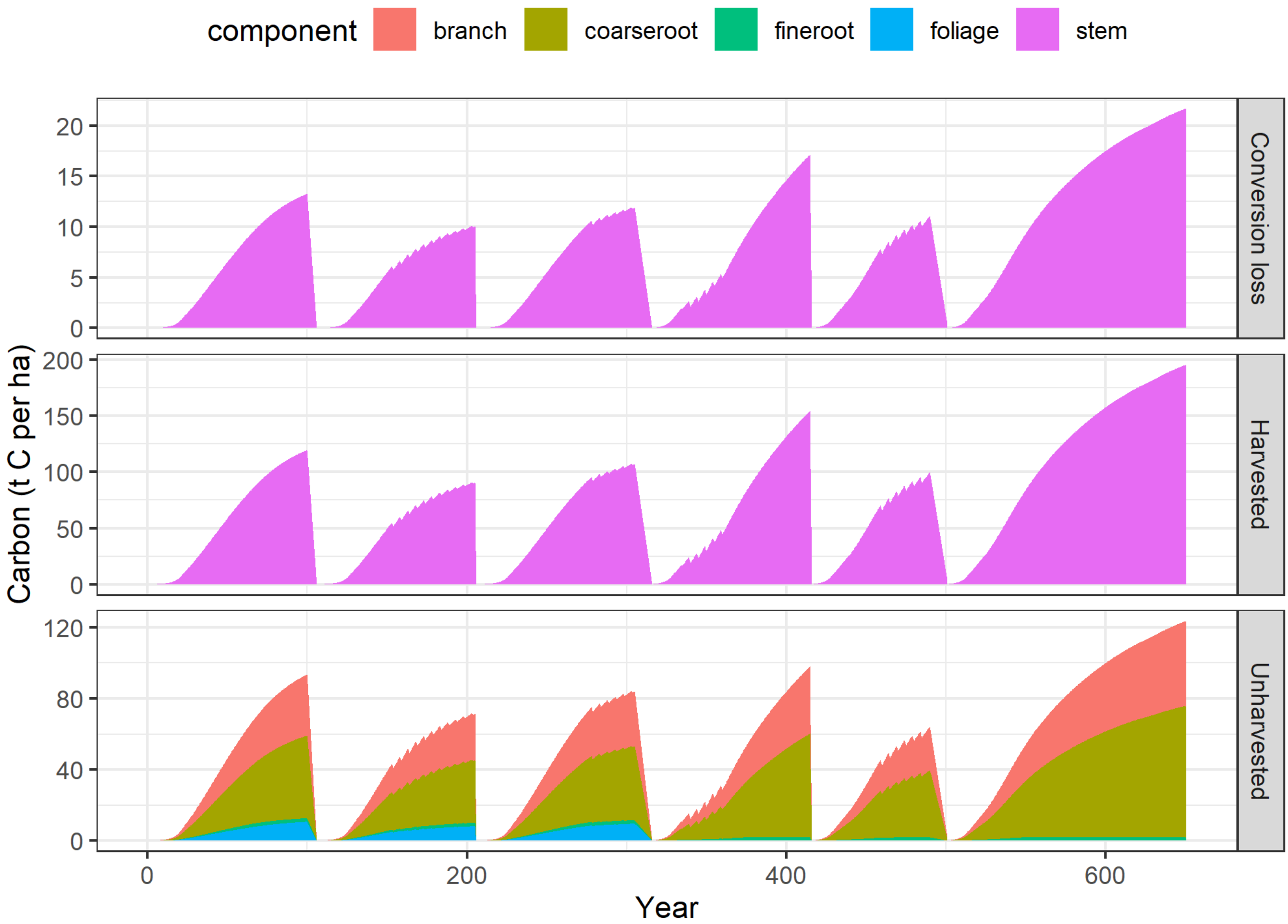

Figure 7. Example output from the harvest module with carbon stocks per ha broken down by tree component. The top row shows the amount of carbon which is attributed to 'conversion loss' or loss through the harvest process, which is assumed to only affect the stem component. The second row shows the carbon extracted from the site 'harvested', where stems are assumed to be the only component extracted. The bottom 'Unharvested' row shows the carbon stocks from components of trees which are felled but are not extracted and are left on site as 'harvest residue'.

2.2.6. Non-tree vegetation module

Script: Calc_nontree_carbon.R

The CARBINE model also incorporates carbon held in ground layer vegetation. Currently the module only estimates non-tree vegetation carbon when:

- There are no trees on the site (fallow periods)
- When newly planted trees are establishing, up until the point of canopy closure.

The first step is to identify any fallow periods – this is identified by filling in missing years from the dataframe. Then the rate of canopy closure from establishing trees is calculated based on the initial spacing of trees and estimate crown area of trees as they grow. This is then calculated as a fraction of canopy closure (fsc; Figure 8).

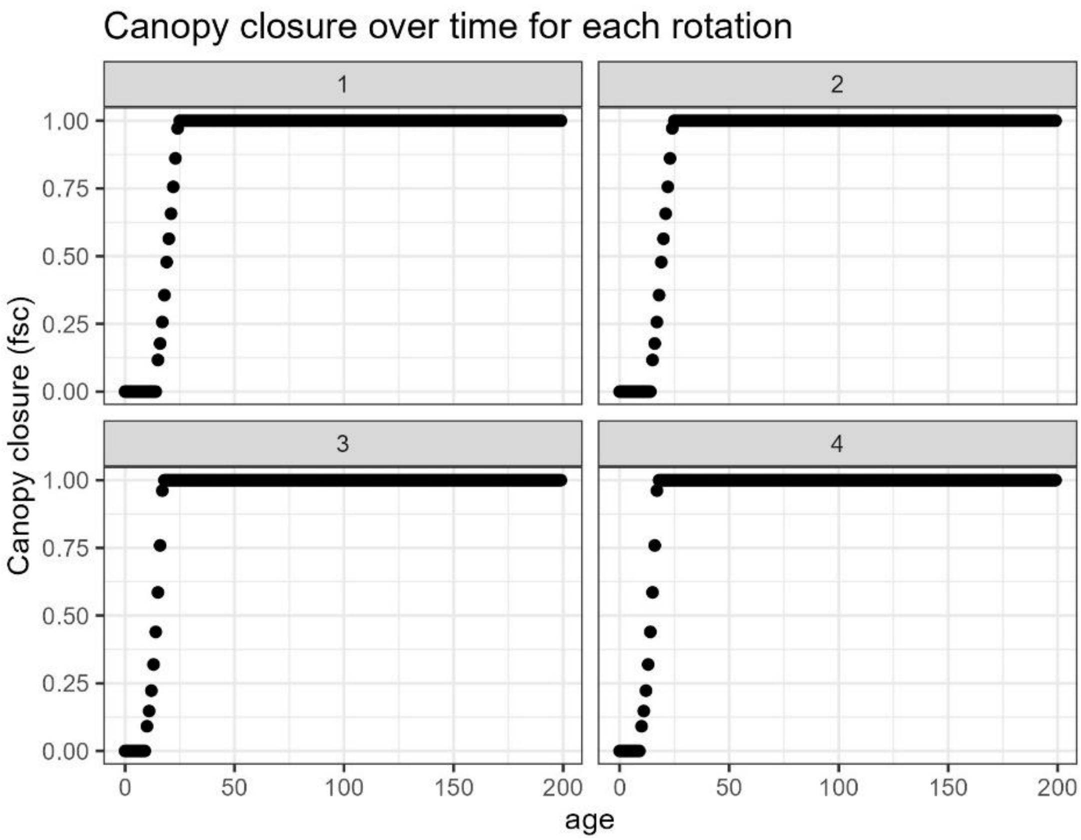

Figure 8. Graphs showing time to canopy closure for four rotations after an initial fallow period.

Before canopy reaches 100% closure (estimated to be around age 15) then there is assumed to be input from non-tree vegetation growing beneath the establishing trees.

The amount of carbon in the non-tree vegetation depends on the previous land use. This is then also affected by the ground preparation method used when the trees are established. Currently these previous land use values are hard-coded but should be updated to be sourced from the region scale controller.

2.2.7. Litter and Deadwood module

Script: Process_weather_data.R

This script is called in the setup stage of CARBINE. The script reads in and prepares the weather data for application in the litter and deadwood module.

Firstly, it calculates evapotranspiration by:

- Calculating the average monthly day length (Dl, hours) by:

$$Dl = 2\frac{HourAngle}{15}$$

  - Where HourAngle is calculated as:

$$HourAngle = \ cos^{-1}\left(-tan(L)\,.\,tan(\emptyset)\right)$$

  - Where L = latitude, and solar declination (*Ø)* is calculated as:

$$\emptyset = 23.45\,sin\left(360\frac{283 + DoY}{365}\right)$$

  - Where DoY = Day of the year.
  -
- Calculating evapotranspiration using the Thornwaite equation:

$$E_p = 10\ x\ 1.6\ \left[\frac{10t_m}{TE}\right]^{\varepsilon}\frac{Dl}{12}$$

  - Where:
    - t_m is the mean monthly temperature of month, *m* (°C),
    - *Dl* is the average day length of the month (hours)
    - ε is a polynomial function:

$$\varepsilon = \ 0.000000675\ TE^3 - \ 0.0000771\ TE^2 + 0.01792\,TE + 0.4923$$

- *TE* is Thornthwaite's temperature equation:

$$TE = \sum_{m=1}^{12} \left({t_m}/{5}\right)^{1.514}$$

- Thornthwaite's temperature equation is an annual temperature value derived from mean monthly temperature (°C), months m=1 to 12.

Script: Calc_decay_rates.R

This script prepares the parameters used in the litter and deadwood module, specifically the allocation of which tree component matter goes to which soil, deadwood or litter pool depending on where they come from (turnover, mortality or harvest). This is set up with a total of nine input files, all stored in a folder 'allocation_matrices'. In this script each file is read in and converted into a matrix format to run smoothly with the main R code.

For the litter decay rate, the code first converts the input csv file into a matrix. The foliage and branch decay rates are then recalculated.

- The foliage decay is re-calculated using an adjustment factor (ψ) the input parameter value multiplied by a calculation from Liski et al. (2002):

  ψ = 1 + 0.094 (mean annual air temperature (°C) – 4) + 0.0023 (summer moisture – E + 50)

Branch decay rate is assumed to be a constant value of 0.22

Deadwood decay rates are input from the parameter file (see Deadwood decay rates), where the value for stem is 0.037 and for coarse root is 0.03.

Script: Calc_litter_deadwood.R

The litter and deadwood module calculates the carbon accumulated in litter and deadwood pools, incorporating annual input from tree senescence, death and harvesting and the decay of such material.

The module is run for both non-deforestation years and deforestation years. The bulk of the calculations take place in a function called 'calc_litter_and_deadwood_func', which both the non-deforestation values and deforestation values are processed through.

Prior to entry into this function, both sets of datasets are formatted for use in the function. This involves combining the inputs for each dataset. For the non-deforestation scenario this includes input from the turnover module, harvest residues and mortality. For the deforestation scenario this includes harvest residues (which already have had dead trees included) and turnover.

Carbon within these outputs are assigned to either the litter or deadwood pool depending on their tree component and the source (turnover, harvest or mortality). As tree components are of different size and location, they have different allocation to either the litter, deadwood or directly to soil pools. This makes use of 'alloc_matrix_lists' which are created in the calc_decay_rates.R' script. The results of this are termed 'gains' as they represent annual inputs into these pools.

The 'calc_litter_and_deadwood_func' is then called, which has the following inputs:

- Input_df = either the dataset for the non-deforested or deforested scenario
- df_nontree_litter = a dataset of nontree carbon stocks generated in the non-tree vegetation module
- pool_start = a dataset which for deforestation years provides the deadwood and litter carbon pool values. For non-deforestation years a dummy dataset is given
- defor_run = a TRUE/FALSE statement to trigger specific actions for the processing of the deforestation scenario only

The main steps of the function are:

1. The carbon values in the input dataset are summed across different stages (crop, thin, mort etc) so there is one row per year.
2. The decay and efficiency parameters are joined to the dataset for each species
3. The number of years for each rotation is extended to the end of the projection period. This enables litter and deadwood pools to continue to represent the accumulation and decay of litter and deadwood across rotations.
4. The accumulation and decay in litter and deadwood pools is calculated within the 'calc_ad' function. Each rotation is run through this function individually. The litter and deadwood pools are calculated by first summing the value of the pool in the preceding year, then multiplying the summed value by the inverse of the decay rate. For deforestation scenarios, the previous pool value is sourced from the 'pool_start' dataframe, which represents the carbon pools calculated in the non-deforestation scenario. This is used otherwise the deforestation scenario would be incorrectly accumulating values across deforestation years, whereas these values should only represent the values for deforestation in each specific year (assuming no deforestation before). From the portion of the litter and deadwood pools that is estimated to decay, the efficiency value is applied to calculate the proportion of decayed material that enters the soil and the proportion that enters the atmosphere.
5. The outputs from the 'calc_ad' function are then summed across tree components. Specific values are also extracted for values of 'decaying_to_soil' are also calculated here.
6. The nontree carbon values are joined to the litter and deadwood pool
7. Values are then summed across rotations (so there is a single value for each year)
8. The specific values used in the soil module SCOTIA are extracted

9. Separate litter and deadwood pool datasets are extracted
10. The multiple outputs are joined in a list which is output from the function

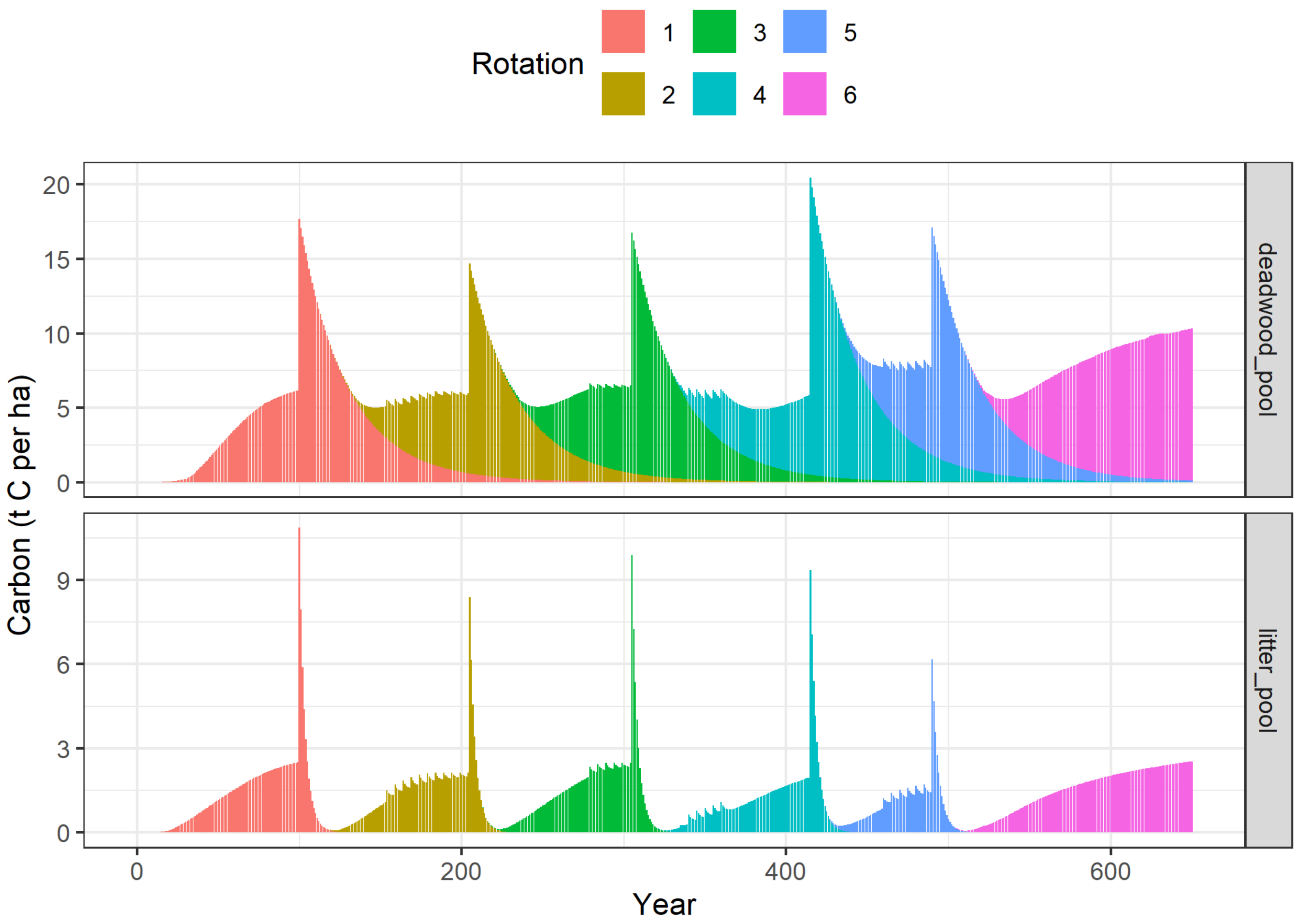

Figure 9. Visualisation of the carbon stocks in the litter and deadwood pools as a result accumulation and decay of litter and deadwood pools for each rotation.

Table 13. Format of output from CARBINE for SCOTIA inputs.

R column name	Description
species	Species
yieldclass	Yield class
management	Management code
rotation	Rotation number
year	Stand year, from year 0 onwards
tree_type	Deciduous or evergreen, passed through from tree metadata
Biomass_fineroot	Biomass of live fineroots (pre-thin, so values from both crop and thin/fell stages), called from the calc_biomass script
carbon_litter_decaying _to_soil_foliage	Carbon in the litter pool derived from tree foliage incorporating accumulation and decay processes. Part of this decayed foliage is allocated to atmosphere and the other to soil, with the soil portion being passed through here
carbon_litter_decaying _to_soil_branch	Carbon in the litter pool derived from tree branches incorporating accumulation and decay processes. Part of this decayed foliage is allocated to atmosphere and the other to soil, with the soil portion being passed through here
carbon_deadwood_decaying _to_soil_stem	Carbon in the deadwood pool derived from tree stems incorporating accumulation and decay processes., with the decayed portion being passed through here

R column name	Description
carbon_deadwood_decaying_to_soil_coarseroot	Carbon in the deadwood pool derived from tree coarseroots incorporating accumulation and decay processes., with the decayed portion being passed through here
carbon_dead_fineroot	Carbon in fineroot component from the 'mort' stage
top_height	Top height of live standing trees (pre-thin) – sourced from biomass module
num_trees	Number of live standing trees (pre-thin) – sourced from M1 prescription script

2.2.8. SCOTIA Soil module

This module uses the SCOTIAR library, which enables the use of the SCOTIA soil carbon model within R. SCOTIA is based on a simplified interpretation of the ECOSSE model developed by Smith *et al* (J Smith *et al.*, 2010; J. Smith *et al.*, 2010). The ECOSSE model was originally developed to allow simulation of soil carbon (and nitrogen) turnover using limited meteorological, land use and soil data available at the national scale. SCOTIA continues this philosophy, using limited available information to make national scale soil carbon change predictions that are relevant to the accurate accounting of the UK greenhouse gas inventory (Randle, 2017).

2.2.8.1. Carbon inputs to SCOTIA

The linked CARBINE-SCOTIA model operates on an enclosed system meaning that all carbon inputs are from crop present in the soil. These inputs include:

- Organic matter inputs direct to the soil (e.g., root turnover)
- Litter decomposition (fermenting material). Carbon content of forest litter transferred to soil via mechanisms such as soil fauna activity and digestion.

- Downward (only) transference of soluble organic carbon through water drainage from one layer to the next.
- Understory vegetation and root exudate contribution.

The full, expanded list of inputs from CARBINE to SCOTIA may be found in

Table **13**.

2.2.8.2. Soil structure

Horizontal soil structure may be split into a series of layers referred to in the soil science community by a series of common names. Plant matter dropped from trees and understory, or litter is described as its own (L) layer. As this matter decomposes, it forms a deeper fermentation (F) layer and an even deeper humic (H) layer, which together form an organic horizon but are distinct, separate layers referred to in the soil structure. Below the F and H layers are a series of deeper horizons, the composition of which depends on the parent material, e.g., mineral layers in mineral soils, further deeper organic horizons followed by mineral layers in organo-mineral soils, or a series of much deeper organic layers in fully organic soils such as peats.

For the purpose of the model, a soil profile is defined according to a series of fixed depth horizontal layers. A sequence of these layers may form a soil horizon. Specifically in SCOTIA, working downwards, above the main soil layers there is first an L layer of recently shed and partially decomposed tree and understory material. The L layer is followed by a deeper F layer consisting of above ground material that has broken down and decomposed to a point where distinct plant material is no longer recognisable as twigs and leaves etc. It should be noted that currently in SCOTIA there is no distinction between the F and H layers, both are counted as one large organic layer. Each layer contains carbon in different pools, see section 1.3.

If a non-forest crop is considered the L and F layers are assumed to contain no carbon, and effectively not to exist.

Soil horizons to 20 cm in depth are considered top-soil, deeper layers as the sub-soil.

The physical characteristics of each layer are distinct, see Table 14. Carbon is added to or lost from each layer. All layers may be set with the same physical characteristics, carbon changing and moving between pools within a layer will cause the composition of said layer to evolve over time.

Soil types are defined by their texture (the ratio of clay, sand, and silt), and by their depth-varying annual reset saturation. The latter is a percentage of saturation between field capacity and full saturation and is used to reset the water content each year.

Table 14. Properties defining each soil type.

Soil type	Texture - Clay (%)	Texture - Sand (%)	Texture – Silt (%)	Saturation reset (%) - Upper layers (≤20cm)	Saturation reset (%) - Lower layers (>20cm)
Sand	5	92	3	0	0
Clay loam	26	35	39	0	0
Clay	60	20	20	0	0
Organo-mineral (pre-afforestation)	60	20	20	100	95
Organo-mineral (post-afforestation)	60	20	20	100	95
Organic (pre-afforestation)	60	20	20	100	100
Organic (post-afforestation)	60	20	20	0	100

Full forest period runs are initialised using the land use change to forests from arable or pasture from SCOTIA, the columns of which are shown in

Table **13**. The forest period timeline is taken from the data frame.

SCOTIA forest period results comprise a data frame with a year (since afforestation) column and a carbon column, where the latter is the sum of the active and inert organic carbon within the soil.

2.2.8.3. Soil organic carbon pools

The soil organic carbon pool makeup of SCOTIA follows that of the RothC carbon model developed by Coleman, Prout and Milne at the Rothamsted Institute, as well as ECOSSE (Smith *et al.*, 2010; Coleman, Prout and Milne, 2024). Within each layer, as described in section 1.2, carbon is assumed to belong to one of 5 separate pools: Resistant Plant Material (RPM), Decomposable Plant Material (DPM), Humus (HUM), Biological (BIO) and Inert material. Additional carbon, not strictly in a distinct pool is dissolved organic carbon (DOC).

Fresh (no decomposition) organic matter, from dead roots, is assigned as either RPM or DPM. The allocation to each pool depends on the physical and chemical structure of the fresh material e.g. woody matter will have a different allocation than roots. The rate at which the RPM and DPM material begin to decompose and the movement of carbon within and between the HUM and BIO pools depends primarily on soil temperature, moisture and pH.

As material moves through decomposition between any two pools CO_2 is released and reactive carbon may be transferred to the BIO and HUM pools. Some carbon is tightly bound to soil components and is therefore inaccessible to soil biota and will not decompose, this is regarded as the Inert material.

2.2.8.4. Spin up

As interactions within soil between layers and the different carbon pools are complex it is inadvisable to begin any model simulation by specifying particular allocations to each carbon pool and subsequently assuming a status of equilibrium will be maintained. A spin-up period is required prior to actual simulation to maintain model stability and accuracy. This is a common process and is seen in both ECOSSE and RothC (J Smith *et al.*, 2010; Coleman, Prout and Milne, 2024).

Before providing tree inputs in the format presented in

Table **13**, a total of ten SCOTIA models are "spun-up" for a period of one thousand years each. These are used to provide a steady initial state for forest-period runs and correspond to all possible combinations of prior land use (arable and pasture), and five soil types.

Once equilibrium is reached decomposition and release of carbon is equal to carbon input and each soil carbon pool is in a stable state.

The results of the spin-up can be extracted using 'scotia_solver_ara$GetSpinUpResults()' command (alternating 'ara' or 'pas' depending on desired output.

2.2.9. Deforestation module

Script: Calc_deforestation.R

The deforestation module is where per ha stand results are multiplied by forested area and deforested area. The outputs of this are stand results per forested area after deforestation, forested area before deforestation and stand results per annual area deforested.

Deforestation is the removal of trees from a site with no intention to replant. Deforestation is by default only modelled from 1990 onwards, but this can be edited in the config file in the 'default_param_options' sheet. Deforestation is assumed to occur at random across all stand prescriptions within a single model run.

The deforestation module largely consists of a single function: 'convert_from_per_ha_values) which is applied to each element of the stand results (tree results, deadwood results, wood products etc). The function takes the carbon stock in each pool and generates three 'versions' of it:

- Carbon stock 'before': carbon stock multiplied by the previous year's forest area after removing areas deforested in that year

- Carbon stock ‘after’: carbon stocks multiplied by the current year’s forest areas after removing areas deforested in that year
- Carbon stock ‘defor’: carbon stocks multiplied by forest area which has been deforested in the current year

3. Model inputs

3.1. Config file

The config file (‘0_carbine_config.xlsx’) should be edited by the user to set the CARBINE run settings, such as project name and run type. The weather file can also be selected in the config file. Currently a single CARBINE run uses a single weather file, so to compare different weather inputs, you will need to create multiple config files, each selecting a different weather file, and complete multiple runs.

Data and graph output options can also be selected in the config file (‘output options’ sheet), and parameter inputs can be changed (‘parameter_inputs’ and ‘default_param_options’ sheets). See the CARBINE-R User Guide for details of how to edit the config file.

The config file needs to be selected by the user at the start of the CARBINE model run. Multiple config files can be prepared and saved under different names and then selected as needed. Note that different project IDs will need to be given otherwise outputs will overwrite each other in different runs.

3.2. Spplist

The spplist file outlines the stand prescription to describe a forest scenario. It specifies the ‘transition years’ where management changes from one type to another. Management changes could include one or more of changes to species, yield class, or thin / fell regime.

The spplist can be generated in different ways. For the GHG inventory, the spplist is generated by Forest Research’s Reconcile program using information from the National Forest Inventory. When generated from this program, it is in a wide format, where each management period is described in a new set of a columns

(Table **15**). In the spplist conversion script, this is extracted and converted to a long format which is more suited for use in R.

Alternatively, the user can define their own spplist inputs using the spplist_template provided (see CARBINE-R User Guide for guidance on how to use the spplist_template).

Table 15. Format and description of the spplist file as output by the Reconcile programme.

Column	Description
Area code	Code which links to a corresponding AREA file which lists the areas planted for different years under this management regime
Species	Species code of each rotation
Utilisation code	A species value which is mapped to estimate wood product allocation.
Yield class	Number representing the yield class of each rotation
Thin type code	The type of thinning in the management regime. (1 = no thin, 2 = thin, 3 = thin , no management = no thin (i.e., code=1) + no fell)
Rotation length	Number of years the rotation exist for (note for LISS rotations this is just an estimate and needs to be re-calculated using M1).
Whether felled or not	A [T]rue or [F]alse of whether the rotation ends in with a clearfell. Combined with thin type code this distinguishes the four management codes.
Fallow period	Number of years after a clearfell before the next rotation is planted.
Transition year	The year in which the next management period begins. This column doesn’t exist if there are no transitions taking place.

3.3. Area file

Area files link the stand prescription from a spplist file to an area of tree planting for multiple planting years. Each area file is named in the format "AREAXXXX" where the X's are replaced with a character-based area code, e.g., AREAAABA. This area code corresponds to the area code in the spplist, allowing the areas in the area file to be matched to the corresponding stand prescription from the spplist file.

Table 16. Example AREA file. There is a duplicated planting year column due to an artefact of the previous model version where planting years were given as a range.

Planting year	Planting year (duplicated)	Area planted (ha)	Inventory year
1500	1500	40	1500
1501	1501	50	1500
1502	1502	100	1500
…	…	…	…

3.4. Species yield class mapping

This file exists because M1 is not able to model all possible species and yield class combinations. For species and yield class combinations that M1 cannot run, the species and yield class is mapped to a similar species and yield class using the file 'spp_yc_map'. Once the data is run through M1, the 'local yield adjustment' value can be multiplied by the volume outputs to estimate the correct volume for the 'true' species and yield class.

Table 17. Format of the spp_yc_map file.

R variable name	Description
species	True species planted

R variable name	Description
yieldclass	True yield class
m1_species	Mapped species to use in M1 model
m1_yc	Mapped yield class to use in M1 model
local_yield_adjustment	A factor to use to adjust the volume outputs from M1 using the mapped species to estimate the volume for the true species

The minimum and maximum range of yield class values in M1 for each species is listed in Table 18A yield class adjustment factor will be applied if the given yield class for the species is outside the range given here. Note that ash and birch are not represented in Table 18, being always mapped to another species.A yield class adjustment factor will be applied if the given yield class for the species is outside the range given here. Note that ash and birch are not represented in Table 18, being always mapped to another species.

Table 18. Parameterised yield class range for each species in M1.

Species	Yield class minimum	Yield class maximum
BE	4	10
CP	6	20
DF	8	24
EL	4	12
GF	12	30
JL	4	14
LP	4	14
NF	10	22
NS	6	22
OK	4	8
PO	4	12

Species	Yield class minimum	Yield class maximum
RON	10	18
SP	4	14
SS	6	24
SY	4	12
WH	12	24
WRC	12	24

3.5. Spacing

Default spacings are used for each species. Currently, the file is set up to have flexibility to change spacing by management code, though currently this is not used, with species having the same spacing under all management codes.

Table 19. Tree spacing used for each species.

Species code	Spacing (m^2)
AH	1.5
BE	1.2
BI	1.5
CP	1.4
DF	1.7
EL	1.7
GF	1.8
JL	1.7
LP	1.5
NF	1.5
NS	1.5
OK	1.2
RON	1.7
SP	1.4
SS	1.7
SY	1.5
WH	1.5
WRC	1.5

3.6. Deforestation

Deforestation is calculated for in CARBINE-R using annual percentage deforestation rates for each stand (e.g. a value of 0.1 = 0.1%). These deforestation rates are currently only available for GHG inventory runs and some test case runs where they are held in a file named 'pdeforest.DAT'. These deforestation rates are added cumulatively to reduce the forested area each year by each year's value.

3.7. Parameters

3.7.1. Fallow period

The fallow period can applied as the values specified in the stand prescription (spplist) or else a default fallow period can be applied by setting a value in the 'default_param_options' sheet of the config file.

Default fallow period not yet implemented in code

3.7.2. LISS overlap period

The LISS overlap period is the number of years in which two consecutive LISS (low impact silvicultural system) rotations overlap each other. The default value is 30, but this can be overwritten within the 'default_param_options' sheet of the config file.

3.7.3. No go period

When a stand of trees approaches the clearfell rotation age, a scheduled thinning that would be very close to the clearfelling event may not be carried out (so as to wait for the harvest at clearfelling). The no go period is the number of years before a clearfelling event during which thinning is avoided. The default value is 0 years (meaning the value is effectively not set, and a scheduled thinning can be carried out just 1 year before the clearfelling event), but this can be overwritten within the 'default_param_options' sheet of the config file.

3.7.4. Thinning cycle

The thinning cycle is the number of years between consecutive thinning events. The default is 5 years, but this can be overwritten within the 'default_param_options' sheet of the config file.

3.7.5. Expansion factor

Expansion factors are values used to estimate the volume of other tree components. These values are used in the biomass module to estimate crown, foliage and coarse root volumes from stem volume.

Table 20. Biomass expansion factors for UK tree species in the CARBINE model. For foliage expiation factors, morphologically similar species were grouped in larger blocks presented in brackets.

Species	Crown Expansion factor (βc)	Coarse Root Expansion factor (βcr)	Foliage Expansion factor (βf)	References
Norway spruce	0.36	0.31	0.13 (Spruces)	(Burger, 1953, 1941; Carey and O'Brien, 1979)
Sitka spruce	0.32	0.49	0.13 (Spruces)	(Burger, 1953, 1941; Carey and O'Brien, 1979)
Scots pine	0.34	0.35	0.08 (Pines)	(Zianis et al., 2005)

Species	Crown Expansion factor (βc)	Coarse Root Expansion factor (βcr)	Foliage Expansion factor (βf)	References
Corsican pine	0.23	0.21	0.08 (Pines)	(Zianis et al., 2005)
Lodgepole pine	0.34	0.36	0.08 (Pines)	(Zianis et al., 2005)
European larch	0.13	0.26	0.015 (Larches)	(Burger, 1945)
Japanese larch	0.18	0.31	0.015 (Larches)	(Burger, 1945)
Douglas fir	0.27	0.29	0.13	(Burger, 1935)
Grand fir	0.25	0.29	0.1 (Firs)	(Burger, 1951)
Noble fir	0.28	0.22	0.1 (Firs)	(Burger, 1951)
Red cedar	0.34	0.27	0.1 (Firs)	(Burger, 1951)
Western Hemlock	0.19	0.22	0.1 (Firs)	(Burger, 1951)
Oak spp.	0.24	0.34	0.02	(Burger, 1947)
Beech spp.	0.26	0.34	0.015	(Burger, 1950)
Nothofagus	0.29	0.38	0.015 (Beeches)	(Burger, 1950)
Birch spp.	0.27	0.36	0.025	(Alam and Nizami, 2014; Lambert et al., 2005; A. Smith et al., 2014; Wang et al., 2000; Zianis et al., 2005)

Species	Crown Expansion factor (βc)	Coarse Root Expansion factor (βcr)	Foliage Expansion factor (βf)	References
Ash spp.	0.27	0.36	0.025 (Birches)	(Alam and Nizami, 2014; Lambert et al., 2005; A. Smith et al., 2014; Wang et al., 2000; Zianis et al., 2005)
Sycamore spp.	0.32	0.39	0.025 (Birches)	(Alam and Nizami, 2014; Lambert et al., 2005; A. Smith et al., 2014; Wang et al., 2000; Zianis et al., 2005)
Poplar spp.	0.35	0.50	0.025 (Birches)	(Alam and Nizami, 2014; Lambert et al., 2005; A. Smith et al., 2014; Wang et al., 2000; Zianis et al., 2005)

3.7.6. Wood basic density

Wood basic density values used in CARBINE vary by species (Table **21**). The format of the parameter file is setup to allow wood density values to vary by tree component. Currently this functionality isn't used as it is currently assumed that wood density values do not vary by component. This input data could be improved when more data becomes available.

Table 21. Wood density values for each species and component.

Species	Stem	Crown	Foliage	Coarse root	Fine root
ash	0.53	0.53	0.53	0.53	0.53
beech	0.55	0.55	0.55	0.55	0.55
birch	0.53	0.53	0.53	0.53	0.53
corsican pine	0.4	0.4	0.4	0.4	0.4
douglas fir	0.41	0.41	0.41	0.41	0.41
european larch	0.45	0.45	0.45	0.45	0.45
grand fir	0.3	0.3	0.3	0.3	0.3
japanese larch	0.41	0.41	0.41	0.41	0.41
lodgepole pine	0.39	0.39	0.39	0.39	0.39
noble fir	0.31	0.31	0.31	0.31	0.31
norway spruce	0.33	0.33	0.33	0.33	0.33
nothofagus	0.49	0.49	0.49	0.49	0.49
oak	0.56	0.56	0.56	0.56	0.56
poplar	0.35	0.35	0.35	0.35	0.35
red cedar	0.38	0.38	0.38	0.38	0.38
scots pine	0.42	0.42	0.42	0.42	0.42
sitka spruce	0.33	0.33	0.33	0.33	0.33
sycamore	0.49	0.49	0.49	0.49	0.49
western hemlock	0.36	0.36	0.36	0.36	0.36

3.7.7. Fine root maximum biomass

Within the biomass module, the per ha fineroot biomass is constrained to a maximum value. This was to prevent fineroot values expanding to what is assumed to be unrealistically large values. The default maximum value for biomass is 4 t biomass ha^{-1} (equivalent to 2 t Carbon ha^{-1}). This value can be changed in the config file in the 'default_param_options' sheet.

3.7.8. Wood carbon content

Wood carbon content is designated to be 0.5 for all species and components, as estimated by Matthews (1993). The IPCC Guidelines (2006) suggest values of 0.46 – 0.5 for broadleaves and 0.47 – 0.55 for coniferous trees.

3.7.9. Turnover rates

A turnover rate is the annual rate things 'drop' from live standing trees, e.g. annual leaf fall for deciduous trees, occasional branch fall etc. Branch and coarse root values are not varied by species (Table **22**), while values for foliage (especially evergreen vs. deciduous) and fine roots are species or group specific (Table **23**). The 'turned over' carbon is either allocated to the litter or deadwood pool depending on the tree component from which it originates (Table **24**).

Table 22. Turnover rates for branches and coarse roots.

Component	Turnover rate (yr^{-1})	Reference
Branches	0.04	Kurz et al. (2009)
Coarse roots	0.02	Kurz et al. (2009); Kurz and Beukema (1996); Li et al. (2003)

Table 23. Turnover rates for foliage and fine roots.

Tree species	Foliage turnover rate (yr^{-1})	Foliage turnover rate - reference	Fine root turnover rate (yr^{-1})	Fine root turnover rate - reference
Sitka spruce	0.2 (Spruces)	(Reich et al., 1996; Ťupek et al., 2015)	0.8	Data from Kielder forest provided by E. Vanguelova (pers. comm.)
Norway spruce	0.2 (Spruces)	(Reich et al., 1996; Ťupek et al., 2015)	1.11 (Norway spruce)	Brunner et al., 2013; Godbold et al., 2003
Red cedar	0.33 (Pines)	(Reich et al., 1996; Ťupek et al., 2015)	1.11 (Norway spruce)	Brunner et al., 2013; Godbold et al., 2003
Western Hemlock	0.25 (Douglas fir)	(Balster and Marshall, 2000; Zhao et al., 2011)	1.11 (Norway spruce)	Brunner et al., 2013; Godbold et al., 2003
Pine species	0.33	(Reich et al., 1996; Ťupek et al., 2015)	0.65 (Scots pine)	Janssens et al., 2002; Konôpka et al., 2006
Douglas fir	0.25	(Balster and Marshall, 2000; Zhao et al., 2011)	0.65 (Scots pine)	Janssens et al., 2002; Konôpka et al., 2006
True firs	0.15	(Balster and Marshall, 2000; Teskey et al., 1984)	0.65 (Scots pine)	Janssens et al., 2002; Konôpka et al., 2006

Tree species	Foliage turnover rate (yr^{-1})	Foliage turnover rate - reference	Fine root turnover rate (yr^{-1})	Fine root turnover rate - reference
Oak	1.0	Kull *et al.*, 2014	0.76	Brunner et al., 2013 Data from Alice Holt forest provided by E. Vanguelova (pers. comm.)
Beech	1.0	Kull *et al.*, 2014	1.11 (Beech)	Brunner et al., 2013
Deciduous broadleaf species	1.0	Kull *et al.*, 2014 (Ťupek et al., 2015)	1.11 (Beech)	Brunner et al., 2013
Larch species	1.0	Kushida *et al.*, 2007 Scher, 2002	1.11 (Beech)	Brunner et al., 2013

Table 24. Allocation of turnover output into litter or deadwood pools.

Component	Destination pool
Foliage	Litter
Branches	Litter
Stem	None
Coarse roots	Deadwood
Fine roots[1]	Deadwood

[1]Note that as fine root decay is 100% there is no carbon stock of fineroots in deadwood. Fineroots would normally be considered too small to be treated as deadwood so their inclusion is more a way of simplifying the code across all components, rather than indicating that fineroots should contribute to the deadwood pool.

3.7.10. Species mapping

The M1 model is not parameterised to run every species and yield class combination. Therefore, where a specific combination is missing, it is mapped to another species to run through M1. If thought to be necessary, to account for differences in mapping, a local yield adjustment may be applied to adjust the volume output of CARBINE to better reflect the expected true values for the input species and yield class. For example, results for yield class 2 are not given in the M1 model, but are extrapolated from yield class 4 for use in CARBINE.

Note that ash and birch do not have any parameterisation in CARBINE, they are always modelled as another species.

Most broadleaf species are only modelled to other broadleaf species in smaller yield classes and are modelled to conifer species for older yield classes. For example, Oak is modelled to oak for yield classes 2 to 8 (2 being based on a local yield adjustment), and then from 10 to 30 are modelled to Scots pine, Norway spruce or grand fir. Note that this kind of mapping is to deal with fringe cases when modelling based on large scale forest inventory data; significant areas of very high yield classes in oak (e.g. above 14) would not be expected in UK forests.

3.7.11. Conversion loss

Conversion loss is the amount of biomass lost due to the felling process. For example, during felling and processing of a tree stem, there is currently assumed to be 10% loss.

Table 25. Default conversion loss used for different species and tree components.

Species	Stem	Foliage	Branch	Coarse root	Fine root
scots pine	0.1	0	0	0	0
sitka spruce	0.1	0	0	0	0
japanese larch	0.1	0	0	0	0
douglas fir	0.1	0	0	0	0
western hemlock	0.1	0	0	0	0
western red cedar	0.1	0	0	0	0
grand fir	0.1	0	0	0	0
oak	0.1	0	0	0	0
beech	0.1	0	0	0	0
sycamore	0.1	0	0	0	0
ash	0.1	0	0	0	0
birch	0.1	0	0	0	0
poplar	0.1	0	0	0	0
sweet chestnut	0.1	0	0	0	0

3.7.12. Harvest proportions

This value represents the proportion of each tree component which is harvested from the site, i.e., taken away from the site for use as a wood product. Currently, values are not species-specific and only stems are assumed to be harvested (Table 26). Note that harvest proportions should be applied after conversion loss is removed. Carbon in harvest residues is either allocated to the litter or deadwood pool depending on the tree component from which it originates (Table 27).

Table 26. Default harvest proportion for different tree components and species.

species	Stem	Foliage	Branch	Coarse root	Fine root
scots pine	1	0	0	0	0
sitka spruce	1	0	0	0	0
japanese larch	1	0	0	0	0
douglas fir	1	0	0	0	0
western hemlock	1	0	0	0	0
western red cedar	1	0	0	0	0
grand fir	1	0	0	0	0
oak	1	0	0	0	0
beech	1	0	0	0	0
sycamore	1	0	0	0	0
ash	1	0	0	0	0
birch	1	0	0	0	0
poplar	1	0	0	0	0
sweet chestnut	1	0	0	0	0

Table 27. Destinations of harvest residue (from both conversion loss and harvest proportion) by component.

Component	Destination pool
Foliage	Litter
Branches	Litter
Stem	Deadwood
Coarse roots	Deadwood
Fine roots	Soil

3.7.13. Bark ratio

This file contains partition factors used to estimate the proportion of 'under bark' volume within the stem volume. This is dependent on tree species and DBH.

The values are sourced from allocation tables from Matthews & Mackie (2006). The partition factors are available for DBH range of 7 to 50. Factors for DBH's greater than 50 cm are capped at the 50 cm value and factors for DBHs less than 7 are calculated to be zero. Factors for DBHs between 7 cm and 10 cm use the 10 cm DBH value. This change was made in the original fortran code by Robert Matthews as the extrapolation of values below 10 cm appeared implausible and overestimated the bark proportion relative to wood.

3.7.14. Sawlog ratio

This file contains partition factors used to estimate the proportion of stem volume which can be taken as saw wood. This is dependent on the tree leaf type (broadleaf or conifer), DBH and thin type. As 'management' rather than 'thin type' is more commonly used in the R version of CARBINE, the corresponding management code to the thin type is used.

The partition factors are available for DBH range of 7 to 50. Factors for DBH's greater than 50 cm are capped at the 50 cm value and factors for DBHs less than 7 are calculated to be zero. The values are sourced from allocation tables from Matthews & Mackie (2006).

3.7.15. Product allocation

This file contains the allocation of raw products (bark, roundwood, sawlogs) to finished products (fuel, paper, particleboard, pallets & fencing, sawn wood) for each species. Note this uses wp_species, and hence holds fewer number of species.

3.7.16. CARBINE product allocation

This file contains a further allocation of products from the intermediate products output from the 'product allocation' factors into the default CARBINE wood product outputs.

3.7.17. Weather

Weather data is used in the litter and deadwood module to estimate decay rates using mean monthly temperatures and total monthly precipitation. Table 28 shows a template format for the weather data file as an example for England, although any area could be used.

Table 28. Example weather data for England.

country	location	latitude	month	mean_temp	precipitation
England	Kielder	55.226	1	2.1	117.6
England	Kielder	55.226	2	1.9	92.2
England	Kielder	55.226	3	4.25	94.6
England	Kielder	55.226	4	6.9	75.9
England	Kielder	55.226	5	11.3	76.7
England	Kielder	55.226	6	15.45	95.5
England	Kielder	55.226	7	18.6	102.5
England	Kielder	55.226	8	18.15	116.2
England	Kielder	55.226	9	14.95	107.7
England	Kielder	55.226	10	10.4	130.6
England	Kielder	55.226	11	2.2	118
England	Kielder	55.226	12	2.35	125.4

3.7.18. Tree radius parameters

The tree radius parameter is used within the non-tree vegetation module to assist estimation of time to tree crown closure (when all crowns touch). A default value of 0.3 is used, and it is input from the param_inputs sheet in the config file.

3.7.19. Litter & Deadwood pool allocation

This has been set up as a series of species-specific matrices, for each species, tree component, source and destination pool option. Currently the values are not species specific and so are summarised below (Table 29). Note that litter and deadwood pools then add to the soil pool through decay.

Table 29. Allocation of carbon from turnover, mortality (dead trees) and harvest residue to different carbon pools.

Source	Destination	Stem	Foliage	Branch	Coarse root	Fine root
Turnover	Litter	0	1	1	0	0
Turnover	Deadwood	1	0	0	1	1
Mortality	Litter	0	1	0	0	0
Mortality	Deadwood	1	0	1	1	1
Harvest residue	Litter	0	1	1	0	0
Harvest residue	Deadwood	1	0	0	1	1

3.7.20. Litter decay rates

Litter decay rates are the annual rate of loss from litter pool. Both foliage and branch values come from Liski et al. 2002. Losses from branch component of litter is assumed to be at a rate of 22% per year. Losses from foliage litter vary depending on whether the foliage is broadleaf or conifer, and with weather conditions. The values reported in Table 30 show the initial values before the effect of weather conditions is calculated, as this will depend on the input climate data. This climate effect (ψ) is calculated from equation by Liski et al. (2002) as:

Equation 1 $\psi = 1 + 0.094\ (\Theta - 4) + 0.0023\ (\Pi - E + 50)$

where Θ = mean annual air temperature (°C)

Π = mean annual rainfall (mm)

E = evapotranspiration from May to September

This climate effect is calculated in the **'process_weather_data.R'** script.

Table 30. Litter decay rates for foliage and branch material. Note that stem, coarseroot and fineroot are given dummy values of 1, as they should not be sources of any litter.

Species type	Species	Stem	Foliage	Branch	Coarseroot	Fineroot
Broadleaf	Ash	1	0.35	0.22	1	1
Broadleaf	Beech	1	0.35	0.22	1	1
Broadleaf	Birch	1	0.35	0.22	1	1
Conifer	Corsican pine	1	0.25	0.22	1	1
Conifer	Douglas fir	1	0.25	0.22	1	1
Conifer	European larch	1	0.25	0.22	1	1
Conifer	Grand fir	1	0.25	0.22	1	1
Conifer	Japanese larch	1	0.25	0.22	1	1
Conifer	Lodgepole pine	1	0.25	0.22	1	1
Conifer	Noble fir	1	0.25	0.22	1	1
Conifer	Norway spruce	1	0.25	0.22	1	1
Broadleaf	Nothofagus	1	0.35	0.22	1	1
Broadleaf	Oak	1	0.35	0.22	1	1
Broadleaf	Poplar	1	0.35	0.22	1	1
Conifer	Red cedar	1	0.25	0.22	1	1
Conifer	Scots pine	1	0.25	0.22	1	1
Conifer	Sitka spruce	1	0.25	0.22	1	1
Broadleaf	Sycamore	1	0.35	0.22	1	1
Conifer	Western hemlock	1	0.25	0.22	1	1

3.7.21. Deadwood decay rates

Decay rates for branches and stem wood are from Kurz et al. (2009).

Table 31. Default deadwood decay rates.

species	stem	foliage	branch	coarseroot	fineroot
ash	0.037	1	0.14	0.03	1
beech	0.037	1	0.14	0.03	1
birch	0.037	1	0.14	0.03	1
corsican pine	0.037	1	0.14	0.03	1
douglas fir	0.037	1	0.14	0.03	1
european larch	0.037	1	0.14	0.03	1
grand fir	0.037	1	0.14	0.03	1
japanese larch	0.037	1	0.14	0.03	1
lodgepole pine	0.037	1	0.14	0.03	1
noble fir	0.037	1	0.14	0.03	1
norway spruce	0.037	1	0.14	0.03	1
nothofagus	0.037	1	0.14	0.03	1
oak	0.037	1	0.14	0.03	1
poplar	0.037	1	0.14	0.03	1
red cedar	0.037	1	0.14	0.03	1
scots pine	0.037	1	0.14	0.03	1
sitka spruce	0.037	1	0.14	0.03	1
sycamore	0.037	1	0.14	0.03	1
western hemlock	0.037	1	0.14	0.03	1

3.7.22. Litter decay efficiency

The decay efficiency describes the proportion of which decaying matter is ‘decayed’ i.e. passes through to the soil, and the proportion that is released to the atmosphere as part of the decaying process.

Table 32. Default litter decay efficiency values.

species	stem	foliage	branch	coarseroot	fineroot
ash	0	0.51	0.45	0	0
beech	0	0.51	0.45	0	0
birch	0	0.51	0.45	0	0
corsican pine	0	0.51	0.45	0	0
douglas fir	0	0.51	0.45	0	0
european larch	0	0.51	0.45	0	0
grand fir	0	0.51	0.45	0	0
japanese larch	0	0.51	0.45	0	0
lodgepole pine	0	0.51	0.45	0	0
noble fir	0	0.51	0.45	0	0
norway spruce	0	0.51	0.45	0	0
nothofagus	0	0.51	0.45	0	0
oak	0	0.51	0.45	0	0
poplar	0	0.51	0.45	0	0
red cedar	0	0.51	0.45	0	0
scots pine	0	0.51	0.45	0	0
sitka spruce	0	0.51	0.45	0	0
sycamore	0	0.51	0.45	0	0
western hemlock	0	0.51	0.45	0	0

3.7.23. Deadwood decay efficiency

The decay efficiency describes the proportion of which decaying matter is 'decayed' i.e. passes through to the soil, and the proportion that is released to the atmosphere as part of the decaying process.

Table 33. Default deadwood decay efficiency values.

species	stem	foliage	branch	coarseroot	fineroot
ash	0.45	0	0.45	1	0
beech	0.45	0	0.45	1	0
birch	0.45	0	0.45	1	0
corsican pine	0.45	0	0.45	1	0
douglas fir	0.45	0	0.45	1	0
european larch	0.45	0	0.45	1	0
grand fir	0.45	0	0.45	1	0
japanese larch	0.45	0	0.45	1	0
lodgepole pine	0.45	0	0.45	1	0
noble fir	0.45	0	0.45	1	0
norway spruce	0.45	0	0.45	1	0
nothofagus	0.45	0	0.45	1	0
oak	0.45	0	0.45	1	0
poplar	0.45	0	0.45	1	0
red cedar	0.45	0	0.45	1	0
scots pine	0.45	0	0.45	1	0
sitka spruce	0.45	0	0.45	1	0
sycamore	0.45	0	0.45	1	0
western hemlock	0.45	0	0.45	1	0

3.7.24. Ground preparation

Selected and input from the config file. The factor is applied to initial soil carbon stocks to represent the impact of different ground preparation practices on soil carbon.

Table 34. Default ground preparation factors.

Name	Description	Factor
None	Natural succession to forest	1
Mounding	The provision of regularly spaced heaps of soil to provide planting spots.	0.6
Ploughing	Removal of all previous vegetation, soil ploughing and cultivation with weed control	0
Scarifying	Preparation of planting positions by scraping off surface vegetation and redistributing brash (if present).	0.6

3.7.25. Previous land use

Selected and input in from the config file. These values represent the assumed carbon stock prior to afforestation.

Table 35. Applied carbon stocks according to previous land use.

Name	Prior carbon content (tC ha^{-1})
Arable crop	8.41
Improved pasture	8.67

3.7.26. F_{CC}

F_{CC} is the fraction or proportion of diagonal distance between trees at which canopy closure is assumed to occur, allowing for interlocking of crowns. The value of F_{CC} is assumed to be greater than 0.5 and less than 1.0. The specific value of F_{CC} will be selected to result in canopy closure roughly around 15 years for a stand of trees of typical yield class under UK conditions. Default is a value of 1. Read in from parameter data.

4. Outputs

4.1. GHG inventory summary output

File Name: ghg_inventory_output

This is the output format used for the GHG inventory and has the file name 'ghg_inventory_output.csv'. For each output value, the carbon stocks are reported for each afforestation year and reporting year, consisting of:

- Carbon stocks for the whole forest including areas that are deforested in the reporting year (prior to deforestation occurring), 'before'
- Carbon stocks for the whole forest excluding areas that are deforested in the reporting year, 'after'
- Carbon stocks for the area deforested in the reporting year, before deforestation occurs, 'defor'.

The output type has a specific format for use in GHG inventory calculations. Some of the reasons behind the formatting are described below:

- Values are grouped by each afforestation year so that a 20-year transition period between forest remaining forest and land converted to forest can be calculated for each reporting year.
- Values for tree carbon 'before' and 'after' subtraction of any losses (e.g. mortality, harvesting) are calculated so that annual net change can be calculated
- The 'after' and 'defor' values for non-tree values (litter, deadwood and soil) are used to calculate the dead organic matter on deforested sites so this can be used to report these carbon stocks after land use change. The 'before' value is vestigial but it can be useful for debugging as it should equal the combined 'after' and 'defor' values.

Multi-stand results are aggregated by summing values across the same afforestation year and reporting year. Therefore, there may be multiple results for each reporting year, depending on the number of afforestation years. The format of this file is described in Table 36.

Table 36. Structure of the ghg_inventory_output file. Carbon values are presented in tonnes, and areas are in hectares. Where values specify that they represent values at the 'end of the reporting year' this indicates that these values account for processes of turnover, mortality, harvesting and decay.

Column name	Description
afforestation_year	Calendar year in which the area is planted with trees for the first time
reporting_year	Calendar year for which carbon stocks are being reported for the given afforestation year
forested_area	Forest area for the given reporting and afforestation years (after deforestation)
deforested_area	Deforested area for the given reporting year and afforestation year
carbon_before_tree_main_crop	Whole tree carbon for the reporting year / afforestation year combination before subtracting any losses on non-deforested land
carbon_after_tree_main_crop	Whole tree carbon after subtracting losses (i.e. turnover, harvest and mortality) on non-deforested land
carbon_above_ground_tree_before_thin	Above ground tree carbon for the reporting year / afforestation year

Column name	Description
	combination before subtracting any losses on non-deforested land
carbon_above_ground_tree_main_crop	Above ground tree carbon (stem, branches, and foliage) for the reporting year / afforestation year combination after subtracting losses (i.e. turnover, harvest and mortality) on non-deforested land
carbon_below_ground_tree_before_thin	Below ground tree carbon (coarse roots and fine roots) for the reporting year / afforestation year combination before subtracting any losses on non-deforested land
carbon_below_ground_tree_main_crop	Below ground tree carbon (coarse roots and fine roots) for the reporting year / afforestation year combination after subtracting losses (i.e. turnover, harvest and mortality) on non-deforested land
carbon_defor_tree_main_crop	Whole tree carbon for the reporting year / afforestation year combination after subtracting losses (i.e. turnover, harvest and mortality) on deforested land
carbon_before_litter	Carbon in the litter pool on both deforested and non-deforested land at the end of the reporting year (for a given afforestation year)

Column name	Description
carbon_after_litter	Carbon in the litter pool on non-deforested land at the end of the reporting year (for a given afforestation year)
carbon_defor_litter	Carbon in the litter pool on deforested land at the end of the reporting year (for a given afforestation year)
carbon_before_deadwood	Carbon in the deadwood pool on both deforested and non-deforested land at the end of the reporting year (for a given afforestation year)
carbon_after_deadwood	Carbon in the deadwood pool on non-deforested land at the end of the reporting year (for a given afforestation year)
carbon_defor_deadwood	Carbon in the deadwood pool on non-deforested land at the end of the reporting year (for a given afforestation year)
carbon_before_ara1	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly arable land use.
carbon_after_ara1	Carbon in soil on non-deforested and deforested land after subtracting any

Column name	Description
	losses at the end of the reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly arable land use.
carbon_defor_ara1	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly arable land use.
carbon_before_ara2	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly arable land use.
carbon_after_ara2	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly arable land use.
carbon_defor_ara2	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly arable land use.

Column name	Description
carbon_before_ara3	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly arable land use.
carbon_after_ara3	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly arable land use.
carbon_defor_ara3	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly arable land use.
carbon_before_ara4	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of organoclay soil type (4) and formerly arable land use.
carbon_after_ara4	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year);

Column name	Description
	assumption of organoclay soil type (4) and formerly arable land use.
carbon_defor_ara4	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organoclay soil type (4) and formerly arable land use.
carbon_before_ara5	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly arable land use.
carbon_after_ara5	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly arable land use.
carbon_defor_ara5	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly arable land use.
carbon_before_pas1	Carbon in soil on non-deforested and deforested land at the end of the

Column name	Description
	reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly pasture land use.
carbon_after_pas1	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly pasture land use.
carbon_defor_pas1	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of sand soil type (1) and formerly pasture land use.
carbon_before_pas2	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly pasture land use.
carbon_after_pas2	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly pasture land use.

Column name	Description
carbon_defor_pas2	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of loam soil type (2) and formerly pasture land use.
carbon_before_pas3	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly pasture land use.
carbon_after_pas3	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly pasture land use.
carbon_defor_pas3	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of clay soil type (3) and formerly pasture land use.
carbon_before_pas4	Carbon in soil on non-deforested and deforested land at the end of the reporting year (for a given afforestation year); assumption of

Column name	Description
	organoclay soil type (4) and formerly pasture land use.
carbon_after_pas4	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organoclay soil type (4) and formerly pasture land use.
carbon_defor_pas4	Carbon in soil on deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organoclay soil type (4) and formerly pasture land use.
carbon_before_pas5	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly pasture land use.
carbon_after_pas5	Carbon in soil on non-deforested and deforested land after subtracting any losses at the end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly pasture land use.
carbon_defor_pas5	Carbon in soil on deforested land after subtracting any losses at the

Column name	Description
	end of the reporting year (for a given afforestation year); assumption of organic soil type (5) and formerly pasture land use.
carbon_after_woodfuel_wp	Carbon in woodfuel from non-deforested areas for the reporting year / afforestation year combination
carbon_after_unextracted_material_wp	Carbon in extractable harvest material which is left on site (e.g. branches) from non-deforested areas for the reporting year / afforestation year combination
carbon_after_particleboard_longlived_wp	Carbon in long-lived particleboard wood products from non-deforested areas for the reporting year / afforestation year combination
carbon_after_particleboard_shortlived_wp	Carbon in short-lived particleboard wood products non-deforested areas for the reporting year / afforestation year combination
carbon_after_pallet_fencing_wp	Carbon in pallet and fencing wood products from non-deforested areas for the reporting year / afforestation year combination
carbon_after_paper_ephemeral_wp	Carbon in ephemeral paper wood products from non-deforested areas for the reporting year / afforestation year combination

Column name	Description
carbon_after_paper_shortlived_wp	Carbon in short-lived paper wood products from non-deforested areas for the reporting year / afforestation year combination
carbon_after_paper_longlived_wp	Carbon in long-lived paper wood products from non-deforested areas for the reporting year / afforestation year combination
carbon_after_structural_wp	Carbon in structural timber wood products from non-deforested areas for the reporting year / afforestation year combination
carbon_defor_woodfuel_wp	Carbon in woodfuel from deforested areas for the reporting year / afforestation year combination
carbon_defor_unextracted_material_wp	Carbon in extractable harvest material which is left on site (e.g. branches) from deforested areas for the reporting year / afforestation year combination
carbon_defor_particleboard_longlived_wp	Carbon in long-lived particleboard wood products from deforested areas for the reporting year / afforestation year combination
carbon_defor_particleboard_shortlived_wp	Carbon in short-lived particleboard wood products from deforested areas for the reporting year / afforestation year combination

Column name	Description
carbon_defor_pallet_fencing_wp	Carbon in pallet and fencing wood products from deforested areas for the reporting year / afforestation year combination
carbon_defor_paper_ephemeral_wp	Carbon in ephemeral paper wood products from deforested areas for the reporting year / afforestation year combination
carbon_defor_paper_shortlived_wp	Carbon in short-lived paper wood products from deforested areas for the reporting year / afforestation year combination
carbon_defor_paper_longlived_wp	Carbon in long-lived paper wood products from deforested areas for the reporting year / afforestation year combination
carbon_defor_structural_wp	Carbon in structural timber wood products from deforested areas for the reporting year / afforestation year combination

4.2. Annual carbon stock outputs

File Name: Annual carbon stocks

This file has a similar format as the ghg inventory output file, but values are summarised within each reporting year only. There is therefore only one value per reporting year in this file and no afforestation year column.

4.3. Single stand annual carbon stock outputs

File Name: Single_stand_annual_carbon

Same format of results as the annual carbon stocks file but with the stand's metadata (e.g. species, management etc) included in the output. These additional metadata columns are shown in Table 37.

Table 37. Description of metadata columns in the single_stand_annual_carbon output file.

Column name	Description
year	Years since stand afforested
rotation	Rotation number
Species	Tree species (code)
wp_species	Mapped tree species used to assign wood product allocation (code)
Yieldclass	Yield class of stand
management	Management code of stand (1-4)
transition_period	Transition period
species_full	Tree species (full common name)
leaf_type	Conifer or broadleaf
tree_type	Evergreen or deciduous
wood_type	Softwood or hardwood
top_height	Top height of the stand
num_trees	Number of standing live trees in the stand

Multi-stand results by stand

File Name: multi_stand_results_by_stand

For multi-stand outputs in the above outputs the carbon values across different stand prescriptions are aggregated within the same reporting year. In this output the stand prescription remains separate and identifiable by a 'stand_id' column (located at the end of file). This file otherwise has the same column heading format as the ghg inventory output file.

4.4. Graphs

At the end of a CARBINE-R model run a number of graphs are generated using the 'annual carbon stocks' file. These provide a quick visualisation of the results, allowing the user to check they look as expected. These graphs are saved into the output folder. For test case runs they will be in a subfolder with the test case number, for other run types they will be saved in a subfolder with the project name as specified in the config file.

4.5. Intermediate outputs

In addition to the main CARBINE-R outputs (described above), the results of intermediate steps of the CARBINE-R model, such as the turnover values are optional outputs. These intermediate outputs can only be output for single-stand runs, as they significantly increase model run time. These outputs can be specified to be generated or not in the 'output_options' sheet in the config file (see the User Guide for more guidance on selecting intermediate graph and data outputs).

4.6. Test case additional outputs

Test cases also output results from individual modules. These are only provided for the last stand run. These outputs are:

- Soil results (ara 1 to 5 & pas 1 to 5): Soil results for forests with either arable ('ara') and pasture ('pas') prior land uses for five different soil types (sand, loam, clay, organoclay & organic).

- Deadwood: Carbon stocks in deadwood pool
- Harvest: Carbon stocks in harvested trees
- Litter: Carbon stocks in the litter pool
- Tree before thin: Carbon in trees before subtracting any losses on non-deforested land in that reporting year
- Tree main crop: Carbon in trees after subtracting losses (turnover, mortality and/or harvest) on non-deforested land in that reporting year
- Vol_harvested: Total volume of trees harvested in that year (default assumption is that only stems are harvested).
- Wood_products_carbon: Carbon in wood products from harvested trees

Other intermediate outputs as data files or graphs can be selected for output in the config file.

5. Glossary & Abbreviations

Table 38. Glossary of technical terms and abbreviations used in the text.

Name	Definition	Source
Age	Stand age in years, from age 0 (planting year) onwards.	
Afforestation year	The year in which direct human-induced conversion of land that has not been forested in the recent past to forested land occurs through planting, seeding and/or the human-induced promotion of natural seed sources, e.g. a transition from pasture or arable land to forest land.	After Matthews, R., Mortimer, N, Lesschen, J-P., Lindroos, T.J., Sokka, L., Morris, A., Henshall, P., Hatto, C., Mwabonje, O., Rix, J., Mackie, E. and Sayce, M. (2015) Carbon impact of biomass consumed in the EU: quantitative assessment. Final project report, project: DG ENER/C1/427. Forest Research: Farnham.

Name	Definition	Source
Basal area	The overbark cross-sectional area of the stem of alive tree, measured at 1.3 m above ground-level, and given in sq metres. The sum of the basal areas of all the trees in an area of woodland expressed on a per hectare basis gives basal area per hectare.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Clearfell	The periodic harvesting of trees in a woodland, involving the complete or near-complete removal of standing trees for commercial utilisation.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Crown	The branches and foliage of a tree.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
Cumulative volume production	The total production of timber volume from a stand up to a given year in the stand's development. It is calculated as the standing volume per hectare attained by a forest stand in a given year plus the sum of per hectare volumes removed as thinnings up to that year.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
DBH	The diameter on the main stem of a tree at 'breast height', i.e., 1.3 m from ground level.	Matthews, R.W. and Mackie, E.D. (2006). Forest Mensuration: a handbook for practitioners. Forestry Commission, Edinburgh. i–vi + 1–330pp.
Deforestation	The direct human-induced conversion of forested land to non-forested land.	UNFCCC, 2001. Decision /CP.7: The Marrakesh Accords (Available at: www.unfccc.int/ cop7/documents /accords_draft.pdf).

Name	Definition	Source
Fallow period	A length of time in between two rotations when trees are absent from the site (minimum length of one growing season)	
Git	Git is a widely used version control system and is used for version control of the CARBINE-R model.	https://github.com/git-guides
ha	Hectare, unit of area of 10 000 m^2, equivalent to 100 m × 100 m (1 ha = 2.47 acres)	Matthews, R.W. and Mackie, E.D. (2006). Forest Mensuration: a handbook for practitioners. Forestry Commission, Edinburgh. i–vi + 1–330pp.

Intermediate thinning	A type of thinning (see *Thinning*) which involves the removal of most of the suppressed and sub-dominant trees, and also the opening up of the canopy by breaking up groups of competing dominant and co-dominant trees. This encourages the development of the remaining trees and leaves an open and fairly uniform stand. The volume of timber removed at a thinning is known as the thinning yield and typically calculated as 5 × 0.7 × yield class, where 5 is the default number of years between thins, 0.7 is the marginal thinning intensity (see *Marginal thinning intensity*) and yield class is the yield class of the trees in question.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
LISS	'Low Impact Silvicultural Systems', are forest management systems intended to reduce impacts, when compared to clearfell systems. LISS includes continuous cover forestry (CCF). Large scale clearfelling is avoided in these management systems. Thinning practice may vary but typically involves gradual removal of the existing stand of trees. At some point in the life cycle of the stand, new trees of the next rotation are planted or regenerate and grow in the space created by the thinnings.	Forestry Commission (2008) Managing Continuous Cover Forests. Operational Guidance Booklet No. 7. Forestry Commission, Edinburgh.

Name	Definition	Source
MAI	A measure of the volume productivity of forest stands (usually even-aged). Mean annual increment is the average rate of cumulative volume production up to a given year. In even-aged stands, it is calculated by dividing cumulative volume production by age.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Management prescription	The combination of initial planting spacing, thinning regime, and age of felling applied to a stand of trees.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
Marginal Thinning Intensity (MTI)	The maximum thinning intensity which can be maintained without causing loss of volume production. This is equivalent to 70% of the yield class each year, when thinning begins at the marginal thinning age.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Multi-stand run	A CARBINE-R model run involving more than one stand prescription, as listed in the spplist file. Outputs of multi-stand runs are summed across different stand prescriptions in the same reporting and afforestation years.	
Neutral thinning	A type of thinning in which the size distribution of the thinnings is identical to the trees left standing.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
Odt	Oven-dry tonne. Unit of mass. When applied to wood, it represents the mass of oven-dried wood in tonnes, not including the mass due to the moisture content of the wood (which may vary considerably).	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Overbark/underbark	Applies to the volume or diameter of wood including or excluding the bark.	Matthews, R.W. and Mackie, E.D. (2006). Forest Mensuration: a handbook for practitioners. Forestry Commission, Edinburgh. i–vi + 1–330pp.
Single-stand model run	A model run where only a single forest type is listed in the spplist file. A single stand run enables more details to be viewed at the per stand scale, such as species and management information.	

Name	Definition	Source
Stand	Defined in CARBINE as an area of trees with a homogenous forest type, that is, with the same combination of tree species, yield class and management prescription applied.	
Stem	The woody material forming the above-ground main growing shoot of a tree. By convention, in UK forest yield models, the stem is taken to include all commercially utilisable woody volume above ground with a diameter greater than 7 cm overbark. This may mean that significant 'straight' branches (i.e., more than 3 m in length and greater than 7 cm in top diameter) are included as part of the main stem volume.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
t	Metric tonne. Unit of mass of 1000 kilogrammes.	
Thinning	The periodic harvesting of trees in a woodland, involving the removal of some trees, generally for commercial utilisation, and the retention of others for future production or long-term retention.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Top height	Top height is the mean height, in metres, of the 100 trees of largest dbh per hectare.	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.
Transition (management)	A change in management, species or yield class for a stand, not necessarily associated with a new rotation.	
Transition (utilisation)	Change in utilisation of wood products.	
WP	Wood products.	

Name	Definition	Source
Yield class	An index used in Britain of the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription. It is measured in cubic metres per hectare per year (m^3 ha^{-1} yr^{-1}).	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

Name	Definition	Source
Yield table	A table giving estimates including volume, dbh and height for standing trees, mortality and thinnings. A yield table therefore shows how a stand of trees develops over time under specified conditions (species, yield class, initial spacing, and management).	Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry Forestry Commission, Edinburgh. i–iv + 1–92pp.

6. References

Alam, K., Nizami, S.M., 2014. Assessing Biomass Expansion Factor of. Open J. For. 4, 181–190.

Balster, N.J., Marshall, J.D., 2000. Decreased needle longevity of fertilized Douglas-fir and grand fir in the northern Rockies. Tree Physiol. 20, 1191–1197. doi:10.1093/treephys/20.17.1191

Brunner, I., Bakker, M.R., Björk, R.G., Hirano, Y., Lukac, M., Aranda, X., Børja, I., Eldhuset, T.D., Helmisaari, H.S., Jourdan, C., Konôpka, B., López, B.C., Miguel Pérez, C., Persson, H., Ostonen, I., 2013. Fine-root turnover rates of European forests revisited: An analysis of data from sequential coring and ingrowth cores. Plant Soil 362, 357–372. doi:10.1007/s11104-012-1313-5

Burger, H., 1953. Holz, blattmenge und zuwachs. XIII mitteilung: fichten im gleichalterigen hochwald. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 29, 38–130.

Burger, H., 1951. Holz, blattmenge und zuwachs. XI mitteilung: die tanne. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 27, 247–286.

Burger, H., 1950. Holz, blattmenge und zuwachs. X mitteilung: die buche. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 26, 419–468.

Burger, H., 1947. Holz, blattmenge und zuwachs. VIII mitteilung: die eiche. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 25, 211–279.

Burger, H., 1945. Holz, blattmenge und zuwachs. VII mitteilung: die larche. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 24, 7–103.

Burger, H., 1941. Holz, blattmenge und zuwachs. V mitteilung: fichten und förhrenverschiedener herkunft auf verschiedenen kulturorten. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 22, 10–62.

Burger, H., 1935. Holz, blattmenge und zuwachs. II mitteilung: die Douglasie. Mitteilungen der Schweizerischen anstalt für das Forstl. Versuchswes. 19, 21–72.

Carey, M.L., O'Brien, D., 1979. Biomass, nutrient content and distribution in a stand of Sitka spruce. Irish For. 36, 25–35.

Godbold, D.L., Fritz, H.-W., Jentschke, G., Meesenburg, H., Rademacher, P., 2003. Root turnover and root necromass accumulation of Norway spruce (Picea abies) are affected by soil acidity. Tree Physiol. 23, 915–921. doi:10.1093/treephys/23.13.915

IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 4: Forest Land.

Janssens, I.A., Sampson, D.A., Curiel-Yuste, J., Carrara, A., Ceulemans, R., 2002. The carbon cost of fine root turnover in a Scots pine forest. For. Ecol. Manage. 168, 231–240. doi:10.1016/S0378-1127(01)00755-1

Konôpka, B., Janssens, I.A., Curiel-Yuste, J., Ceulemans, R., 2006. Fine Root Turnover in a Temperate Scots Pine Forest. Lesn. časopis - For. J. 52, 107–117.

Kurz, W.A., Beukema, S.J., 1996. Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector. Can. J. For. Res. 26, 1973–1979. doi:10.1139/x26-223

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Modell. 220, 480–504. doi:10.1016/j.ecolmodel.2008.10.018.

Kushida 2007

Liski, J., Perruchoud, D. and Karjalainen, T. (2002). Increasing carbon stocks in the forest soils of Western Europe. Forest Ecology and Management, 169, 159–175.

Matthews, G., 1993. The Carbon Content of Trees, Forestry Commission technical paper 4.

Matthews, R.W. and Mackie, E.D. (2006). Forest Mensuration: A handbook for practitioners. Forestry Commission. 978-0-85538-621-4

Matthews, R.W., Arcangeli, C. and Mackie, E.D. (2016) *Corporate QA of high-impact models with applications to estimating or forecasting forest timber, biomass and carbon: key outcomes, policy implications and proposed actions.* Report produced for Research Strategy Management Board as part of FC Science and Innovation Strategy Programme 6. Forest Research: Farnham.

Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. and Dick, E.C. (2016) *Forest Yield: A handbook on forest growth and yield tables for British forestry.* Forestry Commission: Edinburgh.

Reich, P.B., Oleksyn, J., Modrzynski, J., Tjoelker, M.G., 1996. Evidence that longer needle retention of spruce and pine populations at high elevations and high latitudes is largely a phenotypic response. Tree Physiol. 16, 643–7.

Sher 2002.

Smith, A., Granhus, A., Astrup, R., 2014. Functions for estimating belowground and whole tree biomass of birch in Norway. Scand. J. For. Res. 29, 568–582. doi:10.1080/02827581.2014.951389

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D., Richards, M., Hillier, J., Flynn, H., Wattenbach, M., Aitkenhead, M., Yeluripati, J., Farmer, J., Milne, R., Thomson, A., Evans, C., Whitmore, A., Falloon, P., Smith, P., 2010a. Estimating changes in Scottish soil carbon stocks using ECOSSE. II. Application. Clim. Res. 45, 193–205.

doi:10.3354/cr00899

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D., Richards, M., Hillier, J., Flynn, H., Wattenbach, M., Aitkenhead, M., Yeluripati, J., Milne, R., Thomson, A., Evans, C., Whitmore, A., Falloon, P., Smith, P., 2010b. Estimating changes in Scottish soil carbon stocks using ECOSSE. I . Model description and uncertainties. Clim. Res. 45, 179–192. doi:10.3354/cr00899

Thompson, D.A., Matthews, R.W., 1989. The storage of carbon in trees and timber. Forestry Commission Research Information Note 160. Forestry Commission: Edinburgh.

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate Geographical Review, 38(1), 55–94.

Ťupek, B., Mäkipää, R., Heikkinen, J., Peltoniemi, M., Ukonmaanaho, L., Hokkanen, T., Nöjd, P., Nevalainen, S., Lindgren, M., Lehtonen, A., 2015. Foliar turnover rates in Finland — comparing estimates from needle-cohort and litterfall-biomass methods. Boreal Environ. Res. 20, 283–304.

Wang, J.R., Letchford, T., Comeau, P., Kimmins, J.P., 2000. Above- and below-ground biomass and nutrient distribution of a paper birch and subalpine fir mixed-species stand in the Sub-Boreal Spruce zone of British Columbia. For. Ecol. Manage. 130, 17–26. doi:10.1016/S0378-1127(99)00193-0.

Zhao, J., Mainwaring, D.B., Maguire, D.A., Kanaskie, A., 2011. Regional and annual trends in Douglas-fir foliage retention: Correlations with climatic variables. For. Ecol. Manage. 262, 1872–1886. doi:10.1016/j.foreco.2011.08.008

Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. Silva Fenn. Monogr. 4, 63.

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