Associate Editor Decision: Reconsider after major revisions (07 Mar 2017) by Christopher A. Williams

Comments to the Author:

You are encouraged to submit a revised version of the paper reflecting the changes described in your Author Comments of the open discussion.

The revised version of the manuscript includes all the specific comments provided by referees (in particular, the conclusions were revised, in response to the reviewer's comments) plus our main answers to the general comments and key requests coming from the discussion. Any further change is highlighted in the revised version of the manuscript. In particular:

- Please add the new figure (drafted in response to Reviewer 1) summarizing the average C increment and transfers between forest pools and with the atmosphere. Include corresponding new discussion similar to that in Author Comment 1. Please also explain why dead wood and litter shows such a large reduction over the time period when living biomass shows such a large increase and soil carbon is relatively stable.
  The new figure (named Figure 2) was added and discussed as suggested (L. 253-267)
- Briefly note in the manuscript specific information about what this study offers beyond previous work (as drafted in the response to Reviewer 2).
  See the conclusion, L. 657-663
- Address all specific comments of reviewers as promised in the Author Comment responses to individual reviews.
  All the specific comments were addressed.
- Reduce and focus text wherever possible. Address minor English errors throughout. Also work to improve text flow as suggested by Reviewer 3.
  The text was further revised, also to improve text flow.
- RC2, L40: include this explanation in a revised version.
  Further details were already reported in the text.
- RC,2, L138-139: clarify along the lines of the response.
  The explanation was included in the text (L. 147-150).
  As discussed in AC3, add at least some descriptive comparison of the approaches taken by CMB26 and EFISCEN.
  Some comment regarding the use of CBM and EFISCEN and based on the AC3 suggestions was added to the conclusions
- As discussed in AC3, consider adding discussion of the possible limitations of having adopted administrative, country boundaries to organize the modeling effort rather than ecoregional or physical/biological attributes (as discussed in AC3).
- As discussed in AC3, we added some further discussion in the text, L. 472 -478

Response to RC #1

The European forest sector: past and future carbon budget and fluxes under different management scenarios by Pilli et al.

Many thanks for this critical and constructive review. As suggested, we may add a box-and-arrow figure (Figure 1 reported below), highlighting the annual fluxes between the pools and the annual stock change. This may certainly help the reader to summarize the net fluxes between the pools, including the difference between the Net Carbon Stock Change (i.e., -109.5 TgC, reported as C removals from the atmosphere) and the Net Sector Exchange, due to the HWP pool.

Based on this figure, we see that "living biomass" and "felling" (including removals and harvest primary residues), have a positive net C balance. The negative balance reported for dead wood and litter is probably influenced by the (average) effect of the natural disturbances occurred during the period 2000 – 2012. These disturbances have moved part of the living biomass to DOM (through wind storms and fires) and to the atmosphere (through fires), but, through salvage logging after the main storms, they have also (indirectly) moved part of dead wood to the HWP pool.
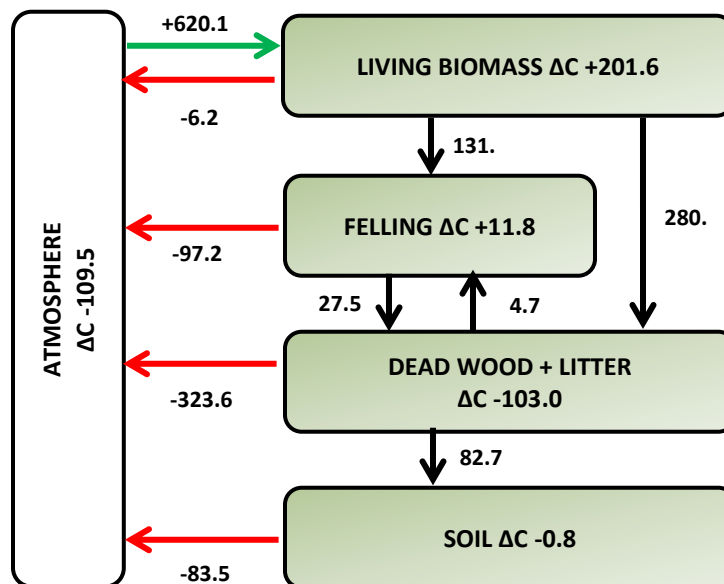

Figure 1: summary of the average C increment and transfers between forest pools and with the atmosphere (in Tg C yr^{-1}, for the historical period 2000 – 2012). The pool increments are shown in each box as ΔC, transfers between pools are reported by black arrows and transfers from/to the atmosphere are reported by green and red arrows, respectively (with positive or negative values, reported from a forest perspective).

CBM estimates of soil C are assumed to include the belowground slow (i.e., humified organic matter in the mineral soil) and very fast (i.e., dead fine roots in the mineral soil, approximately < 5 mm diameter) pools to a depth of 1 meter (Kurz et al., 2009). Due to the short time frame considered by our study (12 yrs.), we could not highlight any significant variation of the soil C stock. Indeed, the slightly negative C stock change reported in the figure (-0.8 Tg C yr.) is mainly due to the effect of deforestation and, overall,

the soil C stock is stable. But we agree that, the soils are presumably accumulating carbon as forests are getting older.

The absolute total heterotrophic respiration (R_h) estimated by our study is 40% higher than the value reported by Karjalainen et al. (2003): i.e., 403 Tg C yr^{-1}, against 245 Tg C yr^{-1}. However, if we compare the relative emissions due to R_h with the total NPP, the estimates are not so different: 59% of the NPP is lost as heterotrophic respiration, according to Karjalainen et al., and 65% according to our study. This last amount is due to the specific assumptions made in the present study, based on a preliminary comparison between the model output and specific studies available at regional and country level (Pilli et al., 2013 and 2016). Similarly to other soil models, the results provided by CBM are also influenced by the uncertainty in model initialization. For the initialization of DOM pools (including soil), we assumed that the historic natural disturbance regime is a stand-replacing fire (or clear-cut) with a disturbance-return interval of 100-250 years (Kurz et al., 2009, Pilli et al., 2013). Therefore, the initialization assumption of the CBM model reflects changes in disturbance regime at the start of the simulation, relative to the historical conditions. However, the observed stocks may not be in equilibrium due to disturbances and very long turnover times of stable compounds (Wutzler and Reichstein, 2007).

The soil C stock (including litter and dead wood) was initialized by Karjalainen et al. (2003) by setting the soil compartments to a "steady state" with the input of the period 1990-1995. The same authors, however, highlighted the lack of empirical data to estimate the C stock in the soil.

Thank you for your specific comments on the text, they will be included in the revised version of the manuscript.

Additional references:

Wutzler, T. and Reichstein, M. Soils apart from equilibrium - Consequences for soil carbon balance modelling. Biogeosciences 4, 125-136, DOI: 10.5194/bg-4-125-2007, 2007

Response to RC #2

The European forest sector: past and future carbon budget and fluxes under different management scenarios by Pilli et al.

Many thanks for this critical and constructive review.

Regarding your general comments, our study is based on the application of the Carbon Budget Model (CBM) to National Forest Inventory (NFI) or Forest Management Plans (FMP) input data, combined with additional information provided by FAOSTAT (on the historical harvest removals), by other research institutes (i.e., the European Forest Institute database on the forest storms), by literature or directly provided by countries.

The CBM is a well-known and documented forest inventory model (Kull et al., 2016) largely applied in many scientific studies and different countries (see for example, between the most recent scientific publications, Kim et al., 2016; Smyth et al., 2014; Pilli et al., 2013). The NFI and FMP input data applied by model are generally public available, see Tab. 1, with few exceptions (where we received some personal communications by country's experts), highlighted on the same table. The main input data used to define the harvest demand and the main disturbances are also public available (see FAOSTAT and EFI web sites).

The principle of transparency, requires clear explanations of methods to allow full understanding of the methodologies and data behind the estimates (IPCC, 2010). In this sense, we respectfully disagree with the reviewer, our results are not based on a "black box", and the fact that CBM is not an "open source" model, doesn't mean that this is not transparent. On the contrary, our estimates were based on a transparent model framework (all model details are described in the model's user guide, Kull et al., 2016), using public available data. A synthesis of the general framework followed to apply the CBM model to each country is reported in Figure 1, based on the suggestions reported by the IPCC check list for documenting the application of a Tier 3 model-based approach at the local level (IPCC, 2010).
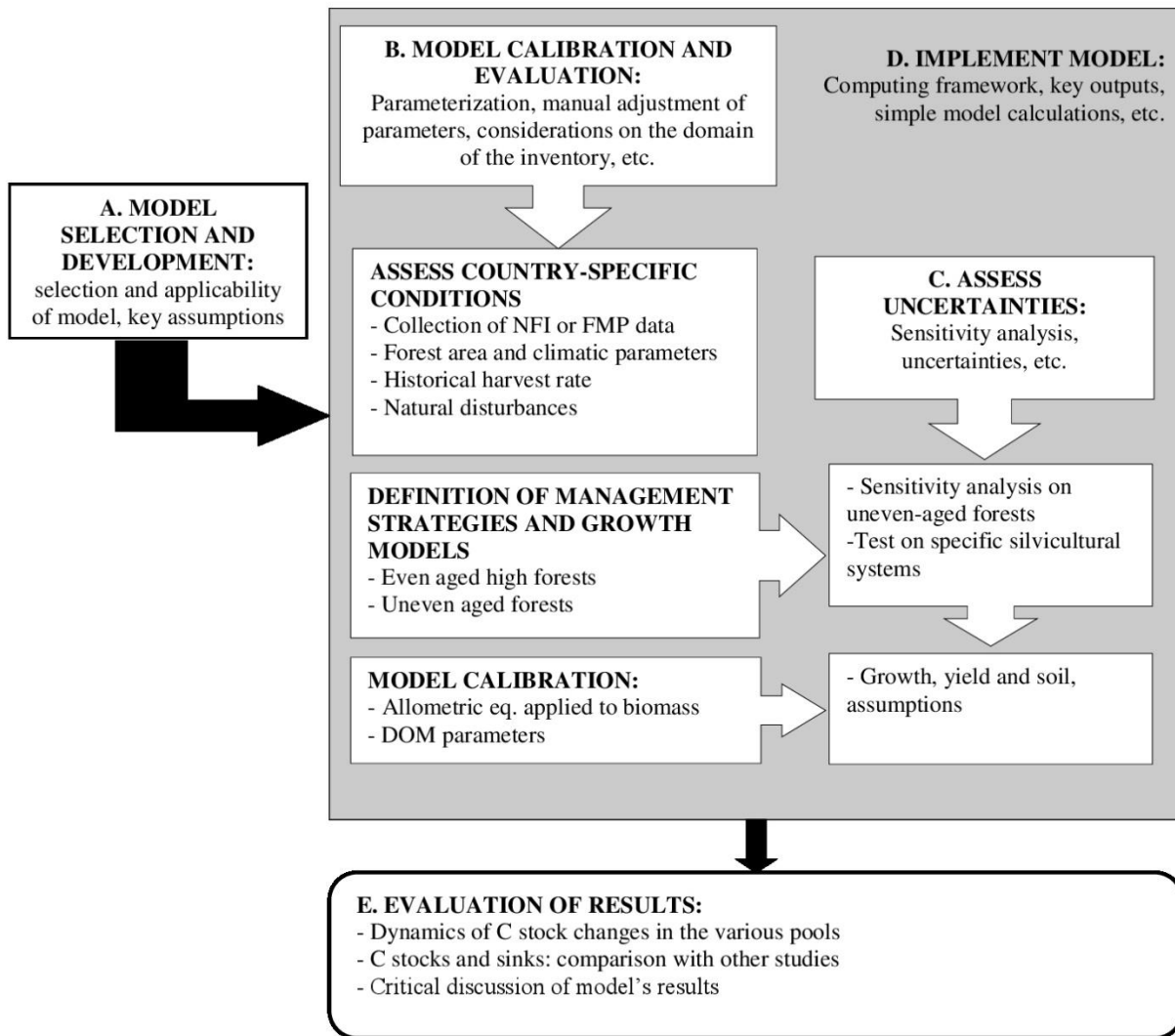
Figure 2: General framework followed to apply the CBM model to country-specific case studies. The capital letters (A to E), refer to the main paragraphs reported by the IPCC check list for documenting the application of a Tier 3 model-based approach at the local level (IPCC, 2010).

If useful, additional details on our methodological assumptions and input data can be certainly added (also as supplementary materials). However, in our opinion, the current version of the manuscript already provides general information and many references about the model framework and our methodological assumptions. As noticed by the reviewer, the paper is already quite long, and we will try to further synthetize our results and discussion, without adding further information already provided by previous studies.

As highlighted by the reviewer, the manuscript provides important information for countries' planning and international agreements. In this paper, however, we focus on the forest C fluxes and stocks related to the interactions between biological, physical and human processes and between a terrestrial life system

(i.e., the forest system) and the atmosphere. In this sense, in our opinion, the manuscript corresponds to the objectives of this journal, achieving an interdisciplinary view of these interactions.

Apart from some important update on our input data (see again Tab. 1), in comparison to other previous studies (Pilli et al., 2016a and b), in the present work, (i) we quantified in detail the C fluxes and stocks between the forest pools and the atmosphere, including Net Primary Productivity (NPP), Net System Exchange (NSE) and Heterotrophic respiration (Rh); (ii) these and many other quantities were quantified not only for the historical period 2000 – 2012 but even to 2030, under different model scenarios. None of these elements was considered by our previous studies.

Specific comments:

1. L. 16, we would edit the text, as suggested.

2. L. 23, we will carefully check the abstract.

3. L. 31 – 32: our study distinguished the forests existing in 1990, defined as Forest Management area (FM) by the land use change (due to afforestation and deforestation) occurred on this area (see also point 7). In many European countries, due to an ageing process, part of the FM area is getting older and despite the increasing NPP, the greater increase of heterotrophic respiration leads to a decrease of the forest C sink. This confirms an age-related decline in the productivity of the European forests (Zaehle et al., 2006), and it is consistent with the results from other studies in the literature, suggesting some signs of C sink saturation in existing European forest biomass (Nabuurs et al., 2013).

4. L. 40, as explained on paragraph 2.3, our study confirms that the build-up of biomass stocks results from woody NPP, exceeding losses by harvest and natural disturbances. This relationship can be also analyzed by comparing the evolution of the biomass as a function of the NPP, i.e., the turnover time (τ). Through a statistical analysis, we compared the τ of each country, highlighting some statistical difference (we can identify at least three groups of countries and turnover times). This means that, contrary to the assumptions proposed by other authors, this relationship cannot be assumed as a constant for all the European countries.

5. L. 58, we would edit the text, as suggested.

6. L. 132, we would edit the text, as suggested.

7. L. 138-139, in order to model the land use change (i.e., afforestation and deforestation) occurred on the European forest area, we need to define a benchmark (i.e., a baseline) for the forest area existing in a certain year. To be consistent with other study and to provide more useful information (also at country level), we prefer to use the Kyoto Protocol base year, assuming the 1990 as base year. In this context, forest area existing in 1990 is generally defined as "Forest management" area.

8. L. 399, the forest ecosystem balance reported by Figure 4 is given by difference between the main input (i.e., the NPP) and outputs (Rh, harvest and natural disturbances) quantified at country level.

9. L. 469, we would edit the text, as suggested.

10. L. 490, we would edit the text, as suggested.

11. Thank you, we appreciate this

12. L. 588, we would edit the text, as suggested.

13. L. 590, thank you for this suggestion, we would consider this for our ongoing work. Since the current model framework is not considering the effect of climate change, at this stage, we would prefer to compare our results with similar studies, such as the models reported by Tupek et al. 2010. However, we are currently working to include the effect of climate change, on a longer time frame, linking CBM with process-based models, such as the models considered by the CMIP5 archive. However, this is part of our ongoing working program, not considered in the present study.

14. L. 613 – 638, generally, the purpose of the Conclusions is highlight the main findings (i.e., conclusions) and provide an explanation of the importance and relevance of the study. In this sense, we think that conclusions should recall some of the main results reported above. In any case, we understand your point and we will review and further summarize this section, as suggested.

15. We will add the acronyms, as suggested.

16. We understand your point, but due to the complexity of the figure we think that it has to be clearly explained in the caption. Anyway, if necessary, we can move part of the text to the methods.

Additional references:

IPCC, Intergovernmental Panel on Climate Change. Use of Models and Facility – Level data in Greenhouse Gas Inventories. (Report of the IPCC Expert Meeting on Use of Models and Measurements in GHG Inventories. 9 – 11 August 2010, Sydney, Australia). Eds.: Eggleston, H.S., Srivastava, N., Tanab,e K., Baasansuren, J., Fukuda, M., GHG Pub. IGES, Japan 2010.

Kim, M., Lee, W.K., Kurz, W.A., Kwak, D.A., Morken, S., Smyth, C.E. and Ryu D. Estimating carbon dynamics in forest carbon pools under IPCC standards in South Korea using CBM-CFS3. iForest - Biogeosciences and Forestry, 1071-1080, DOI, 10.3832/ifor2040-009, 2016.

Kull S.,J. Rampley G.J., Morken S, Metsaranta J., Neilson E.T. and Kurz W.A. Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User's Guide. Canadian Forest Service, Northern Forestry Centre, 2016.

Response to RC #3

The European forest sector: past and future carbon budget and fluxes under different management scenarios by Pilli et al.

Many thanks for this critical and constructive review.

Regarding your general comments on the language, we can certainly improve the text flow, including the captions and the longer sentences. The language will be revised as appropriate.

As highlighted by the Reviewer, the Carbon Budget Model (CBM) and the European Forest Information SCENario Model (EFISCEN) are quite similar, and, of course, we are not claiming that CBM outperforms, or it is better than, EFISCEN. The two models have some similarities and some differences, and for the needs of this study, we selected CBM-CFS3. Both these tools are inventory-based, yield-data driven models, using as main input National Forest Inventory data (Kurz et al., 2009; Schelhaas et al., 2016). Both models have been applied at local (e.g., Pilli et al., 2014 or Kujanpää et al., 2010), national (Stinson et al. 2011 or Forsström et al., 2012) and multi-national scales (Pilli et al., 2016 or Verkerk et al., 2014); both have been used to compare different scenarios, including changes in forest area, harvest demand, management strategies, etc. Both models distinguish the forest area by forest types (FTs) and age classes, eventually defined by administrative regions, owner classes, etc., and they require, for each FT, additional information on the average growing stock and increment (Kurz et al., 2009; Schelhaas et al., 2016).

EFISCEN is basically a matrix model, where the transition between matrix-cells is driven by different processes, such as natural mortality and management regimes. For each five-year time step, a proportion of the area assigned to each cell moves up one age class. For each FT a basic, theoretical management regime of thinning and final cut, defines a "constraint" of what might be felled. As reported by Schelhaas et al. (2016), based on this theoretical management regime, the model searches and might find, depending on the state of the forest, the required harvest volume specified for each region, country and time step.

The CBM is a dynamic simulation model that operates in annual time steps and can represent a wide range of forest management activities, land-use changes, and natural disturbances. It was originally developed and applied by the Canadian Forest Service mainly to even-aged forests (Kurz et al., 2009), but since 2012, the original modelling framework was successfully adapted, and tested in European systems including uneven-aged forests and other management systems, such as shelterwood or coppice (Pilli et al., 2013). One of the main strengths of the CBM is its flexibility in representing almost any possible management system. In the CBM, each disturbance type is controlled through a wide variety of criteria, including spatial and stand characteristics, age, amount of biomass and dead organic matter (DOM) in individual pools, stand history, etc. The impact of each disturbance is further defined using a matrix that describes the proportion of C transferred between pools (i.e., from living biomass to DOM), to the atmosphere (i.e., due to burning of forest residues) and to the forest product sector (i.e., harvest removals). Overall, this integrating framework allows, theoretically, to simulate the effect of any possible management system or natural disturbance event, such as windstorms, fires, insect attacks, etc. This is, in our opinion, one of the main strengths of the CBM and was among the reasons why we selected this very flexible modelling framework.

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As highlighted by the reviewer, our purpose is to apply the same tool and model framework, to 26 different countries. This was also proposed by many authors using the EFISCEN model, but, as known, due to a long silvicultural tradition, the European forests largely differ not only with regard to the forest structure (i.e., species composition and age structure, considered by both these models), but also with regard to the specific managed practices applied at the country level. For this reason, we selected a very flexible tool, that allows us to model a wide variety of management practices and that accommodates a range of input data requirements. Based on the available country-specific information, the model can be run using a unique age class distribution, associated with an average value of volume and increment, without any further distinction between FTs. Alternatively, when additional information is available, it is possible to apply a very detailed analysis, at the regional or country level, further distinguished by FTs, management strategies, ecological regions, etc. Finally, the model can simulate the effect of different natural disturbance events, from fires, typically affecting the Mediterranean countries, to windstorm, mainly affecting central and north European countries, and the subsequent management responses, such as salvage logging. All these elements were implemented within a unique model framework, providing, at the same time, a consistent and complete output, including the annual estimates of C stocks and stock changes for each forest pool. Many of these aspects were also considered by other studies using the EFISCEN model, but in some cases, they focused on the effect of natural disturbances (i.e., Seidl et al., 2014), in other cases on different management practices (even accounting for the effect of climate-change on productivity, but always considering an even-aged sylvicultural system, such as in Schelhaas et al., 2015) or on other additional aspects not (yet) considered by our model framework, such as the maximum potential amount of harvest (Verkerk et al., 2011) or the forest ecosystem services (Verkerk et al., 2014).

In summary, the CBM is a useful, but certainly not exclusive, tool to analyze the forest C dynamics, under different spatial scales and management scenarios. At the same time, using and comparing the results provided by different models, can represent an added value, to improve the confidence in model results, in particular when dealing with projections of the future C sink (Böttcher et al., 2012). A future study aimed at comparing these models, at least at the country level, would further improve our knowledge.

Your question, on the relationship between forest practices and physical/biological system is certainly very interesting, and we could, theoretically, analyze also this issue. In fact, we could use the ecological zones (as considered, for example, by Metzger et al., 2012) rather than the administrative (country) boundaries to summarize the results. A similar approach was already proposed by Stinson et al. (2011) for Canada and by Mascorro et al. (2015) for the Yucatan Peninsula, in Mexico. In these cases, the model stratification was done by both country boundaries and ecological boundaries. In our case, maps of temperature and precipitation classes were projected over a CORINE map and over the European administrative units, following the approach of Pilli, 2012. The resulting combinations of precipitation and mean temperature values were used to define 60 climatic land units (CLUs, as reported in Pilli, 2012, see Figure 1). For each country, the proportion of NFI forest area associated with each CLU, was estimated on the basis of CORINE data. Through this approach, even if our modelling framework was not spatially-explicit, we linked the forest area reported for each country to specific CLUs, associated with values of mean annual temperature and total annual precipitation (the CLU's mean annual temperatures, range from -7.5 to +17.5°). Because in CBM the decomposition rate for each DOM pool is modelled using a temperature-dependent decay rate (Kurz et al., 2009), also in our model framework the decay rate is modified according to the mean annual temperature of each spatial unit. The CBM also uses biomass

turnover rates to represent mortality of biomass and litterfall rates and the transfer of dead biomass to DOM pools. Unfortunately, due to the lack of studies, we could not (yet) define these parameters at regional level, and extensively compare our results with other field measurements. This will be part of future model evaluations.
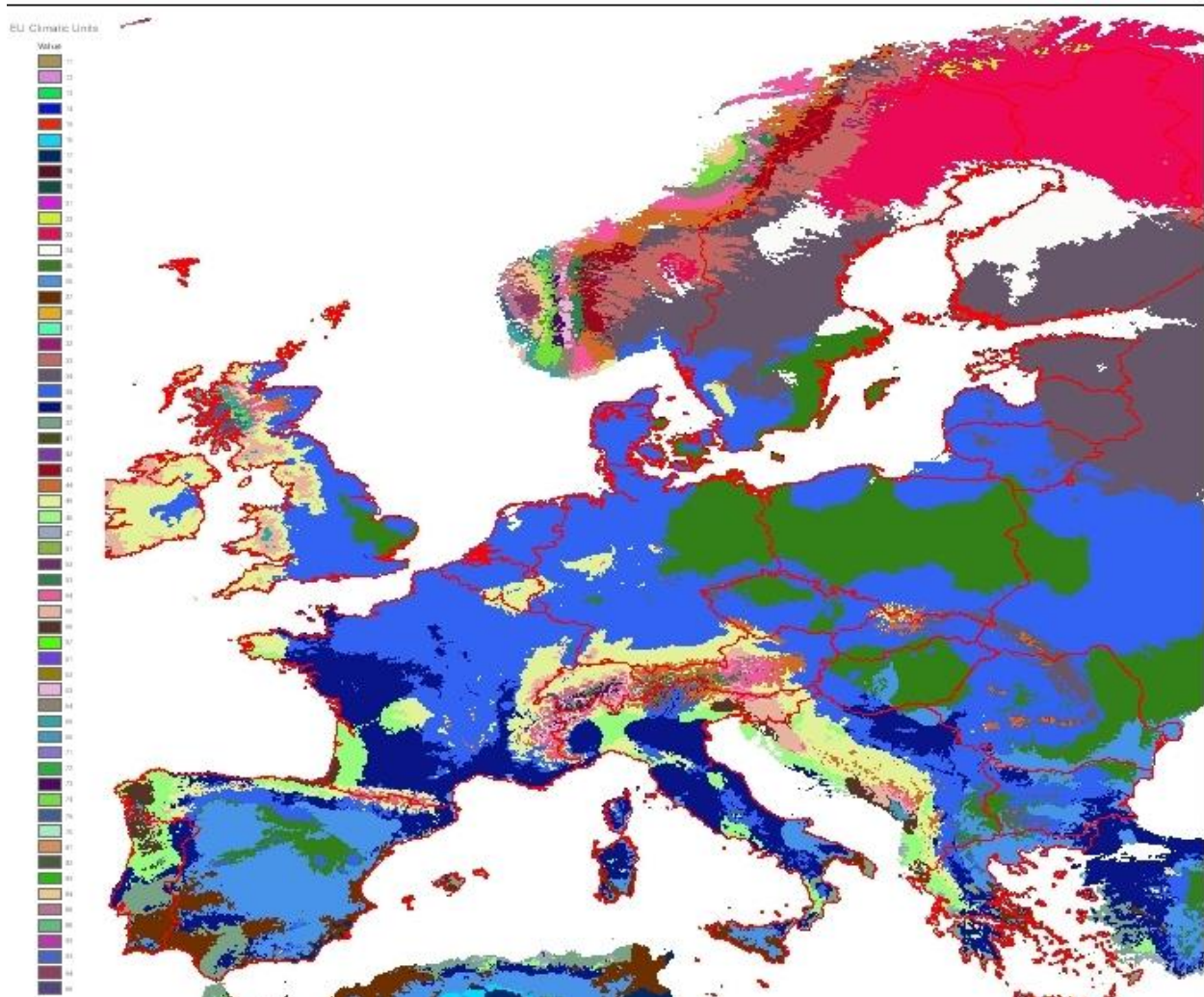

Figure 3: overview of the climatic units (CLUS) defined at European level and used to set the mean annual temperature applied by model.

Specific comments:

1. L. 89, yes, you are correct, biogeochemical will be substituted with biophysical, as suggested.

2. L. 270, yes, here we refer to a model-model comparison, and as you say, the turnover time of each wood commodity (i.e., sawnwoods, wood based panels and paper and paper board) cannot be measured precisely. We based our estimates on the default values reported by the Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol, 2013 (IPCC, 2014). We can highlight this uncertainty, as suggested by the reviewer.

3. L. 376 – 381: Yes, we can further develop this sentence. In particular, if we assume that the biomass removed from deforested areas (i.e., about 5 Tg C yr^{-1}) would be entirely used as fuelwood (FW) or industrial roundwood (IRW), this would reduce the amount of living biomass removed through other management practices (see Fig. 1 on the manuscript, arrows (*E*), (*F*), (*G*)). This would slightly increase the living biomass C stock and, as a consequence, the NBP of the FM area, but it would not affect the direct emissions due to FW and to the decay process affecting IRW, since the absolute amount of FW and IRW would not change. Excluding the effect of the natural turnover rate on the living biomass, the average living biomass (excluding leaves) could, potentially, increase from 7228 Tg C (see Tab 1S) to 7,233 Tg C (i.e., + 0.07% yr^{-1}).

4. L. 481, we will delete the reference to "SAS®" and instead explain that the statistical analysis was performed through the "Proc Reg" procedure, using the R^2 selection method to identify the model with the largest R^2 for each number of variables considered.

5. L. 585 – 589: yes, you are correct, that the yield curves in the model are based on observations, and thus some impacts of environmental changes are represented in the model. However, many yield curves are based on plot measurements over the past decades we therefore cannot make any assumptions about how representative the existing yield curves will be for future environmental conditions. In the absence of environmentally-sensitive yield curves this is the best we (and the entire forest planning community) can do.

6. L. 597: yes, you are correct, ORCHIDEE is a process-oriented model, like JULES. The sentence will be correct.

Additional references:

Böttcher, H., Verkerk, P.J., Gusti, M., HavlÍk, P., Grassi, G.: Projection of the future EU forest CO2 sink as affected by recent bioenergy policies using two advanced forest management models. *Gcb Bioenergy*, *4*(6), 773-783. DOI: 10.1111/j.1757-1707.2011.01152.x, 2012.

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Kujanpää, M., Eggers, J., Verkerk, H., Helin, T., Lindner, M., Wessman, H.: Carbon balance of forest residue collection and combustion in southern-Finland, 18th European Biomass Conference and Exhibition, Lyon, France, pp. 1575-1579, 2010.

Kurz, W.A., Apps, M.J.: A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, Ecol Appl, 9, 526–547. DOI:10.1890/1051-0761(1999)009[0526:AYRAOC]2.0.CO;2, 1999.

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Pilli, R.: Calibrating CORINE Land Cover 2000 on forest inventories and climatic data: An example for Italy, Int J Appl Earth Obs, 19, 59-71. DOI: 10.1016/j.jag.2012.04.016, 2012

Pilli, R., Grassi, G., Cescatti, A.: Historical analysis and modeling of the forest carbon dynamics using the Carbon Budget Model: an example for the Trento Province (NE, Italy), Forest@, 11, 20-35. DOI: 10.3832/efor1138-011, 2014.

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Verkerk, P.J., Mavsar, R., Giergiczny, M., Lindner, M., Edwards, D., Schelhaas, M.J.: Assessing impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests, ISS Environ Sci Tech, 9, 155-165. DOI: 10.1016/j.ecoser.2014.06.004, 2014.

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Blain, D.: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Global change Biol, *17*(6), 2227-2244. DOI: 10.1111/j.1365-2486.2010.02369.x, 2011.

Mascorro, V.S., Coops, N.C., Kurz, W.A., Olguín, M.: Choice of satellite imagery and attribution of changes to disturbance type strongly affects forest carbon balance estimates, Carbon balance and management, 10(1), 30. DOI: 10.1186/s13021-015-0041-6, 2015.

1 **The European forest sector: past and future carbon budget and fluxes**

2 **under different management scenarios**

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4 **Roberto Pilli[1], Giacomo Grassi[1], Werner A. Kurz[2], Giulia Fiorese[1], Alessandro Cescatti[1]**

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1. Abstract

The comprehensive analysis of carbon stocks and fluxes of managed European forests is a prerequisite to quantify their role in biomass production and climate change mitigation. We applied the Carbon Budget Model (CBM) to 26 European (EU) countries, parameterized with country information on the historical forest age structure, management practices, harvest regimes and the main natural disturbances. We modeled the C stocks for the five forest pools plus Harvested Wood Products (HWP), and the fluxes among these pools, from 2000 to 2030. The aim is to quantify, using a consistent modelling framework for all 26 countries, the main C fluxes as affected by land-use changes, natural disturbances and forest management and to assess the impact of specific harvest and afforestation scenarios after 2012 on the mitigation potential of the EU forest sector. Substitution effects and the possible impacts of climate are not included in this analysis.

Results show that for the historical period (2000 – 2012) the net primary productivity (NPP) of the forest pools at the EU level is on average equal to 639 Tg C yr^{-1}, the losses are dominated by heterotrophic respiration (409 Tg C yr^{-1}) and removals (110 Tg C yr^{-1}), with direct fire emissions being only 1 Tg C yr^{-1}, leading to a net carbon stock change (i.e. sink) of 110 Tg C yr^{-1}. Fellings also transferred 28 Tg C yr^{-1} of harvest residues from biomass to dead organic matter pools. The average annual Net Sector Exchange (NSE) of the forest system, i.e. the carbon stock changes in the forest pools including HWP, equals a sink of 122 Tg C yr^{-1} (i.e., about 19% of the NPP) for the historical period and in 2030 reaches 126 Tg C yr^{-1}, 101 Tg C yr^{-1} and 151 Tg C yr^{-1}, assuming respectively a constant, increasing (+20%) and decreasing (-20%) scenario of both harvest and afforestation rates compared to the historical period. Under the constant harvest rate scenario, our findings show an incipient aging process of the forests existing in 1990: although NPP is increasing (+7%), heterotrophic respiration is increasing at a greater rate (+13%) and this leads to a decrease of the sink in the forest pools (--6%) in 2030 compared to the historical period.

By comparing, for each country, the evolution of the biomass as a function of the NPP (i.e., the turnover time) we highlighted at least three groups of countries and turnover times. This means that, contrary to the assumptions proposed by other authors, this relationship cannot be assumed as a constant for all the EU countries, but specific conditions, such as the harvest rate, the current age structure and forest composition, may contribute to the country-specific evolution of biomass stocks.

Commented [RP1]: See specific comments from Rev 2# and our answer

Commented [RP2]: See specific comment from Rev 1#

Commented [RP3]: See specific comments from Rev 2# and our answer

Commented [RP4]: See specific comments from Rev 2#.

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41 The detailed picture of the C fluxes condensed in this study, and their evolution under different
42 harvest scenarios, may represent both a benchmark for similar studies and a basis for broader
43 analyses (e.g. including substitution effects of wood) on the mitigation potential of the EU forest
44 sector.

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46 **Keywords**: EU, Net Primary Production, C fluxes, Harvest scenarios, Carbon Budget Model

47

1. Introduction

Forest management in Europe has a long tradition that has strongly influenced the present species composition (Spiecker, 2003) and it will continue to be the main driver affecting the productivity of European forests for the next decades (Koehl et al., 2010). A comprehensive assessment of the overall carbon stocks and fluxes of managed forests is required, to complement the analyses of climate change impacts on forest productivity and composition (e.g. Lindner et al., 2015). Several studies analyzed the European forest carbon budget from different perspectives and over different time periods (Kauppi et al., 1992, Karjalainen et al., 2003), using different approaches, such as process-based ecosystem models (i.e., Valentini et al., 2000) or estimates based on forest inventories (i.e., Liski et al., 2000). Each of these methods has its strengths and weaknesses (Karjalainen et al., 2003).

Although several studies tried to harmonize different data sources (i.e., Böttcher et al., 2012) and to link or compare the results from different approaches (i.e., Ťupek et al., 2010; Neumann et al., 2015), relevant differences still exist between the national reported values and the calculations from large-scale models (Groen et al., 2013). Atmospheric biogeochemical models focus on long-term physiological responses to climate change, but are not suited for capturing the effect of different management practices (Karjalainen et al., 2003; Ťupek et al., 2010). For analyzing the impact of human activities on the current and near-future forest C stocks and fluxes, inventory–based models are the most appropriate tool. Furthermore, there are still knowledge gaps which should be addressed (Bellassen and Luyssaert, 2014) while also addressing more complex analyses, such as the challenges posed by increasing natural disturbances and other global changes (Trumbore et al., 2015).

In 2003, Karjalainen et al., using an inventory-based model (EFISCEN, Sallnäs, 1990) applied to data from National Forest Inventories (NFIs, mainly from the '90s), quantified forest carbon fluxes at the country and the European level, looking both at the historical period 1990-2000 and at future management and climate scenarios, up to 2050. This analysis can now be updated thanks to the availability of new NFIs, further information from the UNFCCC countries' reports and data provided by other studies (i.e., Luyssaert et al., 2010; Schulze et al., 2010; Ťupek et al., 2010).

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76 The aim of this study is to provide a comprehensive quantification of the carbon stocks and fluxes
77 of the EU forest sector, including country-level details. We used an inventory-based model
78 (Carbon Budget Model, CBM-CFS3, Kurz et al., 2009) and applied it to 26 EU countries for the
79 historical period 2000-2012 and for future scenarios of different harvest and afforestation rates (up
80 to 2030).

81 In particular, we focus on the effects of forest age-structure, natural disturbances, land-use change
82 and management activities on: (i) the amount of carbon stocked in the five forest C pools (i.e.,
83 above- and belowground biomass, dead wood, litter, and soil) and outside the forest (i.e., harvested
84 wood products, HWP), when possible further distinguishing between merchantable biomass,
85 branches, biomass used for energy, etc.; and (ii) the fluxes, i.e., the inputs to and the outputs from
86 each pool, and the exchanges between the forest sector and the atmosphere. Given the relatively
87 short timeframe analyzed in our study (30 years), we do not consider the effects of climate change
88 on forests. Other factors not covered by this study are substitution effects (Sathre and O'Connor,
89 2010; Smyth et al., 2016) and biophysical effects (Naudts et al., 2016, Alkama and Cescatti, 2016).

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91 ## 2. Material and Methods

92 ### 2.1. The Carbon Budget Model (CBM-CFS3) and NFI input data

93 The CBM is an inventory-based, yield-curve driven model that simulates the stand- and landscape-
94 level C dynamics of above- and below-ground biomass, dead organic matter (DOM: litter and dead
95 wood) and mineral soil (Kurz et al., 2009). The model, developed by the Canadian Forest Service,
96 was recently applied to 26 EU countries mainly using NFI input data (Tab. 1), to estimate the EU
97 forest C dynamics from 2000 to 2012, including the effects of natural disturbances and land-use
98 change (Pilli et al., 2016a and b). Here we apply the same methods, data and assumptions as these
99 studies, with the exception of Bulgaria, Ireland, Poland and Romania, where we updated our input
100 data (see Tab. 1 for details). We refer the reader to Kurz et al. (2009) for details on the model and
101 to Pilli et al. (2016a and c) for details on its application to EU countries.

102 [Tab. 1]

The spatial framework applied in the CBM conceptually follows IPCC Reporting Method 1 (Penman et al. 2003) in which the spatial units are defined by their geographic boundaries and all forest stands are geographically referenced to a spatial unit (SPU). Within a SPU, each forest stand is characterized by age, area and 7 classifiers that provide administrative and ecological information; the link to the appropriate yield curves; the parameters defining the silvicultural system such as the forest composition (defined according to different forest types, FTs), the management type (MT), and the main use of the harvest provided by each SPU, as fuelwood or industrial roundwood. From the NFIs of each country we derived: (i) the original age-class distribution (for the even aged forests), (ii) the main FTs based on the forest composition (each FT was assumed to be composed of the main species reported in the NFI, i.e., it was assumed as a pure FT); (iii) the average volume and current annual increment (if possible, defined for each FT) and (iv) the main MTs. These last parameters may include even-aged high forests, uneven-aged high forests, coppices and specific silvicultural systems such as clear-cuts (with different rotation lengths for each FT), thinnings, shelterwood systems, partial cuttings, etc. In few cases, because of the lack of country-specific information, some of these parameters were derived either from the literature or from average values reported for other countries.

In the CBM, species-specific, stand-level equations (Boudewyn et al., 2007) convert merchantable volume per hectare into aboveground biomass, partitioned into merchantable stemwood, other (tops, branches, sub-merchantable size trees) and foliage components. Where additional information provided by NFIs or by literature was available, country-specific equations were selected to convert the merchantable volume into aboveground biomass (Pilli et al., 2013).

We used two sets of yield tables in these analyses (Pilli et al., 2013, Pilli et al., 2016a). Historical yield tables, derived from the standing volumes per age class reported by the NFI, represent the impacts of growth and partial disturbances during stand development. Current yield tables, derived from the current annual increment reported in country NFIs, represent the stand-level volume accumulation in the absence of natural disturbances and management practices.

For 22 countries, we also evaluated the impact of natural disturbance events including storms and ice, fires and bark beetle attacks (Tab. 1). Specific information on the assumptions on natural disturbances can be found in Pilli et al., 2016a and 2016c.

6

The CBM uses biomass turnover rates to represent mortality of biomass and litterfall rates and the transfer of dead biomass to DOM pools (Kurz et al., 2009). Due to the lack of studies, in many cases we could not define these parameters at the regional level. The decomposition rate for each DOM pool, however, is modelled using a temperature-dependent decay rate that determines the amount of organic matter that decomposes each year. For this reason, maps of temperature and precipitation classes were projected over a CORINE map and over the European administrative units, following the approach of Pilli (2012). The resulting combinations of precipitation and mean temperature values were used to define 60 climatic land units (CLUs, as in Pilli, 2012) and, for each country, a portion of the NFI forest area was associated with each CLU, on the basis of CORINE data.

The model provides annual estimates of C stocks and fluxes, such as the annual C transfers between pools, from pools to the atmosphere and to the forest product sector, as well as ecological indicators such as the net primary production (NPP), heterotrophic respiration (R_h) or net biome production (NBP). Afforestation (AR) and deforestation (D) can be represented as disturbance types with their own disturbance matrices and transitions to and from forest land.

In order to model land use changes (i.e., AR and D), we need to define a benchmark (i.e., a baseline) for the forest area existing in a given year. To be consistent with other studies and to provide more useful information (at the country level), we use 1990 as base year, which is also the Kyoto Protocol base year (details in Pilli et al., 2016a). For simulations that started after 1990, this area was decreased to account for the total amount of deforestation reported by each country (KP CRF tables, 2014) between 1990 and time step 0, i.e., the beginning of the model run (which varies by country, as reported in Tab. **1**).

If the NFI reference year was after 2000, we rolled back by 10 years the original NFI age-class distribution (for even-aged forests) in the inventory (Pilli et al., 2013, 2016a) to provide for all EU countries a consistent dataset covering the period 2000–2012.

We considered the historical effect (i.e., up to 2012, depending on the available data) of the main storms and ice damages (16 countries), fires (10 countries) and insect attacks (i.e., bark beetle attacks, for 2 countries; see Tab. 1 and Pilli et al., 2016a).

AR was modeled through country-specific model runs, always beginning in 1990, applying the historical annual rate of AR reported by each country up to 2012 (Pilli et al., 2016b). The total

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162 amount of AR per year was distributed between different FTs, according to the proportional
163 amount of the FM area.

2.2. Harvest demand and carbon flow

165 The main fluxes modelled in our study are: (1) inputs of C from the atmosphere (i.e., NPP) to the
166 forest ecosystem; (2) outputs due to direct C emissions from the forest to the atmosphere and due
167 to harvest activities; (3) internal fluxes (not affecting the total C balance), mainly from the living
168 biomass to the DOM pool (see also Figure 1S in the Supplementary Materials for more details).
169 Carbon enters the forest as CO_2 absorbed from the atmosphere by living biomass (LB); a fraction
170 of this biomass returns to the atmosphere (through natural disturbances such as fires and storms)
171 or moves to the other forest pools (dead wood and litter) through natural mortality and disturbance
172 events. From these pools, C can be directly released to the atmosphere or transferred to the soil
173 pool where some of it can reside for centuries. All these ecosystem carbon fluxes are modeled in
174 CBM with a semi-empirical approach (Kurz et al., 2009).

175 From an ecosystem perspective (Kirschbaum et al., 2001), the sum of all biomass production,
176 during a year, represents the NPP, equal to the difference between the carbon assimilated by plants
177 through photosynthesis (i.e., the Gross Primary Production, GPP) and the carbon released by plants
178 through autotrophic respiration (R_a):

$$NPP = GPP - R_a \quad \text{Eq. (1)}$$

180 Subtracting from this figure all the C losses due to the heterotrophic respiration (Rh, i.e.,
181 decomposition), we estimate Net Ecosystem Productivity (*NEP*):

$$NEP = NPP - R_h \quad \text{Eq. (2)}$$

183 *NBP* is the difference between NEP and the direct losses due to harvest (*H*) and natural
184 disturbances (*D*, e.g., fires):

$$NBP = NEP - H - D \quad \text{Eq. (3)}$$

186 Through the fellings, a fraction of the LB moves to the HWP pool (this is the amount of biomass
187 removed from the forest, i.e. the roundwood removals reported in Figure 1S). Another fraction of
188 biomass is left in the forest as forest residues (i.e., slash, varying according to the specific
189 silvicultural treatments). Fellings can also salvage a fraction of the standing dead trees and move

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190 them from the dead wood pool to the roundwood pool. Adding to the NBP the total changes in the
191 HWP carbon stock (HWP$_{\Delta C}$), we estimate the Net Sector Exchange (NSE, Karjalainen et al.,
192 2003):

$$NSE = NBP + HWP_{\Delta C} \qquad \text{Eq. (4)}$$

194 In this study, we applied the CBM as a timber assessment model, i.e., we defined a certain harvest
195 level and implemented the model to (i) check if it is possible to harvest that amount and (ii) to
196 simulate the forest development under that harvest level (Schelhaas et al., 2007). The total fellings
197 were inferred, for each country, from the amount of roundwood removals reported by FAOSTAT
198 data (FAOSTAT, 2013), further distinguished between industrial roundwood (IRW, used for the
199 production of wood commodities and mainly provided by stems) and fuelwood (FW‑i.e., the wood
200 for energy use, mainly provided by residues, branches and coppices). To provide a consistent
201 estimate of the harvest demand for all the countries, these data were compared and, when needed,
202 corrected with other information from the literature (i.e., to account for the bark fraction or other
203 possible recognized biases; Pilli et al., 2015).

204 The EU-26 total past and three alternative future harvest demands considered in this study are
205 shown in Figure 1. For each country, the total harvest was further distinguished between four
206 compartments providing the total amount of wood expected each year: IRW conifers, IRW
207 broadleaves, FW conifers and FW broadleaves. For each compartment we defined: (i) the FTs (i.e.,
208 broadleaved species for IRW and FW, and coniferous species for IRW and FW), (ii) the MTs (for
209 example coppices for FW broadleaves) and (iii) the silvicultural practices (for example thinnings
210 for FW conifers). Original values of harvest demand expressed as cubic meter were converted to
211 tons of C using species-specific wood densities values and a constant C fraction equal to 0.50
212 (Penman et al., 2003). A further distribution between FTs and MTs associated with the same
213 compartment was based on the total stock of aboveground biomass available at the beginning of
214 the model run. The C annually stocked as harvested wood products (i.e., IRW) was directly derived
215 by the estimates provided by Pilli et al., 2015, based on the same input data used in this study.
216 During the model run, we also quantified the amount of FW provided by branches and other wood
217 components such as the amount of residues moved from the LB to the dead wood pool (see Figure
218 1S‑). A fraction of the LB due to the deforestation could be also used as FW or IRW, but due to

219 the lack of detailed information on this potential use, this amount was not included in the sum of

220 the total roundwood removals; instead it was assumed as direct emission of C to the atmosphere.

221 Three harvest scenarios were explored from 2013 onward (combined with the FM area and the

222 deforestation activities): (i) a constant harvest scenario based on the average historical harvest

223 (2000 – 2012) up to 2030; (ii) an increasing harvest scenario, based on a 20% increase to the 2030

224 constant harvest demand and a linear interpolation between 2013 and 2030; (iii) a decreasing

225 harvest scenario, based on a 20% decrease to the 2030 constant harvest demand and a linear

226 interpolation between 2013 and 2030 (Figure 1). For each future harvest scenario, we distributed

227 the total harvest demand between the four compartments (i.e., IRW and FW, Con. and Broad.),

228 assuming the same proportions as in the historical period, i.e about 62% of the total harvest was

229 used as IRW coming from coniferous species, 19% was used as IRW coming from broadleaved

230 species, 6% was used as FW coming from coniferous species and 13% was used as FW coming

231 from broadleaved species.

232 [Figure 1]

233 We assumed that the harvest demand was entirely provided by the FM area, excluding potential

234 harvest from deforestation. For AR we estimated the maximum potential (and theoretical) harvest

235 from afforested areas, assuming a common set of silvicultural practices for all countries, with a

236 single 15% commercial thinning applied to broadleaved forests 15-years or older and a single 20%

237 commercial thinning applied to coniferous forests 20-years or older (Pilli et al., 2014b).

238 Tab. 2 summarizes all the assumptions on (i) the forest area, assumed as constant FM area minus

239 the annual rate of deforestation; (ii) the effect of natural disturbances, concentrated on the FM area;

240 (iii) the harvest demand, based on FAOSTAT statistics and concentrated on the FM area. After

241 2012, we applied a constant average annual rate of deforestation to the FM area combined with

242 three different harvest scenarios (i.e., constant average, +20% and -20%); for AR, we considered

243 three different annual rates of AR (i.e., constant average, +20% and -20%), and we estimated for

244 each scenario the maximum theoretical amount of harvest potentially provided by the AR area,

245 assuming constant silvicultural practices.

246 [Tab. 2]

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3. Results and discussion

3.1. Carbon balance at EU level

The average total C stock estimated for EU-26, for the main FM pools is equal to 9,417 Tg C for the living biomass; 1,536 Tg C for dead wood; 1,179 Tg C and 7,717 Tg C for litter and soil (to a depth of 1 m), plus 1,843 Tg C, as average amount of C in the HWP pool during the same period (based on the analysis provided by Pilli et al., 2015).

Figure 2 reports the historical (2000 – 2012) C fluxes modelled by CBM at EU level, for the forest area existing in 1990 (i.e., the FM area) and for the HWP pool. Additional data for each C pool and flux and for the area afforested from 1990 to 2012 (AR), are reported in Figure 1S and Tab. 1S in the Supplementary Materials. Living biomass and felling (including removals and harvest primary residues), have a positive net C balance. We estimated a negative balance for dead wood and litter, probably influenced by the (average) effect of the natural disturbances occurred during 2000 – 2012. These disturbances have moved part of the living biomass stock to the DOM (through wind storms and fires) and from this pool to the atmosphere (through fires). At the same time, however, through the salvage of logging residues, the same disturbances have also (indirectly) moved part of this dead biomass to the HWP pool. Due to the short time frame considered by our study (12 yrs. for the historical period), we could not highlight any significant variation of the soil C stock. Indeed, the slightly negative C stock change reported for this pool (-0.8 Tg C yr^{-1}) is mainly due to the effect of deforestation that moves forested lands to other land-use categories (i.e., it is not a soil C loss to the atmosphere, but it is a transfer to other land categories) and, overall, the soil C stock is stable.

[Figure 2]

The estimated average NPP is equal to 620 Tg C yr^{-1} for the FM area (including the effect of deforestation that occurred since 1990) plus 19 Tg C yr^{-1} for the afforestation that occurred since 1990. The total heterotrophic respiration (*Rh*) amounts to 403 Tg C yr^{-1}, mainly due to the decay of the DOM and soil C pools, plus 6 Tg C yr^{-1} from the afforested area.

The direct C emissions related to fire disturbances are about 1 Tg C yr^{-1} (see Figure 1S for details) and are consistent with the emissions reported by the countries to the UNFCCC (2014, KP CRF tables, see Pilli et al., 2016b and 2016c for further details). Other losses from biomass pools are

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Commented [RP8]: See Specific comments from Rev 1#

Commented [RP9]: Taking into account both the comments from Rev. 1 (suggesting to further summarize the information reported on previous Figure 1) and Rev. 2 (criticizing the length of the caption of Figure 1), we moved the figure reported on the previous version to the supplementary materials, leaving only a summary on the main text, now reported as figure 1.

Commented [RP10]: See last comment from Rev 1#

276 related to fellings (about 138 Tg C yr^{-1}) and can be distinguished between wood removals (110 Tg
277 C yr^{-1}) and transfers of biomass residues to DOM pools, (28 Tg C yr^{-1}), which will decay over time
278 (see Figure 1S). A consistent fraction (about 20%) of the fellings are used as fuelwood and thus
279 its C content is directly released to the atmosphere (see Figure 1S and Tab. 1S). As suggested by
280 the 2013 IPCC KP LULUCF Supplement, we assumed the instantaneous oxidation of the amount
281 of harvest used as FW (Hiraishi et al., 2014). The remaining industrial roundwood component can
282 be further distinguished between the C annually stocked as harvested wood products (12 Tg C yr^{-1}
283 based on Pilli et al., 2015) and the C released to the atmosphere due to decomposition (70 Tg C
284 yr^{-1}).

285 We compare our results with figures from the literature (Table 3). Luyssaert et al. (2010) analyzed
286 the results of different methodologies for EU-25 during 1990-2005 and estimated an average
287 annual NPP lower than our estimates (520 ± 75 Tg C yr^{-1}). Karjalainen et al. (2003), estimated an
288 average NPP equal to 409 Tg C yr^{-1}, for 27 EU countries during 1995-2000. The average R_h
289 estimated with CBM (403 Tg C yr^{-1}) is in the range of values reported in Luyssaert et al. (2010),
290 but it is 40% higher than the figure in Karjalainen et al. (2003), probably because of the higher
291 fine turnover rates used in CBM than those used in the Karjalainen et al. study . However, if we
292 compare the relative emissions due to R_h with the total NPP, the estimates are not so different:
293 59% of the NPP is lost as heterotrophic respiration according to Karjalainen et al. (2009), and 65%
294 according to our study. The total emissions from harvested wood products reported by Luyssaert

> **Commented [RP11]:** See Answer and Comments Rev 1#

295 et al. (2010), equal to 87±16 Tg C yr^{-1}, is similar to our estimate. However, applying the IPCC Tier
296 2 method (Hiraishi et al., 2014; Pilli et al., 2015) we estimated a larger C sink for the HWP pool,
297 equal to 12 Tg C yr^{-1} compared to 5 ± 3 Tg C yr^{-1} in Luyssaert et al. (2010). The net-emissions
298 from HWP estimated in our study at the country and EU levels are consistent with the historical
299 (i.e., until 2009) net-emissions reported by Rüter (2011), using a similar modelling approach.

> **Commented [RP12]:** See specific comments and answer for Rev 3#, and also the section added under paragraph 3.4 (Uncertainty)

300 Finally, if we scale our estimates to units of area (see Tab. 2S in the Supplementary Materials),
301 results for NPP and harvest (4.5 Mg C ha^{-1} yr^{-1} and 0.8 Mg C ha^{-1}) are similar to the estimates
302 presented by Schulze et al. (2010) in a study based on a network of eddy-covariance sites across
303 Europe: 5.2 ± 0. 7 Mg C ha^{-1} and 0.6±0.1 Mg C ha^{-1}, respectively.

304 Taking into account all these fluxes, we estimated a total NBP equal to 98 Tg C yr^{-1} and 12 Tg C
305 yr^{-1} for the FM area and the afforested area (146 M ha in total), respectively. Adding to these NPB

306 estimates the C stock increases in the HWP pool, we estimate a Net Sector Exchange (NSE) for

307 the total forest sector of 122 Tg C yr^{-1}. Luyssaert et al. (2010) reported a NBP value of 109 ± 30

308 Tg C yr^{-1} that is similar to our estimate of 110 Tg C yr^{-1} for the FM area.

309 [Tab. 3]

310 The NPP of the FM area in 2030 increases from 620 Tg C yr^{-1} (average 2000 – 2012) to 661 Tg C

311 yr^{-1} (i.e., +6%), 653 Tg C yr^{-1} (+5%) and 669 Tg C yr^{-1} (+8%), assuming a constant, increasing

312 and decreasing harvest scenario, respectively (Figure 3). In 2030, the area of lands afforested since

313 1990 contributes about 39 Tg C yr^{-1} more to the NPP than the average of the period 1990 to 2012

314 and NBP increases from 12 Tg C yr^{-1} (average 2000 – 2012) to about 26 Tg C yr^{-1} in 2030 for all

315 the AR scenarios. As expected, in 2030, the decreasing harvest scenario (combined with a

316 decreasing AR rate) has the highest total NBP (FM+AR), equal to 151 Tg C yr^{-1}. (see Carbon Sink,

317 in Figure 3).

318 [Figure 3]

319 The natural turnover rate (panel B) and the emissions to the atmosphere in 2030 (panel E) for all

320 scenarios are higher than the average historical turnover rate (272 Tg C yr^{-1} for DOM). The forest

321 living biomass and DOM stocks are in fact increasing from 2013 to 2030, under all harvest

322 scenarios because the average age of forests continues to increase even under the higher harvest

323 scenario (see Tab. 1S).

324 Further losses of C (panel A) are due to fires (on average, about 1 Tg C yr^{-1} for all our scenarios,

325 i.e. about 0.3% of the total NPP in 2030) and deforestation (about 11 Tg C yr^{-1}, i.e., 1.7% of the

326 total NPP in 2030).

327 The total amount of harvest removals from the FM area (panel C) varies among the harvest

328 scenarios and equals (in 2030) 108 Tg C yr^{-1}, 128 Tg C yr^{-1} and 88 Tg C yr^{-1} for the constant,

329 increasing and decreasing harvest scenarios, respectively.

330 Harvest removals are reported as FW and IRW (panel D). Using the approach of the 2013 IPCC

331 KP LULUCF Supplement (Hiraishi et al., 2014), we estimated a direct emission of C from the FW

332 harvest, equal to 26 Tg C yr^{-1}, 29 Tg C yr^{-1} and 20 Tg C yr^{-1} for the constant, increasing and

333 decreasing harvest scenarios, respectively. These emissions represent about 4% of the total NPP.

334 The C transferred to IRW can be further partitioned into the amount of C stocked as HWP and the

335 amount released to the atmosphere due to the decay of these products (Hiraishi et al., 2014). The

336 C stock increase of the HWP pool under different future harvest scenarios is reported on the

337 positive y-axis of Figure 3 (panel D). The IRW emissions vary in proportion to the different harvest

338 rates, and represent about 11% of the total NPP. In contrast, the IRW C sink, equal to 12 Tg C yr$^-$

339 ^{1} for the historical period, decreases when assuming a constant (8 Tg C yr^{-1}) or a decreasing (2 Tg

340 C yr^{-1}) harvest scenario. When we assume an increasing harvest, the HWP C sink in 2030 increases

341 slightly from 12 to 13 Tg C yr^{-1}.

342 Subtracting from the initial NPP the emissions due to the natural turnover rate (panel E), natural

343 disturbances and deforestation (panel A) and fellings (panel D), we can estimate the final C sink

344 of (i) the FM area (including the effect of deforestation), (ii) the HWP pool (stored outside the

345 forest), (iii) the AR that occurred from 1990 to 2030 and (iv) the total forest sector sink. The C

346 sink of the FM area (excluding HWP) varies from 98 Tg C yr^{-1} for the historical period, to 92 Tg

347 C yr^{-1}, 61 Tg C yr^{-1} and 123 Tg C yr^{-1} assuming a constant, increasing and decreasing harvest

348 scenario. This means that, even maintaining a constant harvest rate from 2013 to 2030, the final

349 NBP of forests existing in 1990 decreases by 6% in 2030, compared with the historical period.

350 Increasing the harvest demand by 20%, the NBP decreases by 37% in 2030, but in all cases the

351 NBP estimates a C sink. Only when the harvest demand decreases, will the NBP increase by 25%.

352 The declining C sink estimated in the constant harvest scenario, is the results of an increasing NPP

353 (+7%, if compared with the historical period, see Tab. 1S for details), combined, but with an

354 opposite effect, with an increasing natural turnover and consequent emissions from DOM pools to

355 the atmosphere (+13%). This confirms an age-related decline in the productivity of the European

356 forests (Zaehle et al., 2006), and it is consistent with the results from other studies in the literature,

357 suggesting some signs of C sink saturation in existing European forest (Nabuurs et al., 2013).

358 Overall, for the historical period, the NBP of the FM area equals 16% of the NPP (i.e., the input

359 to the forests). This means that about 84% of the NPP is lost due to natural and human activities.

360 In 2030, the proportion of NBP in NPP varies considerably: from 9%, for the increasing harvest

361 scenario, to 18%, for the decreasing harvest scenario. Since a fraction of the NPP is still stocked

362 in the HWP products, adding this amount to the FM NBP we can estimate the total C sink, i.e., the

363 Net Sector Exchange. In this case, the NSE increases to 110 Tg C yr^{-1} (i.e., about 18% of the NPP)

364 for the historical period 2000 – 2012. This value is considerably higher than the NSE reported by

365 Karjalainen et al. (2003), equal to 87 Tg C yr^{-1}, but for a lower area (128 Mha compared to 138

366 Mha) and a slightly different period (1995 – 2000). In 2030, the NSE varies from 100 Tg C yr^{-1} to

367 74 Tg C yr^{-1} and 126 Tg C yr^{-1} assuming a constant, increasing and decreasing harvest scenarios,

368 respectively (excluding AR). This means that, excluding the substitution benefits and avoided

369 emissions from the use of harvested wood products (Lemprière et al. 2013, Kurz et al. 2016, and

370 Smyth et al. 2016):

> (a) With a 20% harvest reduction, the NSE increases by 15% compared to the historical period,
> but the ratio between NSE and NPP remains the same (i.e., the efficiency of the system,
> equal to about 18%).

> (b) With a constant harvest, the NSE decreases by 9% compared to the historical period and
> the ratio with NPP decreases to 15%.

> (c) With a 20% harvest increase, the NSE decreases by 32% compared to the historical period
> and the ratio with NPP decreases to 11%.

378 FW varies proportionally to the harvest scenarios, according to the historical data 2000 – 2012.

379 Therefore, reducing the harvest by 20% will decrease the energy potential of the FW proportionally

380 and, vice versa, increasing the harvest by 20% will increase the energy potential of the FW.

381 Several studies suggest a significant increase in harvest removals at EU level for the next decades,

382 mainly due to increasing wood demand for renewable energy production, i.e., the FW demand

383 (Mantau et al., 2010; UN, UNECE, FAO, 2011; EC, 2013). The EU Reference Scenario 2016 (EC,

384 2016) anticipates a harvest increase of 9% in 2030 compared to 2005, with a share of wood

385 removed for energy production increasing from 18% in 2005 to 28% in 2030. According to the

386 same study, because of ageing managed forests, this would result in a 30% decline of the forest C

387 sink in 2030, compared to 2005. In our study, increasing the harvest by 20% resulted in a slightly

388 larger reduction of the C sink, equal to about 38%. Since, in the increased harvest scenario, the

389 HWP C sink equals 13 Tg C yr^{-1}, reducing the share of IRW, further increases in the FW

390 production, would also further reduce the total C sink.

391 The average annual NBP on AR lands from 1990 to 2012 is equal to 12 Tg C yr^{-1}, i.e., about 62%

392 of the AR NPP. Assuming different afforestation rates from 2012 to 2030, the final NBP in 2030

393 is equal to 26 Tg C yr^{-1}, 27 Tg C yr^{-1} and 25 Tg C yr^{-1}, with a constant, increasing and decreasing

394 AR rate, respectively (Table 3). Compared with the historical period, the ratio between NPP and

395 NBP considerably decreases (about -46%), because the potential amount of harvest on AR lands

396   increases from 1 Tg C yr^{-1} for the historical period, to about 6 Tg C yr^{-1} in 2030 for all three AR

397   scenarios. While the amount of wood available for harvest until 2012 is negligible (because of the

398   young age of the new forests established since 1990), in 2030, the potential amount of harvest

399   from AR increases, but even then it can only provide less than 6% of the total EU harvest. In our

400   study, we assumed that this amount was mainly used as FW, i.e., the C was immediately oxidized.

401   A further potential amount of harvest, eventually used as FW or IRW, can be provided by the

402   biomass removed from deforested areas, equal on average to about 5 Tg C yr^{-1} for the historical

403   period. Due to the lack of detailed information on this use, this amount, equal to about 20 M m^3

404   yr^{-1} (i.e., about 4% of the average amount of harvest from 2000 to 2012), was quantified but not

405   accounted in the sum of the total roundwood removals and included in the total emissions due to

406   deforestation (see Figure 2 and Figure 1S). This simplified assumption is consistent with the 2013

407   IPCC KP LULUCF Supplement (Hiraishi et al., 2014), which suggests to assume an instantaneous

408   oxidation of the harvest originating from deforestation. On the opposite, when assuming that this

409   amount is used as FW or IRW, we should reduce the amount of living biomass removed through

410   other management practices (see Figure 1S, arrows (E), (F), (G)). This would slightly increase the

411   living biomass C stock (see Tab 1S: from 7,228 Tg C to 7,233 Tg C, i.e., + 0.07% yr^{-1}) and, as a

412   consequence, the NBP of the FM area, but it would not affect the direct emissions due to FW and

413   to the decay process affecting IRW, since the absolute amount of FW and IRW would not change.

414   Adding to the previous estimates the C sink related to AR, the total NSE of the forest system in

415   2030 is equal to 126 Tg C yr^{-1}, 101 Tg C yr^{-1} and 151 Tg C yr^{-1}, assuming a constant (harvest and

416   AR rate), increasing and decreasing scenario (see Table 1S). Compared with the historical period

417   (with a total NSE equal to 122 Tg C yr^{-1}) these values are slightly higher (+3%), lower (-17%) and

418   higher (+23%), for the constant, increasing and decreasing harvest and AR scenarios, respectively.

419   Looking at the constant harvest and AR scenarios, these results suggest that the decreasing C sink

420   detected on the FM area is partly compensated by the increasing C sink on the afforested area.

421   These results are based on the assumption that the highest harvest demand is combined with an

422   increasing AR rate, and vice versa. Different combinations of harvest and AR rate however may

423   also be possible (see the Tab. 4) but, excluding the FW energy potential, the maximum C sink is

424   always linked to a reduction of the amount of harvest provided by FM and the minimum C sink to

425   an increasing harvest scenario. Of course, different assumptions about the share of FW and IRW,

426   a detailed analysis of the FW mitigation potential and of the substitution of other materials with

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427 wood products (Sathre and O'Connor, 2010, Lemprière et al., 2013, Smyth et al., 2014 and 2016;
428 Kurz et al. 2016), not considered by our study, may yield different results.

429 [Tab. 4]

3.2. Carbon balance at country level

431 Figure 4 shows, for each country, the average forest ecosystem balance (i.e., the difference
432 between the NPP and R_h, harvest and natural disturbances) estimated by CBM for the FM area, for
433 the historical period 2000 – 2012. The NPP (represented by the green background in Figure 4)
434 ranges from 2.7 Mg C ha^{-1} yr^{-1} for Finland to 9.4 Mg C ha^{-1} yr^{-1} for Ireland; the EU average is 4.5
435 Mg C ha^{-1} yr^{-1}. The lower values estimated for Finland and Spain (3.1 Mg C ha^{-1} yr^{-1}) are probably
436 due to specific climatic constrains, that limit the growing season in northern Europe and in the
437 Mediterranean area (Jarvis and Linder, 2000; Kramer et al., 2000). For Ireland, the high estimated
438 NPP is probably due to the favorable climate as well as the use of intensive silviculture and fast
439 growing species, such as Sitka spruce (Ireland, 2014).

440 The total losses due to natural processes, such as the decomposition of organic matter, fires and
441 human activities (i.e., harvest, orange slice of each external pie in Figure 4) vary between -2.2 Mg
442 C ha^{-1} yr^{-1} in Finland and -8.2 Mg C ha^{-1} yr^{-1} in Ireland. The EU average is -3.8 Mg C ha^{-1} yr^{-1}. As
443 expected, these losses vary proportionally to the absolute NPP value, and on average the total
444 losses amount to about 83% of the NPP. The highest proportion of losses was estimated for
445 Belgium (>95% of the NPP) and the lowest for the UK (<70% of the NPP).

446 The average NBP (white internal pie in Figure 4) is equal to the difference between the average
447 NPP minus the losses due to respiration (R_h), harvest (H) and disturbances (D) and varies between
448 0.1 Mg C ha^{-1} yr^{-1} estimated for Belgium and 2.4 Mg C ha^{-1} yr^{-1} for UK. Adding to the NBP the
449 HWP net sink (also highlighted by the external orange pies on Figure 4), we can estimate the NSE
450 (labels in Figure 4). This amount varies between 0.1 Mg C ha^{-1} yr^{-1} in Belgium and 2.7 Mg C ha^{-1}
451 yr^{-1} in the UK.

452 Since forest losses are due to the combined effect of natural processes and harvest and they directly
453 affect the final NEP, a more detailed analysis of these parameters may provide useful information.

454 [Figure 4]

Commented [RP13]: See specific comments from Rev 2# and our answer

455   [Figure 5]

456   In Figure 5 we distinguished the relative amount of C losses due to 9 different processes, including

457   natural (i.e., fires and release of C due to the decomposition of DOM and soil pools) and human

458   factors (i.e., harvest activities) and we estimated the percentage loss of the total NPP due to each

459   process. The largest release of C to the atmosphere from the forest ecosystem is due to the natural

460   decomposition of dead wood and litter pools (i.e., DOM → atmosphere). In all countries, this

461   covers at least 37% of total losses while at the EU level it equals 51% of total NPP.

462   The second factor contributing to the total absolute amount of losses is generally represented by

463   human activities, i.e., the use of the merchantable wood components as industrial roundwood.

464   Unlike the previous factor, the relative contribution of this factor varies considerably among

465   countries. In some cases, this may represent more than 20% of the total NPP (e.g., Belgium), but

466   in other countries this share may be less than 3% (i.e., Greece and Italy). At the EU level,

467   merchantable wood use represents about 12% of total NPP.

468   Releases of C from soil to the atmosphere represent the third factor contributing to the total losses

469   (on average 13% of the total NPP). Of course, due to the lack of data, and similarly to other soil

470   models (UN, UNECE-FAO, 2011), the results provided by CBM may be influenced by uncertainty

471   in the model initialization that may directly affect the estimate of the C stock change on this pool

472   (Kurz et al., 2009; Pilli et al., 2013). The carbon balance at the country level, in particular for soil

473   and DOM, is also affected by local climatic conditions. In our modelling framework, we linked

474   the forest area to specific CLUs, associated with values of mean annual temperature and total

475   annual precipitation (the CLU's mean annual temperatures range from -7.5 to +17.5°). In CBM

476   the decomposition rate for each DOM pool is modelled using a temperature-dependent decay rate

477   (Kurz et al., 2009) which allowed us to consider the effect of regional climatic on decay. Due to

478   the lack of data, we did not differentiate biomass turnover rates by region.

479   For all EU countries, further losses are due to the use of wood for energy. While the IRW is

480   generally provided by the merchantable wood components (or, in some cases, by salvage logging

481   after storms). based on our assumptions (see also Figure 1S), the FW may be provided through

482   three different sources of materials: merchantable components (e.g., from coppices or early

483   thinnings), other wood components (mainly branches harvested simultaneously with merchantable

484   wood used as IRW) or standing dead trees (i.e., snags, even as salvage logging after fires). The

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485 relative share of these three sources varies considerably among countries but it is generally < 5%.

486 In few countries, the total losses due to the use of wood for energy exceeds 8% of the total NPP

487 (e.g., France), but at the EU level equals, on average, 4%.

488 The total losses due to natural disturbances were only accounted for in 22 countries, while 4

489 countries do not report natural disturbance events. At the EU level, for the historical period 2000

490 – 2012, these represent about 1% of the total NPP. In some countries, however, this percentage

491 may represent, on average, more than 2%. This is the case of Austria, due to the effect of storms

492 and insect attacks, and Portugal due to fires. Natural disturbances may cause direct losses, due to

493 the biomass and dead organic matter burned by fires (i.e., a direct emission of C to the atmosphere)

494 or indirect losses from the forest ecosystem, due to the salvage of logging residues, after the

495 disturbance events or the decay of biomass that was killed during the natural disturbance and

496 transferred to the DOM pools (Pilli et al., 2016b).

497 We also report the relative amount of losses due to deforestation on the FM area. At the EU level,

498 deforestation represents less than 2% of the total NPP and, for the majority of the countries, less

499 than <1%. In few cases, however, due to the relative large amount of deforestation compared with

500 the total FM area (based on the KP CRF tables, 2014), the deforestation losses may be higher than

501 4% (France and Luxemburg) and, for Netherlands, equal to 19% of the total NPP. This country

502 reports an annual rate of deforestation equal to 2,000 ha yr^{-1} (KP CRF, 2014), i.e., about 6% of the

503 FM area.

504 ### 3.3.   Carbon turnover time

505 Overall, our study suggests that, in the majority of European countries, the build-up of biomass

506 stocks results from woody NPP exceeding losses by harvest and natural disturbances, as

507 highlighted by Ciais et al. (2008). While some estimate biomass carbon stocks as a function of

508 NPP minus removals by harvest, this simplified assumption does not take into account the effect

509 of deforestation and other natural disturbances. Some authors highlighted the long-time historical

510 evolution (about 50 years) of this relationship at the EU level, assuming that the slope of the

511 regression line between carbon stocks and NPP was similar between different countries (Ciais et

512 al., 2008; Luyssaert et al., 2010). However, looking at this relationship at the country level, our

513 study shows some interesting differences. The relation between biomass (y) and NPP (x) can be

514 described by a simple linear model: $y = a + \tau*x$, where τ represents the evolution of the dependent

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515   variable as a function of the NPP and the time that carbon resides in the forest system, i.e. the

516   turnover time (in yr., as described by Carvalhais et al., 2014). Through a statistical analysis, using

517   the R^2 selection method to identify the model with the largest coefficient of determination for each

518   number of variables considered, we can estimate both a and τ (and their ±95% confidence

519   intervals) at country level, considering both the aboveground living biomass and the total standing

520   stock (including living biomass, DOM and soil). Looking at the living biomass (Figure 6, panel A

521   and B), we can identify at least three groups of countries and turnover times: the largest group

522   includes 20 countries with τ between 5 and 70 yrs. (for the majority of these countries, $20 \leq \tau \leq 50$,

523   with no statistical difference). All these countries have both an increasing NPP and biomass stock

524   from 2000 to 2012, such as an increasing turnover time during the same period. For three countries

525   (Italy, Lithuania and UK) we estimated a turnover rate > 70, statistically different from the

526   previous group. For Belgium, France and Hungary, the turnover time <5 yrs (in two cases negative)

527   highlights the countries where we estimated a decreasing NPP (and for Belgium a decreasing

528   biomass against time) and a quite constant turnover time from 2000 to 2012. As expected, the

529   turnover time estimated for the total C stock is on average 16% higher than the biomass turnover

530   time (Figure 6, panel C and D). For the Mediterranean countries, where climatic conditions and

531   the effect of fires may reduce the turnover time of the dead wood and litter pool and for a few other

532   countries (i.e., Denmark and Ireland, due to the young age structure) the turnover time of the total

533   biomass is lower than the previous one. For 17 out of 25 countries (for Belgium the analysis was

534   not significant), τ was between 10 and 80 years and in two cases it was again < 0. Due to the effect

535   of management practices and natural turnover rate (i.e., self-thinnings), the average turnover time

536   estimated for the living biomass, equal to 16.4 yrs. (±0.6 yrs.) is significantly lower than the

537   average turnover time estimated for the total stock (25.9±0.8 yrs.). This last value is consistent

538   with the overall mean global turnover rate estimated by Carvalhais et al. (2014), equal to 23^{+7}_{-4}

539   years. Despite the similarities identified for many countries, we highlighted some statistical

540   difference of the turnover time, suggesting that contrary to the assumptions by Ciais et al. (2008)

541   and Luyssaert et al. (2010) this relationship cannot be assumed constant for all European countries.

542   Country-specific forest conditions related to management practices, harvest rates, past age

543   structures and forest composition, have varying impacts on the evolution of biomass stock and

544   NPP. Above all, the turnover time estimated for the living biomass seems to be related to the age

545   structure and management practices. Indeed, countries with older forests (such as UK) and longer

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546 rotation lengths applied to clearcuts, have the highest τ (>80 yrs). In Italy, where clearcuts are often

547 replaced by other silvicultural practices such as thinnings or partial cuts and where a large part of

548 the forest area (mainly coppices) is aging because of a relative low harvest demand (Pilli et al.,

549 2013), τ is also over 80 years. An increasing harvest demand, generally combined with a larger use

550 of final cuts and shorter rotation lengths, gradually reduces the turnover time and the average age

551 of the forests. Moreover, exceptional natural disturbances, such as windstorms or fires, may further

552 modify this parameter. Due to the complex interaction between these variables, further analyses

553 are needed.

554 [Figure 6]

555 **3.4. Uncertainties**

556 Quantifying the overall uncertainty of these estimates is challenging because of the complexity of

557 our analysis. Indeed, the EU estimate is obtained by summing up 26 country level estimates. For

558 each country, the C stock of each pool is obtained by multiplying the area of each age class (further

559 distinguished between different FTs and administrative units) with the corresponding volume and

560 by applying a species-specific equation to convert the merchantable volume to total aboveground

561 biomass (used as a biomass expansion factor). Therefore, we first consider the uncertainty related

562 to the area, the volume and the equation applied to each FT.

563 The uncertainty of the area estimates varies among countries. Generally, the information from east

564 European countries have a higher uncertainty because of low updating frequency or heterogeneous

565 data sources (e.g. for forest in Romania, Blujdea, pers. com.), while the most recent NFIs have

566 lower uncertainty (e.g., <1%, at the country level, e.g. for Germany or Italy). Considering that the

567 average reference year of the NFIs applied by our analysis is 2003 (see Tab. 1) we assume that the

568 uncertainty of the area (at the country level) is equal to 2%.

569 The volume reported by the yield tables applied by CBM derives from a linear interpolation of the

570 volume and increment data reported in each NFI. The uncertainty on these data (when reported)

571 may vary considerably, depending on the relative abundance of each FT (i.e., by the number of

572 plots) but, based on an overview of the NFIs applied to our analysis, we may assume that it is equal

573 to 5% (in most cases, however, the uncertainty estimate is missing).

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574 Estimating the uncertainty related to the biomass equations applied to each FT is even more
575 challenging. These equations were preliminarily selected comparing some values available at
576 country level (for 8 out of 26 countries, considering the main FTs and biomass compartments)
577 with the values estimated through specific multinomial models developed by Boudewyn et al.
578 (2007). For each FT, administrative region and biomass compartment, we selected the equation
579 that minimizes the average sum of squares of the differences between the values predicted by the
580 equations and reported in the literature (see Pilli et al., 2013). Therefore, the uncertainty on this
581 component is related to both the uncertainty of the original values reported in the literature and of
582 the multinomial model selected by our analysis. The first uncertainty may vary considerably,
583 depending on the original data source selected for each country. For example, based on NFI data
584 reported for Italy, the standard error of the aboveground biomass estimated at the regional level
585 may vary between less than 3% to more than 100% (Gasparini and Tabacchi, 2011). For Germany,
586 and for other countries where no detailed information on the biomass was available and this
587 parameter was estimated through allometric equations applied to the original NFI data, the
588 uncertainty may also be higher.

589 The uncertainty related to the capacity of each model to represent the original values was estimated
590 through the mean percentage difference between the predicted and observed values. This may vary
591 considerably, depending on the forest compartment and the species. For Italy, the mean percentage
592 difference between the total aboveground biomass estimated using the selected stand-level
593 equations and the biomass reported by NFI was ±3.8% (Pilli et al., 2013). For other countries, we
594 obtained similar results. Where no data were provided by the literature (i.e., for 18 out of 26
595 countries), we applied the same equations selected for other countries, for similar FTs. Of course,
596 this may further increase the uncertainty of our estimates.

597 Attributing an overall uncertainty equal to 2% (U_A), 5% (U_V) and 3.8% (U_B) to the input data on
598 the area, the volume and the expansion of the volume to total living biomass, respectively, and
599 without considering further possible uncertainties (i.e., of the original input data reported by NFIs
600 and of singular FTs and regions), and actual correlations between NFI measured variables, the
601 overall uncertainty on the living biomass stock may be estimated as (Penman et al., 2003):

602 $$U = \sqrt{U_A^2 + U_V^2 + U_B^2} = 6.6\%$$ Eq. (4)

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The estimates on the C stock change and, indirectly on the fluxes, are affected by additional uncertainties about the amount of harvest and the amount of area affected by natural disturbances. Comparing different data sources such as NFIs or FAOSTAT data, Pilli et al. (2015) highlighted the inconsistencies of harvest statistics and the uncertainties of these data, which may vary considerably among countries. For example, the Italian NFI reports a 13.3% uncertainty on the amount of harvest, while the German NFI reports a 1.2% overall uncertainty. This also affects the uncertainty on the net-emissions associated to the HWP pool, which also depends on the initialization and on the decay rate for each wood commodity (i.e., sawnwoods, wood based panels and paper and paper board), on the relative fraction of HWP coming from domestic forests and on other sources of uncertainty (described in detail by the 2013 IPCC KP LULUCF Supplement, Hiraishi et al., 2014).

Quantifying the uncertainty of the input data for natural disturbances is even more challenging. Due to the lack of data, the uncertainty of land-use change (i.e., afforestation and deforestation), dead organic matter and soil C pools is even higher. Based on the information reported in the countries' Greenhouse Gas Inventories, for the forest land category, the uncertainty reported by the individual EU member states ranges between 15-77% for the living biomass, between 22-113% for dead organic matter and between 13-62% for mineral soils (Blujdea et al., 2015).

Due to the high number of variables and countries considered by our study, the only way to estimate the overall uncertainty would be through a Monte Carlo approach, as proposed for British Columbia by Metsaranta et al. (2010). However, this would require further data at country level. Unfortunately, much of this information is often not available or simply does not exist. The yield curves used in CBM are based on field observations, and thus some impacts of environmental changes are represented in the model. However, many of these curves are based on plot measurements over the past decades, and we therefore cannot make any assumptions about how representative the existing yield curves will be for future (2030) environmental conditions. Since CBM does not account for changes in climate, CO_2 concentration, N deposition etc., there is an additional source of uncertainty in the projections due to missing representation of processes that may lead to an increasing or decreasing trend of NPP and R_h, depending on the initial climatic conditions (Smith et al., 2016, Kurz et al., 2013).

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632 Our NPP estimates may be compared with other values reported in the literature. Ťupek et al.
633 (2010) report the NPP for 24 EU countries (Greece and Croatia were not considered by that study),
634 based on the estimates provided by four different models, for the period 2000 – 2005 (see Tab.
635 3S). Between these models, EFISCEN, i.e. an inventory-based model conceptually similar to CBM
636 (Verkerk et al., 2011), generally estimated a NPP higher than CBM for all countries except Ireland,
637 Slovenia and Spain; the average NPP estimated by this model is 17% higher than our estimate but
638 it is also combined with a higher contribution of R_h, equal on average to 72% in EFISCEN against
639 64% in CBM. ORCHIDEE, a process-oriented model, and BIOME-BGC a climate-based
640 ecosystem model, generally reported a higher NPP than CBM: on average +8% and +16%, for
641 BIOME-BGC and ORCHIDEE, respectively. JULES, i.e. a process-based surface exchange
642 scheme similar to ORCHIDEE, generally estimated a lower NPP than CBM (on average -24% at
643 EU level). Many reasons, such as the use of different data sources, different assumptions on the
644 forest area, the effect of the main natural disturbances (generally not considered by EFISCEN) and
645 silvicultural practices (generally neglected by climate-based ecosystem models) may explain these
646 differences. Looking to the standard deviation estimated by these data series, however, the average
647 NPP estimated by these models (5.54 ±1.19 Mg C ha^{-1} yr^{-1}) is not statistically different from the
648 average value estimated by CBM (5.15±1.42 Mg C ha^{-1} yr^{-1}).

649 Further studies will focus on a specific assessment of these uncertainties, but, in the meantime, to
650 overcome these limitations, we successfully validated our results at the country (for Lithuania) and
651 regional level (Pilli et al., 2014a) and against independent data sources (Pilli et al., 2016a; Pilli et
652 al., 2013).

653

654 **4. Conclusions**

655 This study provides a comprehensive analysis of the main carbon stocks and fluxes in the European
656 forest sector, including country-level details, accounting for forest land-use change, forest
657 management, carbon storage in HWP, and the effects of the main natural disturbances. In
658 comparison to two previous studies based on the same model (Pilli et al., 2016a and b), the present
659 work, quantifies in detail the C fluxes and stocks between the forest pools and with the atmosphere,
660 including NPP, NSE and R_h, up to 2030 and under different model scenarios. For the historical

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period (2000 – 2012 average), we estimated an NPP of 639 Tg C yr^{-1} for total EU forests, consistently with estimates from other studies, and a NSE of 122 Tg C yr^{-1} (i.e., about 19% of the NPP) for the whole forest system, including HWP. Compared with the historic period, the NSE in 2030 is similar (+3%), lower (-17%) and higher (+23%), when assuming a constant, increasing and decreasing scenario for both harvest and afforestation rates. In this study we did not quantify the avoided emissions from the use of wood products and fire wood, and changes in NSE may not be indicative of the overall changes in GHG balance resulting from changes in harvest rates. Increased harvest rates will reduce NSE but provide more wood products that can be used to substitute other emissions-intensive materials and fossil fuels.

For the forest area existing in 1990 (i.e., the FM area), we show a decline in the C sink, assuming a constant harvest scenario, due to increasing releases from decomposition (R_h +13%) as DOM pools increase with increasing biomass stocks. This confirms the results of earlier studies, suggesting some signs of C sink saturation in European forest biomass (Nabuurs et al. 2013). This result, however, should be combined with further analysis, accounting for the ongoing environmental changes, which could have impacts on NPP and R_h that are not represented in the inventory-based model used in this analysis (Kurz et al. 2013). The non-proportional effect of different harvest scenarios on the 2030 C sink of the FM area suggests that the overall growth of the European forests is slightly decreasing, and by increasing the harvest demand by 20%, we are approaching the maximum harvest potential of the pre-1990 forest area.

Overall, our study shows that forest management succeeds in capturing, on average, 12% of NPP, as merchantable wood components, while still allowing ecosystem C stocks to increase. At the country level, we highlighted some statistical differences, suggesting that the relationship between biomass stock and NPP cannot be assumed constant for all EU countries. Specific forest conditions, such as the harvest rate, the age structure and forest composition, may affect the country-specific evolution of biomass, dead organic matter and soil stocks.

Modelling the wide variety of forest structures and management practices in EU forest is challenging. Most of earlier studies focused on specific aspects, e.g. the impact of different policies (e.g., Böttcher et al., 2012), the effect of climate change and management on even-aged forests (Schelhaas et al., 2015), the biomass potential in relation to ecosystem services (Verkerk et al., 2011; Verkerk et al., 2014) and the effect of natural disturbances (i.e., Seidl et al., 2014). By using

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691 a flexible model, which allows to accommodate a wide variety of management practices, input
692 data requirements and natural disturbance events, we managed to explore the forest C dynamics
693 under different management scenarios with a consistent approach in 26 different countries.

694 Along with results provided by other models, the detailed picture of the C fluxes condensed in this
695 study may represent both a benchmark for similar studies and the basis for broader analyses (e.g.
696 including substitution effects of wood) on the mitigation potential of the EU forest sector.

697

5. Author contribution

699 RP carried out the data analysis, in collaboration with GG. WAK and AC helped in the design of
700 the study and the interpretation of results and together with RP and GG wrote the manuscript, in
701 collaboration with GF. All authors read and approved the final manuscript.

6. Competing interests

703 The authors declare that they have no competing interests.

7. Disclaimer

705 The views expressed are purely those of the authors and may not in any circumstances be regarded
706 as stating an official position of the European Commission or Natural Resources Canada.

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Tab. 1: Main parameters applied in the Carbon Budget Model (CBM). Detailed information are in Pilli et al. (2016a) with the exception of Bulgaria, Ireland, Poland and Romania (see the table's notes). The table reports: the National Forest Inventory (NFI) original reference year; the starting year of model application; the base Forest Management area (FM, i.e., area of the existing forests in 1990) area; the additional natural disturbance events considered in the model (F, fire; S storms and ice sleets; I insect attacks).

COUNTRY	Original NFI year	Time Step 0 (yr)	CBM FM area (Mha)[2]	Natural Disturbances
Austria	2008	1998	3.2	S + I
Belgium	1999	1999	0.7	-
Bulgaria[3]	2010	2000	3.6	S
Croatia	2006[1]	1996	2.0	F
Czech Republic	2000	2000	2.6	-
Denmark	2004	1994	0.5	S
Estonia	2000	2000	2.1	S
Finland	1999	1999	21.7	S
France	2008	1998	14.6	S
Germany	2002	1992	10.6	S
Greece	1992[1]	1992	1.2	F
Hungary	2008	1998	1.6	-
Ireland[3]	2005	1995	0.5	F
Italy	2005	1995	7.4	F
Latvia	2009	1999	3.2	S
Lithuania	2006	1996	2.0	S + F+I
Luxembourg	1999	1999	0.1	S
Netherlands	1997	1997	0.3	S
Poland[4]	2010	2000	9.1	S
Portugal	2005	1995	3.6	F
Romania[3]	2010	1990	6.3	-
Slovakia	2000	2000	1.9	S + F
Slovenia	2000	2000	1.1	S + F
Spain	2002	1992	12.6	F
Sweden	2006	1996	22.6	S
United Kingdom	1997	1997	2.5	S + F
EU			138.0	22 countries

1: analysis based on data from Forest Management Plans.
2: FM area used by CBM at time step 0 (see Pilli et al., 2016a for further details).
3: new NFI input data (directly provided by the countries) and methodological assumptions (see Pilli et al., 2016c for details) were applied for Bulgaria, Ireland and Romania, as compared to Pilli et al. 2016b.
4: new NFI input data, reported by the second NFI cycle (2010-2014, Bureau for Forest Management and Geodesy, 2015) were used for Poland, as compared to Pilli et al. 2016b.

Tab. 2: assumptions and main parameters for the model scenarios. FM: Forest Management area, i.e., area of the existing forests in 1990. AR: Afforestation and Reforestation occurred since 1990).

SCENARIOS	Area	Nat Disturbances	Harvest	Deforestation
Constant Harvest	Constant FM area – Def.	Yes, if relevant, from 2000 to 2011 + average constant fire from 2013 to 2030	Historical + Constant from 2013	Yes, historical + constant since 2013
Harvest +20%			Historical + increasing to +20% in 2030	
Harvest -20%			Historical + decreasing to -20% in 2030	
Constant AR	Historical AR rate since 1990 + Constant average AR rate 2013 - 2030	No	Maximum theoretical amount of harvest provided by AR, with constant management practices	No
AR +20%	Historical AR rate since 1990 + increasing to +20% in 2030			
AR -20%	Historical AR rate since 1990 + decreasing to -20% in 2030			

Tab. 3: assumptions and main parameters for the model scenarios, compared with figures from Luyssaert et al. (2010) and Karjalainen et al. (2003). FM: Forest Management area, i.e., area of the existing forests in 1990. AR: Afforestation and Reforestation occurred since 1990.

Comparison between		CBM (Tg C yr^{-1})	Luyssaert[a] (Tg C yr^{-1})	Karjalainen[b] (Tg C yr^{-1})
NPP	FM	620	520 ± 75	409
	AR	19	-	-
R_h	FM	403	287-527	245
	AR	6	-	-
FELLINGS		138	92 ± 16	79.5
HWP		12	5 ± 3	-
NBP FM (with HWP)	Tot	110	109	-

[a] Average for 1990-2005, EU-25
[b] Average for 1995-2005, EU-27

Tab. 4: total C sink estimated by our study for the historical period (average 2000-2012) and ~~in~~ for 2030 resulting from combining (i) different harvest scenarios (Constant, +20% and -20% in 2030, compared with the historical period) applied to the FM area with (ii) different AR scenarios (Constant, +20% and -20% in 2030, compared with the historical period). Grey cells highlight other possible scenarios, not directly considered by our study. FM: Forest Management area, i.e., area of the existing forests in 1990. AR: Afforestation and Reforestation occurred since 1990. HWP: harvested wood products.

Commented [RP24]: See specific comments from Rev 2#

C sink (Tg C yr⁻¹) \ C sink (Tg C yr⁻¹)		AR			
		Historical (avg 2000-2012)	Constant (2030)	+20% (2030)	-20% (2030)
FM (including HWP)		12	26	27	25
Historical (avg 2000-2012)	110	122			
Constant harvest (2030)	100		126	127	125
+20% harvest (2030)	74		100	101	99
-20% harvest (2030)	126		152	153	151

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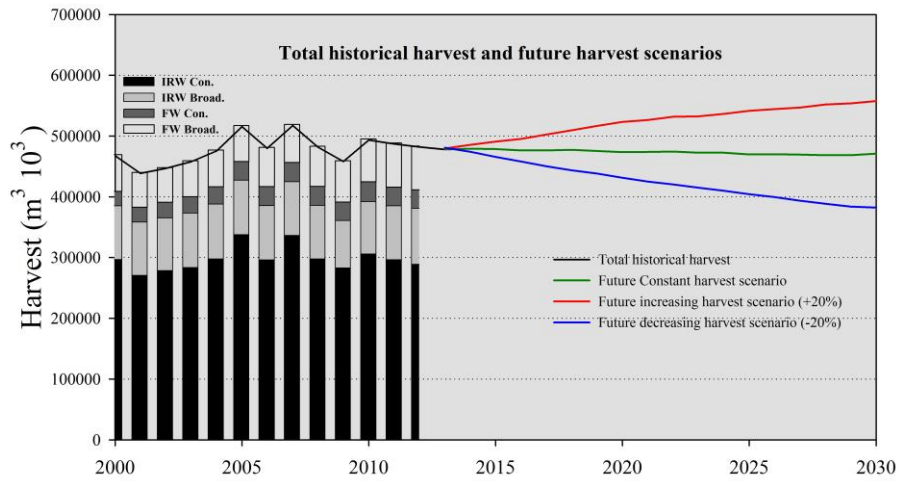
Figure 1: total harvest demand for EU26 (m^3 10^3) for the historical period (2000 – 2012) and for three future scenarios (2013 – 2030), assuming: average constant harvest, increasing harvest demand (i.e., +20% in 2030) and decreasing harvest demand (i.e., -20% in 2030). For the historical period, bars show the share of harvest distinguished between industrial roundwood (IRW) and fuelwood (FW), conifers (Con) and broadleaves (Broad). The same ratios, corrected in proportion to the total harvest demand, were applied to each future harvest scenario.
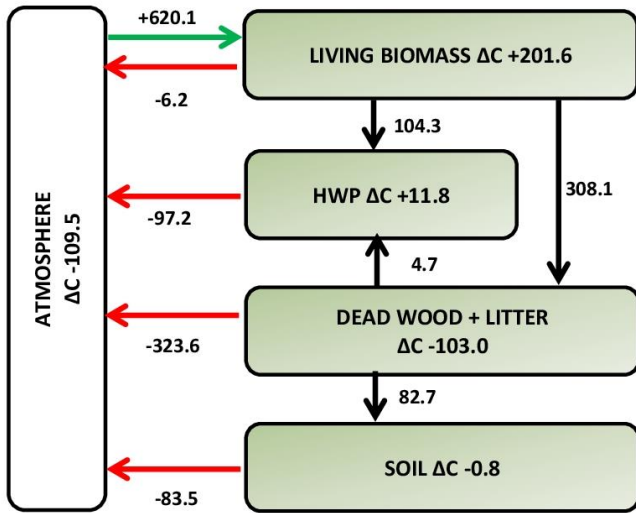
Figure 2: summary of the average C increment and transfers between forest pools and with the atmosphere for the FM area (in Tg C yr^{-1}, for the historical period 2000 – 2012). The pool increments are shown in each box as ΔC, transfers between pools are reported by black arrows and transfers from/to the atmosphere are reported by green and red arrows, respectively (with positive or negative values, reported from a forest perspective).

Commented [RP25]: As suggested by Rev 1# we added this figure and, considering the comments from Rev. 2#, we moved previous Fig 1 to the Supp. Materials

Figure 3: C fluxes for the scenarios: (i) the historical period (average values 2000 – 2012); (ii) the constant scenario (i.e., constant harvest and AR rate); (iii) the increasing scenario (i.e., +20% amount of harvest and AR rate compared to the average historical harvest and AR rate); (iv) the decreasing scenario (i.e., -20% amount of harvest and AR rate compared to the average historical harvest and AR rate). Fo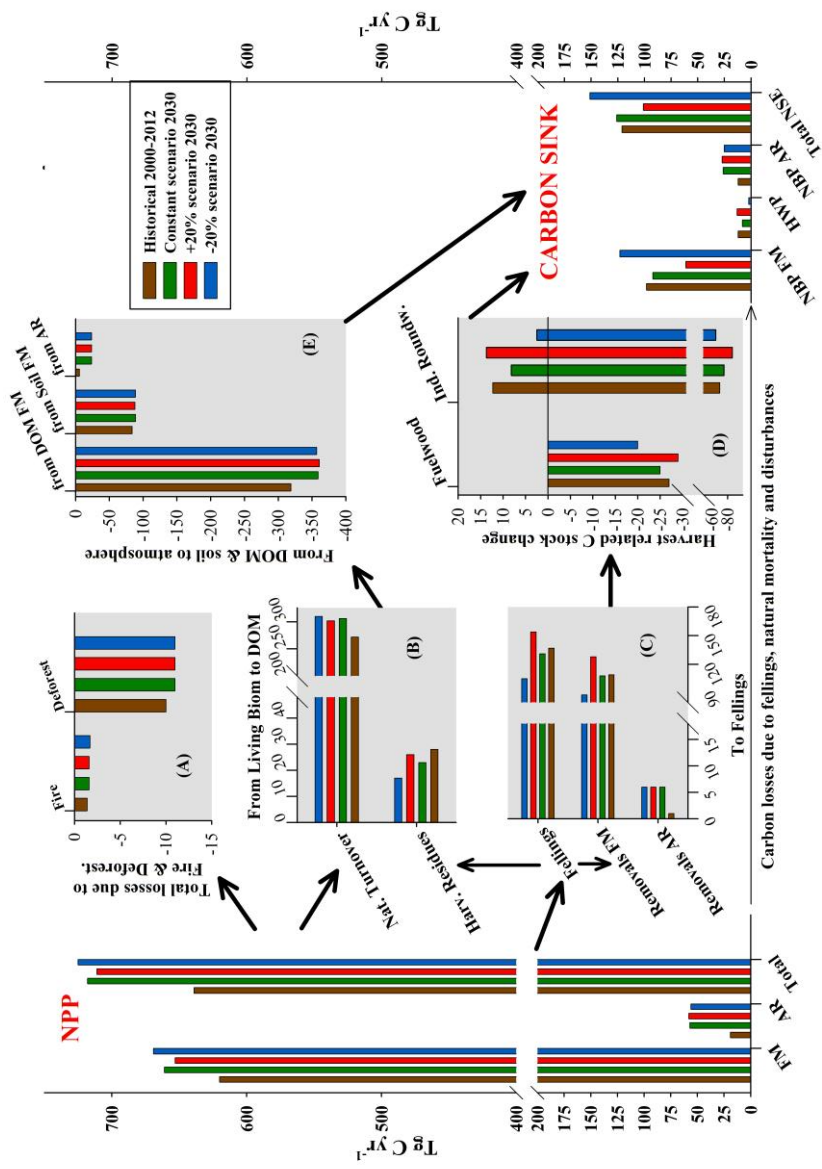r each scenario, the fluxes were further distinguished between (all values in Tg C yr^{-1}): (*NPP*) the Net Primary Production contributed by the FM area (including deforestation), AR, and total (FM+AR); (*A*) the total losses due to natural disturbances and deforestation (i.e., direct emissions to the atmosphere); (*B*) the fluxes of C from the living biomass to DOM pools (i.e., internal fluxes for the forest ecosystem), further distinguished between fluxes due to self-thinnings and to fellings (i.e., the harvest residues, equal to the difference between fellings and harvest removals); (*C*) the total fluxes of C due to fellings and the harvest C removals provided by the FM area and by different AR scenarios; (*D*) this last flux moves from the forest ecosystem to HWP and may be further distinguished between fuelwood (FW, with a direct emission to the atmosphere, reported with negative values) and industrial roundwood removals (IRW), with negative values referred to the C emissions to the atmosphere (due to the decay rate of IRW products and industrial losses) and positive values referred to the HWP C sink, estimated by Pilli et al. (2015a); (*E*) the total C emissions from DOM and soil pools to the atmosphere (for the FM area) and from the afforested area (AR, including both DOM and soil); (*CARBON SINK*) the final C sink, equal to the NPP minus the emissions reported in panels (*A + D +E*), further distinguished between FM area, HWP (i.e., IRW removals), AR and Total. Positive values refer to an input of C to the forest sector (e.g., NPP) or internal fluxes (e.g., from living biomass to DOM), negative values refer to C losses from the forest sector to the atmosphere (e.g., from DOM and soil to the atmosphere).

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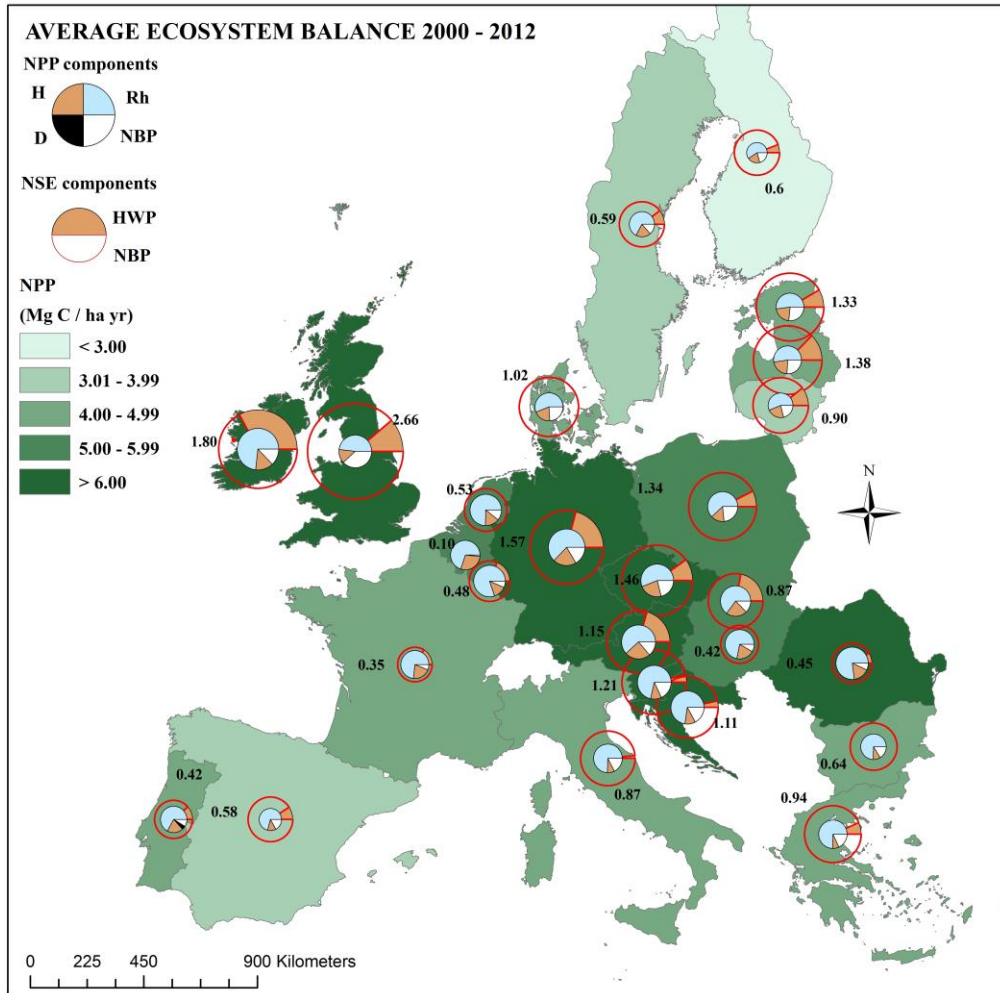
Figure 4: average ecosystem balance of the FM area for the historical period 2000 – 2012. For each country the pies of the internal circles highlight the total losses due to respiration (R_h), harvest (H) and natural disturbances (D), while the average NPP, reported by the green background (in Mg C ha^{-1} yr^{-1}) is proportional to the radius of the inner circle. The remaining white internal pie, equal to the difference between the NPP and losses, quantifies the Net Biomass Production (NBP). Adding to this amount the HWP net sink, reported by the external orange pie, we can estimate the Net Sector Exchange (NSE) reported by the black labels (in Mg C ha^{-1} yr^{-1}) and proportional to the radius of the external circle.

Legend:
- Nat Dist --> HWP
- Nat Dist-->Atmosphere
- Merch-->IRW
- Merch--> FW
- OWCs-->FW
- DOM-->FW
- Deforestation -->Atmosphere

Harvest and Natural Disturbances

Losses as percentage of total NPP

Heterotrophic respiration
- DOM --> Atmosphere
- Soil --> Atmosphere
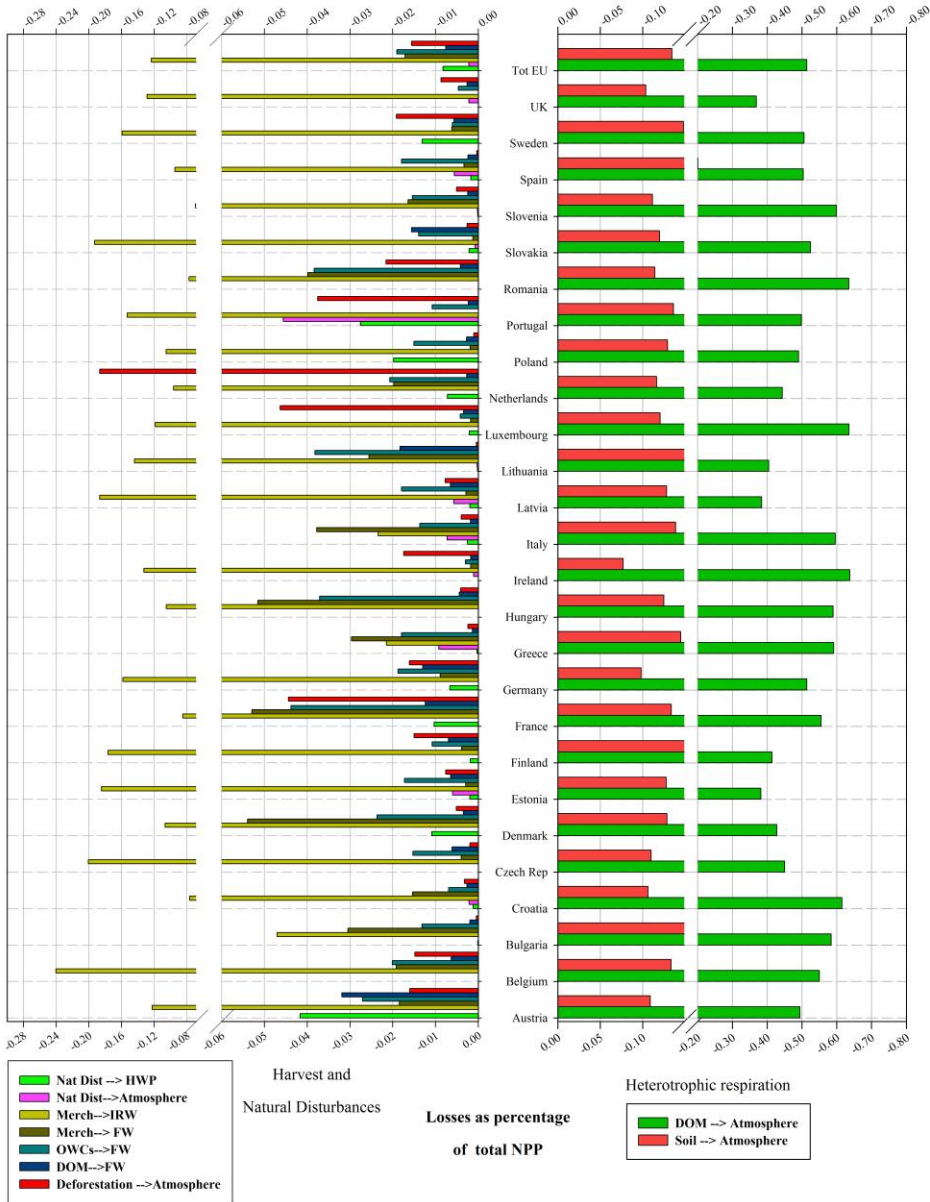
Figure 5: relative amount of C losses estimated as percentage of the total NPP due to (i) the release of C to the atmosphere for the decomposition of DOM and soil pools, on the right panel; and (ii) natural disturbances (i.e., fires), human activities (harvest) and deforestation, on the left panel. Here we report the relative share of losses due to: (i) salvage logging after natural disturbances (Nat Dist → HWP); (ii) release of C to the atmosphere due to natural disturbances

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(Nat Dist → Atmosphere); (iii) Merchantable wood used as IRW (Merch → IRW); (iv) merchantable wood used as FW (Merch → FW); (v) other wood components (i.e., branches, tops) used as FW (OWCs → FW); (vi) snags used as FW (DOM → FW); (vii) release of C to the atmosphere due to deforestation (Deforestation → Atmosphere).

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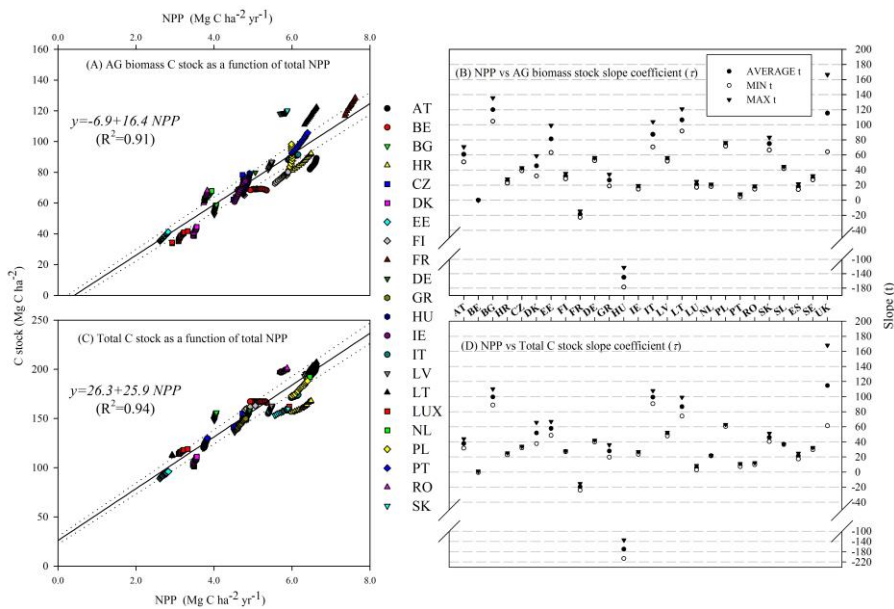
Figure 6: yearly aboveground living biomass (on panel A) and total (on panel C) C stock (Mg C ha^{-1}) as a function of total NPP (Mg C ha^{-1} yr^{-1}), for the historical period 2000 – 2012, excluding possible outliers (i.e., years with a distance greater than 3 interquartile ranges from the median (SAS Institute Inc., 1990)) due to extreme events such as exceptional disturbances. Plots B and D report, for each country, the slope ($\tau \pm 95\%$ confidence interval) of the linear regression model ($y = a + \tau x$) applied to the previous values for each country (reported on the x axis). On plots A and C, we also highlighted the regression model estimated, at EU level, including all the countries, with the corresponding equation and coefficient of regression (R^2).
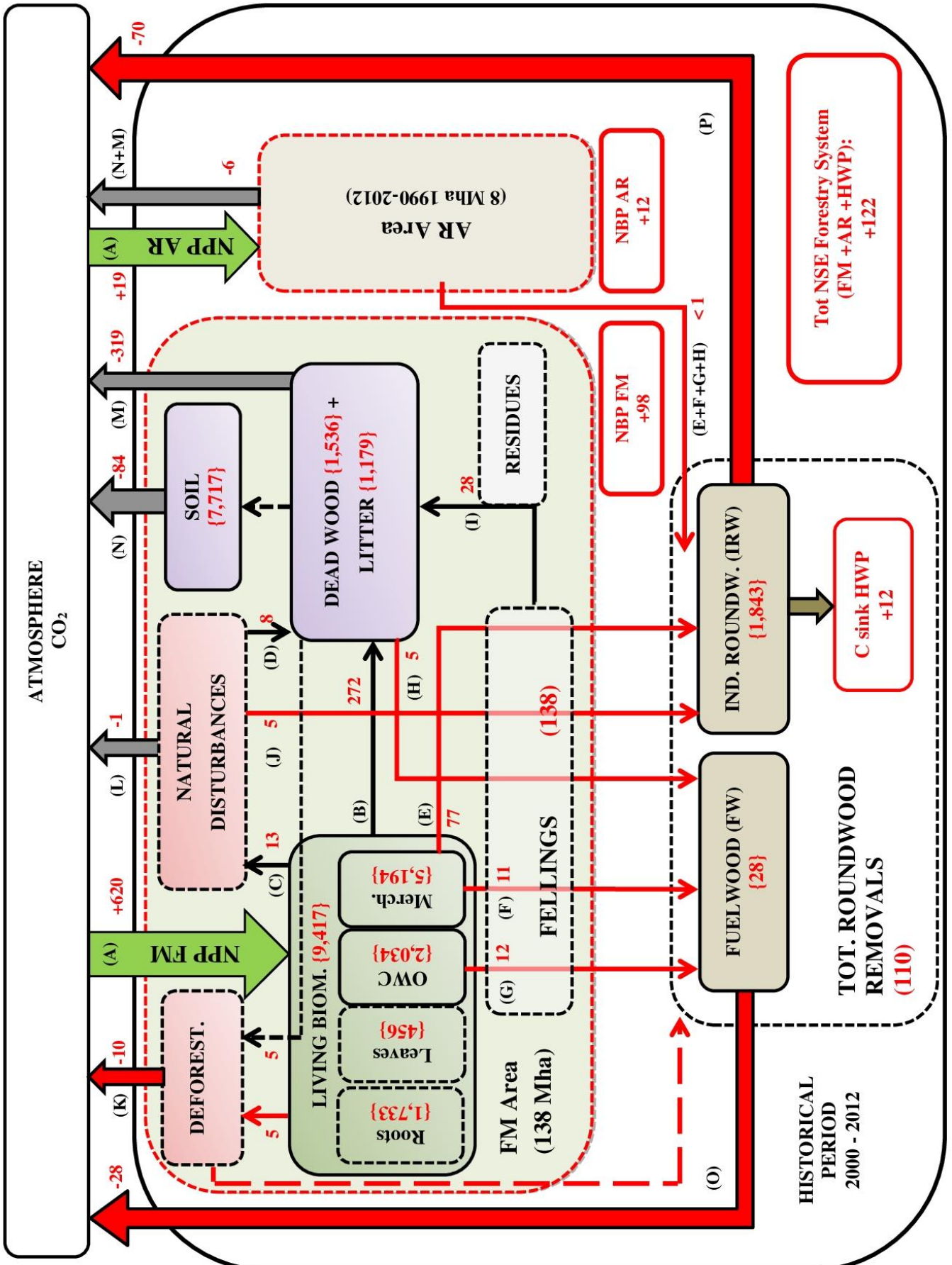
Figure 1S: Forest carbon (C) flow modelled for EU 26 by CBM for the historical period 2000 – 2012, for the forest area (further distinguished between forest management area, FM and afforestation, AR) and main links with the HWP pools, further distinguished between industrial roundwood (IRW) and fuelwood (FW). The main forest pools and fluxes in our analysis are: living biomass (LB), which includes roots, leaves, merchantable tree portion and other wood components (OWCs, branches and tops), dead wood and litter pools (DOM) and soil. C moves from the atmosphere to LB through photosynthesis (*A*) and from there to DOM (black arrows, only highlighted for the FM area) because of litterfall and natural mortality (*B*) and natural disturbance events (fires and storms, arrows *C* and *D*). Red arrows highlight the main C fluxes due to direct human activities: harvest, moves a fraction of the merchantable portion to IRW (*E*) and to FW (*F*), part of the OWCs moves to FW (*G*) and a fraction of the standing dead trees may be collected as FW (*H*). A fraction of the living biomass is left as residues that move from LB to DOM (*I*). Salvage logging (*J*) following natural disturbances moves C from the LB to IRW or FW. Deforestation releases LB and DOM C to the atmosphere (*K*) of which the LB fraction (about 50% of the total C removed by deforestation), could in the future be used as FW or IRW. Due to the lack of detailed information, this amount, highlighted by a red dotted arrow and equal as maximum to about 5 Tg C yr^{-1}, was not included in the sum of the total roundwood removals but reported in total emissions due to deforestation. Further releases are related to natural disturbances, i.e., fires (*L*), and the decay rate of DOM (*M*) and soil (*N*) pools. The C used for energy (FW) is directly released to the atmosphere (i.e, immediate oxidation, *O*) while the C stocked as IRW has a carbon retention time before being emitted to the atmosphere (*P*).

The arrows reported by the figure, such as the C stock of the main forest pools and the total amount of C moved to the IRW and FW pools (further distinguished between broadleaved and coniferous species) were quantified by our analysis (see Results section). The figure reports (inside the main boxes) the average total C stock (red numbers between parenthesis, in Tg C) estimated for EU 26, for the main FM pools (i.e., living biomass and its sub-pools); the total amount of fellings, further distinguished between roundwood removals and harvest residues; the roundwood removals used as fuelwood and industrial roundwood. The fluxes (in Tg C yr^{-1}), reported near the main arrows, are further distinguished between: (1) inputs, i.e., the Net Primary Production (NPP, highlighted by green arrows) distinguished between FM and AR area; (2) outputs (red arrows), including (i) direct C emissions from the forest to the atmosphere; (ii) harvest removals from living biomass and dead wood to the HWP pool (further distinguished between the removals used as FW and IRW) and due to the salvage logging after natural disturbances and provided by AR; (3) internal fluxes (black arrows), from the living biomass to the DOM pool, due to natural processes, to natural disturbances, and to harvest activities (i.e., residues). The total C sink referred to the FM activities (including the effect of deforestation) is equal to the sum of inputs and outputs to/from the FM area. From the total roundwood removals, further releases of C to the atmosphere are due to the direct oxidation of the wood used as FW. The indirect C emissions from the wood used as IRW were estimated as the difference between the total C stock removed as IRW and the average (2000-2012) amount of C stocked as IRW as estimated by Pilli et al., 2015.

Adding to the total C sink of FM, the IRW removals minus the releases from prior years (i.e., C sink HWP) and the C sink of the afforested area, we estimated the Net Sector Exchange (NSE) of the forest sector.

Carbon pools	Sub pools	Historical	Constant	+20%	-20%	Fluxes	Historical	Constant	+20%	-20%
	Tg C	Av 2000-12	2030	2030	2030	Tg C yr^{-1}	Av 2000-12	2030	2030	2030
Living B.		9,417	11,596	11,154	11,758	**NPP FM (*A*)**	**620**	**661**	**653**	**669**
						To DOM (*B*)	272	306	302	310
	Tot ABG	7,684	9,527	9,191	9,693	To IRW (*E*)	77	83	98	67
	Merchantable	5,194	6,594	6,402	6,762	To FW (*F*)	11	11	12	9
	OWCs	2,034	2,401	2,286	2,403	To FW (*G*)	12	12	14	9
	Leaves	456	532	503	529	To HWP (*E+F+G*)	99	105	124	85
	Roots	1,733	2,069	1,963	2,065					
DOM		2,715	2,852	2,827	2,765	To FW (*H*)	5	3	3	2
		0	0	0	0	To atm. (*M*)	319	359	361	357
	Dead wood	1,536	1,531	1,522	1,476	IRW to Atm (*P*)	70	75	85	65
	Litter	1,179	1,321	1,305	1,289		0	0	0	0
Soil		7,717	7,714	7,556	7,557	To atm. (*N*)	84	89	88	89
Harvest	**Tot Removals**	109	108	128	88	Tot HWP (*E+F+G+H+J*)	109	108	128	88
	from LB to FW	22	22	26	18	**HWP C sink**	**12**	**8**	**13**	**2**
	from LB to IRW	77	83	98	67		0	0	0	0
	from Nat.Disturb.	5	1	0	0		0	0	0	0
	from DOM	5	3	3	2		0	0	0	0
	to DOM (residues)	28	23	26	17	To DOM (*I*)	28	23	26	17
Nat Dist.						Tot Losses (*C*)	13	10	7	3
						To DOM (*D*)	8	2	2	2
						To HWP (*J*)	5	1	0	0
						To Atm. (*L*)	1	1	1	1
Deforest		10	11	11	11	To atm. (*K*)	10	11	11	11
Total Area (ha)		**136,700,054**	**134,385,853**	**134,385,853**	**134,385,853**	**C sink FM**	**98**	**92**	**61**	**123**
						C sink FM+HWP	**110**	**100**	**74**	**126**
Afforest.						**NPP AR**	19	57	58	56
						AR to Atm.	6	24	24	24
	From to	1990-2012	1990-2030	1990-2030	1990-2030	**Harvest AR**	1	6	6	6
Total Area (ha)		**8,558,909**	**11,771,101**	**12,204,450**	**11,337,160**	**C sink AR**	**12**	**26**	**27**	**25**
Total Area (ha)		**145,258,964**	**148,471,155**	**148,904,504**	**148,037,214**	**Tot. C sink (NSE)**	**122**	**126**	**101**	**151**

Tab. 1S: the table summarizes the total (i.e., referred to the total forest area) C stock (in Tg C) and the C fluxes (in Tg C yr^{-1}) estimated by CBM at the EU level for the historical period 2000 – 2012 and for 2030, under different scenarios. The letters in Italics between parentheses near the fluxes refer to the arrows reported in Figure 1S Error! Reference source not found.**. The values reported for deforestation are the average of the period 2013 – 2030, to avoid possible differences due to the random distribution of the deforested area during the model run.**

Carbon pools FM area	Sub pools	Historical	Constant	+20%	-20%	Fluxes	Historical	Constant	+20%	-20%
	Mg C ha^{-1}	Av 2000-12	2030	2030	2030	Mg C ha^{-1} yr^{-1}	Av 2000-12	2030	2030	2030
Living B.		**69.87**	**85.56**	**81.10**	**85.48**	NPP(*A*)	**4.54**	**4.84**	**4.77**	**4.90**
						To DOM (*B*)	1.99	2.24	2.21	2.27
	Tot ABG	56.21	69.69	67.23	70.91	To IRW (*E*)	0.56	0.60	0.72	0.49
	Merchantable	37.99	48.23	46.83	49.46	To FW (*F*)	0.08	0.08	0.09	0.06
	OWCs	14.88	17.56	16.72	17.58	To FW (*G*)	0.09	0.09	0.10	0.07
	Leaves	3.33	3.89	3.68	3.87					
	Roots	12.68	15.14	14.36	15.11					
DOM		**19.86**	**20.87**	**20.68**	**20.23**	To FW (*H*)	0.03	0.02	0.03	0.02
						To atm. (*M*)	2.33	2.63	2.64	2.61
	Dead wood	11.24	11.20	11.13	10.80					
	Litter	8.62	9.66	9.55	9.43					
Soil		**56.45**	56.43	55.28	55.28	To atm. (*N*)	0.61	0.65	0.65	0.65
Harvest	**Tot Removals**	**0.80**	**0.79**	**0.93**	**0.64**					
	from LB to FW	0.16	0.16	0.19	0.13					
	from LB to IRW	0.56	0.60	0.72	0.49					
	from Nat.Disturb.	0.04	0.00	0.00	0.00					
	from DOM	0.03	0.02	0.03	0.02					
	to DOM (residues)	0.20	0.16	0.19	0.13	To DOM (*I*)	0.20	0.16	0.19	0.13
Nat Dist.						Tot Losses (*C*)	0.10	0.07	0.05	0.02
						To DOM (*D*)	0.06	0.02	0.02	0.01
						To HWP (*J*)	0.04	0.00	0.00	0.00
						To Atm. (*L*)	0.01	0.01	0.01	0.01
Deforest.		0.07	0.08	0.08	0.08	To atm. (*K*)	0.07	0.08	0.08	0.08
						C sink per ha	**0.71**	**0.67**	**0.45**	**0.90**

Tab. 2S: the table summarizes the C stock (in Mg C ha^{-1}) and the C fluxes (in Mg C ha^{-1} yr^{-1}) estimated by CBM at the EU level for the FM area. The letters in Italics between parentheses near the fluxes refer to the arrows reported in Figure 1S. The values reported for deforestation are the average of the period 2013 – 2030, to avoid possible differences due to the random distribution of the deforested area during the model run.

Country	EFISCEN	BIOME-BGC	ORCHIDEE	JULES	CBM
AT	921	578	612	391	658
BE	834	672	866	529	511
BG	610	431	579	432	401
CZ	858	638	734	451	623
DK	650	600	677	467	470
EE	583	559	667	383	465
Fl	373	456	578	198	273
FR	567	538	535	504	469
DE	812	621	638	485	751
HU	617	556	802	460	508
IE	691	563	577	464	917
IT	510	401	333	437	487
LV	549	602	708	417	467
LT	556	609	719	435	378
LU	972	661	928	515	582
NL	720	622	577	497	577
PL	540	810	716	467	523
PT	344	327	192	438	426
RO	721	616	769	420	596
SK	592	649	859	433	546
SI	598	552	297	477	650
ES	210	353	296	203	314
SE	422	424	507	214	389
UK	642	518	517	447	621
Avg. ± st dev	621±178	557±109	612±185	424±90	515±142

Tab. 3S: the table compared the values reported by Ťupek et al. (2010, Table 2), based on the Net Primary Production (NPP, in g C m^2 yr^{-1}) estimated by four different models (EFISCEN, BIOME-BGC, ORCHIDEE and JULES) with the estimates provided by our study (CBM).