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Integrated modelling approach to assess woody biomass supply, demand and environmental impacts of forest management in the EU

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Abstract:
Forests are at the intersection of European policies on climate, energy and environmental protection and will contribute significantly to the shift of the European economy towards a greater and more sustainable use of renewable resources. Knowledge of the current and future provision and use of woody biomass is necessary to support multiple policies, provide insight into how forest ecosystems and their services will respond to increasing material and energy demand, climate change, and land use competition. The main data source for forest biomass data in the European Union are National Forest Inventories (NFIs). These are carried out based on country-specific requirements and definitions, therefore varying from country to country. The first challenge is therefore the integration of these data into a single modelling platform for simultaneous and seamless processing. Here we describe the efforts of a multi-disciplinary team that has developed modular pan-European modelling set-up to assess the demand and potential supply of woody biomass to the bioeconomy and the impacts of associated harvests using data sourced from heterogeneous NFIs. The modelling framework covers national-level wood-based commodity production and trade, spatially-explicit forest growth and carbon budget, analysis of the role of energy technologies and energy consumption and land-use systems. The hub of this modelling set-up is implemented in a readable and editable modelling script to facilitate dialogue between the modellers. These scripts are where the models meet and exchange data processes for different models, and are capable of resolving issues of thematic and spatial resolution and imputing missing data to enhance the exchange between the models. The philosophy behind this particular set-up is one of furthering policy coherence: to inform different and sometimes conflicting policies using the same base data, modelling framework and expertise in a modular way as well as to provide appropriate and consistent outputs, ranging from environmental indicators to indicators about the wood-based industry.

Keywords: EU Bioeconomy, forest resources, pan-European modelling, open-source software, policy coherence.

1 INTRODUCTION

The EU Bioeconomy strategy and action plan (EC, 2012) aims to shift the European economy towards a greater and more sustainable use of biological renewable resources. Forestry contributes to the EU Bioeconomy through the provision of woody biomass and other non-wood products for material and energy uses. Besides provisioning biomass, European forests are also fundamental in providing cultural and regulating ecosystem services. Several facets of the same coin need to be examined, e.g., economic and social benefits, alongside consequences on the planet's health as a whole.

The forestry sector is in a peculiar situation in Europe, because forests are subject to national- or even regional-level management, yet EU-wide initiatives (e.g., agricultural or biodiversity policies) do affect forest resources. Furthermore there are often cross-border synergies, such as material and energy markets for species that are common in different countries. There is therefore reason to model forest resources at a pan-European scale. Most countries in Europe have data and information systems in place to collect information about their forests. These are usually the National Forest Inventories (Tomppo et al., 2010; Vidal et al, 2016).

Integrated environmental modelling (IEM) is quantitative analysis involving the use of different modelling tools to approach environmental problems in a holistic way (Laniak et al., 2013). It brings pieces of sector-specific models together (Voinov and Schugart, 2013) to form a comprehensive picture of a system's dynamics, possibly at different spatial resolutions. Models from different scientific disciplines are often independently developed so that experts are responsible for their own specific modules, and yet they can be coupled in different ways to answer specific questions raised by the decision maker (Bennett et al., 2013; Voinov and Schugart, 2013; Hamilton et al 2015).

Further developing the interaction between models of wood products market and forest growth described in Jonsson et al. (2018), we discuss here an integrated modelling framework where the forest system interacts with models of energy and land systems. The spatial dimension provides information on the availability of forest land for wood supply, as well as to the location of human induced disturbances for the assessment of impacts on ecosystem services. Finally, we develop an additional model that within the integrated framework ensures quality and consistency in model data exchanges.

2 MODELS & DATA

In the following sections we present a short description of each of the models that are integrated into our forest-sector biomass-assessment system. We limit the descriptions to parts that are relevant to the exchanges between the models. For ease of reading, we do not include the notation in this section.

The Carbon Budget Model (CBM) is an inventory-based, yield-data driven model that simulates the stand and landscape-level carbon dynamics of above and belowground biomass pools, as well as dead organic matter and soil (Kurz et al., 2009). In our modelling environment, simulation units are defined by their age class (10-year intervals) and by unique combinations of six classifiers, divided into two groups: descriptive and geographical. The three descriptive classifiers are 1) forest type, 2) management type, 3) management strategy; while the three geographical classifiers are 1) climatic unit (as described in Pilli (2012), 2) administrative region, and 3) forest location within areas of different availability for wood supply. The CBM is applied to 26 EU countries (all EU countries except Malta and Cyprus) using as input data National Forest Inventories (NFIs) and Forest Management Plans (FMPs) (see Pilli et al., 2017 for details). All input data were preliminarily harmonized both in terms of forest area and for the definition of volume and increment, to be consistent with the most recent information reported by the State of Europe's Forest 2015 (Forest Europe, 2015) and other data sources (i.e., the United Nations Framework Convention on Climate Change). We use CBM to estimate, at country level, the yearly forest biomass dynamics for the historical period from last measurement up to 2015 under the historical harvest rate (detailed information are in Pilli et al. 2016 and 2017), and to forecast the maximum and actual wood supply until 2030 (detailed information in Jonsson et al., 2018).

The Global Forest Trade Model (GFTM) is an economic equilibrium model of global wood products markets, providing projections of consumption, production and international trade. GFTM shares the theoretical formulation based on spatial equilibrium theory in competitive markets for several commodities with other models (Samuelson, 1952). GFTM is static since, given a certain number of iterations (projection periods), the optimal welfare is computed at each iteration with imperfect foresight. Once a solution is reached, parameters of the model are updated based on harvest levels and GDP growth. New resource and productivity constraints are set, and a new iteration begins. GFTM projections cover ten final products, four intermediate products, and four primary products, distinguishing between coniferous and non-coniferous sawlogs, sawnwood, pulpwood, and sawdust. The maximum supply of industrial roundwood as provided by CBM are used by GFTM as upper bounds for the provision of sawlogs and pulpwood, used in the production of wood-based commodities and wood pellets in each EU member state. For countries not modelled by CBM, potential timber supply is derived from data on growing stock and increments, compiled from FAO (2015) and Forest Europe (2015). In these cases, annual potential harvest levels are set equal to annual increment. GFTM derives the market equilibrium, and growing stocks (coniferous and non-coniferous respectively) are updated based on the resulting demand for primary products in non-CBM countries and global sub-regions. For fuller details regarding model structure, assumptions, parameters and input data, we refer the reader to Jonsson et al. (2016), Jonsson & Rinaldi (2017), and Jonsson et al (2018).

The JRC-EU-TIMES (Simoes et al., 2017; Sgobbi et al., 2016) is an energy system model representing the EU 28 and neighbouring countries. The JRC-EU-TIMES model produces projections of the EU energy system, analysing the evolution up to 2050 under different sets of specific assumptions and constraints. The focus of this model is on technology policy. The baseline scenario of JRC-EU-TIMES is always aligned to the latest EU reference scenario (e.g. Capros et al. 2016). The most relevant outputs of the model runs are the annual stock and activity of energy supply and demand technologies for each region and period. This is accompanied by associated energy and material flows including emissions to the atmosphere and fuel consumption, detailed for each energy carrier. Besides technical outputs we obtain, for each year, associated operation and maintenance costs, investment costs for new technologies, and all energy and materials commodities prices (including for emissions if an emission cap is considered). CO_2 prices are also endogenous results of the implemented emission reduction targets and modelled energy systems conditions. The reference biomass potentials are input to the model as documented in Ruiz (2015). Maximum energy available and cost for each biomass type (agricultural, forestry and waste) are defined. For the target of this research, forestry related potentials and associated cost are updated with the outputs derived from GFTM and CBM models, as detailed in Figure 1.

For economic assessments, it is necessary to estimate the procurement costs incurred when cutting, transporting biomass out of the forest to the landing site, and eventually pre-treating the biomass and transporting it to the final users for materials or energy. Here, we assess the costs following an engineering approach (thoroughly described in Uusitalo, 2010, applied e.g. in Magagnotti et al., 2012) which is based on the evaluation of the cost of each operation. In our modelling framework, we have defined two supply chains for each country: a first one that assesses costs for more advanced and mechanized logging systems and a second one that assesses costs for manual, less mechanized techniques. When we combine this information with mapped forest resources, we produce a cost map of forest resources, and thus produce cost-supply curves.

The CLUMondo model builds on the concept of land-use systems, which are typical combinations of land use, land cover and land use intensity (van Asselen and Verburg., 2013). In the context of bioeconomy modelling, this model is not used to simulate net changes in land use systems, but rather to simulate the impacts of changes in forest management intensity on ecosystem services. We benefit from the possibility of representing the multifunctionality of land systems by simulating the trade-offs between ecosystem services within forested areas, given a spatial mapping of forest resources and a harvest intensity. This model and its applications are described further in van Asselen & Verburg, 2013; Eitelberg, van Vliet & Verburg, 2016 and Debonne et al., 2018.

3 BRINGING IT ALL TOGETHER USING FUSION

FUSION (Forestry Unified System for Input and Output geNeration) was conceived to bring together the different approaches related to bioeconomy modelling. It was developed in the GeoDMS language, a modelling environment that opens the possibilities to IEM because the data handlers, integrity checks and efficient use of memory for raster-based processes are implemented. GeoDMS is a modelling framework with calculation engine to process, calculate with and visualize large datasets, including geographic datasets through scripting, allowing for repeatability, transparency and quality control. The GeoDMS uses a data model with semantic arrays. In this way, each array is associated with meta information, used to derive calculation characteristics and check calculation logic. This modelling environment is conducive to bringing together sector-specific models without compromising quality because the control of each model remains under the expertise of each modeller. The GeoDMS environment is an excellent choice for data exchange, however it also possesses powerful tools to enhance the integration of the models. Figure 1 summarises the interaction between the models and the role of FUSION in this interaction.

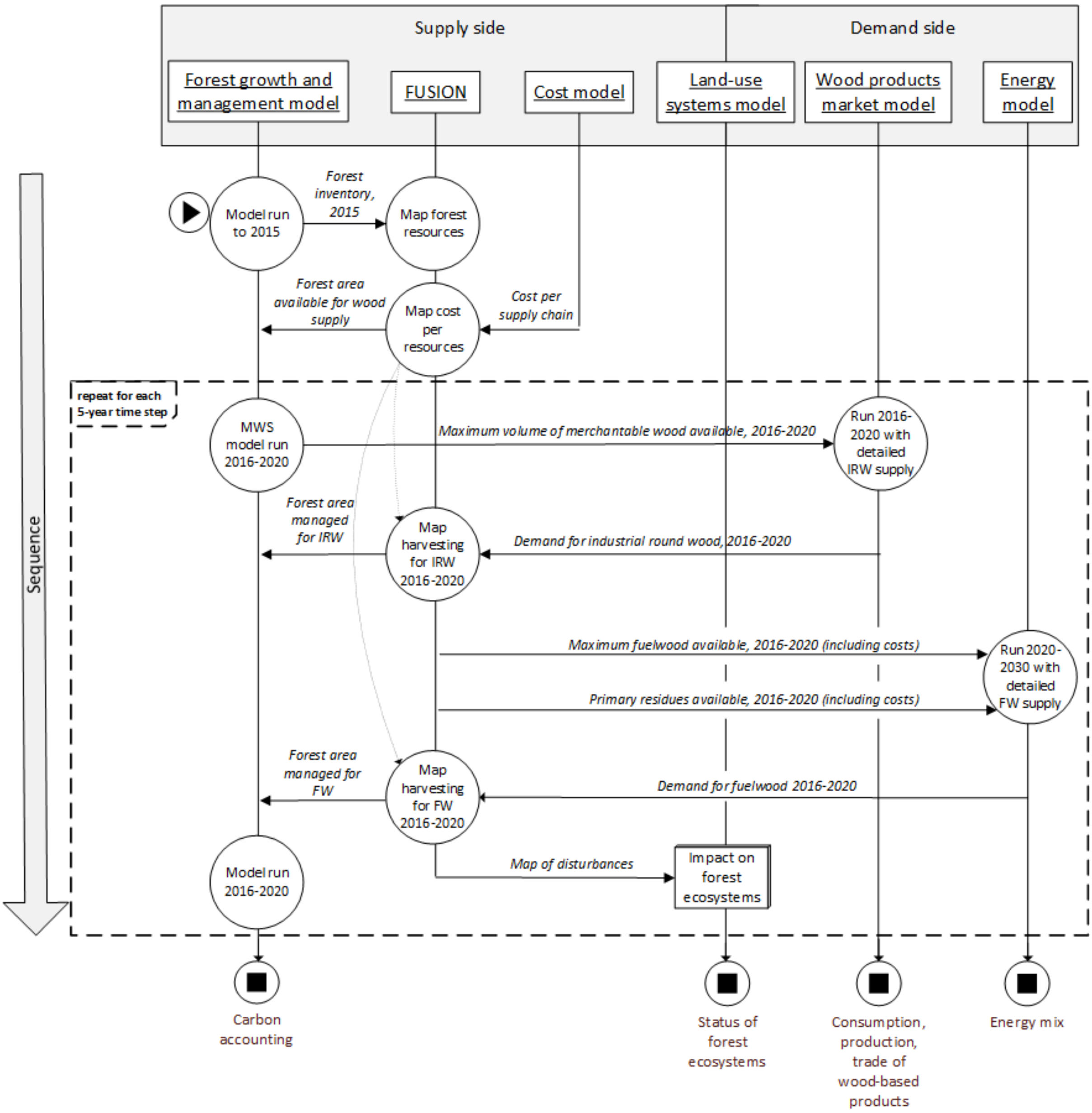

Figure 1. Sequence of data exchange between models.

3.1 Notation and Units

The notation conforms to the following rules: the lower left indicates the main simulation loop both in terms of time (t) and the country (c). If different runs were made for different scenarios, a scenario index would also be in the lower left corner. Upper left indicates different arrays, for example to be applied to all regions, or to all harvested wood products. For raster processing, the notation in the upper left is analogous to layers of maps. Lower right indicates the unique set of attributes defining each row. For simulations units in CBM, these would be the unique set of classifiers. Upper right indicates the value range of data. The variables are described in Table 1.

Table 1. Indices describing the relevant variables.

Index	**Definition**	**Description**
A	Area	Forest area in hectares

aws	Availability for wood supply	Used to denote forests that are a) available for wood supply, meaning that silvicultural treatments are not restricted; b) partially managed, meaning they may produce wood for the market as an effect of silvicultural tending, but final cuts are not allowed; c) not available for wood supply, meaning they are fully protected.
c	Country	Used to denote when data are different from country to country
biomass	Biomass	The output of CBM that allows FUSION to derive volume of wood available from disturbances
cnc	Species grouping as either coniferous or non-coniferous	This is the granularity of the demand from the GFTM model; it is therefore sometimes necessary to classify species into one of these two broad classes.
cu	Climate units	Polygons of different climate units governing growth for different species
D	Demand	Demand can be for volume of wood or can be area, for example, demand for hectares of forest type *f* within region *r* and climate unit *cu*.
DT, dt	Disturbance type	Management treatments than can be applied. These are country and forest-type specific (but not specific to regions and climate units)
E	Elevation	Topographic elevation in m
Eur	Cost	Procurement cost of wood in Eur/m^3
f	Forest type	Species categorisation differs from country to country and may be a single species or a group of species
fw	Fuelwood	Fuelwood is one of the two harvested wood products (HWP) considered; it results from certain disturbance types
G	Age class	Age classes are at 10-year intervals, starting at 0.
hi	Harvest intensity	How much of the total biomass (0-100%) can be obtained from any disturbance type for any given combination of descriptive classifiers (*U*)
hwp	Harvested wood products	Either fuelwood (*fw*) or Industrial roundwood (*irw*)
i	Raster cell	1 cell = 1 hectare
irw	Industrial round wood	Industrial roundwood is one of the two harvested wood products (HWP) considered; it results from certain disturbance types
m	Supply chain mechanisation	The slope and accessibility result affect the type of machinery used, thus whether or not the supply chain is mechanised or manual. This applies to all phases (*p*) of the supply chain (harvesting, transport to the landing site, and processing at the landing site)
N	Transportation network	Accessibility is derived from the roads network
owc	Other wood components	Primary residues left over from harvesting *irw* such as snags, branches and tops
p	Phase of the supply chain	Harvest, moving wood to landing site, and processing at landing site.
spu	Spatial Unit	Intersection between region (*r*) and climate unit (*cu*) in which forest area is constrained for discrete allocation, as defined in Kurz et al. (2009).
r	Region	Regional division differs from country to country
S	Combination of suitability maps	Suitability maps are used in discrete allocation to determine the location of a simulation unit on the raster grid cell.
si	Species	Individual tree species, only used to demote species maps
t	Time	Time step in simulation. Before simulation begins, *t*=0.
U≯	Simulation Unit, descriptive plus geographical	Combination of the age class and five of six classifiers: forest type (*ft*), management type (*mt*), management strategy (*ms*), region (*r*), climate unit (*cu*); *aws* is considered separately.
U	Simulation Unit, descriptive	Combination of age class and the three descriptive classifiers *ft*, *mt*, *ms*. If we use U instead of U≯, it is because we have to maintain the geographical classifiers separately in the notation.
V	Volume	Volume of aboveground forest biomass in m^3
X	Class value	Class value (category) assigned to a raster grid through discrete allocation procedure
y	Year(s)	Used for both single and ranges of years

3.2 Modelling sequence

The modelling sequence is summarized in Figure 1. The initial state for the year 2015 ${}_{c,2015}A_{\,U\nsucc}$, is defined for each country in CBM. In this way, each country may have unique characteristics that describe its combination of 6 classifiers and age class ($U\nsucc$). The initial state is read by FUSION and mapped with the help of Earth Observation data, using an algorithm for discrete allocation. In discrete allocation, we aim to allocate all of the forest area in the base map to a set of categories given by U$\nsucc$ so that $X_i^{U\nsucc} \geq 0$. To do this, we have to differentiate the preferences for the allocation for *U* using suitability maps S_i^U. We use the geographical classifiers *spu* as "fences" to allocate the forest area based on suitability of the descriptive classifiers. Each suitability map is associated to an attribute that makes the forest type unique, one of the descriptive classifiers: management type, management strategy, species; plus age class.

1. Relative probability of presence of species [${}^{spcs}RPP_i$] (de Rigo et al., 2016)
2. Estimated management type, country-specific [${}_{c}^{s}MT_i$]
3. Estimated management strategy, country-specific [${}_{c}^{s}MS_i$]
4. Age class [G_i^f], estimated based on growing stock volume [V_i] from the GlobBiomass global biomass map (Santoro et al., 2018).

Up to now we have ignored the third geographical classifier, "availability for wood supply", *aws*, because FUSION will generate this information based on the spatial location of each *U*. Forest falls within one of three *aws* categories: available for wood supply (FAWS), only partially available, meaning subject to management restrictions (FpAWS), or not available at all for wood supply because it is protected (FnAWS). Since national definitions of FAWS present fundamental differences that limit their comparability, we used an "approach by exclusion," which is to map the forest that is partially or not available due to various constraints, and subtract this area from the existing forest area (Avitabile et al., 2018). The raster representing the 2015 inventory is returned to CBM as a table that now contains a new attribute: ${}_{c,2015}A_{\,U\nsucc,aws}$.

CBM then estimates the maximum wood supply for the first time step of the simulation (2016-2020), applying the appropriate silvicultural treatments according to the new categorization of availability for wood supply. We define the maximum wood supply as the amount of wood available under applicable silvicultural practices, without decreasing the growing stock level in the FAWS. The fraction of industrial roundwood (*irw*, further distinguished between coniferous and non-coniferous) derived from the estimated maximum wood supply by CBM ${}_{c,16-20}^{cnc,irw}V$, is then sent to the economic forest-based sector model (GFTM) and constrains the demand of *irw* (further details are in Jonsson et al., 2018).

GFTM returns the actual harvest demand at country-level for *irw*: ${}_{c,2016-2020}^{cnc}D^{\,irw}$, distinguished between coniferous or non-coniferous (*cnc).* Using this information, with the added value of spatial location of forest resources and associated costs, we assess where wood is most likely to be harvested. We actually assess this at a regional level, and not at a raster-cell level because at this stage, FUSION is no longer operating at a raster cell level. From 2015 onwards, in fact, FUSION has no knowledge of forest growth because growth occurs within the CBM. FUSION therefore proceeds, from >2015, to model at the intersection of the administrative region and climate unit *spu.* The median cost for all of the cells within *spu* is retained. The model will seek to optimize cost and supply based on the demand for *irw*. In order to solve this problem, FUSION must consider availability for wood supply, the three descriptive classifiers and an additional piece of information: cost.

Each cell will have an associated cost that is computed as the sum of all of the phases required in the supply chain, from the harvest phase to transport and processing; and the mechanization of the supply chain used. The cost is computed for each phase of the supply chain (${}_{c}^{p}Eur_{\,m}$) taking into account the location of biomass (e.g., steeper slopes vs. plains; distance to roads) using maps of elevation and transport network. The elevation map was obtained by the Digital Elevation Model over Europe (EU-DEM) produced by the Copernicus Programme for the year 2000, which provides a digital surface model representing the first surface as illuminated by the sensors (EU-DEM, 2013). The map of transport network was obtained by the Open Street Map (OSM) database (OSM, 2017). Cost is then endogenously spatially disaggregated, ${}_{c}^{p}Eur_{\,i}^{\,m}$ so that it may be added as an attribute to the initial state table: ${}_{c,2015}A_{U\nsucc,aws,Eur}$.

A specific disturbance type for any given forest type and *aws* (${}_{c,t}DT\,{}^{dt}_{U,aws}$) is the result of the CBM calibration procedure. The percent biomass in branches and other wood components plus snags produced by the treatment (*owc*), and the type of product generated by the treatment (*cnc*) are also provided by CBM. From this information, in addition to the cost, FUSION allocates the demand for *irw* throughout the country based on two criteria: lowest cost, and the condition that each disturbance type that occurred in the historical period is reflected in the future period.

Once the demand for *irw* has been satisfied and the disturbance types have been computed, it is possible to know the quantity of *owc* that will be generated from the treatments. This is considered a feedstock for the energy model, however it is not cost-free. FUSION computes the cost to process these *owc* that remain as the result of harvesting, and that together with the potential *fw*, are communicated to the energy sector model (EU-TIMES) with the additional attribute of cost associated to removing them from the forest ${}_{c,16-20}^{\;\;fw}V_{\;Eur}$, ${}_{c,16-20}^{\;\;owc}V_{\;Eur}$. In the same way GFTM returned a demand for *irw*, JRC EU TIMES returns the actual harvest demand for fuelwood ${}_{c,2016-2020}D^{\,fw}$ after having computed the energy mix with both available feedstocks.

CBM uses this output to calculate the forest growth until 2020 and then provides a new run for maximum wood supply (MWS 2021-2025). The cycle is repeated: GFTM and JRC EU TIMES use this information to run harvest demand for the next period and so on (as shown in Figure 1).

The *spu* in which the disturbances take place provide information to the land-use systems model on the intensity of management. This affects the ecosystem services that can be provided by the forests. We propose to inform three ecosystem services within this modelling framework, two of which is implicit to the modeling system: carbon sequestration and wood provision. The third ecosystem service is biodiversity.

4 CONCLUSIONS AND RECOMMENDATIONS

This paper describes a modelling set-up that allows the simultaneous assessment of implications of policy and other external drivers on forest resources and woody biomass using sectors, i.e., the forest-based bioeconomy. We propose the integration of a wood products market model; a forest growth and management model; an energy model; a series of functions related to modelling cost of harvesting wood and residues; and a land use systems model. The approach fully accounts for the spatial dimension as to the availability of woody biomass at different costs, as well as to the location of disturbances for the assessment of impacts on ecosystem services. The framework further satisfies our requirements as a multi-disciplinary team in allowing (i) experts to maintain control of their respective models, (ii) minimisation efforts needed for model integration, by introducing an external model that fulfils data transformation, semantic checks etc., (iii) flexibility in outputs to satisfy the criteria of serving different purposes, and (iv) transparency. This approach has considerable policy relevance in enabling analysis of different facets of the forest-based bioeconomy in politically complex debates. Thereby it can be a useful instrument for furthering policy coherence. Obstacles that remain to be overcome are: the lack of seamless European-level databases, detailed enough to allow for pan-European simulation of forest resources; the harmonization of definitions and methodologies for forest monitoring, the spatial detail of forest data, the spatial accuracy of georeferencing of sample units, and the language in which the results are provided. In such a setting, modellers would do well to involve national experts in the configuration and analysis of results of their models.

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[1] https://biobs.jrc.ec.europa.eu/page/biomass-assessment-study-jrc

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