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The JRC Forest Carbon Model: description of EU-CBM-HAT

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Contents

Abstract

The forest carbon model EU-CBM-HAT enables the assessment of forests CO2 emissions and removals under scenarios of forest management, natural disturbances, forest-related conversions and roundwood destinations (industrial roundwood and fuelwood). This model provides for a rule-based harvest distribution based on standing availability in each time step simulated, i.e. status of forest, and applicable silvicultural practices, e.g. eligible age range, periodicity, intervention intensity. *eu_cbm_hat* core package integrates three packages: *libcbm* (as a C++ rewrite of CBM-CFS3 Version 1.2) as the forest growth and disturbances simulator (developed by Forest Carbon Accounting team of the Canadian Forest Service), "COMBO", as the tool for combination of scenarios, and "HAT", as the harvest allocation tool (both in Python, developed by the JRC). The *eu_cbm_hat* is open-source (released and maintained by the JRC), with a dependency to open-source *libcbm* (released and maintained by CFS). The development incorporated into EU-CBM-HAT provides for an increased transparency of the modelling chain for forest-related applications associated with GHG reporting and mitigation strategies. The model was designed to support policy formulation, implementation and evaluation as well as scientific investigations. This report provides both for the scientific background behind the development and the user guidance (building on CBM-CFS3 user's guide).

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1 Introduction

Consistent with the EU on climate law, the JRC mandate includes the analysis of the historical sink and future GHG mitigation potential of the European forests, forestry and forest sector, under different socio-economic scenarios, management systems, wood use, and possibly, climatic conditions. Consequently, an EU forest carbon model, called EU-CBM-HAT, was developed by the JRC to support policy formulation, implementation and ex post-evaluation when forest, forestry and forest sector are relevant. Scientific investigations can be easily implemented given the unlimited combinations of scenarios and freedom to organize the inputs and process the outputs. EU-CBM-HAT enables the assessment of forest CO2 emissions and removals from forestland and its conversions under different scenarios of forest management and natural disturbances, while accommodates scenarios on major categories of roundwood use. It can link to any other model.

The purpose of this technical report is to provide the scientific background for the methodology behind the development of the EU-CBM-HAT and to provide guidance on how to use it. Noteworthy, users must be well aware on CBM-CFS3 User's Guide (Kull et al., 2019). With this report, we aim to increase the transparency along the modelling chain and to support further applications from stakeholders for GHG emissions and removals estimation, reporting and accounting and for simulating different forest management and climate change mitigation scenarios.

With the scientific needs toward an enhanced support for the development and implementation of EU policies related to overall climate neutrality and forests in mind, in the model's development process, the authors focused on following objectives throughout the model's development process:

1. to serve the *EU climate, bioeconomy, land-use, energy and environmental policies* through improved modelling of forest processes specific to forests ecosystems, forest management and forestry sector (i.e. standing stock increment and forest growth, silvicultural practices, main roundwood destinations).
2. to improve the *transparency and reproducibility* of scenarios, assumptions and data from input to output, as well as the interoperability with other models both for the forest sector (e.g. harvested wood products, wood recycling) or economy wide (e.g. substitution with wood, bioenergy needs).
3. to promote *climate and forestry communities with consistent and versatile information on CO2 emissions and volume estimates*, by addressing equally the climate change community which operates with GHG information, i.e. biomass and carbon stocks and stock change and GHG related obligations like time bounded referenced periods and specific year targets, and forestry community, i.e. operating with forestry's volume related indicators like standing stock, increment and roundwood harvest.
4. to package the model so that it can run on cloud platforms and *operate within the JRC integrated modelling framework* in support of EU policy making or scientific activities.

2 Mandate to develop a transparent, reproducible and open-source forest carbon model

2.1 State-of-the-art in forest management and climate policy-oriented modelling

The forest carbon (C) dynamics can be quantified using empirical models, driven by data provided from forest inventories i.e. national forest inventories (NFI) or process-based models, which in turn are driven by the simulation of tree and stand physiological and ecological processes and environmental features (e.g. climate, geography). Typically, the empirical models are standing stock and increment volume oriented, with simple extensions to greenhouse gas (GHG) applications and are best suited for modelling the medium- to short-term evolution of the forest C sink under different management strategies (Böttcher et al. 2008) at national scale. In modelling capabilities, additional to temporal effect of the mitigation efforts the inclusiveness of all GHG sources is key (e.g. Vestin et al., 2022). By simulating the forest growth based on past observations, these models cannot easily determine the potential variations in primary productivity induced by climate change on the short term (Cuddington et al., 2013). On the other hand, modelling the long-term evolution of the forest carbon sink under climate change conditions generally requires the use of process-based climate models, grounded in ecological theories, and meaningful validation. These models however, generally miss detailed information on management practices and forest conditions, as determined from direct field measurements (Pretzsch et al. 2008).

The European Union (EU) promotes and implements various forest-related policy and strategies which are expected to return a European and global benefit, i.e. on climate (e.g. EU climate law, EU LULUCF Regulation 841/2018, EU forestry strategy) and on environment (Natura 2000 network, a bioeconomy for Europe, EU biodiversity strategy for 2030). EU member countries also need models to project forest resources dynamic and how they contribute to implementation of EU and national commitments and development. Many countries developed their own models (Packalen et al., 2014; Vizzarri et. al, 2021) or applied internationally available models, such as EFISCEN (Verkerk et al., 2016) and EFISCEN-space (e.g. Arets and Schelhaas, 2019), or the CBM-CFS3 (Kurz et al., 2009). CBM-CFS3 is applied at country level (i.e. bottom-up approach built on most detailed data, e.g. from NFI plots), like in: Ireland (Duffy et al., 2021), Czech Republic (Ministry of Agriculture et al., 2018), Romania (e.g. Blujdea et al., 2021)., Poland (Ministry of Climate, 2018), Slovenia (e.g. Jevšenak et al., 2020). The CBM-CFS3 is an inventory-based, yield-data driven model that simulates the stand- and landscape-level C dynamics of above- and belowground biomass, dead wood, litter and soil (Kurz et al., 2009).

The JRC has almost a decade of experience in using the CBM-CFS3 at EU (i.e. top-down approach building on aggregate data reported by NFIs, including remote sensing). In support of EU policy, it was applied to 25 MSs, based on a specific parametrization of the original model's assumption, on the EU administrative, ecological and silvicultural conditions (e.g. Pilli et al., 2018). The results were validated by a large number of publications and science reports (e.g. Pilli et al., 2013; Pilli et al., 2022). Continuity in using such an empirical and stand-based model by the JRC in support for the EU policies is justified by the type of data publicly available under current EU forest monitoring and reporting frameworks.

During recent years, the JRC has also integrated CBM-CFS3 with numerous other models, e.g. Land-Use based Integrated Sustainability Assessment modelling platform (LUISA, e.g. Baranzelli et al., 2014); Global Forest Trade Model (GFTM, Jonsson et al., 2015; Rinaldi et al., 2015; Camia et al., 2018; Jonsson et al., 2021), Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA, European Commission; 2016; Mantzos et al., 2016) and CAPRI (Common Agricultural Policy Regional Impact Analysis (CAPRI Modelling System, 2022) in an effort toward an integrated modelling framework including the forest-based bioeconomy (Mubareka et al., 2014, Mubareka et al., 2018; Sahoo et al., 2021).

The evolving JRC modelling framework, as a whole, is defining the standard in data processing, as continuously evolving components move toward updated open-source programming languages, implicitly embraced by the JRC forest-related modelling tools.

2.2 Main development features of EU-CBM-HAT

Here we describe the software and programming changes needed to develop EU-CBM-HAT as an open-source Python package. Some parts of the development have been implemented by the Canadian Forest Service (CFS) while other parts were implemented at the JRC. The Canadian Forest Service developed a new

implementation of CBM (short of CBM-CFS3), in the form of a software package called *libcbm*. Starting from this package, the JRC has developed two modules, a Scenario Combination Tool, called COMBO, and a Harvest Allocation Tool, called HAT. The three packages were integrated within a unique modelling framework, named EU-CBM-HAT.

Despite the success in supporting policy making by CBM-CFS3 (Grassi et al., 2018), the interoperating of CBM-CFS3 with other models has been partially limited not only from the lack of a common base scenario and background assumptions, but also because of technical restrictions. Up to now, the CBM-CFS3, configured for EU, was operated through Microsoft Access graphical user interface which is well suited to calibrate and run individual countries and forestry activities independently, but configuring activities integrated and multiple models runs for all countries at the EU level was quite complex making it hard to reproduce many scenarios with slight variations of the input data. Weak tracking of the assumptions and processing of both the inputs and outputs was also difficult as multiple software were involved in various steps.

The main development targeted by EU-CBM-HAT was the capability to document, automate and reproduce model runs. At the start of the project, we evaluated the option to use either the CBM-CFS3 version or the new implementation called *libcbm*. The CBM-CFS3 is well suited for individual use on a desktop computer, and it is constantly updated to the new carbon accounting standards, but it is based on an aging software stack. Its components make it harder to debug data issues which are likely to arise when working with 27 countries simultaneously, numerous administrative regions, non-standard categorization of nationally available data and along the other dimensions of the data. Issues can lead to errors inside the different software layers of the model such as the Standard Import Tool, the core of the model or the Microsoft Access databases. When an error was returned by one component, we lacked the capability to move up and down the software stack to understand the context of the error. Also, CBM-CFS3 cannot run on Linux-based cloud platforms and therefore limits the interaction with other JRC models to which the forestry model shall plug in. To overcome these limitations, the JRC has been testing *libcbm* since 2020. EU-CBM-HAT is conceptually based on the same modelling theory and input data used by CBM-CFS3, but running on a more flexible system. The *libcbm* is a translation of the model to a modern programming language (a C++ core with a Python interface). A section below on software provides more details on the components and data formats. This package provides a streamlined installation (Annex 1), better error reporting and interoperating features with other software packages in the Python ecosystem.

The second most fundamental development was targeting an increased interoperability of the forest management model with other models, e.g. energy model like POTEnCIA formulating fuelwood demands to the forestry sector, etc. Based on our previous experience, implementing different scenarios within the CBM-CFS3 model was extremely time consuming, involving repetitive iterations on the harvest level, especially for projections on long periods. Indeed, we could combine different harvest levels with various possible management strategies and future afforestation rates (see for example Pilli et al., 2016), as well as potential impact of natural disturbances and climate change, as estimated from different climatic models (see Pilli et al., 2022). To improve the reproducibility of scenario runs we wanted a directory structure that stores model input and output data, in a way that scenarios can be retrieved, modified, mixed and re-run. We wanted to keep track of different run versions for comparison purposes. Such traceability also helps to standardize model output, in a way that is more reusable by other models. With this purpose in mind, we developed COMBO, further integrated with HAT. COMBO allows a flexible association of different forest events, such as natural disturbances, and activities, such as forest management practices and pre-defined roundwood use as industrial roundwood (IRW) and fuelwood (FW). This is achieved by splitting the different activities in separate input files, which are then combined back into a single disturbances input file later sent to *libcbm* for actual run. A combination of scenarios has a name and is described by a configuration file that allows to mix different activities, and to change any input parameter programmatically. Furthermore, to keep consistency within the JRC integrated modelling framework, the "demand" represents the consumption of roundwood and other wood types from domestic harvest, imports and exports. Thus, country's expected production of roundwood represents the domestic harvest, on short "harvest" throughout this report and associated scripts.

A third development was ensuring an annual time step and rule-based distribution of roundwood harvest. Within the CBM-CFS3 version, the allocation of harvest and other disturbance events was based on an expert based and iterative process, which was targeting the total harvest defined for the entire simulation period at the beginning of the simulation. In particular, before running CBM-CFS3, the expected amount of harvest, as defined from historical data sources or different economic models, was preliminary distributed between industrial roundwood and fuelwood, and further attributed to each disturbance event applied within the model run (including salvage logging and any other management practice) for the entire projected period, as defined for each forest type, based on (i) the age structure (used to estimate the clear cut amount), (ii) additional

assumptions on the amount of thinnings and (iii) the total C stock available for each stand, according to the output provided by a preliminary model run (see Pilli et al., 2013). In this way, the amount of harvest not provided from clearcut or salvage logging was further distributed according to the proportion of standing C stock available at each step of the simulation, for each disturbance event, forest type and region. This approach allowed us to model different management systems (including uneven-aged forests) and to calibrate the harvest as a function of the expected amount of wood supply. However, the calibration of the main parameters defining each silvicultural event (e.g. overall intensity, definition of the disturbance matrix, etc.) sometimes was very cumbersome, e.g. consisting in partial running and successive iterations. Moreover, when preliminary distributing the amount of harvest between different disturbance events, the final use of the resulting amount of roundwood was attributed to IRW or FW post-simulation. Some difficulties also arose from the fact that the harvest was generally specified in terms of volume, but natural disturbances and clear-cuts are more often specified in terms of area. Finally, when the harvest expected from input data was not satisfied, there were no error messages, but additional processing was needed to check supply vs. expected harvest. To overcome these limitations, and speed up the calibration process, we developed an additional Harvest Allocation Tool (HAT). Specifically, HAT distributes the amount of harvest formulated separately as IRW and FW expected harvest, according to the amount of biomass available in forests for each time step during the simulation, taking into account the contribution of salvage logging after natural disturbances, and the various management systems defined under different scenarios. Specifically, working with a resolution of a time step of one year facilitates an appropriate simulation based on forest conditions during each simulation. The silvicultural practices and expected roundwood destinations information are described in unique input files, which allow a transparent picture and comparison.

2.3 EU-CBM-HAT software packages

The forest carbon accounting team of the Canadian Forest Service reimplemented the core CBM-CFS3 as a C++ library with interface methods for the Python and R languages. The *libcbm* package was conceived as a generic flux/pool computation and *libcbm* is the main application of the tool. Version 1.0.0 of the *libcbm* package was released in early 2022 on github (https://github.com/cat-cfs/libcbm_py). The input data approach based on csv input files is consistent with the CBM-CFS3. The archive index database (AIDB) is based on SQLite (https://www.sqlite.org/index.html). *libcbm_py* contains a script to translate the AIDB from the old Microsoft Access database format to the new SQLite database format. In the early stages of development, the CFS has developed a suite of tests to ensure compatibility between CBM-CFS3 and *libcbm* where both simulations run in parallel, and results are compared at the end. See also an overview of some of our own comparison for EU countries in Annex 2. Adaptation to the EU datasets was done in collaboration between the JRC and the CFS. Using this tool will also ensure we stay up to date with any new capabilities CFS adds to *libcbm*.

On top of *libcbm*, we created scripts that run our model in a Python package called *eu_cbm_hat*. HAT and COMBO described in the later sections have been implemented as objects inside this package. Python package *eu_cbm_hat* together with rest of simulation infrastructure (e.g. directory and files) required to run a simulation represent the EU-CBM-HAT model.

Although this technical report refers to development designed for the EU block, the tool can be adjusted to any individual EU member country or to any other country, or to any other geographical or administrative scale.

Both projects are released under open-source licences: the Canadian package *libcbm_py* is released by the Canadian Forest Service of Natural Resources Canada under the Mozilla public licence. The European package is released by the European Commission Joint Research Centre under the MIT and EUPL licence. Installation instructions are available on the project gitlab page: https://gitlab.com/bioeconomy/eu_cbm. The maintenance and future development of each package falls within the corresponding institutions.

3 EU-CBM-HAT architecture: combination of scenarios by "COMBO"

EU-CBM-HAT basically works as an integration of two EU specific modules developed by the JRC in collaboration with the CFS, i.e. the "scenario combination tool", COMBO, and the "harvest allocation tool", HAT, both integrated with the "*libcbm*" core, developed by the CFS.

Hierarchically and functionally, the COMBO is overarching the other two modules. The COMBO tool allows combining scenarios including on natural disturbances and human-driven activities under an unlimited number of scenarios. Once the combination of scenarios is defined, the HAT estimates the harvest availability and allocates the industrial roundwood and fuelwood harvest accordingly.

Specifically, EU-CBM-HAT can implement both predetermined events on forests and the forestry. Predetermined events are assumed as driven by forces outside the forestry sector, such as afforestation, deforestation, stand replacing and non-stand replacing natural disturbances. Some of them may result in an unplanned roundwood availability through salvage logging, which would be eligible to contribute to meeting the expected harvests through specific silvicultural interventions, which in turn can be compensated by reduced planned harvest. By opposition, anticipated events are the planned silvicultural interventions, i.e. thinnings, final cuts.

Based on such philosophy, EU-CBM-HAT distinguishes five inputs packages, each one dedicated to a family of events with similar general features: conversion to forests ("afforestation"), conversion from forests ("deforestation"), stand replacing natural disturbances where events trigger of a new stand cycle ("nd_sr"), non-stand replacing natural disturbances which affect various pools without starting of a new stand cycle ("nd_ns"r), and forest management ("mgmt") that include regular silvicultural practices applied to the concerned forests. The denomination of these packages should be taken in a broad sense, so any type of event can potentially fit under one of the packages. As projections may require dynamic changes during the simulated period, COMBO allows maximum flexibility regarding silvicultural practices and wood use type, i.e. unlimited switch across scenarios during the simulated period.

In the architecture of the EU-CBM-HAT there are two levels of input-output information: an upper level where the user provides the assumptions and data common for all EU member states, and a lower level where country specific data, inputs and outputs, are loaded. Each level includes various directories and subdirectories which will be described in detail within the following sections. Both input and output data are organized at the country level, which also allows running scenarios.

3.1 Upper level of the EU-CBM-HAT: input information common at EU level

The upper level of EU-CBM-HAT includes five directories, containing a set of information common for all the EU member states, i.e. valid at EU level (Figure 1). This information is used both by HAT, in distributing the expected harvest, and by *libcbm* for the actual simulation. The country directories contain various predefined templates (downloadable with the installation, see Annex 1) to be filled in by the user (Table 1).

Figure 1. Upper architecture of the input data in the EU-CBM-HAT: overview of the mandatory directory and the files in the "data" directory.

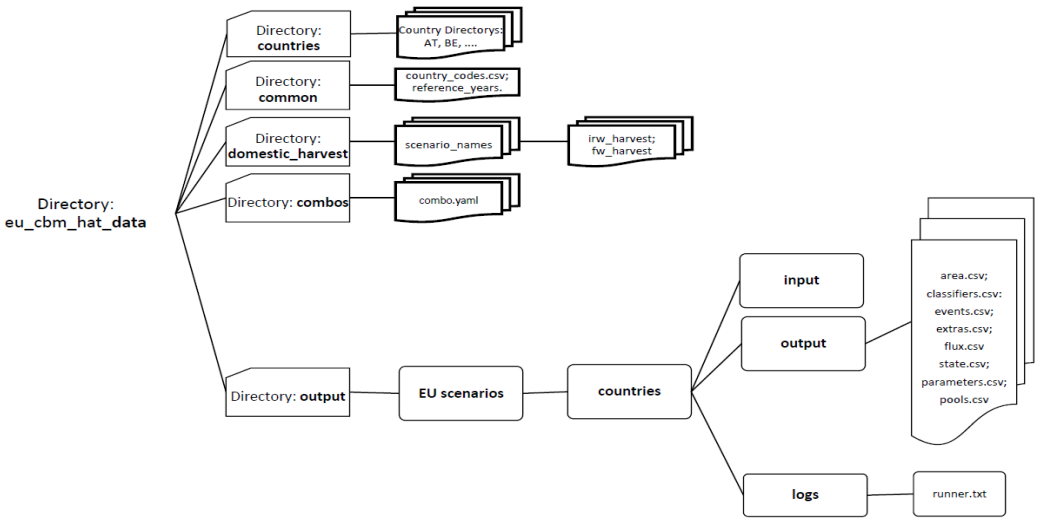


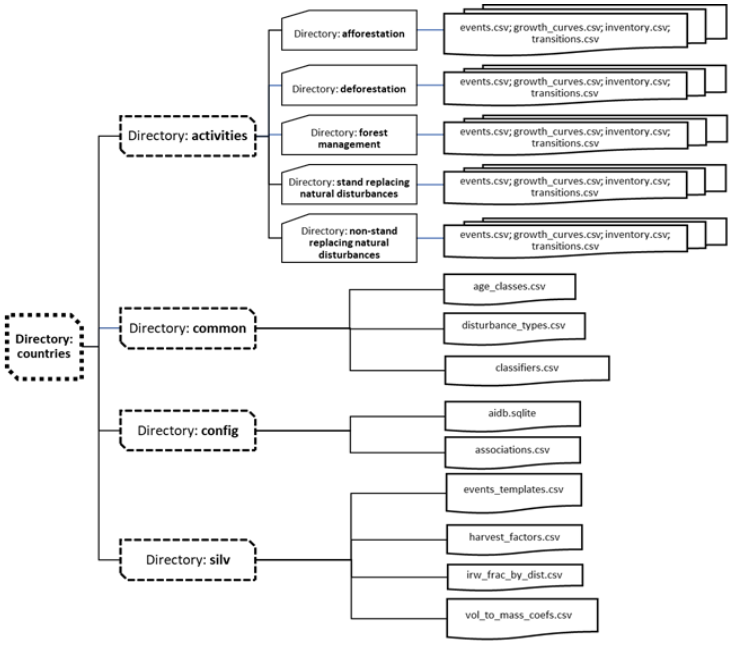
Table 1. Main directories included within EU-CBM-HAT.

Directory name	Description of the directory's content
countries	Country specific data as the lower level of the architecture in Figure 2 and details are reported in Table 2.
common	Info on the applicable forest inventory year in reference_years.csv and international codes of the country (e.g. iso2_code) in *country_codes.csv*.
combos	*.yaml* files which contain explicit information on the combinations of scenarios underlying a unique run, e.g. combination of the scenarios for all input data for the "reference" scenario in reference *.yaml* file.
domestic_harvest	Contains unlimited number of subdirectories, each subdirectory corresponds to one harvest scenario, e.g. subdirectory "reference" for the default dataset. Each such subdirectory includes two files with the time series of the expected harvest distinguished between industrial roundwood (IRW) and fuelwood (FW), i.e. two time series, in irw_harvest.csv, and fw_harvest.csv. The values are defined in 1000m3 under-bark (according the definitions implemented by the UNECE Joint Forest Sector Questionnaire). IRW includes the roundwood which is expected to get a commodity use (i.e. no matter if for sawnwood, panels or pulp). FW includes all the wood components used for energy. Both are defined as roundwood under-bark. Additionally, each subdirectory may contain an additional file rw_harvest.csv reporting the expected roundwood harvest which is used for the calibration of the model during the historical period (i.e. the period of time between the NFI reference year and the beginning of the simulation period), or for post-processing. In fact, the roundwood amount is defined as the sum of IRW and FW under-bark.
output	Contains unlimited number of subdirectories, one subdirectory for each combination of scenarios, e.g. "reference" for the combination of scenarios identified as "reference" for all input data. Each subdirectory matches the *.yaml* file recorded in the "combos" directory, with identic names. Further down, each subdirectory contains three subdirectories: input, output and logs. The input directory contains the files fed into *libcbm* (*.csv* files assembled by COMBO and HAT as a unique set of files requested by the Standard Import Tool (SIT)). The output directory contains the elaboration of harvest by HAT and the final results of the simulation (see also the description of output tables in 3.7 EU-CBM-HAT outputs). The logs directory contains text files as issued by HAT and *libcbm*, describing the progress of the model running, including various diagnostic messages and detailed description of the errors, if any.

3.2 Lower level of the EU-CBM-HAT: country specific inputs

The directory "countries" contains one country-directory for each EU member state identified by the iso2_code of the country (e.g. BE for Belgium, RO for Romania). Inside each country-directory, all the input files are distributed between four directories, as reported on Figure 2 and described in Table 2 .

Figure 2. Lower architecture of the input data in the EU-CBM-HAT: overview of the directories and files included within each "country" directory (corresponding to box "Directory: countries" in Figure 1).



Country specific information is made available to EU-CBM-HAT in four directories as described in Table 2. This information is used to distribute the expected harvest and for the preparation of files required by SIT.

Table 2. Top-down description of the subdirectories included within each country-directory (detailed description in the following sections).

Directory	**Description of content**
common	Three files (see Table 3) with data applicable to all events.
silv	Four files (see Table 3) containing the specifications of the applicable silvicultural practices and characteristics of roundwood use. Further down, each file may contain data for an unlimited number of scenarios.
config	Two files (see Table 3) mapping the AIDB initialization and simulation assumptions.
activities	Five directories with data specific to each of the following five packages: afforestation, deforestation, stand replacing and non-stand replacing natural disturbances and forest management. Further down, each file may contain data for an unlimited number of scenarios (see Table 3).

The subdirectories "common" and "activities" contain specific input files organized according to the information and formats required by the *libcbm*'s SIT. These are consistent with the CBM-CFS3 required inputs (Table 3).

Table 3. Specific input files expected by *libcbm*'s SIT.

SIT country specific input ([1]); file name	**EU-CBM-HAT directory/ies**
Age Classes; *age_class.csv*	common
Classifiers and Values; *classifiers.csv*	common

Disturbance Types; *disturbance_types.csv*	common
Inventory; *inventory_csv* Growth and Yields; *growth_curves.csv* Disturbance Events; *events.csv* Transition Rules; *transitions.csv*	activities/afforestation
	activities/deforestation
	activities/ stand replacing natural disturbances
	activities/non-stand replacing natural disturbances
	activities/forest management

([1]) The content of these files is described in the CBM-CFS3 user's guide (Kull et al., 2019).

3.3 Directory "common": information applicable to all events

This directory includes three input files (as of Table 3), reporting the data common to all disturbance events which may occur in forest; therefore, they are organized as unique input files.

3.4 Directory "silv": description of silvicultural practices, factors for roundwood destination, for volume to biomass conversion and market modifiers

The directory contains the information describing the silvicultural operations and the factors quantifying the IRW and FW shares in the roundwood removal (Table 4). It also includes the factors for the modulation of harvest according to the market demand, as well as the factors for converting volume to carbon content. This information is used by HAT to distribute the harvest across available stands and to prepare the disturbance events data for the actual simulation.

Table 4. Input required by the HAT module in distributing the harvest and constructing the "events" inputs.

File name	**Description of content**
events_template.csv	Provides the description of each silvicultural practice applicable. Silvicultural practices are attached to regular silvicultural interventions in forests, including those following specific natural disturbances (i.e. salvage logging in one or several steps after the natural disturbance event) and roundwood destination (IRW and FW, or FW only). The description includes the combination of classifiers specifying where, and within each age interval, a silvicultural operation is applicable (see Table 5).
harvest_factors.csv	Contains time series with values reporting the market "skew" factor (ϒ). The market factor adjusts the allocation of IRW, based on IRW availability and market shocks during the simulation (see section *4 Distribute the expected harvest: harvest allocation tool (HAT)*). This factor can be applied either for each silvicultural practice, or, as default option, to species' grouping (i.e. coniferous and broadleaved). The default option is that the expected ratio of coniferous and broadleaves wood in IRW harvest has to be provided by the user. The values of ϒ need to be provided for every year during the simulation. The default value is ϒ = 1 when the IRW is allocated strictly according to the biomass availability, according to applicable silvicultural practices. This allocation can be modified by the user (e.g. to increase/decrease the roundwood harvest from final cut in spruce forest in one specific year along the simulated period, see Eq. (9) and Eq. (10) in *4.3 Distribution of the industrial roundwood and fuelwood harvests*). By default, the FW is distributed according to the availability, without possibility to modify it through a market factor.

irw_fract_by_dist.csv	Specifies the expected share of IRW in the roundwood removals for each forest type by each applicable silvicultural practice (see Table 6).
vol_to_mass_coeff.csv	Contains the values of wood density ("wood_density") and the proportion of bark in total standing volume ("bark_frac") for each forest type. It may also contain other input data with the similar aggregation as needed for post-processing (e.g. biomass expansion factor values provided on forest types, etc).

Silvicultural practices resulting in wood removals are listed in the *disturbance_types.csv* file (included under the "common" directory) and described through quantitative characteristics in the *events_templates.csv* input file included within the directory "silv". Their correspondence to AIDB disturbances is specified in *associations.csv*. This last file includes all eligibility criteria linked to the specific silvicultural practices (Table 5). HAT uses this information to distribute the harvest across eligible stands and pools, and builds the events input into *libcbm* module.

Table 5. Description of the silvicultural practices as required by HAT in *events_templates.csv*. This table contains only the elements which are specific to EU-CBM-HAT, in addition to typical descriptors for "events" input required by *libcbm*, described in CBM-CFS3 User's Guide (Kull et al., 2019).

Descriptor	**Description**
scenario	Identifier for the package of input data specific to each assumption, i.e. it allows differentiating between assumptions. Among others, it represents the key in defining combination of scenarios in *.yaml* file.
growth_period	"Cur" stands for input data reflecting the current increment tables, which are applied during the simulation, as opposed to "Init", which represents yield tables used during the initialization period of the simulation (see Pilli et al., 2013, Figure 3), e.g. standing stocks expected at various ages. The corresponding data is provided in the *growth_curves.csv* input file. By default, "Cur" is used.
product_created	The silvicultural practices labelled as "IRW_and_FW" are expected to provide both IRW and FW (i.e. their share in the roundwood harvested is available in the file *irw_frac_by_dist.csv*). Silvicultural practices associated with "FW_only" do provide FW only.
dist_type_name	Denomination of the applicable silvicultural practice, e.g. thinning, with average of 22% intensity per standing volume, etc. This has to correspond to value used for "dist_desc_input" from *disturbance_type.csv* file and "name_input" in the *associations.csv*.
min_since_last_dist	Used by HAT and later libcbm to filter eligible disturbances according to a minimum return time between two consecutive disturbances (see also "dist_interval_bias"). The default value is set to -1, i.e. the return time is not relevant.
max_since_last_dist	The value is always set to -1, i.e. the information is not relevant for HAT.
dist_interval_bias	A value representing the expected period of time (in years) for which the total amount of IRW available through a specific silvicultural practice can be assumed as being entirely removed from forest, in equal shares annually between the two age limits. It is equivalent to the expected disturbance return in the same stand. HAT uses it to annualize the total available amount, resulting in the amount available for each silvicultural intervention in a time step. In general, it is equal to "min_since_last_dist" for non-stand replacing silvicultural interventions. For stand-replacing ones, it is equal to the duration corresponding to the period when termination of all stands in the oldest age

	class is expected, i.e. 20-40 years for shelter-wood systems, or a period equal to the difference of max and min ages for the applicable silvicultural practice. Its value drives the length of the cycles for even-aged stands, as well as the contribution of final cuts to total harvest in a time step.
last_dist_id	Define a successive mandatory silvicultural practice for a prior silvicultural practice (i.e. 2nd cut or final cut in stand replacing by multiple interventions) or following a natural disturbance (i.e. salvage logging).
sw_start/hw_start & sw_end /hw_end	Values representing the start and the end of the stands' age range when a specific silvicultural practice applies. For successive silvicultural practices, these ranges cannot overlap, while they allow gaps, i.e. as to define an age interval when no silvicultural interventions apply.

Note that the silvicultural practices can be changed during the simulation shifting from one scenario (e.g. reference) to another (e.g. close-to-nature) in any time step during the simulation period. The shift has to be defined in *.yaml* before the simulation start (see *3.9 Creating a new combination of scenarios*).

The details regarding the expected roundwood destinations, as IRW or FW are reported in *irw_fract_by_dist.csv* (Table 6). HAT considers the IRW as a generic roundwood category which includes all sorts of roundwood that are expected to have a material use from the following pools: merchantable living biomass, other wood components (including branches and tops, or parts of them), stem snags and branch snags. This file specifies, for all applicable silvicultural practices, the fraction of total roundwood material potentially used as IRW. The remaining fraction is assumed by default as FW, as a collateral product, e.g. if the IRW fraction is equal to 10%, 90% of roundwood removal would be classified as collateral fuelwood.

Table 6. Assumptions and default values regarding the fractions of industrial roundwood in the roundwood removals from forests (*irw_fract_by_dist.csv*).

Descriptor	**Description**
scenario	Name of the applicable scenario within a run; a change to another scenario can occur at any moment in time during the simulation.
softwood_merch softwood_other softwood_stem_snag softwood_branch_snag hardwood_merch hardwood_other hardwood_stem_snag hardwood_branch_snag	Fraction of roundwood material available as IRW from a specified pool by a specific silvicultural practice for each forest type. Fractions have to be generated based on under-bark volume. The roundwood amount removed from a specified forest pool is the product between the standing stock, multiplied by the fraction affected by the silvicultural practice (e.g. 20% of standing biomass and 80% of standing dead wood for commercial thinning), finally split between IRW and FW based on the IRW fraction reported in this cell (e.g. 20%) (see *4.3 Distribution of the industrial roundwood and* fuelwood harvests). The definitions of the four source pools are consistent with the general description reported on the CBM-CFS3 User's Guide.
Default values for IRW fraction[1,2]	
softwood_merch	< 10% for early thinning 30-50% for mid-late thinning 90% for late thinning and final cut

	50% in case of deforestation
softwood_other	0%
softwood_stem_snag	10% for sanitary cuttings 80% for salvage logging in the first year of the disturbance 30% in the second year of the disturbance 0% for the salvage logging in the following years 50% in case of deforestation
softwood_branch_snag	0%
hardwood_merch	10% for early thinning 20-30% for late thinnings 75% for late thinning and final cuts 50% in case of deforestation
hardwood_other	0%
hardwood_stem_snag	20% for sanitary cuttings 80% for salvage logging in the first year of the disturbance 40% in the second year of the disturbance 0% for the salvage logging in the following years 50% in case of deforestation
hardwood_branch_snag	0%

([1]) assuming some of these sources can provide wood for commodity use.
([2]) based on literature, validated runs of CBM-CFS3 and general knowledge (e.g. Luke, 2021; Ruter, 20219; Skogsstyrelsen, 2022;).

Note that the fraction of IRW can be changed for any time step during a simulation, i.e. shifting from one scenario to another (e.g. reference scenario to high-harvesting-protocol). Moreover, the shift to a new wood use scenario can be done independently by the shift to a new scenario regarding the silvicultural practices, e.g. they can occur at different moments during the simulation. The shifts have to be defined in *.yaml* file before the simulation start.

Finally, wood density and bark fractions are used by HAT to convert back and forth from carbon to volume, in order to allocate the harvest according to the availability in the standing stocks (Table 7). The values are provided for forest types only. See section *4.4 Uncertainty and inconsistency in distributing the harvests* for the discussion on how these factors can influence the emissions and removals projections of EU-CBM-HAT.

Table 7. Input data for conversion of volume to biomass and bark fraction in standing volume in *vol_to_mass_coefs.csv*.

Descriptor	**Description**
wood_density	Wood density coefficient, i.e. a constant non-age dependent value, reported in t dry matter per 1 m3 and derived from a literature review. Generally, it is a country specific average value, as reported, for example, in the country's National Inventory Report to GHG inventory submitted by the country to UNFCCC. It needs to be consistent with Boudewyn eqs. selected for the conversion of volume to biomass.
bark_frac	Bark's fraction of the merchantable volume, i.e. a constant non-age dependent parameter, as a percentage in the standing volume (%).

3.5 Directory "config": mapping simulation assumptions to generalized assumptions

The directory contains country specific information allowing SIT to map the specific assumptions of each simulation to the parameters stored in the AIDB (Table 8) as generalized assumptions. EU CBM-HAT uses the customized archive index database for European Union countries (Pilli et al., 2018), which was improved along the EU-CBM-HAT development with additional explicit fluxes, i.e. from merchantable, other wood components, stem and branch snag pools, to product pool.

Table 8. Files placed within the "config" directory.

Input file name	Description of the information contained
AIDB	Country specific archive index database.
associations.csv	File displaying complete list for mapping the codes from input data to corresponding categories from AIDB, e.g. classifiers to classifiers, disturbance types to disturbances types, etc.

The *association.csv* file includes the mapping rules for running the simulation (Table 9) for all activities, e.g. each classifier and disturbance need to be mapped to a corresponding item in the AIDB. Missing elements trigger a message at the begging of the simulated period (after the calibration, see *6 Automatic checks of the input data and error messages during the runs*).

Table 9. Example of mapping of the input data with AIDB categories in *associations.csv*. The "name_input" is the name used for that respective category across the input data files, while the "name_aidb" is the name for the corresponding item in the AIDB.

Category	name_input	name_aidb
MapAdminBoundary	Luxembourg	Luxembourg
MapEcoBoundary	CLU24	CLU24
MapSpecies	.....	.....
MapDisturbanceType	Generic 5%	generic 5% mortality
MapSpecies	non-forest to species or forest types	Average

3.6 Directory "activities": input data describing disturbance events

The disturbance events assumptions are included within the directory "activities" and defined in five different subdirectories: afforestation, deforestation, stand replacing and non-stand replacing natural disturbances, and forest management. While each subdirectory contains four files necessary to describe relevant inputs for that family of events, only files from the subdirectory forest management are mandatory with data (Table 10). This means that for other family of events empty tables are accepted, e.g. assuming there is no scenario for a specific type of disturbance, or there is no specific assumption regarding the inventory, growth curves or transitions relevant for that disturbance. In such cases, the information provided for forest management is implicitly used (as submitted in subdirectory "mgmt"). By default, the installation of EU-CBM-HAT provides for the full set of required files.

Table 10. Generic description of the content of the mandatory input for disturbance events.

Required files	Description of the content
events.csv	Time series including the expected intensity of each disturbance event (natural disturbance, silvicultural practice), further

	distinguished by classifiers, and defined as area affected from a disturbance event, or as amount of C removed (i.e. for thinnings), or proportion of eligible stands affected from a specific event.
growth_curves.csv	Two data series with growth curves reporting the standing stock volume in m3 per ha on the applicable age classes for each combination of classifiers. One data series represents the "Init" including the yield curves derived from the NFI standing stock volume along the applicable age classes. These curves are used for the initialization of the carbon stocks in soil, litter and dead wood pools, and to determine the carbon stock in living biomass at the beginning of the simulation period (i.e. time step 0). See Pilli et al., 2013 Figure 3 for an illustration. The second data series labelled as "Cur" represents the expected cumulated net increment of the standing stock volume along the applicable age classes (e.g. as retrieved from NFI). This curve is used to simulate the biomass growth during the simulation. Across the input tables the information on which yield curve is required is defined in the column "growth_period". Alternative growth and yield scenarios can be defined, e.g. under modified environmental conditions.
inventory.csv	Forest inventory data in the initial year of the simulation, distinguished between classifiers, with the area distributed on age-classes or age simply. It should also contain the non-forest area expected to be afforested during the entire simulation period.
transitions.csv	Transition rules defining changes following specific disturbance events (i.e. in case of afforestation or deforestation, or stand replacing disturbance events), e.g. from one forest type to another.

In all these files, wildcards can be used instead of explicit classifiers.

Before the model run, HAT merges all these inputs into unique set of files in SIT required format (as defined in Table 3), and pushes them to *libcbm* for the actual simulation of the time step.

3.6.1 Defining simulations regarding the conversion to forests

The inputs related to the conversion to forests are provided in the subdirectory "afforestation" (Table 11), including a time series of the area afforested for the entire projected period. Each of these files contain packages of input data on the applicable scenarios (e.g. scenario "3 billion trees pledge", scenario "natural expansion", etc).

Table 11. Specific input data required for the conversion to forest.

Required files	**Description of the content**
inventory.csv	Total area (in ha) available to be converted to forests during the entire simulation period. All classifiers have to be defined.
growth_curves.csv	Increment curves (in m3 per ha on age class) for each combination of classifiers. These curves will only include the current increment curves (i.e. "Cur") since they are not subject to initialization period and also assumes that there are no silvicultural intervention during a transition period from non-forest to forest. Optionally, these curves can be afforestation specific (e.g. applying for the transition period from non-forest to forest), but a transition to general curves should be applied sometime later in order to ensure consistency within typical forests in the country. These forests become subject

	to forest management, so contribute to satisfy the expected harvest, at any point in time as defined in *events_template.csv*.
events.csv	Area to be afforested for each year during the simulation (in ha per year). It has to be split on forest types, while the other classifiers can be defined by wildcards.
transitions.csv	Transition rules associated with the conversion from non-forest to forest land, e.g. continue labelling conversions throughout the entire simulation period. Filling in adequately this file, i.e. using a peculiar classifier for such events, would allow the user to track afforestation related emissions and removals during the entire simulated period.
associations.csv	Mapping to non-forest soils in AIDB corresponding to non-forest land before afforestation.

3.6.2 Defining simulations regarding the conversions from forests

The inputs related to conversions from forest to other land categories are provided in the subdirectory "deforestation" (Table 12). The roundwood removals associated with the conversion from forest is classified as salvage logging from predetermined events and contributes with priority to satisfying the annual expected harvest (with shares between IRW and FW as defined in *irw_fract_by_dist.csv*). Each of these files contain all info required for the applicable scenarios (e.g. "historical rate of deforestation", "minimum historical rate", etc).

Table 12. Specific input data required for the conversion from forests.

Required files	**Description of the content**
events.csv	Time series with total area (in ha) or total volume (in tC) to be converted from forests during the entire simulation period. Generally, a random allocation across all classifiers applies.
transitions.csv	Defining transitions would allow tracking such conversions throughout the simulation period, e.g. in terms of land uses to which conversion takes place. Filling in adequately this file, i.e. using a peculiar classifier for such events, may allow the user to track deforestation area during the entire simulated period.
irw_fract_by_dist.csv	Defines the share of IRW for the harvested roundwood. A default value of 50% applies, given fact that it may affect stands at any age.

3.6.3 Defining simulations regarding the natural disturbances

All inputs related to natural disturbances are organized on two types of data reported on the following subdirectory: stand replacing ("nd_sr") and non-stand replacing natural disturbance events ("nd_nsr") as of Table 13. Information on the occurrence and magnitude of natural disturbances is exogenous, defined as time series for the entire projected period. As such, EU-CBM-HAT does not predict future disturbances scenarios, but demonstrate its ability to accommodate the impacts of such future disturbance events as defined by the user. Each of these files contains packages of input data on the applicable scenarios (e.g. "disturbances at historical level", "insect attacks only", etc). Salvage logging following natural disturbances are considered as predetermined events.

Table 13. Specific input data required for the natural disturbances.

Required files	Description of the content
events.csv	Time series with the intensity of each natural disturbance, defined as amounts based on volume (converted to tC removed from forests), area (in ha) or proportions (% of area) in a wide format table with annual time step until the end of the simulation (cells can be empty for any time step).
growth_curves.csv	Optionally, a different "Cur" curve can be applied after the natural disturbances, modifying the growth as a post-event change.
transitions.csv	Any specific transition rules linked to such disturbance events, e.g. to a new forest type.

3.6.4 Defining simulations regarding forest management

All inputs related to forest management activities are contained in the subdirectory "mgmt".

Any model run by EU-CBM-HAT, normally, includes two periods.

The so-called *historical period*, is used for model's calibration (i.e. comparing, before 2020 the model output with other independent data sources). For this period, the input data reported on the *events.csv* has to be complete, as SIT requires, in explicitly defining the characteristics of the silvicultural practices applied, i.e. intensity and frequency of the silvicultural practices, the corresponding amount of harvest, according to the recorded statistics (e.g. FAOSTAT, NFI, national statistics), practically the data organized as of old CBM-CFS3 inputs. Optionally, in order to ensure a realistic age class representation at the end of calibration period, they should explicitly include the area affected by stand-replacing disturbance events (i.e. clear-cuts) and/or the contribution of salvage logging to harvest. Four specific files are required to simulate the forest management during the calibration period (Table 14).

Table 14. Specific input data required for forest management, for both calibration and simulation period.

Required files	Description
inventory.csv	Forest inventory data in the initial year of the simulation. Information is organized on classifiers with area distributed on age-class.
growth_curves.csv	Contains the yield ("Init") and increment ("Cur") curves for the relevant combination of classifiers. These would be used both for calibration and simulation period.
events.csv	Time series with data for the historical period used for calibration, i.e. from the last before the last inventory year to 2020 (or another). For the period after the last year of the calibration period, e.g. post-2020, the table remains empty, as all required information would be calculated by HAT and make it available for inspections and post-checks in the directory output/...../output/events.csv.
transitions.csv	Implement changes caused by disturbances, e.g. to a new forest type, expected during both the calibration and simulation period as called by the applicable scenario.

Within the subsequent period, i.e. the so-called *simulated period* (e.g. from 2021 onward), COMBO and HAT bring together the inputs from all types of disturbance events to be simulated during the simulated period in a unique forest management boundary where country specific silvicultural interventions are applied. This means that all pre-determined disturbances will contribute to shaping the forest dynamics and satisfying the harvests, for example, and land afforested earlier becomes subject to silvicultural practices, as well as a forest affected by a natural disturbance may be subject to salvage logging. For the simulated period, while

COMBO constructs the overall scenario to be run from the different scenarios on activities (e.g. "business-as-usual" for afforestation, "close to nature" for forest management, etc), HAT distributes the IRW and FW to disturbance events based on the input information in the corresponding files (e.g. *events_template.csv*, *irw_frac_by_dist.csv*, *irw_harvest.csv* and *fw_harvest.csv*) in the SIT required format. The complete files generated this way can be visualised at the end of the simulation in the output directory (see *3.7 EU-CBM-HAT outputs*).

3.7 EU-CBM-HAT outputs

The directory "output" contains two subdirectories (as of Table 1 and Figure 1) with the HAT prepared "input" and the actual "output" of the simulations.

The directory "input" contains inputs prepared by HAT as *.csv* files in SIT required format (as of Table 3). These files represent a compilation of user's input data for the calibration period and only the predetermined events (natural disturbances, deforestation) and afforestation for the simulated period.

The subdirectory "output" contains the results of the simulations for both the calibration and simulated periods (Table 15), a complete set of inputs either from user and HAT. Results data are available at the most detailed scale simulated, by all combination of classifiers and time step of one-year. In order to get a complete picture of the calibration and simulation these files need to be explored.

Table 15. Output files of EU-CBM-HAT.

Output files	**Description**
area.csv	Dynamic of area.
classifiers.csv	Classifiers according to input data
events.csv	Contains HAT prepared target amounts for the silvicultural practices assumed to occur as of silvicultural practices described in events_templates.csv. It does not include the target amounts for salvage logging (see step 1 in *4.1 HAT concept*) for which the information is available in the corresponding input files. In the *events.csv* the measurement type may be changed compared to actual input, given HAT processing all inputs in terms of mass (M).
extras.csv	Overview table prepared by HAT providing estimates for generic indicators at the time step resolution, i.e. quantities are the totals for the time step. The indicators refer to total annual amounts of IRW and FW expected from salvage logging. This file can be used as a first step in checking the result of the simulation.
flux.csv	Dynamic of the amounts of carbon transferred between various pools.
pools.csv	C stocks dynamics for all pools.
state.csv	Age and age class dynamic.
params.csv	Spatial and temporal tracking of disturbance events

Output files are saved in a country directory identified by country's iso code, e.g. there is no EU aggregation predefined in EU-CBM-HAT (see *3.8 Exploration of EU-CBM-HAT results* for more details).

The *extras.csv* and *events.csv* files are specific outputs provided from EU-CBM-HAT, (see Table 12 and Table 13). The purpose of these additional files is to increase the transparency on the internal processing applied from HAT and to allow quick checks of the simulations.

Specifically, *extras.csv* presents the results aggregated by the time steps for the simulated period (Table 16).

Table 16. Definitions of the aggregated indicators as reported in *extras.csv*. All values in this file are volume under-bark (m3) for the annual time step virtualized by HAT for the simulated period (calibration period excluded).

Indicator	**Description of the indicator**	**Quantitative relation to other indicators**
Fluxes to products from salvage logging		
irw_predetermined fw_predetermined	Target volume to be generated only from salvage logging (i.e. natural disturbances and deforestation) or from predetermined silvicultural practices (i.e. clear cut areas defined for the simulated period). It should be noted that only salvage in the year when natural disturbance occurs is included (i.e. if there is any salvage logging in the years following the natural disturbance, the corresponding contribution to satisfying expected harvest is taken into account by HAT, see *4.2 Treatment of salvage logging, or* irw_salv_avail & fw_salv_avail below).	
Expected harvests formulated by exogenous models (e.g. economic models)		
harvest_irw_vol harvest_fw_vol	Expected harvest of IRW and FW.	Original values according to the files from directory "domestic_harvest".
Remaining unsatisfied amounts after any supply from salvage loggings		
irw_salv_avail fw_salv_avail	Target volume to be further satisfied from salvage logging in the year(s) following the natural disturbances, i.e. such volume is harvested with priority in the time step before distributing the remaining amount. Noteworthy, any amount available from salvage logging in the following years is accounted by HAT with higher priority in distributing the expected harvest for the predefined number of time steps (i.e. if salvage is planned to occur in the two years following the event, silvicultural practices associated with salvage logging need to be specified in *events_template.csv*). For example, in order to harvest in two years, salvage can be set to 60% in the first year and 100% in the second year).	100% of the amount of irw_salv_avail is allocated by HAT in the time step. 100% of the amount of fw_salv_avail is allocated by HAT in the time step.
remain_irw_harvest remain_fw_harvest	Target volume to be further satisfied after any supply from predetermined disturbances.	remain_irw_harvest= harvest_irw_vol- irw_predetermined remain_fw_harvest= harvest_fw_vol-fw_predetermined

Satisfying fully the IRW expected harvest		
tot_irw_vol_avail tot_fw_vol_avail	The annual total volume that is eligible to be harvested in the time step according to the applicable silvicultural practices and the "market factor".	tot_irw_vol_avail = Σ irw_avail (see *events.csv*, see Table 13) tot_fw_vol_pot = Σ fw_avail (see *events.csv*, see Table 13)
Satisfying fully the FW expected harvest		
still_remain_fw_vol	The annual total volume of FW which was not satisfied from salvage logging and as collateral to IRW production. This amount should be satisfied through specific FW dedicated silvicultural interventions (i.e. disturbances classified as "fw_only" in *events_templates.csv*).	still_remain_fw_vol = harvest_fw_vol - remain_fw

The *events.csv* provides explicit results of HAT processing at the spatial resolution corresponding to the most detailed combination of classifiers, silvicultural interventions, and age, for each time step during the simulated period (calibration period excluded) (Table 17).

Table 17. Definitions of the disaggregated indicators from *events.csv*. The measurement unit for these indicators is volume under-bark (m3) unless reported otherwise for the specific indicator (see proportions or amount).

Indicator	**Description**	**Formulas**
irw_pot fw_pot	Total standing volume of IRW and FW potentially available, i.e. eligible, to be removed assuming applicable silvicultural rules and constraints in the time step, before the application of market factor.	
irw_avail fw_avail	Total standing volume of IRW and FW potentially available to be removed assuming applicable silvicultural rules and constraints in the time step and modified by the market factor.	irw_avail = irw_pot * $\gamma\ market$ (see *4 Distribute the expected harvest: harvest allocation tool (HAT)*)
irw_norm	Proportion of IRW available for a particular combination of classifiers and silvicultural practices compared to the total IRW available, i.e. eligible, in the time step.	irw_norm (%) = irw_avail/Σ irw_avail
irw_need	Target volume of IRW to be removed from each forest corresponding to a combination of classifiers and silvicultural interventions for the respective time step.	remain_irw = Σ irw_need
irw_frac	The impact of removed IRW in irw_avail, i.e. the proportion (%) that is actually removed from the standing volume available in the time step. It has general information purpose, i.e. for assessing the target supply vs. availability.	
fw_colat	The amount of FW collateral to IRW production, i.e. the amount of fuelwood which is expected from	(see *4 Distribute the expected harvest: harvest allocation tool*

	fully satisfying the IRW harvest.	*(HAT)*
fw_norm	Proportion (%) of standing volume of FW available for a particular combination of classifiers and silvicultural practices compared to the total FW available, considering only fuelwood dedicated silvicultural practices, i.e. defined as "fw_only" in the *events_templates.csv*.	fw_norm (%) = fw_avail/Σ fw_avail
fw_need	Target volume of FW satisfied by the application of FW dedicated silvicultural practices.	
amount	Target amount of carbon (in tons of C) to be removed from forest corresponding to a combination of classifiers and silvicultural interventions for the respective time step. Notably, HAT converts any type of input to mass (carbon) targets, e.g. natural disturbances input may be defined in terms of area.	Amount = irw_need * wood density * $C_{fraction}$ (see *4 Distribute the expected harvest: harvest allocation tool (HAT)*

3.8 Exploration of EU-CBM-HAT results

EU-CBM-HAT does not have a graphical user interface. It delivers output data in the form of Pandas data frames, a standard data science tool which opens a wide range of data manipulation, plotting and automation possibilities. Moreover, there is not a unique result file, so to analyse C stocks, C fluxes and related events, all output *.csv* files must be merged upon common keys. To facilitate this merge, *eu_cbm_hat* provides, with the installation, a script which aggregates simulation results in a unique data frame and parquet file, making it available for further data processing through any data science software

The exploration scripts used by the team during the EU-CBM-HAT development are all available for download at the installation from: https://gitlab.com/bioeconomy/eu_cbm.

3.9 Creating a new combination of scenarios

With the installation, a dataset called "reference" scenario for a mock country ZZ is provided as the default version of input data.

In order to run a new combination of scenarios, they should be defined using a text editor following the steps in Table 18. The existing files associated with the reference scenario can be used as templates for the new scenario.

Table 18. Steps to define a new combination of scenarios, ZZ is the name of a mock country

File location and description	**Default templates**
Add data specific to the "new_scenario" in each relevant input file. The assumptions have to be identified as "new_scenario" on the column "scenario" across all files. The time series has to start with the year simulated by the HAT, e.g. 2021, if the calibration period finished 2020.	For example, in case of a new scenario for afforestation, specific records must be added in: *events.csv, growth_curves.csv, inventory.csv, transitions.csv*. in ...\ *eu_cbm_data*\countries\ZZ\activities\afforestation. Also, information specific to the new assumptions must be added in the following files contained in the other directory (as explained above in Lower level of the EU-CBM-HAT: country specific inputs): *eu_cbm_data*\countries\ZZ\common - on the new disturbance types; *eu_cbm_data*\countries\ZZ\config - for the changes in the AIDB and association file;

	eu_cbm_data\countries\ZZ\silv – description of the silvicultural practices and wood use.
Add data on IRW and FW expected harvest in the new directory.	*irw_ harvest.csv*, *fw_harvest.csv*, *rw_harvest.csv* in the directory *eu_cbm_data*\domestic_harvest\new_scenario.
Compile a new *.yaml* file with the combination of scenarios desired. *NB.* A *.yaml* file is a configuration file that can be edited with a text editor.	Create a new file in *eu_cbm_hat*\combos: *new_scenario.py*.
Create a new class and import the corresponding module in the file __init__.py in ...*eu_cbm_hat*\combos of the *eu_cbm_hat*.	Add the new class [...new_scenario...] and import the new module [...new_...] in __init__.py, by paying attention to consistency of names, e.g. class name: "New_scenarios", short_name: "new_scenarios".

4 Distribute the expected harvest: harvest allocation tool (HAT)

4.1 HAT concept

HAT represents EU-CBM-HAT's own module for the distribution of the roundwood expected harvest according to the simultaneous availability of IRW and FW from applicable silvicultural practices in eligible stands. Conceptually, to allocate the IRW and FW harvests, HAT estimates the roundwood amount that ca be virtually harvested in a time step based on total availability in the eligible pools from the eligible stands defined according to predefined silvicultural practices criteria.

This solution is consistent with the forest management approach where decisions regarding harvesting amount are mostly based on the availability in the standing stock, within the sustainability criteria applicable by country's forestry. This approach is also taken due to type of data run internally by *libcbm*, i.e. amount of C stock in the standing pools. Meanwhile, other approaches may consider the ratio of harvest over the annual increment (e.g. Government Offices of Sweden, 2019; Department of Agriculture, Food and the Marine Ireland, 2019), or various threshold parameters, e.g. based on the diameter or areas, applied individually or in combination (e.g. Ministry of Agriculture and Forestry Finland, 2019).

In distributing the harvests, HAT applies the same rules regarding silvicultural practices as *libcbm* will in the actual simulation. These rules include:

(i) the definition of the standing pools targeted to provide a certain contribution to the harvest;

(ii) the definition of the age ranges when respective silvicultural practices can be applied;

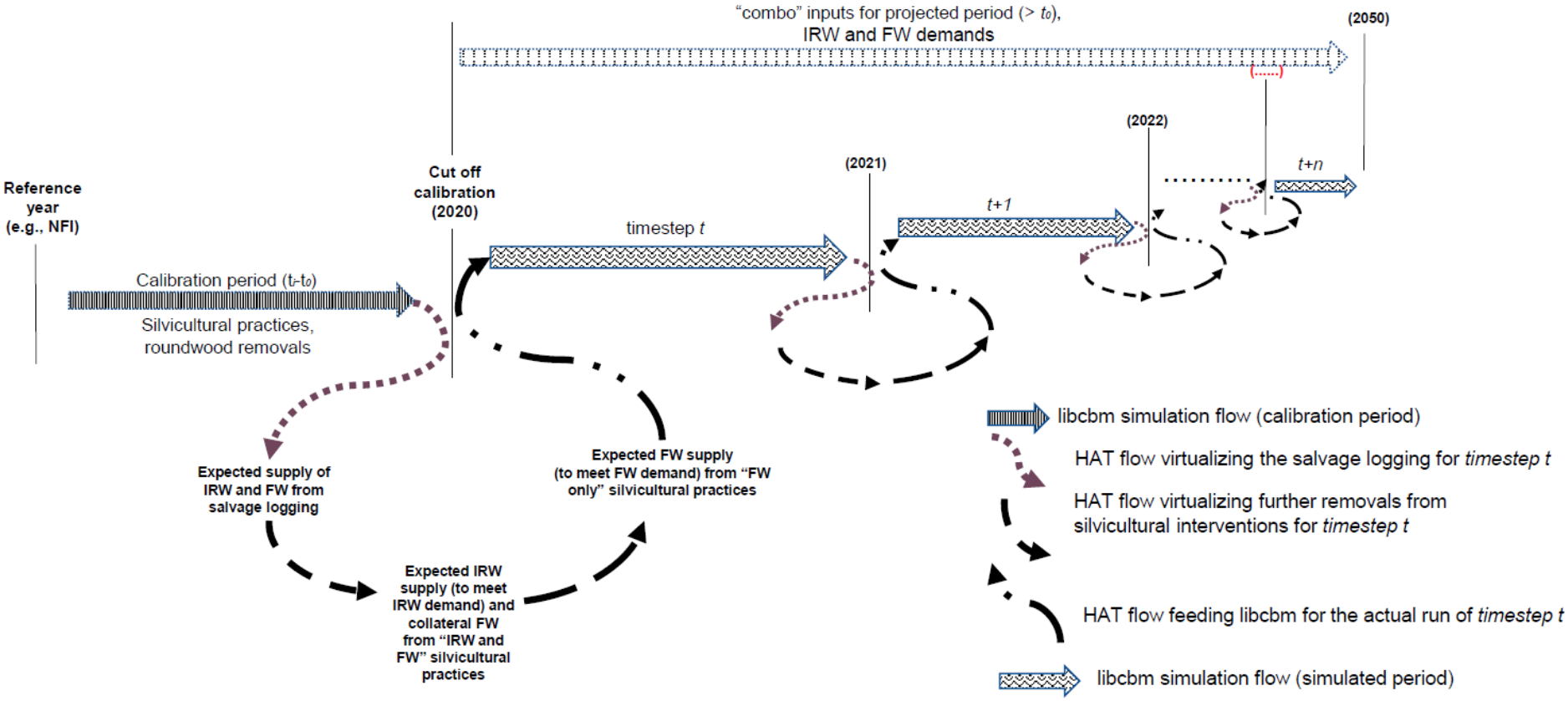
(iii) the period of expected return to the same stand for the following silvicultural intervention, and,

(iv) the type of product expected from a silvicultural intervention ("IRW and FW", or "FW only").

In defining the availability of roundwood for harvesting, HAT simultaneously checks the eligible fluxes to the wood product pool from four standing pools, i.e. merchantable over-bark (o.b.), other woody components, stem snags and branch snags. The availability is given as a combination of the characteristics of each silvicultural practice (e.g. intensity of removals for relevant pools) and pools' status (e.g. the removable quantity and expected quality of roundwood). The expected quality of roundwood removals refers to the share of IRW in the total roundwood removal to result from that type of silvicultural intervention (see Table 6) . This approach makes HAT to mimic the real-life process, where the amount of harvest provided from a stand always contain a fraction that only can be used for energy (e.g. Routa et al., 2012; Ikonen et al., 2003; Bosela et al., 2016; Węgiel et al., 2018; Jansone et al., 2017; Ruter, 2021; Schulze et al., 2022). This is more insightful than simply assessing the roundwood amount available as a merchantable standing stock is only designed for IRW or FW. This approach attempts to improve the link between roundwood quality and silvicultural interventions.

HAT assesses the availability and distributes wood harvest into silvicultural practices in every time step, at the detail defined by the combination of classifiers. The assessment of the roundwood availability and distribution of expected harvest is completed only after the natural disturbances and associated silvicultural operations have been pre-processed for each time step. Thus, the availability of standing timber stocks is the result of forest growth and natural disturbances, re-evaluated at the beginning of each time step.

Figure 3. Representation of HAT procedure behind estimating the standing stocks availability and distribution of IRW and FW harvests, and the interaction between HAT and *libcbm*. Dotted lines represent the virtualizing of the silvicultural operations which define the events to be applied in a certain time step (t). The years mark a 'calibration period' and EU climate policy landmark years (e.g. 2020, 2050).



HAT focuses on distributing IRW with priority over FW, while also targeting first the availability from salvage logging over silvicultural practices. This capability is implemented through the three consecutive steps (Figure 3) as follows:

Step 1: estimate the expected amounts of IRW and FW available from predetermined disturbances in the time step *t*, i.e. salvage logging from natural disturbances and deforestation, as well as any predefined silvicultural intervention (e.g. clear cut defined as area, if needed). This means that HAT first implements the silvicultural practices associated with disturbances which typically result in salvage logging (i.e. natural disturbances and deforestation).

Step 2: estimate the expected amount of IRW provided through silvicultural practices associated with salvage logging in the year after the natural disturbance events and regular silvicultural practices in the stands available in the respective time step t, e.g. all the stands not subject to predetermined disturbances or to other silvicultural restrictions, like e.g. time elapsed since the last silvicultural intervention, as described in the *events_templates.csv*. In this phase, HAT distributes only the difference between the total IRW harvest and the IRW to be provided as of Step 1. Given the standing roundwood quality and wood exploitation efficiency, some FW amount would inherently result as collateral FW, which together with FW from salvage logging would contribute to reach the FW harvest.

Step 3: estimate the remaining amount needed to fully satisfy the FW expected harvest, according to the availability of roundwood from stands where fuelwood dedicated silvicultural practices may take place, e.g. such as pre-commercial thinning, coppices, as described in the *events_templates.csv*.

The amounts of IRW and FW acquired from all three steps are cumulated and then passed to *libcbm* for the actual running of the respective time step *t*. In case the expected harvest is not satisfied in one time step, explicit messages are issued while the output files provide for all the relevant quantities (see *6 Automatic checks of the input data and error messages during the runs*).

4.2 Treatment of salvage logging

HAT accounts the salvage logging first, before allocating the expected harvest. Specifically, HAT can account for the salvage logging in one or several successive time steps, as follows:

"One-year-go" when both the natural disturbance event and the salvage logging associated with it occur in the same time step, so a direct transfer from living biomass pool, i.e. from "merchantable" to "products" is defined via the AIDB's disturbance matrix. This is implemented as part of predetermined disturbances in Step 1 above;

"Multiple-years-go", when the natural disturbance event is applied in one time step and salvage logging in two or more subsequent time steps. For the time step of the disturbance event there is a transfer of affected live biomass to dead organic matter pools (i.e. to stem snags). Then, in the following time step(s) a fraction from "dead organic matter" pools will be transferred to the "product" pools through annual silvicultural practices corresponding to salvage logging(s) operations. This is implemented as part of silvicultural practices in Step 2 above.

4.3 Distribution of the industrial roundwood and fuelwood harvests

HAT performs a volume-based allocation of the roundwood harvest based on the standing availability of IRW and FW across eligible resources. Eligibility is defined by a specific combination of classifiers, applicable silvicultural practices and other constraints (e.g. period since last intervention, coniferous and broadleaves share of IRW in the expected roundwood removal).

The following pattern of calculation is used by HAT to calculate the amount of roundwood to be harvested within the time step *t*.

To distribute the roundwood harvests across applicable silvicultural practices HAT operates all internal calculations as volume under-bark.

On HAT side, the expected harvests are formulated as volume under-bark while the internal processing of *libcbm* is defined as over-bark. HAT does the conversion with two parameters: the bark fraction b and the basic wood density ρ. Expected basic wood density is the ratio between oven-dry mass (at 0% moisture) and green volume (water-saturated wood volume, i.e. fresh state) in g/cm3 (e.g. Vieilledent et al., 2018). The relationship between the under-bark volume V_{ub} and the over-bark volume V_{ob} is expressed as:

$$V_{ub} = V_{ob} * (1 - b) \qquad \text{Eq. (1)}$$

or

$$V_{ob} = \frac{V_{ub}}{(1-\mathrm{b})} \qquad \text{Eq. (2)}$$

On the *libcbm* side, the C stocks simulated at the end of the previous time step (*t-1*) and C fluxes associated with predetermined disturbances virtualized for time step *t*, are first converted to volume under-bark (i.e. the same unit used as for IRW and FW harvests) according to the following steps.

The carbon in any pool, i.e. merchantable biomass (M_{ob}), expressed in terms of C, as simulated by *libcbm*, is converted to the volume over bark:

$$M_{ob} = V_{ob} * \rho * 0.49 \qquad \text{Eq. (3)}$$

where:

0.49 is assumed as a constant carbon fraction of wood material (IPCC, 2006).

Further on, the volume under-bark can be calculated from the *libcbm*'s C stocks and fluxes with this generic equation:

$$V_{ub} = \frac{M_{ob}}{\rho * 0.49} * (1 - b) \qquad \text{Eq. (4)}$$

In order to estimate the amount of roundwood potentially available, HAT applies Eq. 4 to fluxes to products from predetermined disturbances and to the eligible stocks of four eligible pools in the eligible stands. As a general rule, the available amount of IRW in the four pools for each set of classifiers i and disturbance event *d*, in time step t, is annualized by dividing the part of the eligible standing stocks to be moved to product's pool by the disturbance event *d*, by the return period *σ (*i.e. the "bias" defined as the minimum number of years between two consecutive disturbance events affecting the same stand, as defined within the *events_template.csv).* Eventually, the annualized availability is further modified by an annual market factor γ taking into account possible further deviations due to specific market contingencies. Therefore, for a specific silvicultural practice *d* applied to a combination of classifiers *i*, the amount of biomass potentially available as IRW at the time step *t* ($Mav_{i,d}^{t}$ in tC) is estimated as:

$$Mav_{i,d}^{t} = \frac{M_{i,d}^{t-1} * f_d}{\sigma} * f_{IRW} \qquad \text{Eq. (5)}$$

where:

$M_{i,d}^{t-1}$ is the total amount of the standing stocks in the eligible pools for the relevant combination of classifiers extracted from *libcbm* output for the time step (*t-1*), in the eligible age range attributed to the silvicultural practice *d* (as defined within the *event_templates.csv*), applied to the classifiers' combination *i*;

f_d is the share (%) of standing stock in the eligible pools moved to the product pool through the specific silvicultural intervention *d*, according to the matrix defined within the AIDB (e.g. 85% of the stems and 50% of the stem snags, for a final cut);

σ is the return period assigned to disturbance event d (in years). In a sustainably managed forest in Europe, tending or harvest in a specific stand takes place once in about 10 years (e.g. Schall and Ammer, 2013; Schulze et al., 2022);

f_{IRW} is the share (%) of roundwood of industrial quality from the roundwood amount to be removed from the forest (according to the input defined in file *irw_frac_by_dist.csv*).

Once $Mav_{i,d}^{t}$ is estimated for each applicable disturbance event *d*, it is converted to roundwood volume under-bark available for harvesting within the time step *t* ($Vav_{i,d}^{t}$ in m³ u.b.) through Eq. (4):

By performing this operation for all applicable silvicultural practices and classifiers' combinations, HAT estimates the total potential roundwood volume available in the time step *t*. For each time step, the sum of all volumes represents the total potentially available in the time step, while the proportion of participation of each silvicultural practice allows distributing the harvest proportionally across availability. Specifically, HAT calculates the corresponding normalized values, or the fraction of available roundwood ($Firw_{i,d}^{t}$) in the total as the sum of all available volumes, for a given silvicultural practice *d* for each forest type, applied to a set of classifiers *i*, within the time step *t*, as follows:

$$Firw_{i,d}^{t} = \frac{Vav_{i,d}^{t}}{\sum Vav_{i,d}^{t}} \qquad \text{Eq. (6)}$$

The harvest is finally distributed amongst different classifiers and silvicultural intervention events according to the corresponding fraction estimated within Eq. (6). The proportions should sum to one for a time step.

Such an approach allows to estimate the potential contributions of each silvicultural intervention assuming a strict application of the forest management rules through defined silvicultural practices. Still, different exogenous scenarios, e.g. energy or economic, or other forest management scenarios, may require a deviation from this pattern. For this reason, a market skew factor (γ) allows modifying such allocation. In this case a deviation 'harvest factor' is used instead of using the normalized value F generated from Eq. (7), as follows:

$$F_{i,d,market}^{t} = \frac{V_{i,d}^{t}}{\Sigma V_{i,d}^{t}} * \Upsilon_{market} \qquad \text{Eq. (7)}$$

where:

γ_{market} is a factor adjusting the proportion of actual roundwood amount distributed on a combination of classifiers. The proportions should sum to one for a given product (IRW or FW) and a given time step *t*, in order to avoid modifying the target harvest. Assuming the market demand is different from the available proportion of coniferous and broadleaves in the eligible stands, γ_{market} can be used to allocate a higher roundwood harvest to the coniferous stands.

γ_{market} is exogenously defined as a fraction in the *harvest_factors.csv* file. The data input for γ_{market} addresses the IRW harvest, while no market factor is applied for FW, meaning that HAT distributes the FW expected harvest along all classifiers proportionally to the available stock in eligible stands under the applicable FW-dedicated silvicultural practices.

γ_{market} can be applied on coniferous and broadleaves as default version, or alternatively, on forest types and silvicultural practices. The application of these options is automatically implemented by HAT, and simply depends on how harvest factor data is filled in in the *harvest_factor.csv*.

The default version of the EU-CBM-HAT assumes the market factor is implemented on the grouping of coniferous and broadleaves, as the most aggregated indicator of the market influence. In doing this, first, HAT estimates the proportion of each group of conifers and broadleaves in the total annualized available volume under-bark (Eq.8) by summing the proportions *F* corresponding to original contribution for each forest type and silvicultural disturbance event (as of Eq. 6). The aggregation of normalized values by group is written as follows:

$$\sum_{Con} F_{i,d}^{t} + \sum_{Broad} F_{i,d}^{t} = 1 \qquad \text{Eq. (8)}$$

where:

F is the aggregated fraction for each of the two groupings, estimated by HAT as the sum of the actual contribution of each forest type and silvicultural practice within the coniferous and broadleaves groups in the year *t*, non-dimensional.

Then, the HAT joins the user-defined expected proportion Υ for the coniferous and broadleaves groups, for each time step *t* during the simulation. The sum of the harvest factors in *harvest_factor.csv* has to respect the rule:

$$\Upsilon_{i,d\ Con}^{t} + \Upsilon_{i,d\ Broad}^{t} = 1 \qquad \text{Eq. (9)}$$

The original proportion of participation for each forest type and silvicultural practices is then modified internally by HAT, as example for coniferous:

$$Firw_{i,d\ applied}^{t} = Firw_{i,d}^{t} \frac{\Upsilon_{i,d\ Con}^{t}}{\sum_{Con} Firw_{i,d}^{t}} \qquad \text{Eq. (10)}$$

where:

$Firw_{i,d}^{t}$ - fraction estimated for each silvicultural practice for each forest type within coniferous and broadleaved groups, according to Eq. (6).

Further on, the harvest is redistributed taking into account the adjusted *F* values (Eq. 11), as follows:

$$D_{i,d}^{t} = D * Firw_{i,d\ applied}^{t} \qquad \text{Eq. (11)}$$

where:

D – harvest under-bark for each silvicultural practice for each forest type.

The alternative version to default one assumes that, instead of aggregation of coniferous and broadleaved groupings, EU-CBM-HAT allows implementing a modified contribution on each silvicultural operation on each forest type. The expected values of the market factors have to be exogenously generated and introduced in *harvest_factor.csv*, detailed specifications of harvest factor values. In this case, the default value is equal to 1. If modulation is needed, the values should be modified in a way that would consider keeping the harvest quantity at the same level.

Further on, HAT estimates the production of FW collateral to IRW production from the virtualization of the regular silvicultural practices designed to satisfy IRW, as such silvicultural practices are labelled as "IRW and FW" in *events_template.csv*. The collateral FW is estimated at the same level of detail to which the IRW availability is calculated, as follows:

$$f_{FW}{}_{i,d}^{t} = 1 - f_{IRW}{}_{i,d}^{t} \qquad \text{Eq. (12)}$$

where:

f_{IRW} - share of industrial roundwood in removals associated with silvicultural practices on combination of classifiers as of *irw_frac_by_dist.csv*.

Finally, any remaining unsatisfied amount of fuelwood harvest, i.e. after deducting FW from salvage logging and collateral FW, is satisfied from fuelwood dedicated silvicultural practices (labelled as "FW_only" in *events_template.csv*). The availability of FW is calculated in the same way as IRW (i.e. Eq.1 to Eq.6), assuming that the harvest is distributed following a fraction-based allocation of availability across eligible combination of classifiers and stands.

As the very last step, HAT prepares the *events.csv* input in the format required by SIT, by converting the under-bark volumes (m3) determined as harvestable in the time step to mass (tC) following backward the same procedure reported in (Eq. 4).

4.4 Uncertainty and inconsistency in distributing the harvests

Back and forth calculations through HAT (see *4.3 Distribution of the industrial roundwood and fuelwood harvests*) for distributing the harvests and how *eu_cbm_hat* supplies that targeted amounts may result in some inconsistencies, as follows:

- The estimates of IRW and FW associated with a certain silvicultural practice calculated by HAT and resulting from *libcbm* running represent different things. HAT estimates the average availability across applicable age range, so there are no target stands attached to these values. Meanwhile for *libcbm* the supplied amounts are attached to stands eligible as of the respective silvicultural practice, i.e. "older stands first" so selecting the stands with highest biomass first in distributing the expected harvest. The effect is expected to be negligible on the simulation results, although it may become relevant when the harvests target the maximum wood supply, e.g. not all standing availability may be captured.
- The *eu_cbm_hat* uses two types of data for the conversion of biomass-to-volume under-bark, and vice versa. HAT uses two non-age dependent coefficients with constant value: the share of bark and the wood density (via input file: *vol_to_mass_coefs.csv*). Meanwhile, libcbm relies on age-dependent, non-linear volume-to-biomass equations (Boudewyn et al., 2006), because of the asynchrony of accumulation of standing biomass vs. merchantable volume or the actual proportion of non-stem compartments in total aboveground biomass vary during the age in general, e.g. influenced by the silvicultural practices. Because of the mismatch between these two types of data, inconsistency of the volume-to-biomass input or biomass-to-volume output may occur. To minimize such errors the strategy has to ensure full consistency between the values of the two types of data when sampled data is used (e.g. from NFIs), or when selecting the best match from the Canadian library of Boudewyn eqs. (as the table in AIDB when download and install CBM from https://www.nrcan.gc.ca/climate-change/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107). Since the shares of wood density and bark in

total aboveground biomass vary with the age, a meaningful approach corresponds to looking to mature stands, i.e. older age classes (e.g. over 20-30 age) as far as the proportion of mature wood to entire stem wood is significant. This is expected to result in negligible effect on the projected estimates when appropriate input data and processing are involved.

- The conversion of *eu_cbm_hat* outputs, i.e. C stocks and fluxes, to volume under-bark corresponding to the harvest is assuming the same conversion parameters for all standing pools subject to harvesting, i.e. stemwood, other wood components and snags. HAT uses the same conversion value for all assuming that any pool subject to harvesting has the same characteristics as living stemwood. This is supported by the fact that the decayed wood in advanced stages of decomposition is most likely not subject to harvesting, and in any case not for industrial roundwood. This is expected to have a negligible effect on the projections or harvest supply.
- HAT converts the measurement type compared to actual input, given HAT is processing all inputs in terms of mass (M), but the impact on the simulation is negligible as HAT ensures full correspondence between volume-biomass-area-proportion.

5 Calibration

The EU-CBM-HAT allows executing a calibration, i.e. for the period for which historical data is available. The calibration period is specified by the “reference_year” which is the inventory's year, i.e. the first calibrated year is the following year after, and the “base_year”, which is the first simulated year, e.g. 2021.

Unlike HAT which requires separate inputs for IRW and FW harvests, the calibration can be done on total roundwood harvest (i.e. the sum of IRW and FW). Nonetheless, different formulation of harvest targeted for calibration and simulated period may introduce a sudden change across all forest state indicators and roundwood removal structure, e.g. allocation between coniferous and broadleaved groupings or contribution of volumes or areas of the final cut and thinnings, for which reason additional checks are needed. Normally, the application of a harvest factor similar to calibration period should solve the problem.

6 Automatic checks of the input data and error messages during the runs

Inherently, mismatches may occur in setting up the databases, especially when new scenarios are set. EU-CBM-HAT performs some automatic checks of consistency across input data (at least for the errors which were identified during the development and testing). Most of the checks are performed in the earliest stages of a simulation, in order to minimize the time lost by the user in fixing any error. Specifically, in case of inconsistent inputs, while the simulation will stop and print one of the following *error messages* (Table 19).

Table 19. Messages printed by the EU-CBM-HAT in case of errors generated by inconsistent inputs (list is not exhaustive).

Message	**Most likely explanation, and solution**
"Undefined classifier values detected: classifier: 'forest_type', values: ['PA']"	The classifier list is missing one criterion which is used by other inputs.
"missing classifiers combination"	Inconsistent combination of classifiers among various inputs.
"doubling the age ranges for various disturbances"	*events_template.csv* contains multiple silvicultural practices which include overlaps in defining the applicable age range, instead successive with continuity or gap have to be defined.
"columns must have matching elements counts"	Mismatches within or between *events_template.csv*" and *irw_frac_by_dist.csv.*
"Names don't match IDs in ...\ _data\countries\ZZ\silv\events_templates.csv'". *NB*. ZZ is the name of the country subject to simulation).	Mismatch regards the combination of classifiers between *disturbance_type.csv* and *events_templates.csv* files. An explicit list of non-matching or missing information is provided in the editor.
"The file ...*eu_cbm_hat* data\output\hat\ZZ\0\input\csv\classifiers.csv' has 1 empty lines".	Any of the input files contains an empty line.
"Exception: There is remaining fw harvest this year: .... m3, but there are no events that enable the creation of FW only.".	Silvicultural practices targeting "fw_only" are missing from *events_template.csv.*
"ValueError: You probably have two or more rows in your events file which both have the same classifier values. Hence one cannot convert it from wide to long format."	*events.csv* file contains repeated identical classifiers and disturbances, to remove the rows with identical combination.

Sometimes, the simulation stops and an empty message is displayed as an AssertionError, i.e. something happen that the programmers thought impossible to occur. The first hint in finding the source of such error should be from identifying the stage where the simulation stopped. For example, when the message occurs after the editor displaying "INFO - Calling the cbm_simulator", the error is most likely linked to inconsistencies in the input data, which were not identified by the automatic checks (in Table 5). If the error message is displayed after editor prints "INFO - Carbon pool initialization period is finished ... " then the error is most likely related to HAT processing.

In all cases of error messages, the editor prints a general message: "ERROR - Runner '.../ZZ/0' encountered an exception. See log file" – so directing the user to look for more information in the logfile "output/0/logs/runner.txt".

As the EU-CBM-HAT is under continuous development, more checks will be added regularly. Users are encouraged to submit test cases and new checks to the code repository.

7 Conclusions

EU-CBM-HAT provides CO2 removals and emissions simulations related to forest management in support of EU climate law and GHG mitigation policies. It allows for the calibration at the national scale for the historical period against the national statistics reported internationally or nationally.

One of the main strengths consists in its ability to easily combine unlimited number of scenarios for any management and exogenous events (as natural disturbances, market demands for industrial roundwood and fuelwood) occurring throughout simulation period, and for handy tracking and referencing them.

Another major strength is a module distributing the harvest according to the simultaneous availability of IRW and primary FW from eligible silvicultural practices associated with standing stocks in merchantable wood, other wood components, stem and branch snags.

This report is intended as a scientific and technical background of EU-CBM-HAT development and is complementary to the CBM-CFS3 user's guide (Kull et al., 2019).

One major limitation of EU-CBM-HAT is related to *libcbm* requirement of a very specific format of volume-to-biomass equation which is a format unavailable for EU countries, i.e. which rely on expansion factors applied to standing stocks volume or individual tree allometry expanded to stand scale. In order to make these measurements available, collaborative activities, e.g. with NFIs, may be planned for the future.

Another limitation may be that exogenous data is required for natural disturbances and forest land conversions, there is no development expected on these issues.

Further and deeper integrations of EU-CBM-HAT within the JRC's AFOLU modelling framework are expected. Upstream integration is expected with models on energy e.g. POTEnCIA (Mantzos et al., 2016) or economic models, e.g. CAPRI (Modelling System, 2022). Further downstream integration with a wood use and wood products carbon storage model, wood products recycling and wood substitution of energy and carbon intensive materials, i.e. with GFTM (Global Forest Trade Model, e.g. Jonsson et al., 2015) or GFPM (Global Forest Production Model, Buongiorno et al., 2003). Deeper elaboration of roundwood harvest on industrial roundwood and fuelwood would make EU-CBM-HAT suitable for assessing the economic linkages of different forest management options and actual wood use based on roundwood grading.

EU-CBM-HAT is in essence a non-spatial, but a spatially referenced model. This means that during the simulation the original spatial structure maybe lost, although the representation of forest management remains realistic at aggregated scale. Consistent with the geo-spatial version, the Generic Carbon Budget Model (GCBM) launched by NRCAN (e.g. Shaw et al., 2021), or independently, a spatially explicit version can be the following development step, e.g. by linking it with EU biomass maps (European Commission, 2020). Nevertheless, a major difficulty to overcome in applying a spatial explicit version is the availability of data for the initial year of the simulation (i.e. standing volume at an adequate resolution to represent forest status and management interventions).

Although EU-CBM-HAT was developed for further use by the JRC, the goal is to make it available and accessible to others outside the JRC. It can be applied both for GHG reporting and accounting (e.g. including annual time steps, all C pools, etc.) and for simulating different forest management and climate mitigation scenarios, both at EU or EU member state level. EU-CBM-HAT is freely available to any user, while the current version allows for refinement and adjustments, as needed. Updates are documented on the software source page. The model is in continuous operational development, while currently used to set up databases for an eventual EU "forest management reference scenario", i.e. incorporating data for pre-2020. Following Technology Readiness Levels (TRL) grading (European Commission, 2017), the current released version of EU-CBM-HAT falls under TLS 8 (System complete and qualified) and TLS 9 (Actual system proven in operational environment).

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List of abbreviations and definitions

AFOLU	Agriculture, Forestry and Other Land Use
AIDB	Archive Index Database
C	carbon
C++	Programming language
CBM	short of CBM-CFS3
CBM-CFS3	Carbon Budget Model of the Canadian Forest Service
CFS	Canadian Forest Service
COMBO	scenario combination tool of the EU-CBM-HAT
.csv	Microsoft Excel comma separated value file
CLU	Climatic units
Cur	Volume data corresponding to increment tables
DBH	Diameter Breast Height
EFISCEN	European Forest Information SCENario Model
EU	European Union
EUPL	European Union Public Licence
FAOSTAT	Food and Alimentation Organization statistics
FW	Fuel Wood
GHG	Greenhouse Gas
GUI	Graphical User Interface
HAT	Harvest Allocation Tool of the EU-CBM-HAT
HWP	Harvested Wood use type
IRW	Industrial Roundwood
Init	Volume data corresponding to yield tables
JRC	Joint Research Centre of the European Commission
LUISA	LUISA Territorial Modelling Platform
LULUCF	Land Use, Land Use Change and Forestry
MIT	Software licence by Massachusetts Institute of Technology
MS	Member State(s) of the European Union
NFAP	National Forestry Accounting Plan
NFI	National Forest Inventory
NRCAN	National Resources Canada/Ressources naturelles Canada
nsr_nd	Non-Stand Replacing Natural Disturbances
o.b.	over-bark
OWC	Other Woody Component
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
QA/QC	Quality Assurance, Quality Control
SIT	Standard Import Tool
sr_nd	Stand Replacing Natural Disturbances

TRL	Technology Readiness Levels
UNECE	United Nations Economic Commission for Europe
u.b.	under-bark
UNFCCC	United Nations Framework Convention on Climate Change
ZZ	country example containing complete templates for all input data
.yaml	'YAML Ain't Markup Language' file type

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Annexes

Annex 1. EU-CBM-HAT installation instructions

The software packages are under active development. Make sure to regularly update them to the latest version. This installation method will change, and the updated installation method will be made available in the repository:

https://gitlab.com/bioeconomy/eu_cbm/eu_cbm_hat.

Install EU-CBM-HAT using pip:

```
pip install git+https://gitlab.com/bioeconomy/eu_cbm/eu_cbm_hat.git
```

Install the *libcbm* package developed by the Forest Carbon Accounting team of the Canadian Forest Service:

```
pip install git+https://github.com/cat-cfs/libcbm_py.git
```

The Archive Index Databases (AIDB) can be quite large and that is why we put it in a separate git repository. Clone the repository containing the AIDB:

```
git clone git@gitlab.com:bioeconomy/eu_cbm/eu_cbm_aidb.git
```

By default, the data is located in your home directory "~/repos/eu_cbm_data/" and the AIBD in "~/repos/eu_cbm_aidb/", but you can define the following environment variables to tell the model where the data are located:

```
export EU_CBM_DATA="path_on_your_computer/eu_cbm_data/"
export EU_CBM_AIDB="path_on_your_computer/eu_cbm_aidb/"
```

It is necessary to create symbolic links between the AIDB and the data repository. This can be achieved by entering the following at a python prompt:

```
from eu_cbm_hat.core.continent import continent
for country in continent: country.aidb.symlink_all_aidb()
```

To run the test country ZZ at a Python prompt, see the version of the script that can run without *eu_cbm_data* at:

https://gitlab.com/bioeconomy/eu_cbm/eu_cbm_hat/-/tree/main/scripts/running

As development of the package continues through time. It is recommended to regularly update both *libcbm* and *eu_cbm_hat* to the latest versions:

```
pip install --upgrade git+https://gitlab.com/bioeconomy/eu_cbm/eu_cbm_hat.git
pip install --upgrade git+https://github.com/cat-cfs/libcbm_py.git.
```

Annex 2. Own test of consistency of *libcbm* and *cbm-cfs3*

The *libcbm* requires the same input as CBM-CFS3 (see the CBM-CFS3 User's Guide for further detailes). The CBM's SIT works for both in the same way, and it accepts only data provided in a specific format.

Existing EU database allowed testing the two versions. The consistency between the *libcbm* and CBM-CFS3 was checked by running exactly the same assumptions (i.e. same Archive Index Database, or aidb for the respective country) and datasets for the historical period (i.e. from the available initial year reported as the inventory year until 2015) for all 25 countries in the EU cbm-cfs3 database.

The percentage difference between results by each model was checked for the initialized stocks (i.e. time step 0) and the stocks achieved during the simulation (i.e. time step 15) for the 25 countries as Member States of the EU. Checks were done using the estimates aggregated country scale.

For the time step 0, there was no difference among the countries for the initialized stocks for any carbon pool.

For time step 15, there were no differences for 11 countries. Consequently, we can safely appreciate that the two models provide for fully consistent results. For the remaining 14 countries, there were differences as

shown in **Table A*1***. Apparently, such differences exist because the simulation assumptions include natural disturbances which are randomly allocated by the models, so they result in slightly different values of the carbon stocks for each model. Differences are larger dead organic matter pools than for living biomass, while they are larger for small pools (e.g. snags) than for large pools (merchantable, soil organic matter).

Table A1. Maximal deviation of *libcbm* vs. *cbm-cfs3* carbon pools in the time step 15 across the 25 member states compared (in %, rounded to 0.5pp).

Carbon pools	*libcbm*/*cbm-cfs3* carbon pools	Deviation (%)
Living biomass pools	softwood_coarse_roots	±3.5
	softwood_foliage	±3
	softwood_merch	±3
	softwood_other	±3
	hardwood_foliage	±1
	hardwood_merch	±1
	hardwood_coarse_roots	±1
	hardwood_other	±1
	softwood_fine_roots	±1
	hardwood_fine_roots	±1
Dead organic matter pools	softwood_stem_snag	±14
	softwood_branch_snag	±11
	above_ground_fast_soil	±3
	below_ground_fast_soil	±2
	hardwood_branch_snag	±2
	hardwood_stem_snag	±2
	medium_soil	±1
	above_ground_very_fast_soil	±1
	below_ground_very_fast_soil	±1
	above_ground_slow_soil	±1
	below_ground_slow_soil	±0
	low_ground_very_fast_soil	±0
	above_ground_very_fast_soil	±0.5

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