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Assessing forest availability for wood supply in Europe

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ABSTRACT

The quantification of forests available for wood supply (FAWS) is essential for decision-making with regard to the maintenance and enhancement of forest resources and their contribution to the global carbon cycle. The provision of harmonized forest statistics is necessary for the development of forest associated policies and to support decision-making. Based on the National Forest Inventory (NFI) data from 13 European countries, we quantify and compare the areas and aboveground dry biomass (AGB) of FAWS and forest not available for wood supply (FNAWS) according to national and reference definitions by determining the restrictions and associated thresholds considered at country level to classify forests as FAWS or FNAWS.

FAWS represent between 75 and 95 % of forest area and AGB for most of the countries in this study. Economic restrictions are the main factor limiting the availability of forests for wood supply, accounting for 67 % of the total FNAWS area and 56 % of the total FNAWS AGB, followed by environmental restrictions. Profitability, slope and accessibility as economic restrictions, and protected areas as environmental restrictions are the factors most frequently considered to distinguish between FAWS and FNAWS. With respect to the area of FNAWS associated with each type of restriction, an overlap among the restrictions of 13.7 % was identified. For most countries, the

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differences in the FNAWS areas and AGB estimates between national and reference definitions ranged from 0 to 5 %. These results highlight the applicability and reliability of a FAWS reference definition for most of the European countries studied, thereby facilitating a consistent approach to assess forests available for supply for the purpose of international reporting.

1. Introduction

The provision of transparent, comparable and consistent information by European countries on the availability of wood is necessary for the development of forest associated policies and to support decision-making (Vidal et al., 2016). Wood is the main source of financial revenue from forests, and its demand is rapidly growing (EC, 2013). Since forests are large carbon pools, estimating carbon storage in trees and harvested wood products provides key information to be included when reporting measures aimed at reducing greenhouse gas (GHG) emissions (UNFCCC, 1992). The relevance of including forests and their mitigation capacities is also emphasized repeatedly in the Second commitment period of the Kyoto Protocol and the Paris Agreement on Climate Change (EC, 2015). Wood can be used as a replacement for fossil fuels (Bais-Moleman et al., 2018) and therefore, constitutes a key energy source considered in the Renewable Energy Directive (EC, 2009). Furthermore, wood is an increasingly important raw material for emerging bio-based industries (EC, 2013; Pelli et al., 2018), as stated in the updated European Bioeconomy Strategy (EC, 2018a, c).

The European Forest Strategy (EC, 2013) recognizes the need to increase our understanding of the complex environmental and societal challenges that the forest sector is facing. The strategy also indicates that relevant variables should be harmonized at European level. Furthermore, harmonized forest inventory data are vital to the success of efforts to assess forest-based resource availability at a pan-European scale (Mubareka et al., 2018).

The importance of reporting on forest available for wood supply (FAWS) with regard to the maintenance and enhancement of forest resources and their contribution to the global carbon cycle is reflected in the Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development (Sachs, 2012) and in the agreed criteria and indicators (C&I) for sustainable forest management (SFM) assembled in the latest update of the Report on the State of Europe's Forests (SoEF) (FOREST EUROPE, 2015a). Reporting on forest carbon stocks and changes has gained particular importance following a legislative proposal by the European Union, which requires that Land Use, Land-Use Change and Forestry (LULUCF) activities along with emissions from forests should be accounted for according to a forest reference level (EC, 2018b). With this aim, parties should develop a business-as-usual-projection of the average annual net emissions or wood removals from managed forest land (using the same forest management as in the reference period) to establish a baseline within the territory of a member state (Krug, 2018; Vauhkonen and Packalen, 2018). Hence, determining forest available (FAWS) or not available (FNAWS) for wood supply and the biomass stocks of these areas, is critical (EC, 2018b).

The method for the estimation of forest area and biomass available for wood supply at national level differs from one country to another. National Forest Inventories (NFIs) provide robust and reliable information on forests. Nevertheless, estimates of forest indicators provided by different countries are not directly comparable due to: (i) different definitions or interpretations of the related concepts (such as FAWS area, or biomass compartments considered); (ii) data availability; and (iii) different time frames as each NFI refers to a specific time period (Tomppo et al., 2010; Vidal et al., 2016). In order to improve the comparability of forest information provided by NFIs at European level, reference (or harmonized) definitions must be established. Additionally, transformations of national estimates into comparable data associated with reference definitions (called bridging functions) should be developed (McRoberts et al., 2012; Ståhl et al., 2012). In this regard, a reference definition of FAWS for harmonized reporting was established by Alberdi et al. (2016) based on the definition of the Temperate and Boreal Forest Resources Assessment (TBFRA) 2000 (UNECE/FAO, 2001). The definition from TBFRA, also used in SoEF 2015 (FOREST EUROPE, 2015a), is the following: “Forest where any legal, economic, or specific environmental restrictions do not have a significant impact on the supply of wood. This includes: areas where, although there are no such restrictions, harvesting is not taking place, for example areas included in long-term utilization plans or intentions”. This definition is differently interpreted by countries, so it is necessary to make it less ambiguous. The Alberdi et al. (2016) definition distinguishes environmental (e.g. protected areas), social (e.g. recreational areas) and economic categories (e.g. profitability), enumerating the restrictions to be considered when classifying forests as FNAWS and therefore identifying FAWS. This definition will be used for SoEF 2020 reporting (FOREST EUROPE, 2015b). A first attempt to examine the applicability of the Alberdi et al. - (2016) FAWS reference definition in four European countries was undertaken by Fischer et al. (2016). They found that comparable information was available on environmental restrictions but difficulties exist in reporting economic restrictions. Nevertheless, Alberdi et al. (2016) and Fischer et al. (2016) concluded that FAWS estimates were not easily comparable and that there was still a need for further analysis to investigate the relevance of different restrictions and their thresholds.

The European Forest Strategy (EC, 2013) recognizes the need to increase our understanding of the complex environmental and societal challenges that the forest sector is facing. The strategy also indicates that relevant variables should be harmonized at European level. Furthermore, harmonized forest inventory data are vital to the success of pan-European efforts to assess forest-based resource availability at a pan-European scale (Mubareka et al., 2018).

In an attempt to address these issues, NFI information with regard to a harmonized definition of FAWS and related restrictions from thirteen European countries representing almost 50 % of the European forest area was compiled. This paper aims to: (i) quantify harmonized FAWS and FNAWS area and aboveground dry matter biomass (AGB), (ii) determine the restrictions and thresholds considered at country level to differentiate FAWS and FNAWS in Europe, and (iii) compare the area and biomass of FAWS and FNAWS according to both the national and the reference definitions as well as to analyze the consistency of international information on FAWS.

2. Material and methods

2.1. Data and reference definitions

The data used in this study are based on NFI estimates of forest area and AGB for FNAWS assessed from the datasets of thirteen European countries which participated in the project “Use of National Forest Inventories data to estimate area and above ground biomass in European forests not available for wood supply” in the context of the Framework contract for the provision of forest data and services supporting the European Forest Data Centre of the Joint Research Centre of the European Commission: Austria, Czech Republic, Germany, Iceland, Ireland, Italy, Norway, Portugal, Romania, Slovakia, Spain, Sweden and Switzerland. In total, these countries account for 46 % of the European forest area, excluding the Russian Federation (FOREST EUROPE, 2015a).

The estimates followed agreed reference definitions for FNAWS and AGB. However, the definition of forest area that was considered was country-specific, although the majority of national definitions and international definitions are in line with the definition of forest established by FAO (UNECE/FAO, 2000; FAO, 2004, 2012) and adopted as the reference definition by the European NFIs (Vidal et al., 2008): "*Forest is a land spanning more than 0.5 ha with trees higher than 5 m and a crown cover of more than* 10 %*, or trees able to reach these thresholds in situ. For tree rows or shelterbelts, a minimum width of 20 m is required. It does not include land that is predominantly under agricultural or urban land use*."

The reference definition of AGB includes the biomass of the following components of standing and living trees (Avitabile and Camia, 2018; Gschwantner et al., 2009, 2019; Korhonen et al., 2014): (i) Aboveground part of stump (including bark); (ii) Stem from stump to stem top of the tree including bark (threshold for diameter at breast height and stem top diameter of 0 cm); (iii) Dead branches; (iv) Living branches; (v) Foliage. Thus, the AGB definition includes all the components of a standing living tree above ground level, including stump, but not the below-ground part of the stump. Trees below 1.3 m in height and shrubs are not included in the selected AGB reference definition.

The reference definition according to Alberdi et al. (2016) considers forests as FAWS where restrictions do not have a significant impact on the current or potential supply of wood. These restrictions can be based on legal acts, management decisions or other factors and are divided into environmental, social or economic restrictions.

Environmental restrictions should consider the protected areas, protected habitats or species, and also those protective forests meeting the above requirements. Age or diameter class restriction should not be taken into account (except in the case of protected ancient forest). *Social restrictions* include restrictions to protect aesthetic, historical, cultural, spiritual, or recreational values, areas where the owner has made the decision to cease wood harvesting in order to focus on other goods and services (e.g. leisure, landscape, aesthetic value). Finally, *economic restrictions* are considered those affecting the economic value of wood utilization (profitability). These include: accessibility, slope and soil condition. Short-term market fluctuations should not be considered.

FNAWS is considered forest which is not available for wood supply and therefore, all forest which is not considered FAWS. When establishing a harmonized definition of FAWS and FNAWS, the following rules of thumb applied:

1 A significant impact occurs when harvesting is totally prohibited or when restrictions severely limit the feasibility of cuttings. When restrictions do not severely limit commercial utilization of wood in an area, it should be considered available for wood supply, even if current harvesting is for auto-consumption only, or no harvest at all is taking place. Conversely, when restrictions limit the feasibility of commercial wood utilization, even if there are occasional cuttings for auto-consumption or other small-scale interventions of a non-commercial nature, the forest should be considered as FNAWS.
2 It would be preferable to estimate protected areas belonging to FNAWS according to the International Union of Conservation of Nature classification (www.iucn.org) including the categories "Strict Nature Reserve" and "Wilderness Area" in particular; or the Ministerial Conference on the Protection of Forests in the Europe classification (MCPFE, 2003), including categories "No Active Intervention" and "Minimum Intervention". The previously mentioned categories should be included whereas the inclusion of others such as National Parks and species protected by law would depend on national laws and the way in which these areas are managed.
3 Regarding the assessment of availability for wood supply, the following recommendations were proposed for reporting: (i) the three different categories should be accounted for separately if possible (environmental, social, and economic); (ii) restrictions considered for each category should be specified if possible (e.g. protected

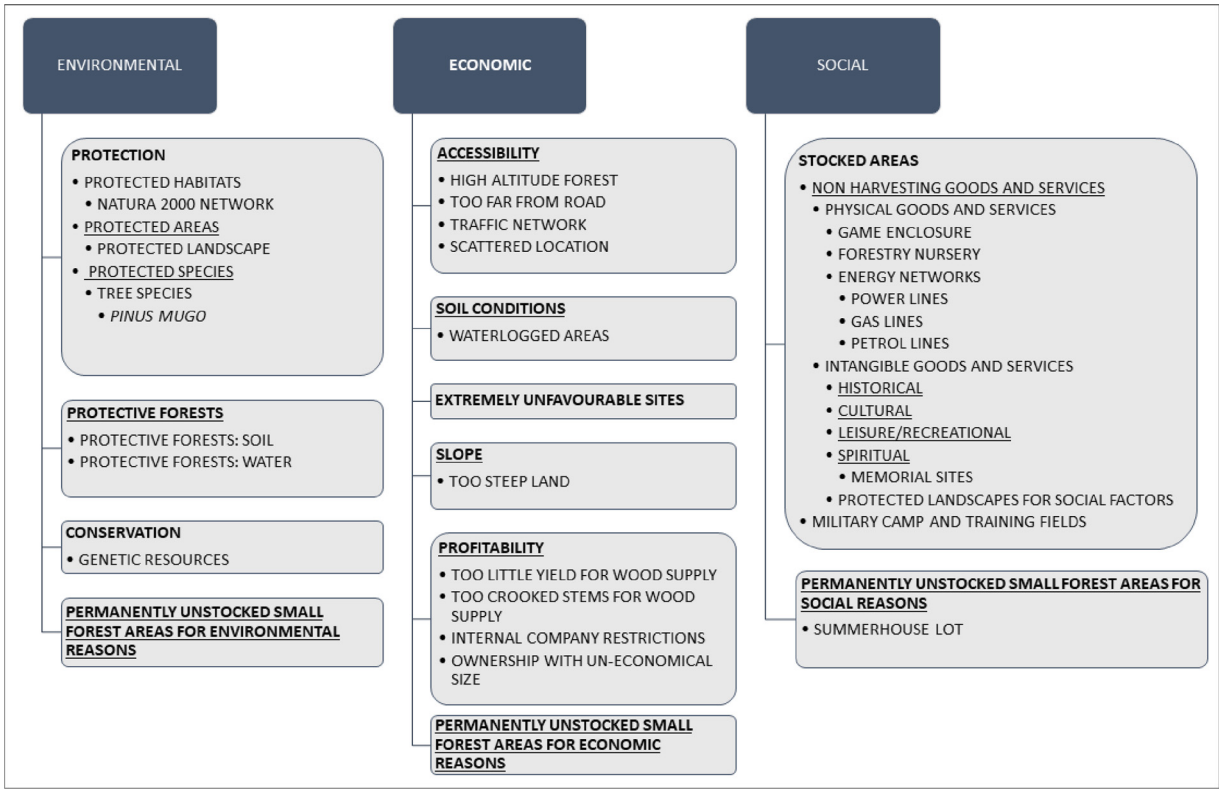

Fig. 1. Agreed restriction list to assess forest not available for wood supply (FNAWS) area and aboveground dry biomass (AGB) in 13 European countries. Underlined restrictions are considered in the reference definition.

areas, protected species).
4 Small areas with permanent absence of stock could be considered as not available for wood supply.

2.2. FNAWS restrictions and bridging function

The information regarding country-specific restrictions and their respective thresholds (if they were explicitly defined) were provided by the thirteen countries. From this information along with the enumerated restrictions in the reference definition, a hierarchical nested restriction list grouped by categories (economic, environmental and social) and subcategories (covering the different topics of each category) was elaborated, identifying the restrictions considered for the national estimates and those included in the reference definition. In Fig. 1, the nested restriction list is shown, and the restrictions considered in the reference definition are underlined (meaning that these should be taken into account by all countries if the information is available). These underlined restrictions could also be country-specific if they are accounted for the national definition, while the restrictions which are not underlined are only country-specific. This hierarchical nested restriction list complements the reference definition.

Each NFI plot was then characterized as forest/non-forest, and in the case of significant wood availability restrictions, environmental, economic or social conditioning was determined. Each FNAWS plot could be characterized with one or more restrictions. Additionally, AGB was quantified in each plot based on the recorded NFI field data. These FAWS/FNAWS classifications were performed according to i) the national definition and ii) the reference definition of FNAWS. The national data are transformed into comparable estimates between countries through "bridging functions" according to the NFIs harmonization processes (Ståhl et al., 2012). Therefore, the classification of plots considering harmonized restrictions provides the bridging function for the harmonization process (Tomppo and Schadauer, 2012), allowing the estimation of harmonized results (according to the reference FNAWS definition) from the national estimates.

2.3. Estimations of FNAWS area and AGB (E-forest system)

To produce the harmonized results for forest area and AGB (total and by restriction) at national and European level, a common estimation system was used: the *E-Forest* system (Avitabile and Camia, 2018).

The *E-Forest* system is a database and data analysis tool developed within the data and service-provisioning framework by the European National Forest Inventory Network (ENFIN) and the Joint Research Centre (European Commission), managed by the ENFIN consortium. The following data from the NFIs included in this study were uploaded in the form of standardized csv-files to the system database:

1 Sampling frame: surface area of the country covered by the NFI sample, by sampling strata if needed
2 Location list of sample plot centers, with associated statistical weight of the plots
3 For all plots: indication of whether the plot center belongs to non-forest land, FAWS or FNAWS, according to the national and the reference definition. In the case of plots classified as FNAWS, indication of the restriction categories limiting the wood supply chose
4 For all plots: the local density of the target variable (AGB, in t ha^{-1}), derived from NFI field measurements, according to the AGB reference definition

The *E-Forest* estimators can be applied to an arbitrary region of Europe (in this study, we chose thirteen countries). The estimators are design-consistent in the estimation of totals and mean spatial densities of target variables for any geographic sub-domain. In this study the sub-domains are FAWS and FNAWS and the target variable is AGB. The same estimators are also used when estimating the (unknown) surface area of FNAWS and FAWS. In the derivation of the variance (precision) estimators, sample plot centers are assumed to be generated in the sampling frame independently from each other. The auto-correlation between plots of the same cluster, however, is taken into account (Mandallaz, 2007).

The method used to obtain the estimators is described in the annex. The E-Forest system error approximation is half the width of the 95 % confidence interval (Table 1).

2.4. Data analysis

The percentage of the total forest area accounted for by harmonized FNAWS and AGB was calculated for each participating country. These percentages were classified into different ranges of FNAWS proportions at country scale (0–10%, 10–20%, etc.). The FAWS area and AGB were then calculated by exclusion (eq. 1 and eq.2):

Table 1
Forest not available for wood supply (FNAWS) area and aboveground dry biomass (AGB, average value per hectare) and forest available for wood supply (FAWS) percentages of the total forest area and biomass according to the harmonized definition for the participating European countries. Values have been computed using the E-forest estimator.

Countries	Reference year	FNAWS area (1000 ha)	Error of FNAWS area (1000 ha)	Relative error of FNAWS area (%)	Percentage of FNAWS area (%)	Percentage of FAWS area (%)	FNAWS AGB (t ha^{-1})	Error of FNAWS AGB (t ha^{-1})	Relative error of FNAWS AGB (%)	Percentage of FNAWS AGB (%)	Percentage of FAWS AGB (%)	Number of NFI plots in total forest area
Austria	2007-2009	196.1*	11.6	5.9	5.5	94.5	118.6	5.2	4.4	3.5	96.5	9426
Czech Republic	2001-2004	163.4	7.3	4.5	5.9	94.1	182.3	5.5	3.0	5.1	94.9	13,758
Germany	2012	339.2	14.5	4.3	3.1	96.9	172.3	4.8	2.8	2.9	97.1	57,053
Iceland	2010-2014	12.6	2.4	19.0	35.2	64.8	15.9	4.2	26.2	37.2	62.8	642
Ireland	2006	99.3	6.3	6.3	17.5	82.5	106.1	6.6	6.2	16.6	83.4	1418
Italy	2005	594.5	19.4	3.3	6.8	93.2	80.7	2.8	3.4	5.3	94.7	6826
Norway	2008-2012	4942.3	105.5	2.1	41.1	58.9	31.6	0.9	2.8	21.7	78.3	11,578
Portugal	2005-2006	1333.1	21.3	1.6	49.2	50.8	47.6	1.1	2.4	55.7	44.3	6759
Romania	2008-2012	863.3	23.0	2.7	23.8	76.2	182.4	3.2	1.7	13.5	86.5	19,756
Slovakia	2005-2006	196.5	17.4	8.8	13.9	86.1	156.8	12.1	7.7	7.2	92.8	1385
Spain	1997-2007	887.2	11.8	1.3	4.8	95.2	54.8	0.8	1.4	5.8	94.2	82,749
Sweden	2009-2013	4892.5	116.1	2.4	17.6	82.4	46.0	0.9	1.9	12.0	88.0	30,604
Switzerland	2004-2006	60.8	3.5	5.8	5.1	94.9	122.2	5.7	4.6	3.2	96.8	5920

Error is defined as half the width of the 95 % confidence interval.
* FNAWS area of the accessible forests (excludes inaccessible forests areas in the Alps).

FAWS (area) = Total Forest (area) – FNAWS (area) (1)

FAWS (AGB) = Total Forest (AGB) – FNAWS (AGB) (2)

The ranking of the three main groups of restrictions (environmental, social and economic) was then analyzed, taking into consideration the harmonized FNAWS area and AGB for the participating countries. To further examine the significance of the different groups of restrictions for FNAWS area and AGB, we computed the proportion between the two predominant groups of restrictions (economic and environmental).

Since each FNAWS plot can be characterized by more than one restriction, the sum of the area or AGB per restriction or group of restrictions (economic, environmental and social) may be greater (due to overlaps) than the total area or AGB of FNAWS of the participating countries.

The importance of each restriction for the assessment of the total harmonized FNAWS area and AGB was analyzed considering the information from all participating countries, and the potential overlaps between each restriction were calculated by subtracting the differences in area and AGB between them.

Finally, to study the progress towards a harmonized assessment of FAWS and FNAWS in Europe, the differences between the national and harmonized FNAWS area and AGB were analyzed together with the dissimilarities with the national values reported for international reporting in SoEF 2015. The challenges associated with divergences in the baseline national definitions and associated restriction thresholds were also examined.

3. Results

3.1. Area and AGB of FNAWS in Europe

The share of FNAWS at national scale ranges from 3.1%–49.2 % for forest area and from 2.9%–55.7 % for AGB (Table 1). However, FNAWS represent between 3 and 24 % of forest area and AGB for most of the

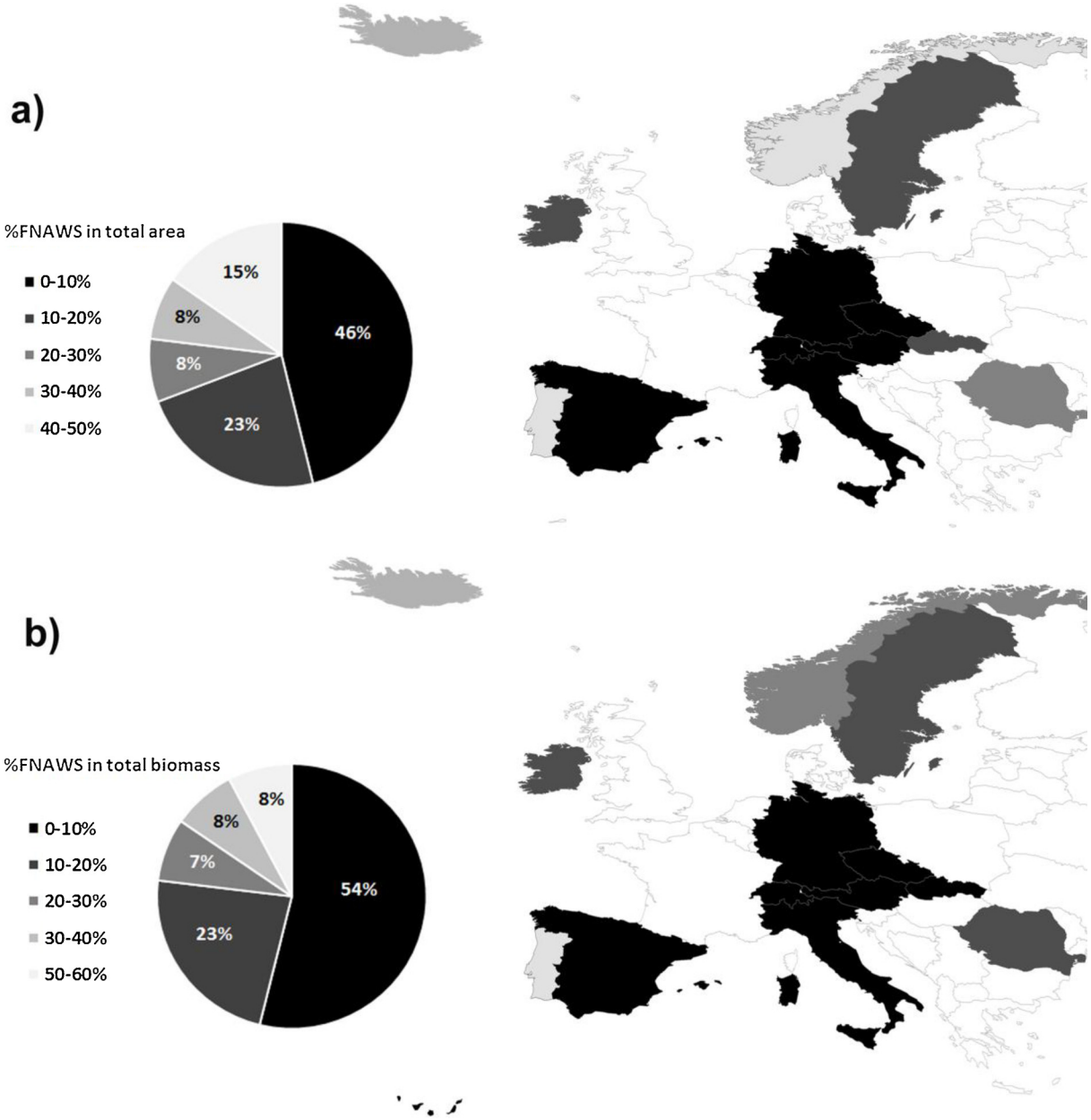

Fig. 2. Percentage of harmonized FNAWS a) area, and, b) aboveground biomass (AGB), compared to the total forest land and biomass of each European participating country estimated by E-forest. Pie-charts indicate the percentage of European countries with different ranges of FNAWS area and biomass.

participating countries with the exception of Iceland, Norway and Portugal (Table 1, Fig. 2). The error for FNAWS area and biomass is below 5 % for most of the countries (Table 1).

3.2. Restrictions and thresholds considered to estimate harmonized FNAWS

Economic factors are the most frequent restrictions considered by the 13 participating countries to define FNAWS, accounting for 67 % of total FNAWS area and 56 % of total FNAWS AGB (Fig. 3a), followed by environmental restrictions (32 % and 43 %, respectively). In contrast, social restrictions only account for 0.8 % and 1.4 % respectively. The proportion between economic and environmental restrictions is 68 % and 57 % when considering the total area and AGB of the participating countries, respectively. However, the greatest percentage of FNAWS in both area and AGB corresponds either to environmental restrictions or to economic restrictions depending on the countries (Fig. 3b). Environmental restrictions are predominant in the Czech Republic, Portugal, Slovakia and Spain, while economic restrictions predominate in the rest of the countries (Fig. 3b). In two cases, Portugal and Sweden, the economic - environmental restrictions proportion differed between area and AGB: (i) in Portugal, the proportion for area is 0.33 while for biomass it is 0.22, indicating the predominance of environmental restrictions; (ii) in Sweden, although economic restrictions rank higher than environmental restrictions in FNAWS area assessment (0.64), the opposite occurs in the case of AGB (0.48).

Regarding the contribution of each restriction, the most important restriction is profitability (economic restriction), accounting for more than 40 % and 20 % of total harmonized FNAWS area and AGB respectively (Fig. 4). Slope and accessibility (economic restrictions), and protected areas (environmental) are also frequently considered by most countries (percentages raging between 10 % and 18 % of FNAWS area and AGB.

The total overlap between restrictions covers 13.7 % of FNAWS area (2.01 million ha). The two groups of restrictions with the greatest overlap are environmental and economic restrictions (72.6 %; Fig. 5). The area shared between “protected areas” and “too little yield for wood supply” accounts for the greatest percentage within this group (35 %), followed by the area shared between “Natura 2000 areas” and “too little yield for wood supply” (15 %). Certain restrictions within the same group (environmental or economic) also display overlaps. With respect to environmental restrictions, the overlap between “Protected area IUCN” and “Natura 2000 network” is particularly notable, as it occurs in more than 25 % of the overlapping area. Among the economic restrictions, “land too steep” and “too little yield for wood production” show the greatest overlap, although in this case it is less than 1 %.

Table 2 presents a summary of the quantitative thresholds considered by each country per restriction and by category. Even though important restrictions limiting FAWS such as protected areas are based on legal instruments, most of the information available on quantitative thresholds corresponds to the economic group of constraints. Slope, low yield and accessibility are the restrictions most commonly used to assess the availability of wood supply. Of these, the thresholds for slope and low yield are almost identical between the participating countries (slope > 35 % and yield < 1 $m^3\,ha^{-1}$). However, the thresholds considered to define accessibility limitations vary considerably between the countries.

3.3. Differences between national and harmonized FNAWS estimates, and consistency with the international FAWS reporting

In this study, we found little or no differences (0–5%) between the national and reference definition for both FNAWS area and AGB (Fig. 6). In particular, the difference was less than 5 % for 84 % of the forest area and 76 % of the AGB of the participating countries. Only two countries for area and three for AGB showed differences greater than 5 % in FNAWS estimates.

Differences were found between FAWS reported to SoEF 2015 and those obtained in this study when applying the national and reference definition and the harmonized estimator. The differences were only partially due to the temporal differences among the figures, since we used the most recent data available with a reference year that was often close to or the same as that of SoEF 2015 (Fig. 7). The figures for FAWS area provided for SoEF 2015 are lower for most of the countries compared to our estimates. The differences between the estimates using the

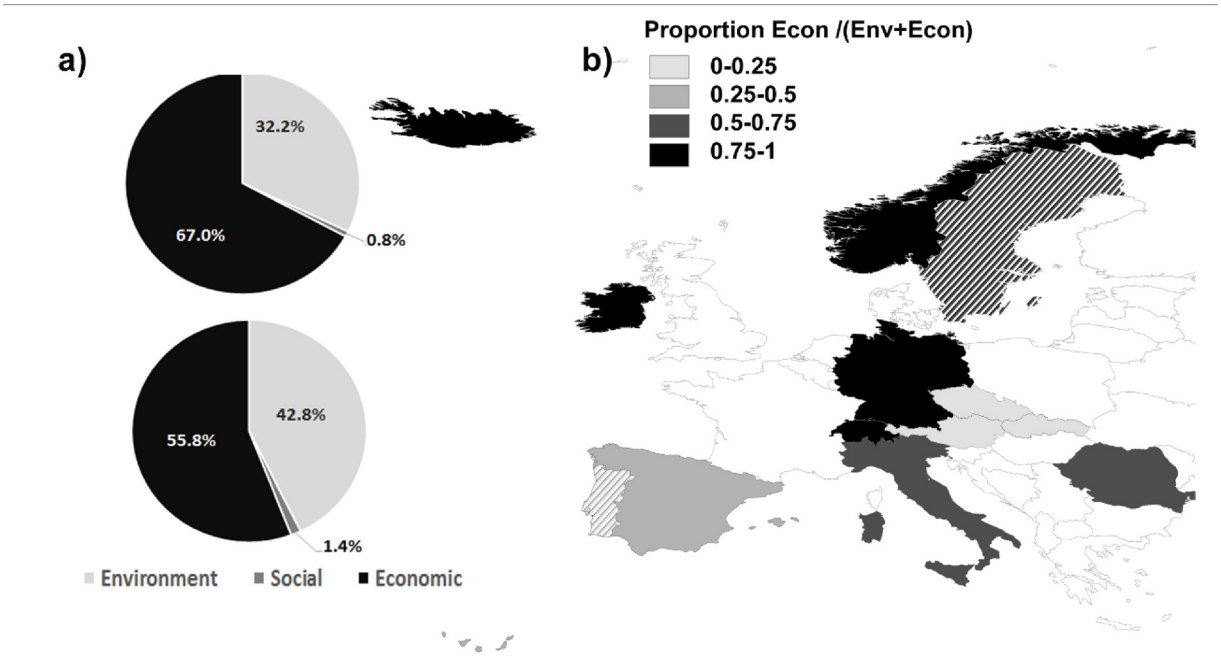

Fig. 3. Groups of restriction used for accounting harmonized FNAWS in Europe. a) Percentage of FNAWS area (above), and, aboveground biomass (AGB) (below) associated with environmental, social and economic restrictions in the participating countries. b) Map showing different ranges of the proportion economic restrictions / (environmental + economic restrictions) used for assessing FNAWS area and aboveground biomass (AGB) for each participating country. Crosshatched colours in Portugal and Sweden indicate different proportion ranges for FNAWS area and biomass.

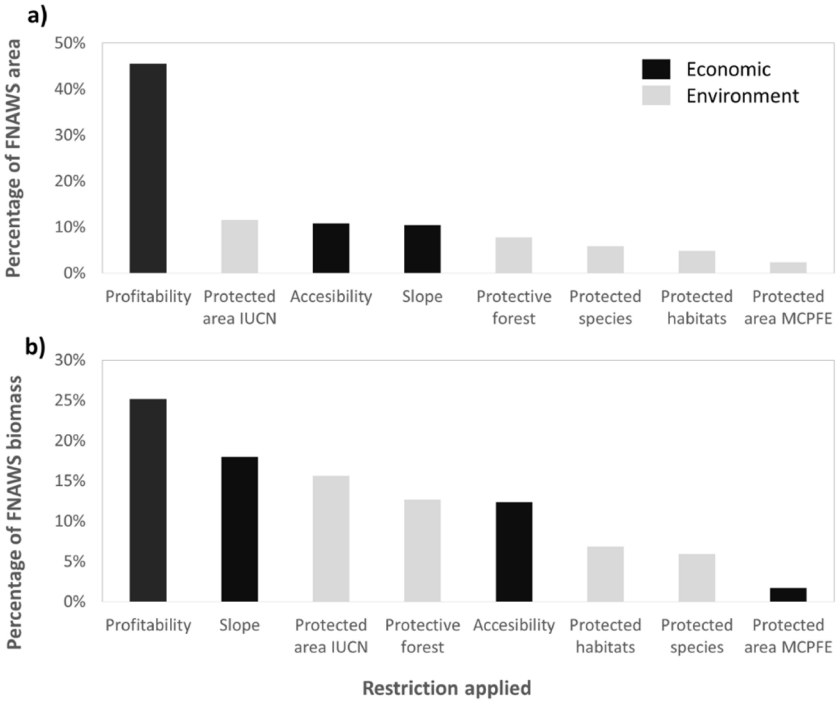

Fig. 4. Importance (%) of each restriction to the total FNAWS harmonized a) area and b) aboveground biomass (AGB) for the European participating countries (only restrictions with more than 1 % are shown). Dark grey indicates economic restrictions and light grey, environmental restrictions.

reference and SoEF definition range between 1 % (Ireland and Czech Republic) and 15 % (Portugal and Spain) in absolute values. The FAWS estimates provided to SoEF were greater than the harmonized values for five countries: Portugal, Norway, Slovakia and Ireland. When comparing SoEF values with national estimates, they were greater in the cases of Portugal and Slovakia only.

4. Discussion

The comparability of FAWS and FNAWS among European countries is of importance not only at national scale but also internationally for the development of forestry management policies and decision making. However, the harmonization of a forest indicator is highly challenging, since the use and management of forest resources vary greatly across Europe and depend on factors such as local social and economic situations, history, traditions and government policy (EEA, 2015). In this study, harmonized estimates of FAWS and FNAWS for both area and AGB are presented for the first time at European level on an area representing almost half of the total forest area in Europe and all the European biogeographical regions.

The ratio of FAWS/FNAWS area and AGB provided in this paper for thirteen countries provide decision-makers with valuable information to respond to the increasing demand for biomass worldwide and quantify the availability of biomass that can be mobilized sustainably (Camia et al., 2018).

In relation to previous FAWS and FNAWS estimates provided in international reporting, this study further advances the harmonization process by using reference definitions, a common estimator (E-Forest) (Avitabile and Camia, 2018; Vidal et al., 2016) and a re-classification approach such as a bridging function, where the NFI plots are classified according to a national definition and the reference definition (according to an agreed list of restrictions).

The use of a common estimator that can work at European scale is of major importance for the assessment and estimation of forest indicators at EU level and for the Forest Information System for Europe as requested in the European Union Forest Strategy (EC, 2013). The European Forest Strategy aims to collect harmonized Europe-wide information on the multifunctional role of forests and forest resources integrating several modules, such as bioeconomy or forest ecosystem services. The main aim of these international requirements is to support and implement European environmental policies as well as to identify appropriate forest management practices (Vidal et al., 2016). In this context, providing geolocated, comparable, reliable estimates of FAWS area and biomass together with their error estimates at European level would enhance our ability to better assess the ecosystem services through mapping the forests and wood availability in each country; assessing the carbon sequestration in non-managed or 'close to nature' managed forests as well as traditionally managed forests; improved forecasting of carbon changes, wood and timber products as well as biomass energy, thus improving the economic valuation of the related forest ecosystem services provided by European forests. Additionally, our results may impact European bioeconomy policy, as FAWS is a key input for forest trade models, models of forest resources or decision-making models for forest managers. All the above mentioned information needs have direct links with different Directives and Regulations or other policy measures, the main ones being: Bioenergy (Renewable energy Directive, EU 2018/2001), Rural development (Directives EU, 1303/2013, EU 1305/2013, EU 1306/2013 and EU 1310/2013 are relevant for the regulation of the European Agricultural Fund for Rural Development and for the implementation of rural development programmes 2014–2020), Climate change (legislation dealing with the monitoring, accounting and reporting of information relevant to climate change: Regulation EU 525/2013; Decision EU 529/2013; Regulation EU 2018/1999; and Regulation EU 2018/841); Bioeconomy (Communications of the European Bioeconomy Strategy and its update EU 2012/0341 and EU2018/673), Industry and Trade (EU Timber Regulation, EU 995/2010, 2010). Our results reveal differences with respect to the information provided up to now at European scale coming from SoEF 2015, which in most countries show lower values than when they are harmonized.

The main differences between the results of this study and the values reported in SoEF 2015 (Fig. 7) can be explained by: (i) improvements in existing sources of information and the use of new data sources; (ii) uncertainty due to approximated geolocation of the

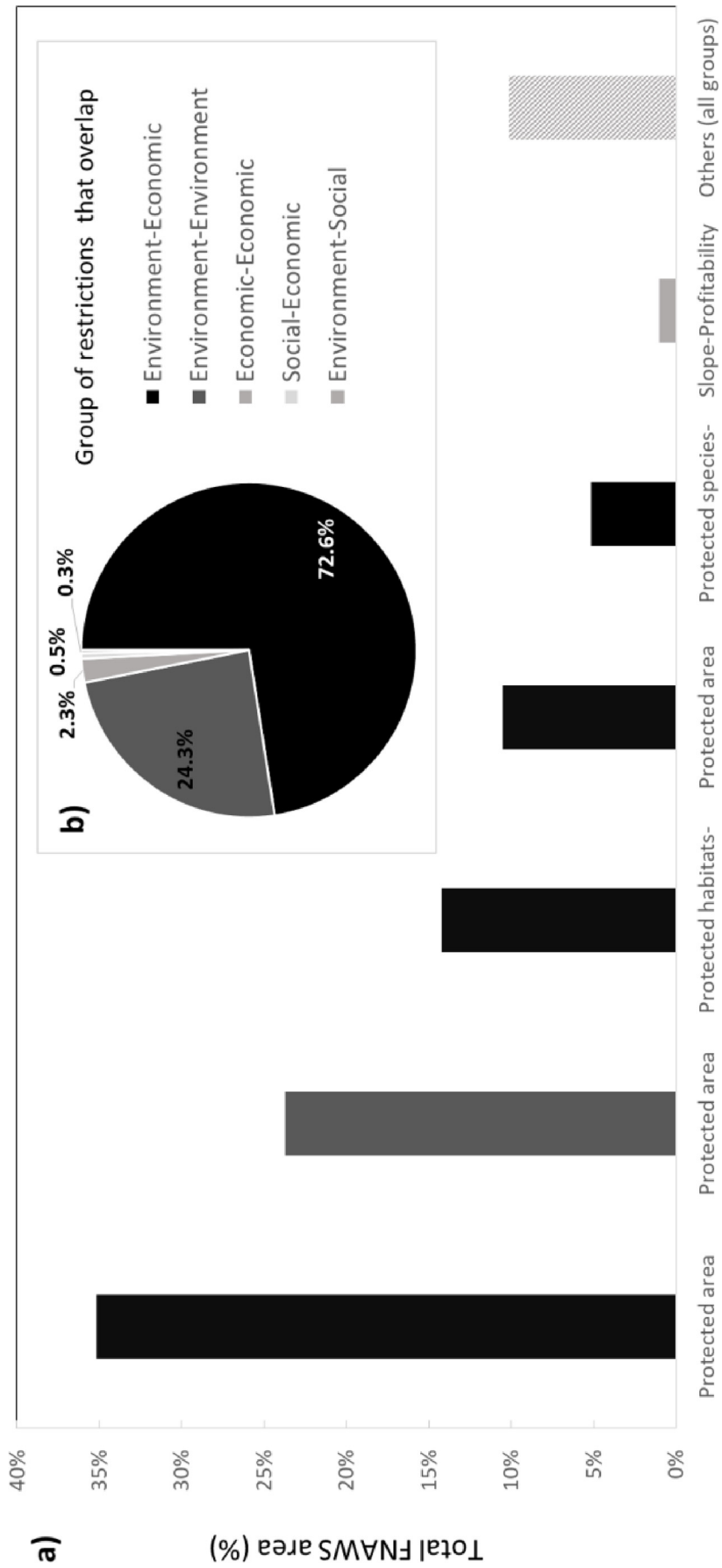

Fig. 5. Overlaps between a) restrictions and b) type of restrictions for accounting FNAWS area in Europe.

Table 2
Quantitative restriction thresholds used for different participating countries when assessing harmonized FNAWS area and aboveground dry biomass (AGB). The thresholds used by most countries are reported in bold.

Category	Harmonized restriction	Thresholds	Number of countries
Economic	Accessibility	Extraction distance (generally to road) of more than 500 m	1
		Extraction distance (generally to road) of more than 1500 m	**2**
		High altitude forests (> 2000 m asl)	1
		Difficulty due to topographic factors such as cliffs and rockiness	1
	Slope	**Steep slopes > 35%**	**3**
		Steep slopes > 50%	1
		Steep slopes > 58%	**2**
		Steep slopes > 90%	1
	Profitability	**Annual volume increment smaller than 1 m^3 ha^{-1} $year^{-1}$**	**2**
		Additional restriction for stands with annual volume increment smaller than 2 m^3 ha^{-1} $year^{-1}$	1
	Permanently unstocked small forest areas	Linear features ≥6 m from pithline to pithline; incl; firebreak, rideline, forest road. Also includes small bare areas ≥400 m^2 and ≤1000 m^2 and timber stacking area.	1
Environmental	Protective forest	Laminar erosion greater than 50 t ha^{-1} $year^{-1}$	1
	Permanently unstocked small forest areas	Linear features ≥6 m from pithline to pithline; incl: hedgerow setback, riparian zone, shrubs on forest land, water bodies.	1
Social	Gas line	Linear feature ≥6 m and ≤40 m	1
	Permanently unstocked small forest areas	Linear features ≥6 m from pithline to pithline; incl: building setback, forest edge set-back, road set-back.	1
	Power line	Linear feature ≥6 m and ≤40 m	1

restrictions or; (iii) use of different restrictions in the different definitions.

In Slovakia and the Czech Republic, forest management plans (stand-level inventory) are used for reporting to SoEF, while in this study NFI plots were considered. In the case of Iceland, the assessment of FAWS for the SoEF 2015 was carried out indirectly by analyzing the classification of NFI sample plots, firstly by classifying them according to forest use and secondly according to forest purpose, while this study used an improved classification scheme for the NFI plots. In Spain the main difference between FNAWS estimation according to the national and the reference definitions is the inclusion of one economic restriction; accessibility. As regards the differences in relation to the SoEF estimation, the information source for soil erosion was modified to use the National inventory of soil erosion (1:25,000) instead of the National map of erosive status (1:1,000,000). Sweden includes approximately 1 million ha of forest in "Voluntarily protected areas" under SoEF reporting, but these areas are not geo-referenced, i.e. impossible to assign to NFI plots and thus are not included in this study. Similarly, the FNAWS area in Austria includes the inaccessible forests in the Alps but these areas are excluded in our estimates.

In Portugal and Norway, national and SoEF estimates for FNAWS differ by less than 1 % but larger differences are found with the FAWS estimates using the reference definition. The main reason why this occurs in both countries is the consideration of different economic restrictions. In Portugal the slope restriction is included in the harmonized estimates but not in the national estimates, and this restriction represents an important contribution to the area of FNAWS at national level (around 16 %). In Norway, the main reason is that site-related economic restrictions (slope and accessibility) are considered only in the reference definition.

Fewer differences were observed between national and harmonized estimates compared to the information provided for the SoEF report. In this respect only Norway and Portugal showed differences greater than 5 %. This implies a step forward towards complete harmonization at national and international level. The results presented reveal the importance of clarifying the definitions used for international reporting, and the progress made by the different countries in determining FAWS.

In recent studies concerning FAWS harmonization, Alberdi et al. (2016) and Fischer et al. (2016), reported that environmental restrictions and specifically "protected areas" were considered by 79 % of the countries, while few considered economic restrictions. However, the present study reveals that in the analyzed area, economic restrictions are the most important group of restrictions for classifying FNAWS in Europe, followed by environmental restrictions. However, the data and methods used vary. Alberdi et al. (2016) report the results of a questionnaire on a partly differing set of NFIs (from 31 countries in total) while Fischer et al. (2016) consider the area and growing stock of five European NFIs (Italy, Ireland, Spain, Sweden and Switzerland).

The established list of national restrictions includes small permanently unstocked forest area in the three macro categories (environmental, economic and social), which represents a slight modification of the definition provided by Alberdi et al. (2016). The adaptation was made to reflect its inclusion by some countries as part of the forest area.

Although this harmonization is based on a common understanding of the meaning of FAWS and on a common FNAWS estimation method, due to the contextual variation among the different countries, the thresholds for each restriction (defining the inclusion or exclusion of the area as FAWS) remain country-specific. The most important restrictions found in our study area are three economic factors (profitability, accessibility and slope) and one environmental factor (protected areas). Alberdi et al. (2016) provide ranges for common thresholds based on expert judgment for the economic restrictions in order to estimate the area of FAWS. However, according to the present study, these could be adjusted by reducing the ranges as follows: (i) accessibility: between 0.5–2 km, (ii) slope: 35–90%; (iii) productivity: Annual volume increment: 1-2 m^3 ha^{-1} $year^{-1}$). With regard to these restrictions, accessibility is defined using different variables such as horizontal distance to road (Norway), or difficulty for field accessibility on foot due to topographic factors such as cliffs and rockiness (Spain). The slope thresholds vary from 35 % (in Romania, Italy, Portugal and Mediterranean area of Spain) to 90 % (Switzerland) (Table 2). The minimum productivity to be considered as available for wood supply differs between countries, ranging from 1 m^3 ha^{-1} $year^{-1}$ in Sweden, Norway and Germany to 2 m^3 ha^{-1} $year^{-1}$ in Italy. National and regional circumstances together with technological advances need to be taken into consideration, as silvicultural and harvesting practices differ from one country to another.

For international reporting (such as SoEF), a time series of values must be presented. The relevance and thresholds of restrictions are not static variables. Forest conservation has become a major objective in most European countries, leading to the declaration of new protected areas and the imposition of limitations on the harvesting of wood in certain areas. Vauhkonen and Packalen (2017) referred to these forests as forests with restrictions on availability for wood supply (FRAWS). To

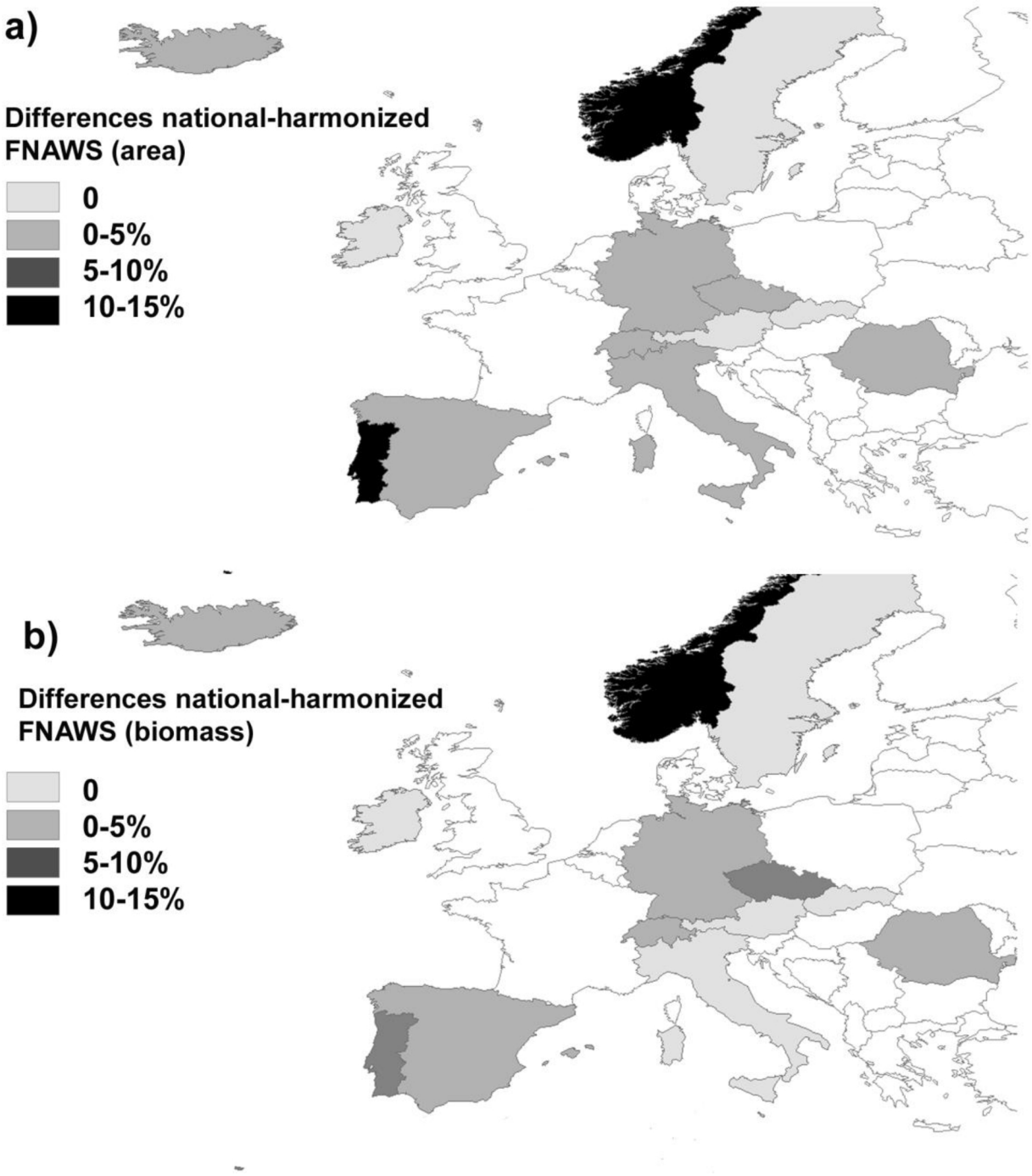

Fig. 6. Range of differences in percentage between national and harmonized estimates of FNAWS in Europe when comparing a) area, and, b) aboveground biomass (AGB).

establish a clear definition of the meaning of "significant impacts on wood supply" (in the definition of FAWS), an alternative approach was proposed in Alberdi et al. (2016), based on the area or growing stock estimates in forest areas classified by the proportion of wood resources that can be utilized. However, insufficient information is available as yet for this approach. The establishment of environmental restrictions is generally reflected in legal or administrative restrictions. Economic restrictions can vary widely since techniques, cost-effectiveness and market-prices can change considerably over time. Additionally, considering a single national threshold for each economic restriction could lead to errors in the estimates. These factors highlight the difficulties involved in correctly delimiting the time series of the FNAWS area restricted by economic factors. Finally, social aspects of forests, compared with environmental and economic aspects, are highly varied and complex to measure (Vierikko et al., 2008) and are not usually adequately described in NFIs. Proposals for new social indicators are being developed under the DIABOLO project (http://diabolo-project.eu/), which may lead to improvements in the estimates of FNAWs due to social restrictions (Atkinson et al., 2019).

Differences exist among the different countries as regards the assignment of each restriction to the three restriction categories. For instance, in the Slovak Republic, protective forests are considered those with steep slopes and smaller annual volume increment and thus, slope and volume increment are included as environmental restrictions.

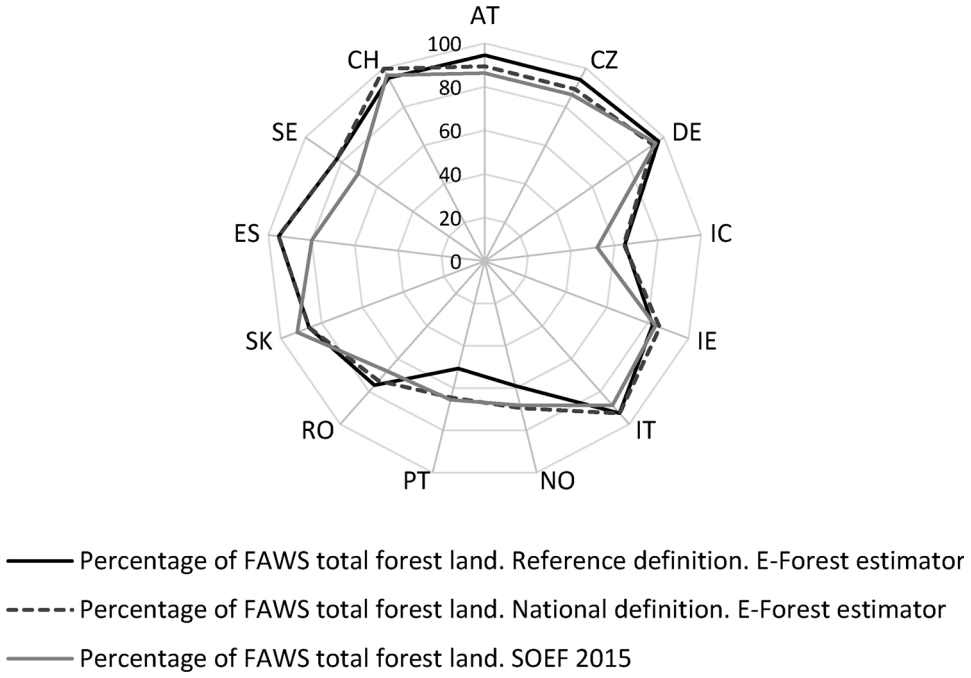

Fig. 7. Comparison of FAWS estimates referenced to: (i) national definition and estimated with E-Forest estimator; (ii) reference definition and estimated with E-Forest estimator; (iii) FAWS information provided by each country for the Status of European Forest 2015.

Hence, certain restrictions may be assigned either to economic or to environmental groups, possibly leading to differences in the attribution of FNAWS. When attempting to identify restrictions derived from or included in other more relevant restrictions, we found an overall overlap of only 13.7 % between all restrictions considered in this study, confirming the necessity to consider all of them in order to achieve accurate FNAWS estimation.

5. Conclusions

This is the first attempt to provide harmonized estimates of FAWS using a common estimator for European NFIs. Harmonized estimates could be of major relevance for the provision of geolocated, comparable and robust assessments at EU level to support and implement several European environmental policies as well to identify appropriate forest management practices.

The list of agreed restrictions presented in this study will be of particular use to gain a more complete picture of the limitations associated with wood mobilization in European Forests.

FNAWS represent between 3 and 24 % of both forest area and AGB in the majority of the European countries included in the analyses. Consequently, in most countries, the share of FAWS area and AGB is more than 75 % of the total forest land and AGB respectively.

Most of the countries showed differences ranging from 0 to 5 % in area and AGB between estimates based on national and reference definitions of FNAWS. The differences were only greater in two countries, Norway and Portugal. These results point to the suitability of the reference definition and methodology for most European countries and the potential use of FAWS and FNAWS for international reporting in Europe given the comparability and consistency of the estimates. However, greater differences were detected in comparison with the international information for SoEF 2015, highlighting the advisability of continuing with the forest data harmonization efforts at European scale.

Author contributions

Iciar Alberdi. Coordination, national estimation of FNAWS, data analysis, results analysis and elaboration of the paper

Susann Bender. National estimation of FAWS, data processing and analysis, reviewing and commenting the manuscript

Thomas Riedel. National estimation of FAWS, data processing and analysis, writing of manuscript and writing the Annex

Valerio Avitable. Results review and reviewing and commenting the manuscript

Olivier Bouriaud. National estimation of FNAWS, reviewing and commenting the manuscript

Michal Bosela. National estimation of FNAWS, reviewing, commenting and editing the manuscript

Andrea Camia. Results review and reviewing and commenting of the manuscript

Isabel Cañellas. National estimation of FNAWS, reviewing, reviewing and commenting the manuscript

Francisco Castro Rego. National estimation of FNAWS, reviewing and commenting the manuscript

Christoph Fischer. National estimation of FNAWS, reviewing and commenting the manuscript, and writing the Annex

Alexandra Freudenschuß. National estimation of FNAWS, reviewing and commenting the manuscript

Jonas Fridman. National estimation of FNAWS, reviewing and commenting the manuscript

Patrizia Gasparini. National estimation of FAWS, reviewing and commenting the manuscript

Thomas Gschwantner. National estimation of FNAWS, data analysis, reviewing, commenting and editing the manuscript

Silvia Guerrero. National estimation of FNAWS, commenting the manuscript

Bjarki Thor Kjartansson. National estimation of FNAWS, reviewing and commenting the manuscript

Milos Kucera. National estimation of FNAWS, reviewing, commenting the manuscript

Adrian Lanz. National estimation of FNAWS, reviewing, commenting the manuscript and elaborating the Annex

Gheorghe Marin. National estimation of FNAWS, reviewing, commenting and editing the manuscript

Sarah Mubareka. Results review, reviewing and commenting the

manuscript

Monica Notarangelo. National estimation of FNAWS, reviewing and commenting the manuscript

Leónia Nunes. National estimation of FNAWS, reviewing and commenting the manuscript

Benoit Pesty. Data analysis of FNAWS and commenting the manuscript

Tomas Pikula. National estimation of FNAWS, reviewing and commenting the manuscript

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Maria Rizzo. National estimation of FNAWS, reviewing and commenting the manuscript

Vladimir Seben. National estimation of FNAWS, reviewing and commenting the manuscript

Arnór Snorrason. National estimation of FNAWS, reviewing and commenting the manuscript

Stein M. Tomter. National estimation of FNAWS, reviewing and commenting the manuscript

Laura Hernández. National estimation of FNAWS, data analysis, results analysis and elaboration of the paper

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Annex A

In the E-Forest system, the estimator employed for the total of a target variable in an arbitrary region l of interest is:

$$\hat{T}_l = \lambda_l^* \hat{Y}_l = \lambda_l^* \frac{\sum_{j\in l} b_{j.(e)} w_{j.l} \tilde{y}_{j.l}}{\sum_{j\in l} b_{j.(e)} w_{j.l}}$$

and the standard error of $\hat{T}_l$ (half width of the 95 % confidence interval) is approximated by

$$\hat{S}\langle \hat{T}_l \rangle = \lambda_l^* \hat{S}\langle \hat{Y}_l \rangle = \lambda_l^* \left[\frac{\sum_{j\in l} b_{j.(e)} \left(\frac{w_{j.l}}{\bar{w}_l}\right)^2 (\tilde{y}_{j.l} - \hat{Y}_l)^2}{(m_l' - 1) \sum_{j\in l} b_{j.(e)}} \right]^{1/2}.$$

In these formulae, j indicates the clusters, $w_{j.l}$ is the number of plots associated with cluster j and with plot centre located in estimation cell l, and $\tilde{y}_{j.l}$ is the average of the local densities of the target variable (above-ground biomass) provided on these plots. Under single plot sampling, $w_{j.l} = 1$.

$b_{j.(e)} = a_{j.e} \frac{\lambda_e}{\sum_{j\in e} a_{j.e}}$ is the weight of cluster j in the estimation. It is calculated from the NFI provided sampling weights $a_{j.e}$ of clusters contained in an NFI sampling stratum e of known surface area λ_e. Under single plot sampling, the clusters are, in fact, plots (clusters of size 1). The terms $m_l' = \frac{(\sum_{j\in l} b_{j.(e)})^2}{\sum_{j\in l} b_{j.(e)}^2}$ and $\bar{w}_l = \frac{\sum_{j\in l} b_{j.(e)} w_{j.l}}{\sum_{j\in l} b_{j.(e)}}$ adapt to the specific situation of unequal cluster weights in a stratum and cluster sampling, respectively.

The estimator contains an approximate solution for the case when the available sampling frames (the NFI sampling strata) do not cover the entire estimation cell j of interest, a case which does not occur, however, in this study. The estimate $\hat{T}_l$ refers in such a case to the total of the target variable in the reduced part of the estimation cells which are covered by NFI sampling strata, and the size of this reduced part of the estimation cells is approximated by $\lambda_l^* = \frac{1}{L_e} \sum_{j\in l} b_{j.(e)} w_{j.l}$, where L_e is the nominal number of plots per cluster in stratum e. Note, that the realised number $w_{j.e}$ of plots of a cluster j in stratum e may be smaller than L_e, notably when j is near the stratum boundary and some of the plot centres are outside e.

The E-Forest system approximates the error (half width of the 95 % confidence interval) of the ratio of two estimated totals, $\hat{R}_{X/Z.l} = \frac{\hat{T}_{X.l}}{\hat{T}_{Z.l}}$, as follows:

$$\hat{S}\langle \hat{R}_{X/Z.l} \rangle = \frac{1}{\hat{Y}_{Z.l}} \left[\frac{\sum_{j\in l} b_{j.(e)} \left(\frac{w_{j.l}}{\bar{w}_l}\right)^2 (\tilde{u}_{j.l} - \bar{\tilde{u}}_l)^2}{(m_l' - 1) \sum_{j\in l} b_{j.(e)}} \right]^{1/2}$$

where

$$\tilde{u}_{j.l} = \tilde{y}_{X.j.l} - \tilde{y}_{Z.j.l} \hat{R}_{X/Z.l}$$

$$\bar{\tilde{u}}_l = \frac{\sum_{j\in l} b_{j.(e)} \tilde{u}_{j.l}}{\sum_{j\in l} b_{j.(e)}}$$

This estimator is used, for example, in the estimation of the average (harmonized) above-ground biomass per ha forest (not) available for wood supply.

Half the width of the 95 % confidence intervals given in Table 1 has been calculated as twice the standard error of the estimates

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