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The European forest sector: past and future carbon budget and fluxes under different management scenarios

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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 quantified 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 the main C fluxes as affected by land-use changes, natural disturbances and forest management and to asses 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 fellings (110 Tg C yr^{-1} due to removals), 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 dead organic matter pools. The average annual forest Net Sector Exchange (NSE), i.e. the carbon stock changes in the forest pools plus HWP, equals 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 for the forests existing in 1990: despite the NPP is still increasing (+7%) the greater increase of heterotrophic respiration (+13%) leads to a decrease of the sink in the forest pools (- 6%) in 2030 compared to the historical period.

The detailed picture of the C fluxes within the EU forest sector condensed in this study, and their evolution under different harvest scenarios, provide a useful framework for more detailed future analyses (spatially or temporally) on the mitigation potential of the forest sector. Overall, our study confirms that, in the majority of European countries, the build-up of biomass stocks results from woody NPP exceeding losses by timber harvest and natural disturbances. However, at the country level, we highlighted some statistical differences, suggesting that this relationship cannot be assumed as constant for all European countries. Specific forest conditions, such as the harvest rate, the current age structure and forest composition, may have a different impact on the country-specific evolution of biomass stocks.

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

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 the purpose of 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 referred to 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 national forest inventories (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).

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

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

1. Material and Methods

1.1. The Carbon Budget Model (CBM-CFS3) and NFI input data

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

[Tab. 1]

The spatial framework applied by the CBM conceptually follows IPCC Reporting Method 1 (Kurz et al., 2009) 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, and 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 defined: (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. Due to the lack of country-specific information, in a few cases, some of these parameters were obtained either from the literature or assuming the 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 (a summary is reported in Tab. 1), including storms and ice, fires and bark beetle attacks. Specific information on the assumptions on natural disturbances are reported by Pilli et al., 2016a and 2016c.

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 (Rh) or net biome production (NBP). Afforestation and deforestation can be represented as disturbance types with their own disturbance matrices and transitions to and from forest land.

The total forest area reported in the NFIs was scaled to the forest management (FM) area of the existing forests in 1990 (see Pilli et al., 2016a for further details). This area was further 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 (varies by country, 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).

Afforestation and reforestation (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 amount of AR per year was distributed between different FTs, according to the proportional amount of the FM area.

1.2. Harvest demand and forest flow

Figure 1 shows the general carbon flow in the European forest sector (i.e., including FM and HWP). Carbon enters the forest as CO_2 absorbed from the atmosphere by living biomass (LB); a fraction of this biomass returns to the atmosphere (through natural disturbances such as fires and storms) or moves to the other forest pools (dead wood and litter) through natural mortality and disturbance events. From these pools, C can be directly released to the atmosphere or transferred to the soil pool where some of it can reside for centuries. All these ecosystem carbon fluxes are modeled by CBM with a semi-empirical approach (Kurz et al., 2009).

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

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

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

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

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

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

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

[Figure 1]

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

The EU-26 total past and three alternative future harvest demands considered in this study are shown in Figure 2. For each country, the total harvest was further distinguished between four compartments providing the total amount of wood expected each year: IRW conifers, IRW broadleaves, FW conifers and FW broadleaves. For each compartment we defined: (i) the FTs (i.e., broadleaved species for IRW and FW broadleaves, and coniferous species for IRW and FW conifers), (ii) the MTs (for example coppices for FW broadleaves) and (iii) the silvicultural practices (for example thinnings for FW conifers). Original values of harvest demand expressed as cubic meter were converted to tons of C using species-specific wood densities values and a constant C fraction equal to 0.50 (Penman et al., 2003). A further distribution between FTs and MTs associated to the same compartment was based on the total stock of aboveground biomass available at the beginning of the model run. The C annually stocked as harvested wood products (i.e., IRW) was directly derived by the estimates provided by Pilli et al., 2015, based on the same input data used in this study.

During the model run we also quantified the amount of FW provided by branches and other wood components such as the amount of residues moved from the LB to the dead wood pool (see Figure 1). A fraction of the LB due to the deforestation could be also used as FW or IRW, but due to the lack of detailed information on this potential use, this amount was accounted into the sum of the total roundwood removals.

Three harvest scenarios were explored from 2013 onward (combined with the FM area and the deforestation activities): (i) a constant harvest scenario based on the average historical harvest (2000 – 2012) up to 2030; (ii) an increasing harvest scenario, based on a 20% increase to the 2030 constant harvest demand and a linear interpolation between 2013 and 2030; (iii) a decreasing harvest scenario, based on a 20% decrease to the 2030 constant harvest demand and a linear interpolation between 2013 and 2030 (Figure 2). For each future harvest scenario, we distributed the total harvest demand between the four compartments (i.e., IRW and FW, Con and Broad.), assuming the same proportions as in the historical period, i.e, about 62% of the total harvest was used as IRW coming from coniferous species, 19% was used as IRW coming from broadleaved species, 6% was used as FW coming from coniferous species and 13% was used as FW coming from broadleaved species.

[Figure 2]

We assumed that the harvest demand was entirely provided by the FM area, excluding the possible amount of harvest provided by deforestation. For AR we estimated the maximum potential (and theoretical) amount of harvest provided by afforested areas, assuming a common set of silvicultural practices for all the countries, with a single 15% commercial thinning applied to broadleaved forests 15-years or older and a single 20% commercial thinning applied to coniferous forests 20-years or older (Pilli et al., 2014b).

Tab. 2 summarizes all the assumptions on (i) the forest area, assumed as constant FM area minus the annual rate of deforestation; (ii) the effect of natural disturbances, concentrated on the FM area; (iii) the harvest demand, based on FAOSTAT statistics and concentrated on the FM area. After 2012, we applied a constant average annual rate of deforestation to the FM area combined with three different harvest scenarios (i.e., constant average, +20% and -20%); for AR, we considered three different annual rates of AR (i.e., constant average, +20% and -20%), and we estimated for each scenario the maximum theoretical amount of harvest potentially provided by the AR area, assuming constant silvicultural practices.

[Tab. 2]

2. Results and discussion

2.1. Carbon balance at EU level

Figure 1 (see red numbers) summarizes the historical (2000 – 2012) C fluxes modelled by CBM at EU level, for the forest area existing in 1990 (i.e., the FM area), for the area afforested from 1990 to 2012 (AR), and for the HWP pool (additional data are reported in Tab. 1S in the Supplementary Materials). 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, 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)

The main fluxes modelled in our study (arrows in Figure 1) are: (1) inputs of C from the atmosphere (i.e., NPP) to the forest ecosystem distinguished between the areas of FM and AR; (2) outputs due to direct C emissions from the forest to the atmosphere and due to harvest activities; (3) internal fluxes (not affecting the total C balance), mainly from the living biomass to the DOM pool.

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 (R_h) amounts to 403 Tg C yr^{-1} mainly due to 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} and are consistent with the emissions reported by the countries to the UNFCCC (2014, KP CRF tables, see Pilli et al., 2015b and c for further details). Other losses from biomass pools are related to fellings (about 138 Tg C yr^{-1}) and can be distinguished between wood removals (110 Tg C yr^{-1}) and transfers of biomass residues to DOM pools, (28 Tg C yr^{-1}), which will decay over time. A consistent fraction (about 20%) of the fellings are used as fuelwood and thus its C content is directly released to the atmosphere (as suggested by the 2013 IPCC KP LULUCF Supplement, we assumed the instantaneous oxidation of the amount of harvest used as FW, Hiraishi et al., 2014). The remaining industrial roundwood component can be further distinguished between the C annually stocked as harvested wood products (12 Tg C yr^{-1} based on the estimates provided by Pilli et al., 2015) and the C released to the atmosphere due to decomposition (70 Tg C yr^{-1}).

We compare our results with figures from the literature (Table 3). Luyssaert et al. (2010) analyzed the results of different methodologies for EU-25 during 1990-2005 and estimated an average annual NPP lower than our estimates (520 ± 75 Tg C yr^{-1}). Karjalainen et al. (2003), estimated an average NPP equal to 409 Tg C yr^{-1}, for 27 EU countries during 1995-2000. The average R_h estimated with CBM is considerably higher than the figure in Karjalainen et al. (2003), but is in the range of values reported in Luyssaert et al. (2010). The total emissions from harvested wood products reported by Luyssaert et al. (2010), equal to 87±16 Tg C yr^{-1}, is similar to our estimate, but, applying the IPCC Tier 2 approach (Hiraishi et al., 2014; Pilli et al., 2015) we estimated a larger C sink for the HWP pool, equal to 12 Tg C yr^{-1}, and to 5 ± 3 Tg C yr^{-1} in Luyssaert et al. (2010). The net-emissions from HWP estimated in our study at the country and EU levels are consistent with the historical (i.e., until 2009) net-emissions reported by Rüter (2011).

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

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Taking into account all these fluxes, we estimated a total NBP equal to 98 Tg C yr^{-1} and 12 Tg C yr^{-1} for the FM area and the afforested area (146 M ha in total), respectively. Adding to these NPB estimates the C stock increases in the HWP pool we estimate a Net Sector Exchange (NSE, Karjalainen et al., 2003) for the total forest sector of 122 Tg C yr^{-1}, Luyssaert et al. (2010) reported a NBP value of 109 ± 30 Tg C yr^{-1} which is similar to our estimate of 110 Tg C yr^{-1} for the FM area.

[Tab. 3]

Results are summarized in Figure **3** where we compare the historical fluxes (2000–2012) with the future scenarios of harvest and AR. In 2030, the NPP of the FM area increases from 620 Tg C yr^{-1} (average 2000 – 2012) to 661 Tg C yr^{-1} (i.e., +6%), 653 Tg C yr^{-1} (+5%) and 669 Tg C yr^{-1} (+8%), assuming a constant, increasing and decreasing harvest scenario, respectively.

In 2030 the area of lands afforested since 1990 contributes about 39 Tg C yr^{-1} more to the NPP than the average of the period 1990 to 2012 and NBP increases from 12 Tg C yr^{-1} (average 2000 – 2012) to about 26 Tg C yr^{-1} in 2030 for all the AR scenarios. As expected, in 2030, the decreasing harvest scenario (combined with a decreasing AR rate) has the highest total NBP (FM+AR), equal to 151 Tg C yr^{-1}. (see Carbon Sink, in Figure 3).

[Figure 3]

The natural turnover rate (panel B) and the emissions to the atmosphere in 2030 (panel E) for all scenarios are higher than the average historical turnover rate (equal to 272 Tg C yr^{-1} for DOM). This is due to the fact that the forest living biomass and DOM stocks are increasing from 2013 to 2030, under all harvest scenarios because the average age of forests continues to increase even under the higher harvest scenario (see Figure 1S).

Further losses of C (panel A) are due to fires (on average, about 1 Tg C yr^{-1} for all our scenarios, 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 total NPP in 2030).

The total amount of harvest removals from the FM area (panel C) varies among the harvest scenarios and equals (in 2030) 108 Tg C yr^{-1}, 128 Tg C yr^{-1} and 88 Tg C yr^{-1} for the constant, increasing and decreasing harvest scenarios, respectively.

The harvest removals can be further distinguished between the amount of harvest used as FW and as IRW (panel D). Using the approach of the 2013 IPCC KP LULUCF Supplement (Hiraishi et al., 2014), we estimated a direct emission of C from the FW harvest, equal to 26 Tg C yr^{-1}, 29 Tg C yr^{-1} and 20 Tg C yr^{-1} for the constant, increasing and decreasing harvest scenarios, respectively. These emissions represent about 4% of the total NPP. The C transferred to IRW can be further partitioned into the amount of C stocked as HWP and the amount released to the atmosphere due to the decay of these products (Hiraishi et al., 2014). The C stock increase of the HWP pool under different future harvest scenarios is reported on the positive y-axis of Figure 3 (panel D). The IRW emissions vary in proportion to the different harvest rates, and represent about 11% of the total NPP. In contrast, the IRW C sink, equal to 12 Tg C yr^{-1} for the historical period, decreases assuming a constant (8 Tg C yr^{-1}) or a decreasing (2 Tg C yr^{-1}) harvest scenario. When we assume an increasing harvest, the HWP C sink in 2030 increases slightly from 12 to 13 Tg C yr^{-1}.

Subtracting from the initial NPP the emissions due to the natural turnover rate (panel E), natural disturbances and deforestation (panel A) and fellings (panel D), we can estimate the final C sink of (i) the FM area (including the effect of deforestation), (ii) the HWP pool (stored outside the forest), (iii) the AR that occurred until 2030 and (iv) the total forest sector sink. Under different harvest assumptions the C sink of the FM area (excluding HWP) varies from 98 Tg C yr^{-1} for the historical period, to 92 Tg C yr^{-1}, 61 Tg C yr^{-1} and 123 Tg C yr^{-1} assuming a constant, increasing and decreasing harvest scenario. This means that, even maintaining a constant harvest rate from 2013 to 2030, the final NBP of forests existing in 1990 decreases by 6% in 2030, compared with the historical period. Increasing the harvest demand by 20%, the NBP decreases by 37% in 2030, but in all cases the NBP estimates quantify a C sink. Only when the harvest demand decreases will the NBP increase by 25%. The declining C sink estimated in the constant harvest scenario, is the results of an increasing NPP (+7%, if compared with the historical period, see Tab. 1S for details), combined, but with an opposite effect, with an increasing natural turnover and consequent emissions from DOM pools to the atmosphere (+13%). 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).

Overall, for the historical period, the NBP of the FM area equals 16% of the NPP (i.e., the input to the forests). This means that about 84% of the NPP is lost due to natural and human activities.

In 2030, the proportion of NBP in NPP varies considerably: from 9%, for the increasing harvest scenario, to 18%, for the decreasing harvest scenario. Since a fraction of the NPP is still stocked in the HWP products, adding this amount to the FM NBP we can estimate the total C sink, i.e., the Net Sector Exchange. In this case, the NSE increases to 110 Tg C yr^{-1} (i.e., about 18% of the NPP) for the historical period 2000 – 2012. This value is considerably higher than the NSE reported by Karjalainen et al. (2003), equal to 87 Tg C yr^{-1}, but for a lower area (128 Mha compared to 138 Mha) and a slightly different period (1995 – 2000). In 2030, the NSE varies from 100 Tg C yr^{-1} to 74 Tg C yr^{-1} and 126 Tg C yr^{-1} assuming a constant, increasing and decreasing harvest scenarios, respectively (excluding AR). This means that:

(a) Reducing the harvest by 20%, increases the NSE 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) In the constant harvest scenario the NSE decreases by 9% compared to the historical period and the ratio with NPP decreases to 15%.

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

The FW amount varies proportionally to the different harvest scenarios, according to the historical data 2000 – 2012. Therefore, reducing the harvest by 20% will decrease the energy potential of the FW proportionally and, vice versa, increasing the harvest by 20% will increase the energy potential of the FW.

Several studies suggest a significant increase in harvest removals at EU level for the next few decades, mainly due to increasing wood demand for renewable energy production, i.e., the FW demand (Mantau et al., 2010; UN, UNECE, FAO, 2011; EC, 2013). The EU Reference Scenario 2016 (EC, 2016) anticipated a harvest increase of 9% in 2030 compared to 2005, with a share of wood removed for energy production increasing from 18% in 2005 to 28% in 2030. According to the same study, because of an ageing process of managed forests, this would result in a 30% decline of the forest C sink in 2030, compared to 2005. In our study, increasing the harvest by 20% resulted in a slightly larger reduction of the C sink, equal to about 38%. Since, in the increased harvest scenario, the HWP C sink equals 13 Tg C yr^{-1}, reducing the share of IRW, further increases in the FW production, would also further reduce the total C sink.

The average annual NBP on lands afforested from 1990 to 2012 is equal to 12 Tg C yr^{-1}, i.e., about 62% of the AR NPP. Assuming different afforestation rates from 2012 to 2030, the final NBP in 2030 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 AR rate, respectively (Table 3). Compared with the historical period, the ratio between NPP and NBP considerably decreases, to about 46%, because the potential amount of harvest on AR lands increases from 1 Tg C yr^{-1} for the historical period, to about 6 Tg C yr^{-1} in 2030 for all three AR scenarios. While the amount of wood available for harvest until 2012 is negligible (because of the young age of the new forests established since 1990), in 2030, the potential amount of harvest from AR increases, but even then can only provide less than 6% of the total EU harvest. In our study, we assumed that this amount was mainly used as FW, i.e., the C was immediately oxidized.

A further potential amount of harvest, eventually used as FW or IRW, can be provided by the biomass removed from deforested areas, equal on average to about 5 Tg C yr^{-1} for the historical period. Due to the lack of detailed information on this use, this amount, equal to about 20 M m^3 yr^{-1} (i.e., about 4% of the average amount of harvest from 2000 to 2012), was quantified but not accounted in the sum of the total roundwood removals and included in the total emissions due to deforestation (see Fig. 1).

Adding to the previous estimates the C sink related to AR, the total NSE of the forest system in 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 AR rate), increasing and decreasing scenario (see Table 1S). Compared with the historical period (with a total NSE equal to 122 Tg C yr^{-1}) these values are slightly higher (+3%), lower (-17%) and higher (+23%), for the constant, increasing and decreasing harvest and AR scenarios, respectively. Looking at the constant harvest and AR scenarios, these results suggest that the decreasing C sink detected on the FM area is partly compensated by the increasing C sink on the afforested area. These results are based on the assumption that the highest harvest demand is combined with an increasing AR rate, and vice versa. Different combinations of harvest and AR rate however may also be possible (see the Tab. 4) but, excluding the FW energy potential, the maximum C sink is always linked to a reduction of the amount of harvest provided by FM and the minimum C sink to an increasing harvest scenario. Of course, different assumptions about the share of FW and IRW, a detailed analysis of the FW mitigation potential and of the substitution of other materials with wood products (Sathre and O'Connor, 2010, Lemprière et al., 2013, Smyth et al., 2014), not considered by our study, may yield different results.

[Tab. 4]

2.2. Carbon balance at country level

Figure 4 reports, for each country, the average forest ecosystem balance estimated by CBM for the FM area, for the historical period 2000 – 2012. The NPP (reported by the green background on Figure 4) varies between about 2.7 Mg C ha^{-1} yr^{-1} estimated for Finland to about 9.4 Mg C ha^{-1} yr^{-1} estimated for Ireland, and at EU level it is equal on average to 4.5 Mg C ha^{-1} yr^{-1}. The lower values estimated for Finland and Spain (3.1 Mg C ha^{-1} yr^{-1}) are probably due to specific climatic constrains, that limit the growing season in northern Europe and in the Mediterranean area (Jarvis and Linder, 2000; Kramer et al., 2000). For Ireland, the high estimated NPP is probably due to the favourable climate as well as the use of intensive silviculture and fast growing species, such as Sitka spruce (Ireland, 2014).

The total losses due to natural processes, such as the decomposition of organic matter, fires and human activities (i.e., harvest, orange slice of each external pie in Figure 4) vary between -2.2 Mg 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 expected, these losses vary proportionally to the absolute NPP value, and on average the total losses amount to about 83% of the NPP. The highest proportion of losses was estimated for Belgium (>95% of the NPP) and the lowest proportion for the UK (<70% of the NPP).

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

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

[Figure 4]

[Figure 5]

In Figure 5 we distinguished the relative amount of C losses due to 9 different processes, including natural (i.e., fires and release of C due to the decomposition of DOM and soil pools) and human factors (i.e., harvest activities). The largest release of C to the atmosphere from the forest ecosystem is due to the natural decomposition of dead wood and litter pools (i.e., DOM → atmosphere). In all the countries, this factor covers at least 50% of the total losses and at EU level equals 60% of the total losses.

The second factor contributing to the total absolute amount of losses is generally represented by a human activity, i.e., the use of the merchantable wood components as industrial roundwood. Unlike the previous factor, the relative contribution of this factor varies considerably among countries. In some cases, this may represent about 25% of the total losses (i.e., Belgium, Czech Republic, Estonia and Latvia) but in other countries this share may be less than 10% (i.e., Bulgaria, Romania, Croatia, Greece, Italy and Slovenia). At the EU level, merchantable wood use represents about 15% of the total loss of C from the forest.

Releases of C from soil to the atmosphere represent the third factor contributing to the total losses (on average 15% of the total). These losses vary between less than 15% (in 14 countries) to more than 20% (estimated for Spain and Finland). Of course, due to the lack of data, and similarly to other soil models (UN, UNECE-FAO, 2011), the results provided by CBM may be influenced by uncertainty in the model initialization that may directly affect the estimate of the C stock change on this pool (Kurz et al., 2009; Pilli et al., 2013).

For all EU countries, further losses are due to the use of wood for energy. While the IRW is generally provided by the merchantable wood components (or, in some cases, by salvage logging after storms), based on our assumptions (see Figure 1), the FW may be provided through three different sources of materials: merchantable components (e.g., from coppices or early thinnings), other wood components (mainly branches harvested simultaneously with merchantable wood used as IRW) or standing dead trees (i.e., snags, even as salvage logging after fires). The relative share of these three sources varies considerably among countries but it is generally < 10% of the total losses. In few countries, the total losses due to the use of wood for energy exceeds 10% (Denmark, France, Hungary and Lithuania), but at the EU level equals, on average, 5%.

The total losses due to natural disturbances were only accounted for in 22 countries, while 4 countries do not report relevant disturbance events. At the EU level, for the historical period 2000 – 2012, these represent about 1% of the total losses from the forest ecosystem. In some countries, however, this percentage may represent, on average, more than 5% of the total losses. This is the case of Austria, due to the effect of storms and insect attacks, and Portugal due to fires. Natural disturbances may cause direct losses, due to the biomass and dead organic matter burned by fires (i.e., a direct emission of C to the atmosphere) or indirect losses from the forest ecosystem, due to the salvage of logging residues, after the disturbance events or the decay of biomass that was killed during the natural disturbance and transferred to the DOM pools (Pilli et al., 2016b).

We also report the relative amount of losses due to deforestation on the FM area. At the EU level, deforestation represents about 2% of the total losses and, for the majority of the countries, deforestation is less than <1%. In a few cases, however, due to the relative large amount of deforestation reported by some countries compared with the total FM area (based on the KP CRF tables, 2014), the deforestation losses may be higher than 5% (France and Luxemburg) or even equal to 21% of the total losses, for the Netherlands. This country reports an annual rate of deforestation equal to 2,000 ha yr^{-1} (KP CRF, 2014), i.e., about 6% of the FM area.

2.3. Carbon turnover time

Overall, our study confirms that, in the majority of European countries, the build-up of biomass stocks results from woody NPP exceeding losses by harvest and natural disturbances, as highlighted by Ciais et al. (2008). While some estimate biomass carbon stocks as a function of NPP minus removals by harvest, this simplified assumption does not take into account the effect of deforestation and other natural disturbances. Some authors highlighted the long-time historical evolution (about 50 years) of this relationship at the EU level, assuming that the slope of the regression line between carbon stocks and NPP was similar between different countries (Ciais et al., 2008; Luyssaert et al., 2010). However, looking at this relationship at the country level, our study shows some interesting differences, even considering a shorter historical period (i.e., 2000 – 2012). The relation between biomass (*y*) and NPP (*x*) can be described by a simple linear model: $y = a + \tau * x$, where τ represents the evolution of the dependent variable as a function of the NPP and the time that carbon resides in the forest system, i.e. the turnover time (in yr., as described by Carvalhais et al., 2014). Through a statistical analysis (SAS®), we can estimate both *a* and τ (and their ±95% confidence intervals) at the country level, considering both the aboveground living biomass and the total standing stock (including living biomass, DOM and soil). Looking to the living biomass (Figure 6, panel A and B), we can identify at least three groups of countries and turnover times: the largest group includes 20 countries with τ between 5 and 70 yrs. (for the majority of these countries, $20 \leq \tau \leq 50$, with no statistical difference). All these countries have both an increasing NPP and biomass stock from 2000 to 2012, such as an increasing turnover time during the same period. For three countries (Italy, Lithuania and UK) we estimated a turnover rate > 70, statistically different from the previous group. For Belgium, France and Hungary, the turnover time <5 yrs (and generally negative) highlights the countries where we detected a decreasing NPP (and even a decreasing biomass against time, in case of Belgium) and a quite constant turnover time from 2000 to 2012. As expected, the turnover time estimated on the total C stock is on average 16% higher than the previous one (Figure 6, panel C and D). For the Mediterranean countries, where the climatic conditions and the effect of fires may reduce the turnover time of the dead wood and litter pool and for few other countries (i.e., Denmark and Ireland, due to the young age structure) the turnover time of the total biomass is lower than the previous one. For 17 out of 25 countries (for Belgium the analysis was not significant), τ was between 10 and 80 years and in two cases it was again <0. Due to the effect of management practices and natural turnover rate (i.e., self-thinnings), the average turnover time estimated for the living biomass, equal to 16.4 yrs (±0.6 yrs) is significantly lower than the average turnover time estimated for the total stock (25.9±0.8 yrs). This last value is consistent with the overall mean global turnover rate estimated by Carvalhais et al. (2014), equal to23^{+7}_{-4} yrs. and with other estimates reported by the same authors. Despite the similarities identified for many countries, we highlighted some statistical difference of the turnover time, suggesting that contrary to the assumptions by Ciais et al., 2008 and Luyssaert et al., 2010 this relationship cannot be assumed as a constant for all the European countries. Country-specific forest conditions related to management practices, harvest rates, past age structures and forest composition, have varying impacts on the evolution of biomass stock and NPP. Particularly, the turnover time estimated for the living biomass seems to be related to the age structure and to the management practices applied at the country level. Indeed, countries with older forests (such as UK) and longer rotation lengths applied to clearcuts, have the highest τ (>80 yrs). This is, for example, the case in Italy where clearcuts are often replaced by other silvicultural practices such as thinnings and partial cuts, and a large amount of the forest area (mainly coppices) is aging because of a relative low harvest demand (Pilli et al., 2013). An increasing harvest demand, generally combined with a larger use of final cuts and shorter rotation lengths, gradually reduces the turnover time and the average age of the forests. Moreover, exceptional natural disturbances, such as windstorms or fires may further modify this parameter. Due to the complex interaction between these variables, further analyses are needed.

[Figure 6]

2.4. Uncertainties

Quantifying the overall uncertainty of these estimates is challenging because of the complexity of our analysis. Indeed, the overall estimate, at the EU level, is obtained by summing up 26 estimates provided at the country level. For each country, the C stock of each pool is obtained by multiplying the area of each age class (further distinguished between different FTs and administrative unit) with the corresponding volume and by applying a species-specific equation to convert the merchantable volume to total aboveground biomass (used as a biomass expansion factor). Therefore we should first consider the uncertainty related to the area, the volume and the equation applied to each FT.

The uncertainty of the area estimates varies among countries. Generally, the information from east European countries may have a higher uncertainty because of low updating frequency or heterogeneous data sources (e.g. for forest in Romania, Blujdea, pers. com.), while the most recent NFIs have lower uncertainty (e.g., <1%, at the country level, e.g. for Germany or Italy). Considering that the average reference year of the NFIs applied by our analysis is 2003 (see Tab. 1) we may assume that the uncertainty of the area (at the country level) is equal to 2%.

The volume reported by the yield tables applied by CBM derives from a linear interpolation of the volume and increment data reported by each NFI. The uncertainty on these data (when reported) may vary considerably, depending on the relative abundance of each FT (i.e., by the number of plots) but, based on an overview of the NFIs applied by our analysis, we may assume that it is equal to 5% (in most cases, however, the uncertainty estimate is missing).

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

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

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

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

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 percentage uncertainty equal to 13.3% on the amount of harvest, while the German NFI reports an overall uncertainty equal to 1.2%. 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 of our estimates would be through a Monte Carlo approach, as was proposed by Metsaranta et al. (2010) for British Columbia. However, this would require further data at the country level. Unfortunately, many of this information is often not available or simply does not exist (in particular for the historical period). Finally, 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 Rh, depending by the initial climatic conditions (Smith et al., 2016, Kurz et al., 2013).

Our estimates of NPP may be compared with other values reported in the literature. Ťupek et al. (2010) report the NPP for 24 EU countries (Greece and Croatia were not considered by that study), based on the estimates provided by four different models, considering the period 2000 – 2005 (see Tab. 3S). Between these models, EFISCEN, i.e. an inventory-based model conceptually similar to CBM (Verkerk et al., 2011), generally estimated a higher NPP than CBM for all the countries except Ireland, Slovenia and Spain; the average NPP estimated by this model is 17% higher than our estimate but it is also combined with a higher contribution of R_h, equal on average to 72% in EFISCEN against 64% in CBM. BIOME-BGC and ORCHIDEE, both climate-based ecosystem models, generally reported a higher NPP than CBM: on average +8% and +16%, for BIOME-BGC and ORCHIDEE, respectively. JULES, i.e. a process-based surface exchange scheme, generally estimated a lower NPP than CBM (on average -24% at EU level). Many reasons, such as the use of different data sources, different assumptions on the forest area, the effect of the main natural disturbances (generally not considered by EFISCEN) and silvicultural practices (generally

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neglected by climate-based ecosystem models) may explain these differences. Looking to the standard deviation estimated by these data series, however, the average NPP estimated by these models (5.54 ±1.19 Mg C ha^2 yr^{-1}) is not statistically different from the average value estimated by CBM (5.15±1.42 Mg C ha^2 yr^{-1}).

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

3. Conclusions

This study provides a comprehensive analysis of the main carbon stocks and fluxes in the European forest sector, including country-level details, accounting for forest land-use change, forest management, carbon storage in HWP, and the effects of the main natural disturbances.

The total average NPP of forests and lands afforested since 1990 estimated at the EU level for the historical period (2000 – 2012) was equal to 639 Tg C yr^{-1} and is consistent with the estimates provided by other studies. The losses are dominated by heterotrophic respiration (409 Tg C yr^{-1}) and fellings (110 Tg C yr^{-1} due to harvest removals) while direct fire emissions are only 1 Tg C yr^{-1}. Fellings also transferred 28 Tg C yr^{-1} of harvest residues from biomass dead organic matter pools. The final NSE, including HWP carbon storage, equals 122 Tg C yr^{-1} (i.e., about 19% of the NPP) for the historical period. In 2030, the total NSE of the forest system is equal to 126 Tg C yr^{-1}, 101 Tg C yr^{-1} and 151 Tg C yr^{-1}, respectively assuming a constant, increasing (+20%) and decreasing (-20%) scenario for both harvest and afforestation rates compared to the historical period. Compared with the historical period these values are similar (+3%), lower (-17%) and higher (+23%), for the constant, increasing and decreasing harvest and afforestation rates scenarios, respectively.

For the pre-1990 forest area (i.e., the FM area), we show a decline in the C sink, assuming a constant harvest scenario, due to increasing releases from decomposition (Rh +13%) as DOM pools increase with increasing biomass stocks. This confirms the results proposed by other studies, suggesting some signs of C sink saturation in European forest biomass, mainly due to age-related decline in growth rates (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 increasing the harvest demand by 20%, we are approaching the maximum harvest potential of the pre-1990 forest area.

With this study, we synthesized in a unique detailed framework the forest C flows at the EU and country level, providing a useful tool for a better understanding of the C fluxes arising from the forest sector and the foundation for future analyses of the climate change mitigation potential (i.e., the sink in the forest and HWP C pool). We provided a first assessment of the possible, short-term, evolution and interaction between these fluxes, under different future harvest scenarios. Overall, our study confirms that, in the majority of European countries, the build-up of biomass stocks results from woody NPP exceeding losses by timber harvest and natural disturbances. However, at the country level, we highlighted some statistical differences, suggesting that this relationship cannot be assumed as constant for all European 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.

Author contribution

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

Competing interests

The authors declare that they have no competing interests.

Disclaimer

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

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Tab. 1: summary of the main parameters applied by the CBM model for each country. Detailed information are reported in Pilli et al. (2016a) with the exception of Bulgaria, Ireland, Poland and Romania (see the table's notes). The table reports: the NFI original reference year; the starting year of model application; the base Forest Management (FM) 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 that characterize the model scenarios in this study.

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 that characterize the model scenarios in this study, compared with the main results reported by Luyssaert et al. (2010) and Karjalainen et al. (2003).

		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

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Tab. 4: total C sink estimated by our study for the historical period (average 2000-2012) and in 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.

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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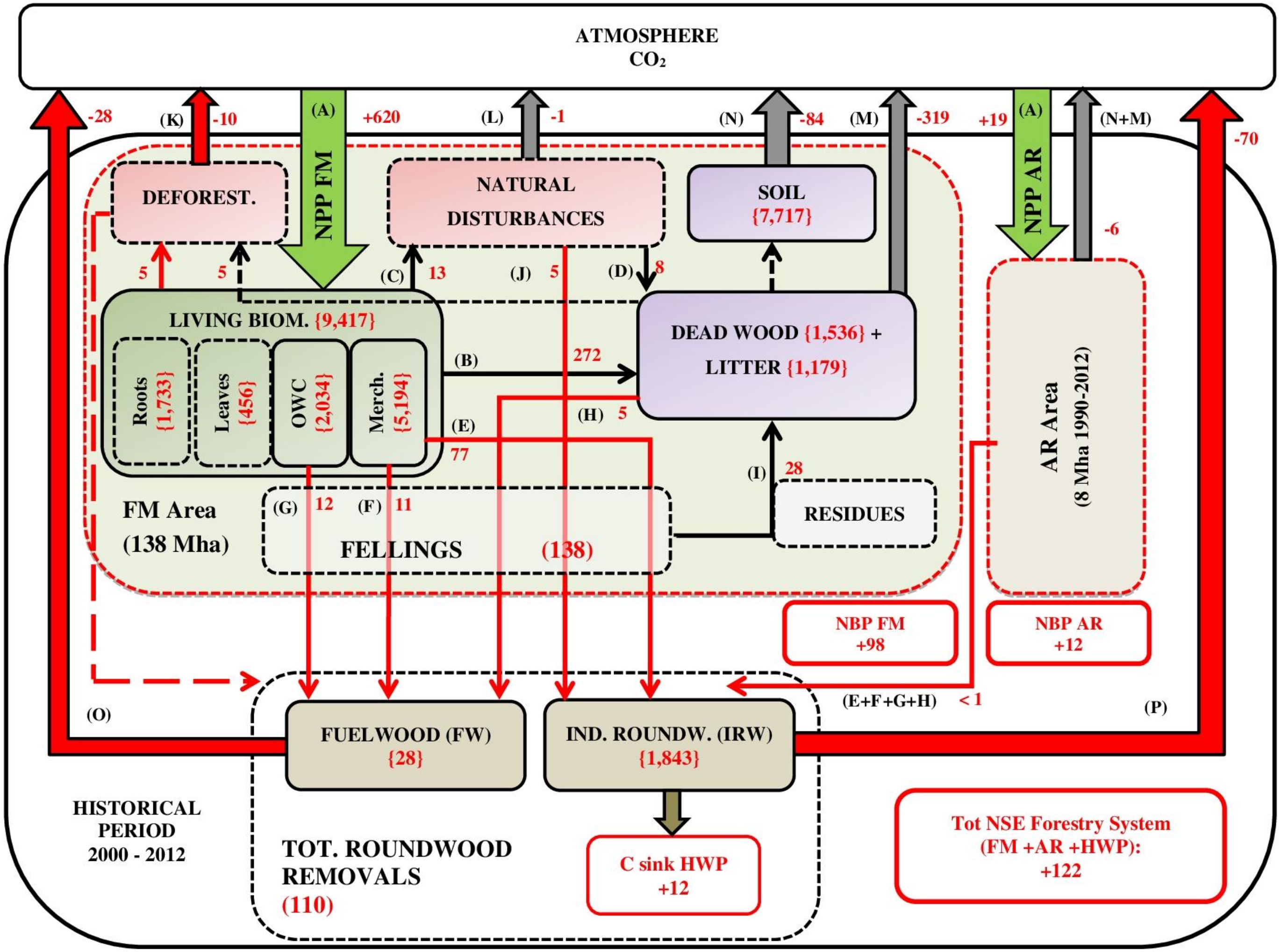

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Figure 1: Forest carbon (C) flow modelled for EU 26 by CBM for the historical period 2000 – 2012, for the forest area (further distinguished between forest management area, FM and afforestation, AR) and main links with the HWP pools, further distinguished between industrial roundwood (IRW) and fuelwood (FW). The figure highlights the main forest pools and fluxes considered by our analysis: living biomass (LB) further distinguished between roots, leaves, merchantable tree portion and other wood components (OWCs, such as branches and tops), dead wood and litter pools (DOM) and soil. The C moves from the atmosphere to the LB through photosynthesis (*A*) and it naturally moves (black arrows, only highlighted for the FM area) from the LB to DOM because of litterfall and natural mortality (*B*) and natural disturbance events (i.e., in our study, mainly fires and storms, highlighted by arrows *C* and *D*). The red arrows highlight the main fluxes of C due to direct human activities. Due to the harvest, a fraction of the merchantable portion moves 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 will be left in the forest as forest residues moving from LB to DOM (*I*). In case of natural disturbance events, a fraction of C can move from the LB to IRW or FW, due to salvage logging (*J*). Due to deforestation, the C stocked by LB and DOM pools will be released to the atmosphere (*K*). Between this amount, the LB fraction, equal to about 50% of the total C removed with deforestation, could be eventually used as FW or IRW, but due to the lack of detailed information on this use, this amount, highlighted by a red dotted arrow and equal as maximum to about 5 Tg C yr^{-1}, was not accounted in the sum of the total roundwood removals but included between the 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 (i.e., C sink HWP) and the C sink of the afforested area, we estimated the Net Sector Exchange (NSE) of the forest sector.

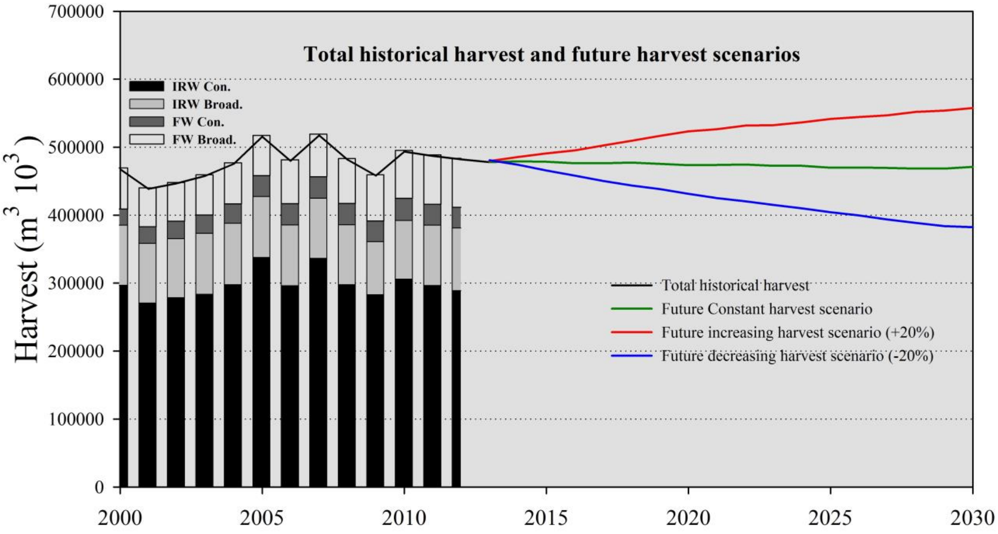

Figure 2: total harvest demand for EU26 (m^3 10^3) for the historical period (2000 – 2012) and for 3 future scenarios (2013 – 2030), assuming: average constant harvest, increasing harvest demand (i.e., +20% in 2030) and decreasing harvest demand (i.e., -20% in 2030). For the historical period, bars show 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.

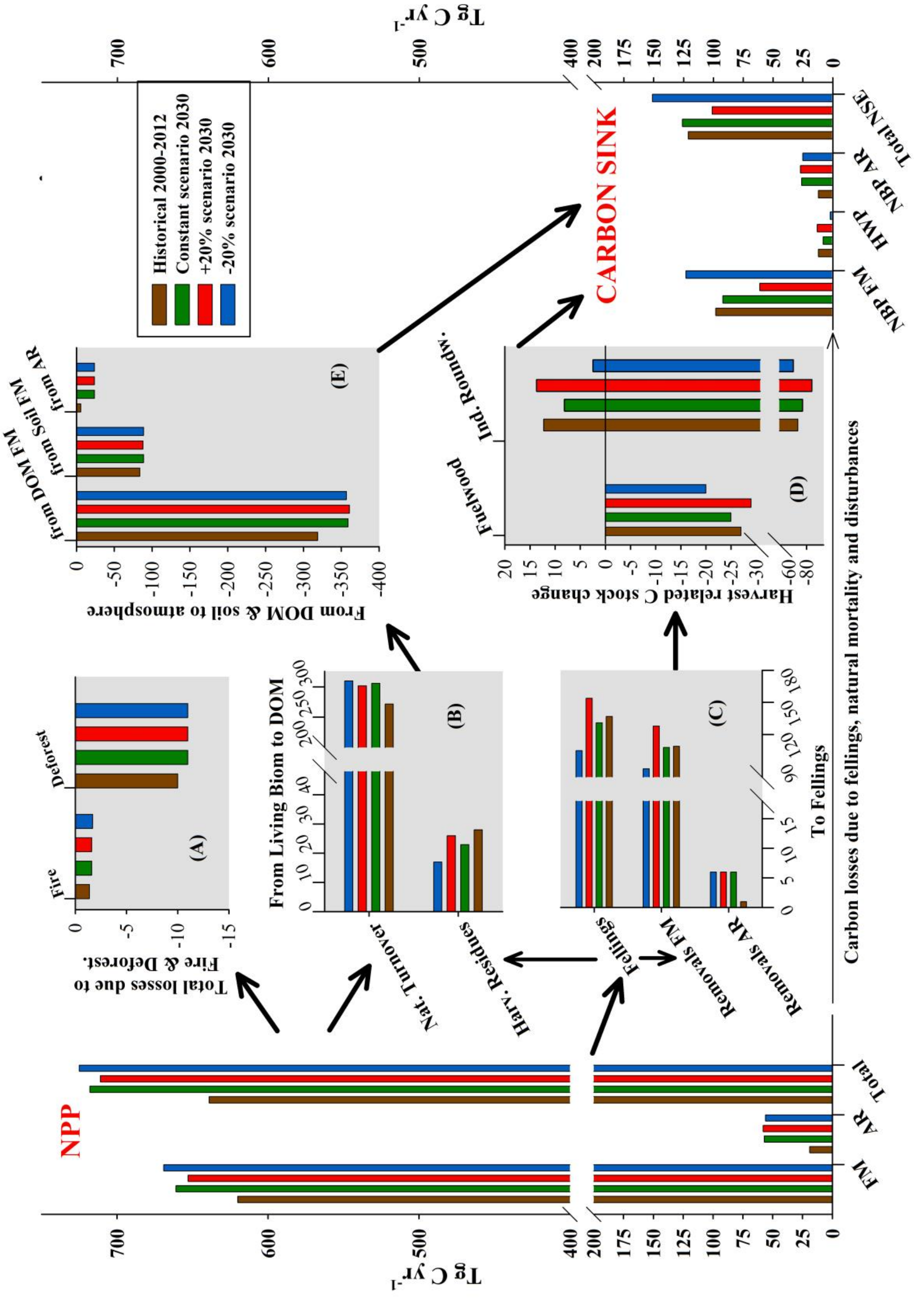

Figure 3: the figure highlights the fluxes of C under the following scenarios : (i) the historical period (average values 2000 – 2012); (ii) the constant scenario (i.e., constant harvest and AR rate); (iii) the increasing scenario (i.e., +20% amount of harvest and AR rate compared to the average historical 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). For 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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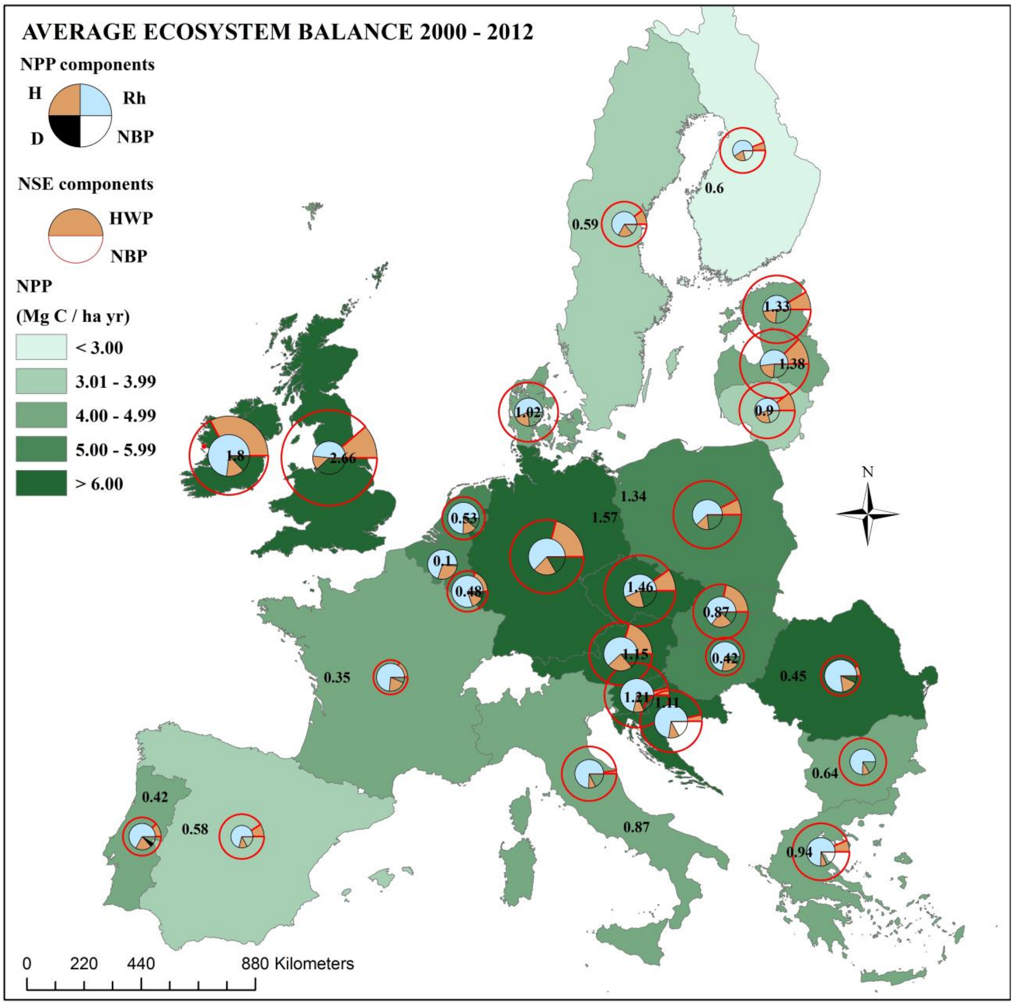

Figure 4: the figure highlights the average ecosystem balance of the FM area for the historical period 2000 – 2012. For each country the pies of the internal circles highlight the total losses due to respiration (Rh), harvest (H) and natural disturbances (D), while the average NPP, reported by the green background (in Mg C ha^{-1} yr^{-1}) is proportional to the radius of the circle. The remaining white internal pie, equal to the difference between the NPP and the previous 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.

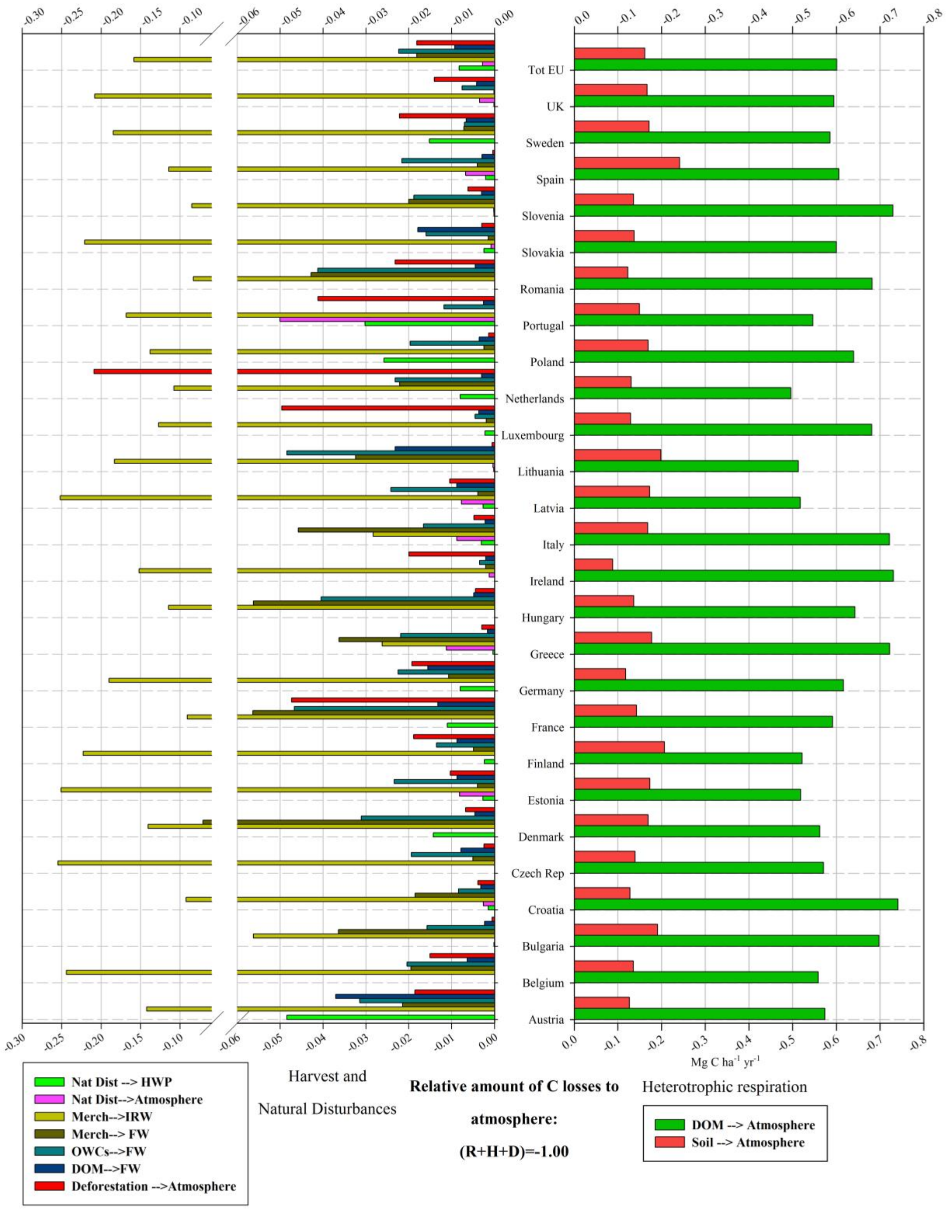

Figure 5: the figure reports, for each country and at the EU level, the relative amount of C losses (R_h+D+H) due (i) to the release of C to the atmosphere for the decomposition of DOM and soil pools, on the right panel; and (ii) to natural disturbances (i.e., fires), human activities (harvest) and deforestation, 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 (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). The sum of the proportion of all the components equal 1.

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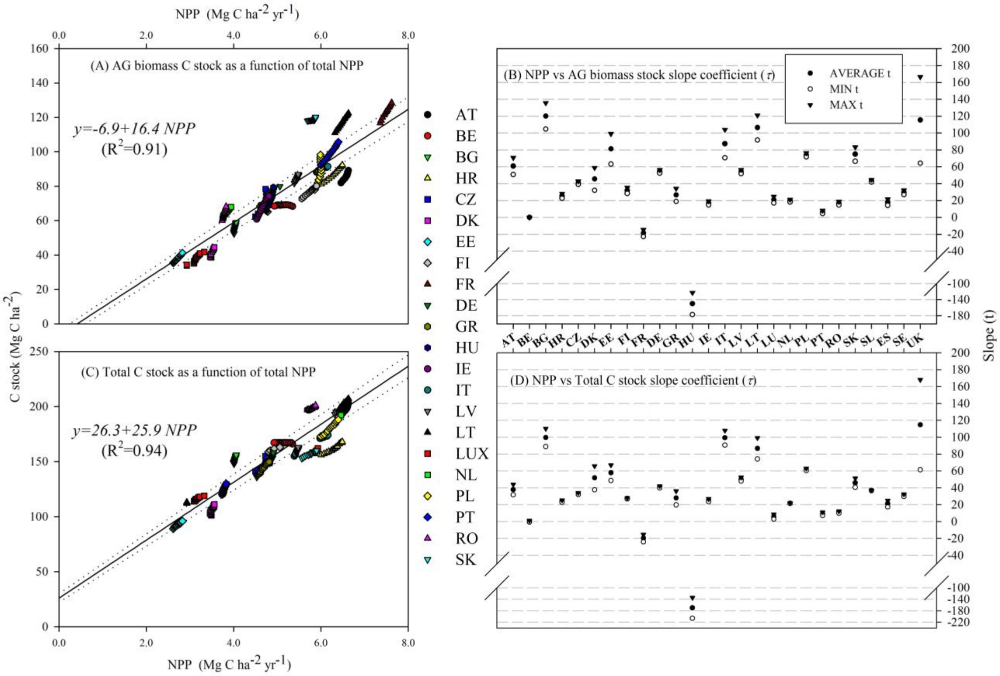

Figure 6: Plots A and C report, for each country, the yearly aboveground living biomass (on panel A) and the total (on panel C) C stock (Mg C ha^{-1}) as a function of total NPP (Mg C ha^{-1} yr^{-1}), for the historical period 2000 – 2012, excluding possible outliers (i.e., years with a distance greater 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).