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The Biomass of European Forests

An integrated assessment of forest biomass maps, field plots and national statistics

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Authors

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Abstract

Forest biomass is a relevant source of energy and material for the European bioeconomy. The JRC Biomass Assessment Study recognized the need for an up-to-date, harmonized and spatially-explicit estimate of the biomass stock in Europe to better understand its current and future contribution to a sustainable bioeconomy. In this perspective, the present report provides an overview of existing forest biomass data in Europe, describes the methodologies used to harmonize and compare them, and proposes an improved biomass map consistent with the forest inventory data.

An analysis of the existing biomass data showed that European countries employ different forest and biomass definitions and provide estimates that refer to different periods and spatial scales. It is therefore essential to perform steps to harmonize the national biomass data and existing biomass maps to perform any meaningful pan-European assessment.

The biomass data provided by the National Forest Inventories (NFIs) were first harmonized among each other in terms of biomass definition thanks to a dedicated effort and collaboration of 26 European NFIs. They were then further harmonized with the biomass maps for forest definition and reference year using forest cover maps and a forest growth model within the JRC Biomass Assessment Study. The national statistics were also harmonized by the NFIs regarding the forest area and biomass available for wood supply, using the same reference definition and common criteria to assess wood availability and related restrictions.

This data harmonization effort produced a reference database of forest biomass in Europe, which includes statistics at sub-national scale and field plots, both harmonized for biomass pool and reference year. The reference database was used to assess the uncertainties of publically-available biomass maps at different spatial scales. A dedicated analysis quantified the impact of the harmonization of the reference data on the maps validation, highlighting the essential role of the harmonization procedure to obtain reliable results.

The validation exercise indicated that, overall, the biomass maps have relatively low accuracy for Europe, especially at local scale, and suggested the need for an improved product. Thus, the map with the highest accuracy was further improved applying a bias-removal approach, where the reference data were used to quantify and remove the systematic difference of the map with the harmonized statistics. The result is a biomass map of Europe at 1 ha resolution for the year 2010 in line with the reference statistics in terms of forest area and biomass stock.

The harmonized biomass map along with the harmonized statistics on biomass stock and biomass available for wood supply support an improved estimation of the current and potential supply of biomass resources from European forests as well as their availability and cost, towards a better assessment and modelling of the role of forest biomass in the European bioeconomy.

Lastly, this study provides an overview of the current status and the upcoming developments in the field of satellite, airborne and terrestrial remote sensing of forest biomass. As these new technologies are rapidly maturing and becoming operational, they open the possibility for an integrated monitoring system that allows the detailed, frequent and accurate estimate of the forest resources.

1 Introduction

Within the JRC Biomass Assessment Study[1] the need for an updated, harmonized and spatially-explicit estimate of forest biomass stocks in Europe, supporting the European bioeconomy, has been identified. As a contribution towards this aim, the present report provides an overview of existing forest biomass data in Europe, describes the methodologies used to harmonize and compare them, assesses the agreement of the existing biomass maps with the reference data, proposes a biomass map that is consistent with the harmonized national forest inventory data, and provides an overview of the current status and the upcoming developments in the field of forest biomass monitoring with remote sensing. This study is based and expands upon the findings presented in Avitabile and Camia (2018). An overview of this study is provided in Figure 1 and described below.

Biomass data are here distinguished in three different categories:

— Biomass statistics

— Biomass plots

— Biomass maps

Biomass statistics are derived from National Forest Inventory (NFI) data and provide estimates of forest area, total forest aboveground biomass stock and mean forest aboveground biomass density at sub-national and national scales. Biomass plots are ground observations of forest properties acquired by the NFIs to estimate biomass density at local scale and to derive the biomass statistics at sub-national and national scales. Biomass maps are usually derived from remote sensing data calibrated with ground measurements and provide wall-to-wall estimates of biomass density at regional level.

Every European country has a NFI system often repeated every 5 – 10 years from which it is possible to obtain reliable statistics on forest biomass resources (Vidal et al., 2016). However, the NFI statistics are not always recent or frequently updated, often do not provide the fine-scale spatial distribution of biomass, and are based on country-specific definitions and inventory designs that make their integration for a regional (i.e., European) assessment of biomass resources difficult (Lawrence et al., 2010; McRoberts et al., 2010; Neumann et al., 2016).

Similarly, the biomass plots acquired by the NFIs provide high-quality estimates of forest biomass at local scale but they follow the respective national definitions and timeframes, are affected by the errors inherent in the estimation of biomass from tree parameters using allometric equations and expansion factors, and are often not publicly available for security and privacy reasons.

Various biomass maps have been produced by research organizations at the European or global scale during the last decade, mostly independently from the NFIs. These maps provide continuous biomass estimates over forested areas at moderate spatial resolution (100 m – 1 km). However, the level of reliability of their estimates is not clear and often questioned, since the remote sensing signals used for the estimations are only indirectly related to the biomass density of vegetation and the maps do not provide complete and transparent accuracy information due to the scarcity of reference data (Hill et al., 2013).

Hence, there is a need to combine and reconcile data from "top-down" global or regional biomass maps produced by the remote sensing community with "bottom-up" national data from the NFIs (plots and statistics), which are the official estimates provided at the national and international levels (e.g., reporting to UNECE, FAO and UNFCCC) (Duncanson et al., 2019; Herold et al., 2019). The assessment and comparison of existing data is the first and necessary step to quantify their agreement, identify gaps and define strategies for improving the estimation of the forest biomass stocks in Europe.

The comparison of the biomass datasets is challenged by the fact that European countries employ different forest and biomass definitions and provide estimates that refer to different periods and spatial scales. For this reason, it is essential to harmonize the national biomass statistics among each other (Chapter 2) and with the biomass maps (Chapter 4) in order to perform a meaningful comparison (Chapter 5) and integration (Chapter 6). Similarly, the biomass plots derived from various NFIs and used for the validation of the maps need to be harmonized among each other and with the biomass maps (Chapter 3) (Figure 1).

This data harmonization is a large and often underestimated effort, and it is a key aspect of this study. The NFI data (statistics and plots) were first harmonized among each other in a dedicated effort performed by the European NFI organizations and then harmonized with biomass maps using modelling approaches within the JRC

[1] https://ec.europa.eu/knowledge4policy/projects-activities/jrc-biomass-assessment-study_en

Biomass Assessment Study. Forest cover maps matching the NFI estimates of forest area were also used to compare biomass statistics and biomass maps over the same forest extent.

Then, the NFI biomass data were used to assess and improve the biomass maps. The error of the biomass maps is composed by two factors: the random component, or the spread of random errors, and the systematic component, or the systematic difference between the map and the reference data (the bias).

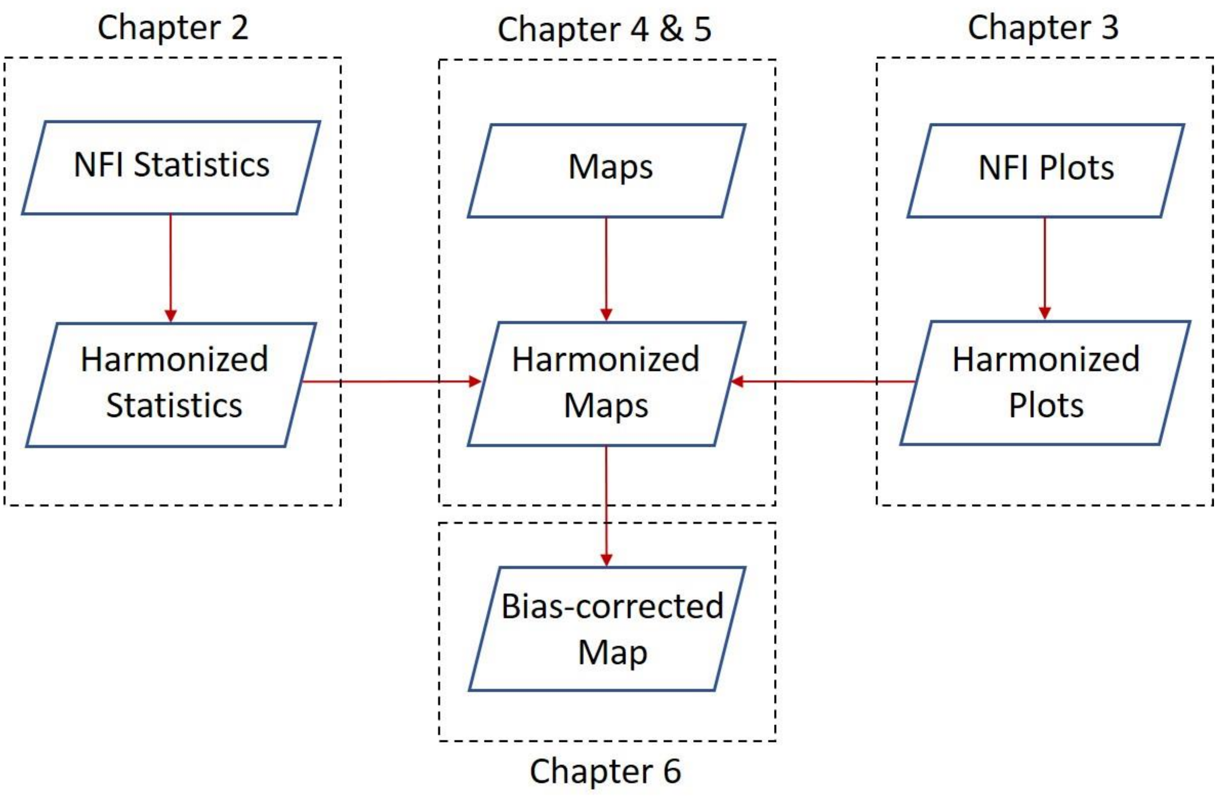
The bias is often due to systematic errors in the calibration data, inaccurate model parameters and limited sensitivity of the remote sensing data to biomass variability. With biomass maps, spatial aggregation tends to compensate (and thus reduce) the random errors but it does not affect the bias. However, the bias can be reduced using reference data obtained from a statistical sample and an unbiased estimator, such as the NFI statistics. For this reason, the harmonized NFI biomass statistics were used to remove the systematic under- or over-estimation of the map estimates compared to the reference statistics at sub-national scale.

This study consists in the comparison of the harmonized biomass maps, statistics and ground data to better assess the uncertainties of the maps and to integrate them using a bias-correction approach that produced a novel biomass map for Europe in line with the national forest reference values (available online at the link indicated in section 6.2).

This study also reports the harmonized statistics of Forest Available for Wood Supply (FAWS) and related biomass stock. As for the biomass data, the national statistics on FAWS were harmonized among each other by the NFI organizations in a study supported by the JRC, using a reference definition and common criteria for wood availability (Chapter 2). These statistics were not used to assess the biomass maps, as the maps refer to the total standing biomass in the forest and not to the fraction that is available for wood supply.

The harmonized biomass data described in this Report, namely the bias-corrected biomass map, the harmonized statistics on forest biomass and on biomass available for wood supply, are an input to the JRC Biomass Assessment Study modelling platform. These data directly contribute to better estimate the potential supply of biomass resources from European forests as well as their availability and cost, towards an improved assessment of the role of forest biomass in the European bioeconomy (Mubareka et al., 2018).

Figure 1. Overview of this Report and related chapters. All datasets (statistics, maps and plots) refer to forest aboveground biomass.



2 Biomass statistics

In most European countries, statistics on forest biomass at national and sub-national scales are produced by the NFI institutions (Tomppo et al., 2010, Vidal et al., 2016). Recently, the access to the NFI data has been facilitated as several countries provide online open-access to their statistics. However, the biomass data provided by the countries are not directly comparable because they employ:

- different forest definitions;
- different growing stock and biomass definitions (i.e., the statistics may refer to different parts of the tree or exclude trees below a minimum diameter);
- different approaches to estimate the biomass from the tree parameters (i.e., allometric equations or biomass conversion and expansion factors);
- different timeframes (i.e., each NFI refer to a specific period);

In addition, also the uncertainty (i.e., the sampling error) of the biomass statistics may not be directly comparable because it is based on different sampling designs and procedures to estimate the biomass stock of the study area from the plot data.

The NFI data are also periodically compiled by international organizations for regional and global assessment purposes, such as FAO's Forest Resource Assessment (FRA) reports (FAO, 2020) or the State of Europe's Forests (SoEF) reports (FOREST EUROPE, 2015a). With these initiatives, forest area and biomass statistics are made openly available at national scale. Even though the biomass statistics produced for the international reporting present some level of harmonization, typically in terms of forest definition and reporting period, the harmonization is often performed with a simple adjustment based on expert knowledge or linear extrapolation, which limits the accuracy and comparability of the biomass estimates.

For this reason, during the last years the European forestry community have performed dedicated harmonization actions focusing on forest volume statistics, such as the European Cooperation in Science and Technology (COST) Action E43 (COST Action E43, 2010) and the Distributed, Integrated and Harmonized Forest Information for Bioeconomy Outlooks (DIABOLO) project (DIABOLO, 2015). Such initiatives, funded by the European Commission, have established reference definitions and bridging functions for common reporting, and produced harmonized stem volume estimates for Europe (Tomter et al., 2012; Gschwantner et al., 2019).

With regard to biomass data, the JRC supported a dedicated effort to address the differences indicated above and to achieve a better harmonization of the forest biomass statistics in Europe. The harmonization of the differences related to the biomass pool was performed by a dedicated effort of 26 European NFI institutions under the coordination of the European Network of Forest Inventory (ENFIN) (Section 2.1), while the harmonization of the different timeframe (temporal harmonization) was achieved with a modelling approach within the JRC (Section 2.2). The best available data for each European country were compiled in a reference dataset of biomass statistics at national or sub-national level (Section 2.3), which was then used to assess the biomass maps (Chapter 5).

Similarly, JRC supported a dedicated effort to harmonize the statistics related to the forest area and biomass that is available for wood supply (thus, a fraction of the total forest area and standing biomass). The existing data were harmonized for 20 European countries using a common definition and methodology by a dedicated effort of the respective NFI institutions, and compiled with the best available data for the other countries in a reference dataset for Europe (Section 2.4).

2.1 Harmonization of biomass pool

Since 2008 the Joint Research Centre of the European Commission is running Framework Contracts for "the provision of forest data and services in support of the European Forest Data Centre (EFDAC)". The Framework Contracts, awarded to consortia of NFI organizations coordinated in the ENFIN network, have been established to address the need for comparable and harmonized forest information in Europe through targeted and ad-hoc requested Specific Contracts (SCs). The objective is to provide decision-makers with processed, quality-checked and policy-relevant forest data, which is in line with the objectives of ENFIN to promote NFIs, harmonise forest information and support decision makers in a broad range of forest related policies (http://enfin.info/).

In this context, during the period 2014-2016 the JRC launched two Specific Contracts (SC13 and SC17), which aimed to develop and apply a methodology for the harmonized assessment of forest biomass at European level. In total, 26 NFI institutions worked together under the scientific and administrative coordination of ENFIN to identify a harmonized biomass definition and a common estimator, which were applied to the NFI data to obtain biomass estimates referring to the same biomass pool and estimation method for all countries.

The harmonized definition includes all aboveground biomass compartments of the living trees, namely the aboveground part of the stump, the stem from stump to top, dead and living branches, and foliage. The common estimator, called e-Forest and developed within the Specific Contract 8, is a design-based unbiased estimator applicable to any cell in Europe regardless of the stratification, point weighting and use of clusters in the original NFI data (Lanz, 2012).

Using the common definition and estimator, the SC13 and SC17 produced harmonized and comparable biomass estimates at national and sub-national levels for 26 European countries (Henning et al, 2016; Korhonen et al., 2014). The biomass estimates referred to the areas defined as forest according to the FAO FRA reference definition (FAO, 2000), if the countries had sufficient information to apply this definition.

In particular, the harmonized biomass statistics produced within the two specific contracts consist of:

— the forest area (in hectares);

— the total biomass stock, and its standard error (in units of tons);

— the mean biomass density, and its standard error (in units of tons/ha).

The 26 countries provided four different estimates of the total biomass stock and mean biomass density. These four estimates were obtained using the national or the harmonized definition of biomass in combination with the national or the harmonized (e-Forest) estimator (Figure 2, Figure 3). The estimates were derived from a total of 516,394 field plots located in a forest area of 154 million ha, and were provided for species groups (broadleaves and coniferous) and also for individual species.

In the present study, the harmonized biomass statistics from SC13 and SC17 were compiled, screened for errors, checked for consistency with published statistics, and analysed (Avitabile and Camia, 2018). The results show that the total forest biomass for the 26 countries (spatial extent shown in the inset of Figure 4) is 4.1% higher using the harmonized definition compared to the value based on the national definitions (applying the national estimators). This is due to the fact that several countries use a national definition that does not include all aboveground biomass compartments, such as leaves or stumps. Specifically, the total biomass using the harmonized definition was significantly higher than the value based on the national definitions for 10 countries (AT, BG, CH, ES, FR, HR, HU, PT, RO, SE), smaller for 3 countries (BE, IE, IT), while no significant difference was found for 13 countries (CY, CZ, DK, FI, DE, IS, LV, LT, NL, NO, PL, SK, RS) (Figure 2, Figure 3). Here, significance is assessed with reference to the sampling errors provided with each estimate.

Interestingly, the results were more influenced by the biomass definition than the estimator used, since the use of national or harmonized estimator usually did not provide significant differences, confirming the reliability of the harmonized estimator. Since the national estimator provides estimates with smaller sampling error than the harmonized estimator and no significant differences, this study used the statistics based on the national estimators and harmonized definition.

The analysis of the harmonized biomass statistics by tree species and species groups showed that the total biomass stock of the 26 countries is almost equally stored between conifers (50.4%) and broadleaves (49.6%), with most biomass found in *Picea sp.* (22%) and *Pinus sylvestris* (19%), followed by *Fagus sylvatica* (11%), *Quercus robur* (7%), *Betula sp.* (7%) and *Quercus cerris* (4%). *Abies sp.*, *Alnus sp.*, *Carpinus sp.*, *Fraxinus sp.* and *Populus sp.* contributed individually to about 2% of the biomass stock, *Pinus pinaster*, *Castanea sativa*, *Quercus lepidobanalus*, *Larix decidua*, *Acer sp*. and *Pinus nigra* accounted individually for about 1% of the stock, and all other species for <1% (Figure 4).

The results of SC13 and SC17 represent a major step ahead towards a fully harmonized assessment of forest biomass resources in Europe, and strengthened the collaboration of the NFI institutions among each other and with the European Commission. Compared to the values reported at national or international level (such as the FRA or SoEF reports), the biomass statistics produced within SC13 and SC17 have the advantage to refer to the same biomass pool using a common methodology. In addition, the biomass statistics are provided at sub-national scale, which for most countries corresponds to the NUTS-2 level, while the international reports provide data only at national scale.

Figure 2: Total forest aboveground biomass stock per country, using the national or harmonized definitions in combination with the national or common estimators. The error bars represent the sampling error (data source: Henning et al., 2016; Korhonen et al., 2014)

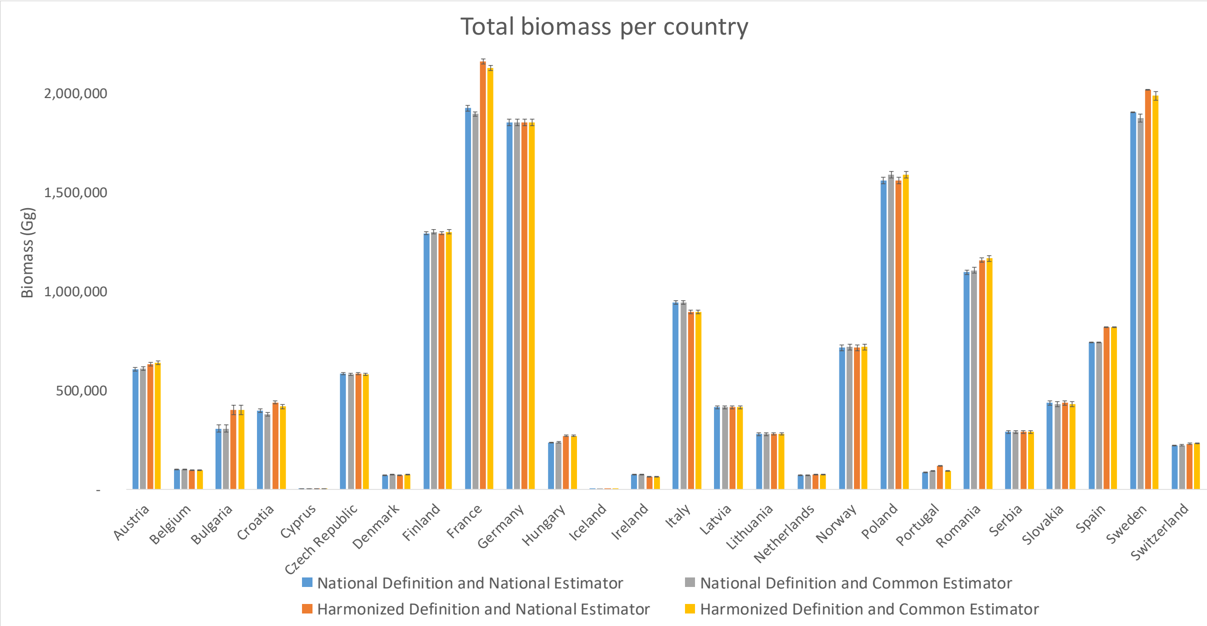


Figure 3. Mean forest aboveground biomass density per country, using the national or harmonized definitions in combination with the national or common estimators. The error bars represent the sampling error (data source: Henning et al., 2016; Korhonen et al., 2014)

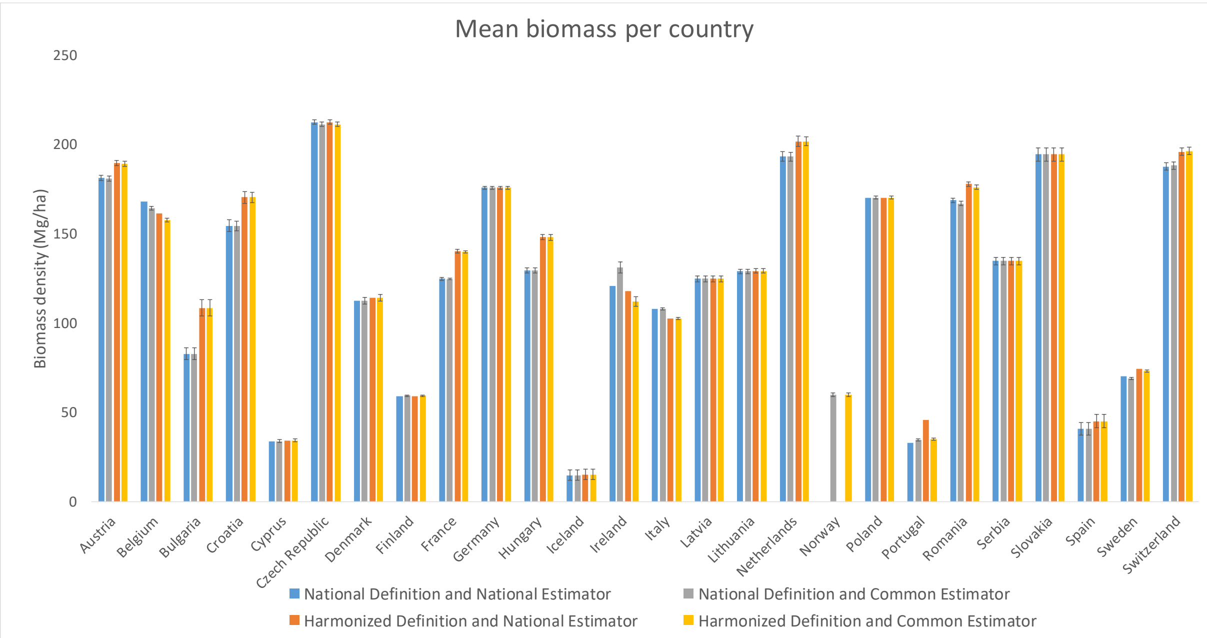
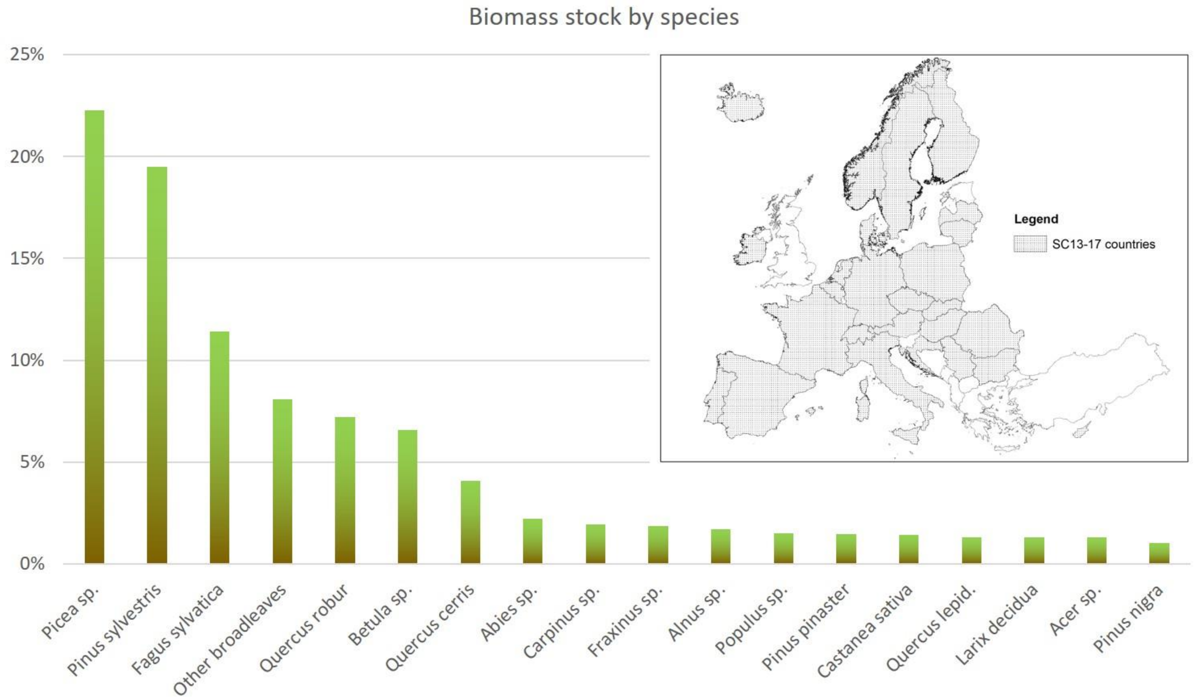


Figure 4. Contribution (in %) of the tree species to the total biomass stock of the 26 countries participating to the SC13-17. The inset shows the countries participating in the SC13-17 (data source: Henning et al., 2016; Korhonen et al., 2014).



2.2 Temporal harmonization

Each NFI acquires ground data during different years that do not correspond across countries. Consequently, the SC13 and SC17 biomass statistics reported above (Section 2.1) are not temporally harmonized but range from 2001 to 2013. Given that the biomass stock may change substantially in a time span of 12 years because of forest growth, mortality and harvest as well as changes in forest area (deforestation or afforestation), the biomass statistics from SC13 and SC17 were further harmonized to the reference year of the biomass maps (2000 and 2010) by the JRC using the Carbon Budget Model (CBM).

The CBM is an inventory-based, yield-curve-driven model that simulates the stand- and landscape-level carbon dynamics of all forest carbon pools (Kurz et al., 2009). The model, developed by the Canadian Forest Service, was adapted by the JRC to the specific European conditions and applied to the European Union (EU) countries to estimate the forest carbon dynamics (Pilli et al., 2016a, 2016b, 2017).

The CBM requires several pieces of information to model the fluxes and stocks in all forest carbon pools. The model is parameterized with country information at national or sub-national scale on age structure, management practices, harvest regimes and the main natural disturbances. The CBM was calibrated only for countries within the EU using the NFI data as reported by open-access website or directly provided by the national authorities, based on national definitions and methods and not harmonized for biomass pool.

In this study, the CBM was used to update the SC13-SC17 biomass statistics to the reference year of the biomass maps (see Chapter 4) by processing separately the data provided by each NFI, starting from the original NFI reference year and running the model until the reference year of the maps (2000 and 2010). Since the CBM input data were not harmonized for biomass definition, it was used only to quantify the percentage biomass change (gain or loss) between the NFI and the reference year. Then, the percentage change was applied as a correction factor to the SC13-SC17 statistics to update them to the reference year.

Since the CBM was applied to a predefined forest area, excluding land use change dynamics due to afforestation and deforestation, the temporal harmonization was performed for the SC13-SC17 statistics of biomass stock[2] (Mg) and biomass density (Mg/ha), maintaining the forest area constant. Therefore, the resulting statistics considered only the biomass changes related to forest growth, mortality and harvest but did not include the changes in forest area.

[2] 1 Mg = 1 metric ton

The temporal harmonization was performed for 21 EU countries, for which the SC13-SC17 biomass statistics were available and the CBM was parametrized. When the spatial scale of the estimates provided by the CBM was coarser than that of the SC13-SC17 statistics, the percentage change was computed at the coarser scale and then applied to the SC13-SC17 values. This approach allowed to maintain the higher spatial detail of the SC13-SC17 statistics assuming that, within a country, the rate of biomass change is relatively uniform within the sub-national administrative units.

2.3 Reference biomass statistics

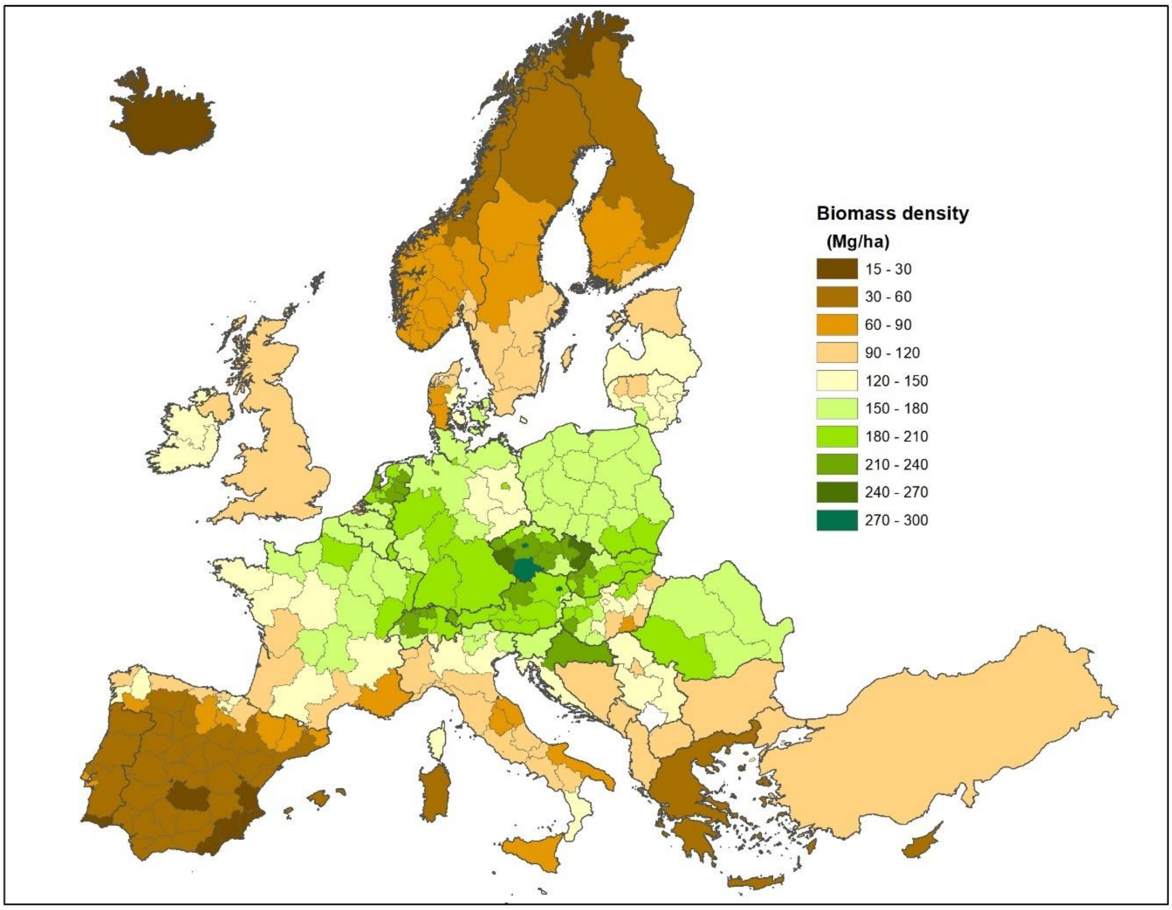
The best available data were compiled in a reference dataset of biomass statistics for Europe at national or sub-national level. As indicated above, it was not possible to perform a full harmonization of the biomass statistics for all European countries. The statistics were harmonized for biomass pool and reference year for the 21 EU countries included in the SC13-SC17 for which CBM was parametrized (AT, BE, BG, CZ, DE, DK, ES, FI, FR, HR, HU, IE, IT, LT, LV, NL, PL, PT, RO, SE, SK). For the five countries included in SC13-SC17 but not calibrated for CBM (CH, CY, IS, NO, RS), the SC13-SC17 statistics harmonized only for the biomass pool were used. For all 26 countries, the biomass statistics refer to the forest area reported by the source NFI.

For the remaining European countries, the reference statistics were taken from the SoEF 2015 Report (FOREST EUROPE, 2015a). The SoEF Report provides time series of forest statistics at national scale for the period 1990 - 2015 and refers to the FAO forest definition. However, the statistics produced by the CBM were preferred, when available, for two reasons. Firstly, the SC13-SC17 data are available at sub-national level, providing a much higher detail on the spatial distribution of the biomass stocks. Secondly, the SoEF harmonization of forest definition and reference year usually is not based on data modelling but rather it is performed either with a linear extrapolation of the NFI data, or using expected values based on expert knowledge (e.g., in national forecasts or outlook studies), or it is not performed and the closest available NFI values are used. The harmonization approach used for each country is indicated in the Country Reports of FOREST EUROPE (2015a).

The SoEF Report published in 2015 was used because it provided the most updated and revised values at the time of writing. However, the SoEF 2015 Report provides the biomass stock for the period 1990 – 2010 only in terms of total (aboveground + belowground) carbon, while the two components are reported separately for the year 2015. For this reason, the carbon stock data were first converted to biomass using 0.5 as carbon fraction for dry biomass (IPCC, 2006). Then, the aboveground biomass for the period 1990 – 2010 was computed as a fraction of the total biomass, assumed to be equal to the ratio between aboveground biomass and total biomass in 2015. Differently from the statistics derived from CBM that refer to the forest area in the year of the NFI, the biomass statistics provided by the SOEF refer to the forest area of the reference year.

The reference dataset of biomass statistics used in this study consists of a collage of the best available values at the highest spatial resolution, which ranges from NUTS 3 administrative units to national level. The biomass density and the spatial detail of the reference statistics for the year 2010 are presented in Figure 5, where the data at sub-national scale are derived from SC13-SC17 and the data at national scale are derived from the SoEF 2015 Report. Figure 5 reports the density of aboveground biomass (Mg/ha) within forest. The reference database can be further updated to recent years using the CBM and the latest SoEF statistics to match the reference year of new biomass maps that will be released.

Figure 5. Map of the reference biomass statistics, expressed as biomass density of the forest area (Mg/ha).



2.4 Biomass available for wood supply

The knowledge of the amount and spatial distribution of the Forest Available for Wood Supply (FAWS) is key to assess the woody biomass potentially available in European forests and more generally to assess the state of forest resources. For these reasons, reporting on FAWS has been included in the Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development (Sachs, 2012) and in the criteria and indicators for sustainable forest management of the 2015 SoEF Report (FOREST EUROPE, 2015a).

The definition of FAWS was initially established by FAO (1948) and then modified with the FAO Global Forest Resources Assessment 2000 (FAO, 2001). Later, in the period 2010 - 2014 the COST Action FP1001 improved and harmonized data and information on the potential supply of wood resources at European level (COST 4137/10, 2010). Under the framework of the COST Action and based on the FAO (2001) definition, a reference definition for harmonizing reporting was formulated and agreed upon. This definition, used also in the SoEF Report (FOREST EUROPE, 2015b), identifies FAWS as "forests where there are no environmental, social or economic restrictions that could have a significant impact on the current or potential supply of wood" (Alberdi et al., 2016).

However, notwithstanding the reference definition, the FAWS estimates in the international reporting are of limited comparability because of the different interpretation of the definitions or the use of different restrictions and related thresholds (Alberdi et al., 2016; Fischer et al., 2016). In addition, the FAWS data available in the international reporting are limited to summary statistics at national scale, while a more detailed spatial information is needed to better assess and model the potential supply, and related costs, of woody biomass from the European forests.

2.4.1 Harmonization of national data

Given these limitations, during the period 2017 - 2019 the JRC supported two service contracts (SC18 and SC19) with 22 European countries where the respective NFI institutions assessed, in a harmonized approach, the main restrictions to wood availability and quantified the forest area and biomass stock available for wood supply (Alberdi et al., 2017, 2019, 2020). Considering that the national definitions of FAWS present fundamental differences that limit their comparability (Alberdi et al. 2016), the dedicated service contracts focused on a more comparable attribute: the Forest NOT Available for Wood Supply (FNAWS).

The two service contracts involved a number of countries to represent the different environmental conditions and restriction for wood supply of the European territory. Namely, the 22 countries participating in the methodological analysis were AT, BG, CH, CZ, DE, DK, ES, FR, HU, IE, IS, IT, LT, LV, NL, NO, PO, PT, RO, SE, SK, SI. The area and biomass of the FNAWS were then estimated for 20 countries, i.e., all participanting countries besides FR and DK.

The work performed by the NFIs within SC18 and SC19 produced three main outcomes. First, according to the FAWS reference definition, it was identified and agreed upon a reference definition for FNAWS (Alberdi et al., 2020). The definition was accompanied by an explanation of the key terms, a harmonized list of restrictions to wood supply, and the comparison of the national and harmonized definitions.

Second, the FAWS/FNAWS area and biomass were quantified using the NFI plot data and a common estimator at national and sub-national level, applying both the national and the reference definitions. The results are based on the same methodology and data used in the SC13 and SC17 for the calculation of the harmonized biomass stock (see Section 2.1), making the statistics on total standing forest biomass and the fraction available for wood supply directly comparable. The results were also compared with the FAWS statistics reported in the SoEF 2015 Report (FOREST EUROPE, 2015a).

Third, the limitations to the availability of forest for wood supply were assessed using a common and detailed list of restrictions, which allowed to quantify the impact of each restriction at regional, national and sub-national level for the 20 countries involved in the study. A detailed analysis of the results for the 13 countries involved in the SC18 is reported by Alberdi et al. (2020).

In summary, compared to the SoEF reports, the FAWS data of SC18 and SC19 have the advantage to use a common definition and methodology and to provide statistics of forest area and biomass available for wood supply for 20 European countries at national and sub-national scales with a detailed quantification of the restrictions to wood availability. However, these data were not harmonized for reference year and therefore they refer to the period of the related NFIs, ranging between 2002 and 2014.

2.4.2 Restrictions to the use of forest for wood supply

The SC18 and SC19 found that both the forest area and the biomass stock available for wood supply was larger than 85% for 17 of the 20 countries involved in the study. The differences between FAWS estimates based on national and harmonized definitions were small, suggesting that the harmonized definition was appropriate, while large differences among the countries were found in the role of the restrictions.

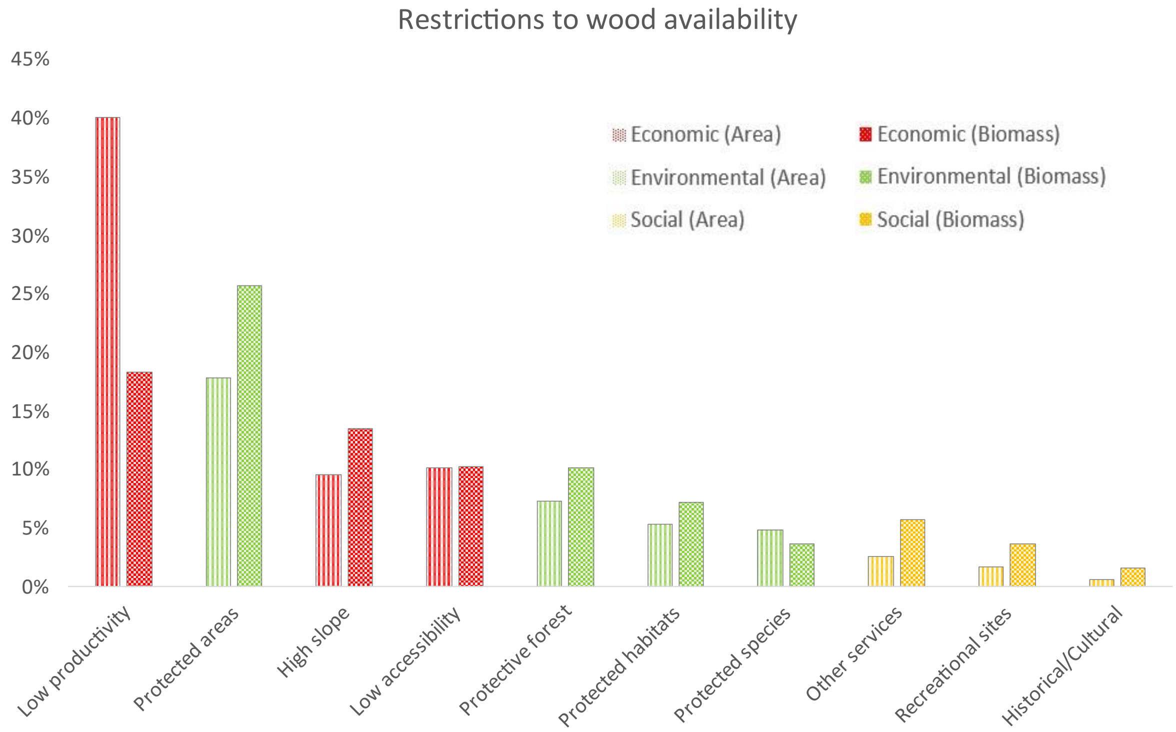
Overall, the economic restrictions were responsible for 60% of the forest not available in terms of area but only 42% in terms of biomass, as they affected forests often characterized by low productivity and hence low biomass stock. Instead, the environmental restrictions were responsible for 35% of the forest not available in terms of area but 47% in terms of biomass, because they included protected areas with old-growth forests characterized by high biomass density. The social restrictions played a smaller but not negligible role, being responsible for 5% of the forest not available in terms of area and 11% in terms of biomass (Figure 6).

Among the economic restrictions, the low profitability was the main factor limiting the use of the forest, causing 40% of the area (18% of the biomass) being not available for wood supply, which was mostly located in the low productive Scandinavian forests (Sweden and Norway). The low accessibility to the forests was responsible for 10% of the area (10% of biomass) not available, mostly related to the excessive distance from forestry roads. Similarly, the excessive slope of the terrain caused 10% of the area and 13% of the biomass being not available.

Among the evironmental restrictions, the protected areas, habitats and species all together accounted for 28% of the area and 37% of the biomass not available for wood supply, with the protected areas being the main category (18% of the area and 26% of biomass) followed by protected habitats, mostly represented by the Natura 2000 network, and the protected species, mostly due to oak trees in the Iberian peninsula and Pinus mugo in the Alps. The protective forests, including the forests for soil protection and water regulation, were responsible for 7% of the area and 10% of the biomass not available for wood supply.

Among the social restrictions, the main limiting factor was the use of forest for intangible goods and services, mostly for recreational purposes and to a lesser extent for cultural and spiritual sites. The use of the forests for physical goods and services, such as forestry nursery, game enclosures and power lines, affected a smaller area. However, the specific social restriction was not reported for 37% of the area, where the forest was generically used for non-harvesting goods and services.

Figure 6: Percentage contribution of each restriction to the forest available for wood supply in terms of area (left bars with light colors) and biomass (right bars with dark colors). The restrictions are divided in three main categories: economic (red), environmental (green) and social (orange) restrictions.



2.4.3 Reference database on FAWS

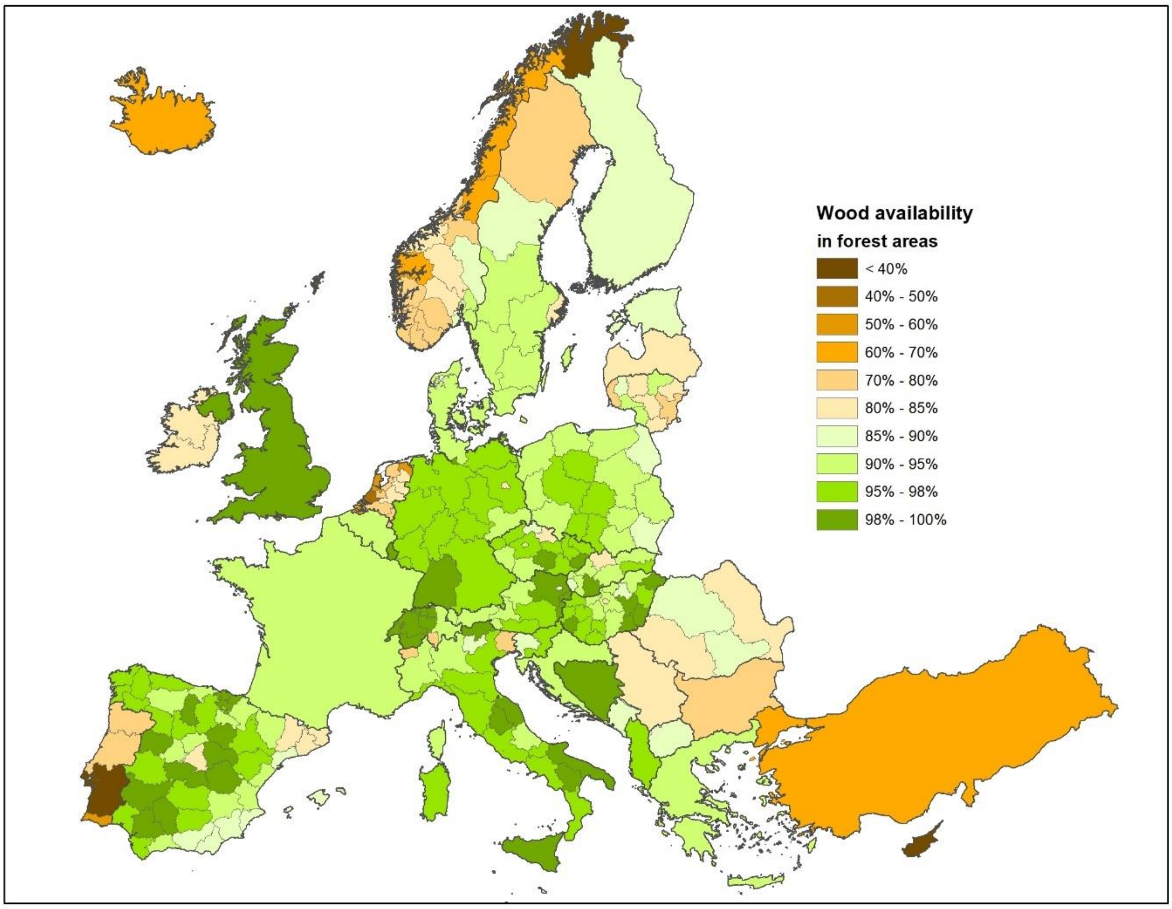
The FAWS results from SC18-SC19 were integrated with the FAWS statistics provided by the SoEF 2015 Report for the remaining countries (AL, BA, BE, CY, DK, EE, FI, FR, GR, HR, LI, LU, ME, MK, RS, TR, UK) into a reference database of FAWS data for Europe, which provides an overview of the wood resources available in the European forests (Figure 7). This database used the SoEF data for the year 2010, as they were closer to the reference years of the NFI data used in the SC18-SC19.

Since the SoEF Report provides the FAWS area and related growing stock volume but not the biomass stock, Figure 7 reports the wood availability for all European countries in relative terms and it refers to the available biomass stock for the countries participating in the SC18-SC19 (data available at sub-national level) and to the available growing stock volume for the remaining countries (data available at national level).

The reference database on FAWS is a compilation of the best data currently available. It shows that in Europe, on average (weighted by the forest area), 85% of the forest area and 89% of the wood is available. In most countries, the FAWS is larger than 80% both in terms of area and biomass, but it tends to decrease in very hot or cold climate, reaching less than 70% in TR and IS, and less than 60% in PT and CY. In case of NO, the FAWS is only 59% in terms of area but 78% in terms of biomass, because most forest areas not available are also characterized by a low biomass density.

As indicated above, the remainder of this Report refers to the total standing biomass and does not distinguish the fraction that is available (or not) for wood supply. However, the harmonized statistics on FAWS are an essential component to better understand and model the factors limiting the forest availability for wood supply in Europe and the potential biomass available in the future. In particular, the SC18-SC19 provided harmonized data on FAWS for 243 sub-national administrative areas, providing a much higher spatial detail of the distribution of the FAWS area, stock and related restrictions compared to the national data. This spatial information is key to quantify the factors limiting the wood availability at local level, to support and guide the mapping of FAWS using remote sensing data, and to model the wood resources available at a fine spatial resolution.

Figure 7. Percentage of wood available in European forests. The percent of wood is in unit of aboveground biomass for countries with data available at sub-national level (countries participating in the SC18-19) and in unit of growing stock volume for countries with data available at national level (data derived from the SoEF 2015 Report).



3 Biomass plots

The NFI statistics on forest biomass are usually derived from field plots using statistical estimators. Field plots are ground measurements of forest properties and tree characteristics (typically, diameter, species and height) from which the tree biomass stock and the plot biomass density are estimated using allometric equations and expansion factors. Thus, field plots provide local estimates and not measurements of biomass, because biomass can only be measured by harvesting and weighing of the dry mass. However, even if affected by uncertainty and not error-free, the plot-level biomass estimates are considered of higher quality than those obtained by remote sensing and are often used for calibration and validation of the biomass maps obtained by satellite data.

More than half million ground measurements within forest land have been acquired in Europe by the NFIs during the last two decades. However, in most countries, the results of the plot measurements are either not accessible to researchers outside the national authorities or available with approximated geolocation because of national security and privacy reasons.

In this study, two types of plot datasets were used:

— SC13-17 plots: a subset of the NFI plots for 26 European countries made available to JRC through the SC13 and SC17 with harmonized biomass definition but approximated location (Section 3.1);

— NFI plots: the NFI plots that are made openly accessible online by the NFI institutions in Europe, either with precise or degraded geolocation (Section 3.2).

Biomass plots are used in this study to assess and validate at local scale existing biomass maps. In particular, the SC13-17 biomass plots were used to assess the biomass maps over the whole Europe (Chapter 5) while the NFI plots with precise geolocation were used to validate the bias-corrected biomass map (Chapter 6).

As with the biomass statistics, the biomass plots need to be harmonized among themselves and with the biomass maps to reduce the temporal and spatial mismatches between plots and maps. The temporal mismatch occurs when the biomass estimates refer to different periods, and is addressed by updating the plots to the reference year of the map using growth rates (Section 3.3.1). The spatial mismatch is due to the difference in spatial resolution between the plots (< 1 ha) and the map cells (1 – 100 ha) or to the approximated plot location, and is addressed by carefully screening the plots to select only those which are representative of the biomass density of the corresponding map cells (Section 3.3.2).

Since the spatial and temporal mismatches can be reduced but not completely removed with the screening and harmonization procedures, and considering that the plots are affected by the errors inherent in the estimation of biomass from tree parameters using allometry, the comparisons of field plots with biomass maps (presented in Chapter 5 and 6) should be considered not as a definitive and precise assessment of the maps accuracy based on "ground truth" but rather as an indication of the maps performance at local scale.

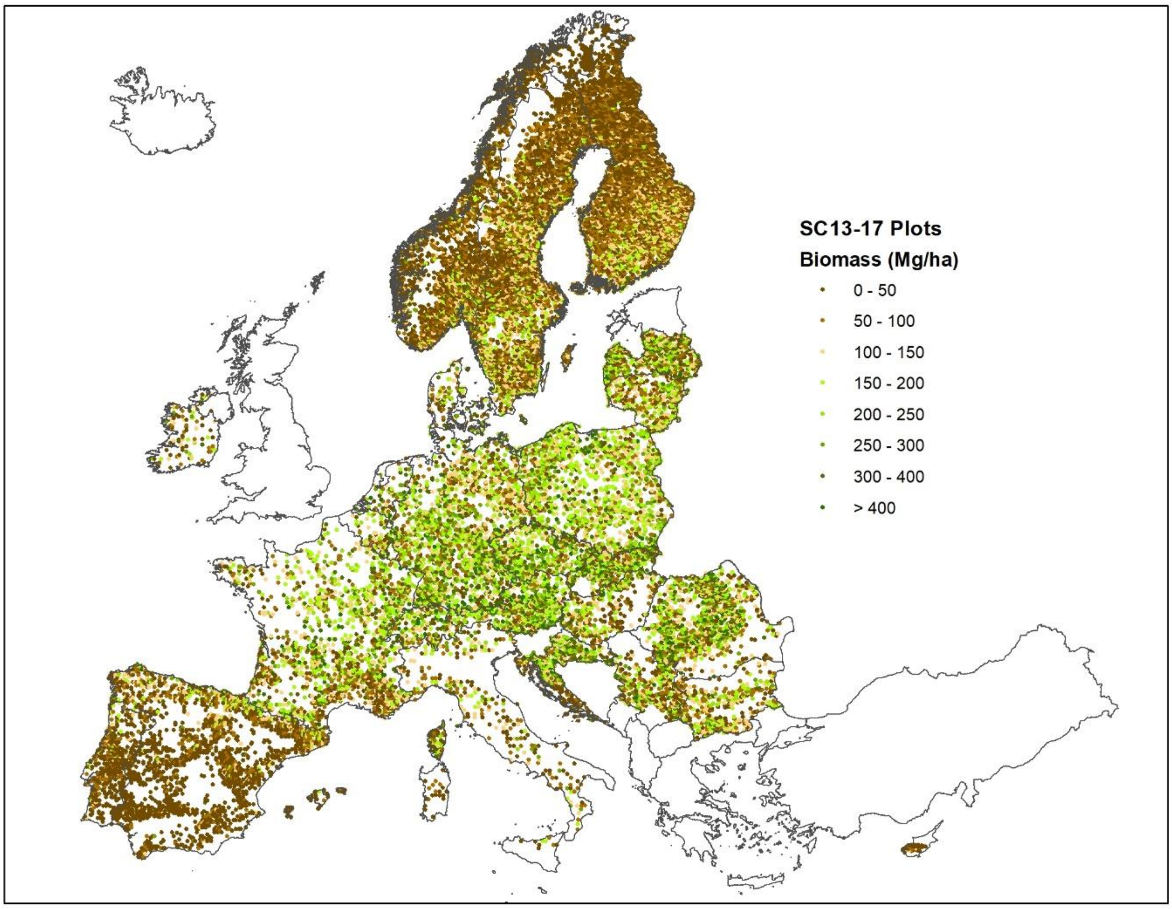
3.1 SC13-17 biomass plots

The 26 European countries that participated to the SC13 and SC17 produced a systematic subset of their NFI plots with biomass estimates harmonized for biomass definition, here called SC13-17 plots. The subset provides the biomass density of one NFI plot for each 8 km Inspire grid cell, for a total of 22,166 field plots distributed throughout Europe (Figure 8). The plots are provided with geolocation approximated to the 1 km Inspire grid.

The SC13-17 plot database needed to be screened and harmonized with the biomass maps to reduce the spatial mismatch caused by the plot approximated geolocation, and the temporal mismatch due to the acquisition of the ground measurements in different years ranging from 2001 to 2013 (Section 3.3).

The number of plots of the SC13-17 database is substantially smaller compared to the number of plots available in the NFI plot dataset (Section 3.2). However, the SC13-17 plot dataset has the main advantages to provide harmonized biomass estimates and to cover most European forests, including several east European countries for which no other plot data are currently available. For these reasons, this dataset provides a unique ground reference database representing the variability of biomass density at local scale across Europe, and can be used to assess the local performance of the biomass maps for Europe (Avitabile and Camia, 2018).

Figure 8. Biomass plots provided by the NFIs within the SC13-17 for 26 European countries with harmonized definition and geolocation approximated to 1 km



3.2 NFI biomass plots

During the last years, a few European NFIs have made their plot-level data freely available online. The plot data are provided in different forms depending on the country, ranging from tree-level measurements to aggregated plot-level information. Currently, six European countries provide open-access plot information: France, Germany, Italy, Spain, Sweden and The Netherlands (Table 1). However, the NFI plot data are provided in a form that may not be readily available for biomass studies, for three main reasons.

Firstly, the plot information is provided with complete geolocation only for Spain, Sweden and the Netherlands, while they are approximated to 1 km resolution for France, Germany and Italy. Knowing the precise geographic location of the plots is very important to compare them with map pixels, especially in European forests characterized by high heterogeneity of tree species and forest structure, which causes high spatial variability of biomass density.

Secondly, the NFIs do not always provide the biomass density of the plots but only the growing stock volume, as in the case of France and the Netherlands. The growing stock volume estimates (unit: m^3/ha) need to be converted to aboveground biomass (unit: Mg/ha) using biomass conversion and expansion factors. The conversion should be done with local and species-specific factors, but they are not always available or easily accessible, and using more generic coefficients (e.g., from IPCC, 2019) may introduce substantial uncertainty in the biomass estimates.

Thirdly, each NFI applies a national definition for forest and biomass, hence the plot values do not refer to the same biomass compartments but present some differences due to the inclusion or exclusion of (e.g.) small branches, foliage, stumps. Moreover, the analysis of the NFI data showed that they present considerable heterogeneity in terms of sampling design (e.g., plot size), time of acquisition and spatial resolution to which are publicly released (Table 1). Such differences need to be taken into account and reduced as much as possible when the plot data were compared with the biomass maps.

In this study only the NFI plots of Spain and Sweden were used to assess the biomass maps because these plots are provided with complete geolocation and biomass density (Chapter 6). Instead, the NFI plots with approximated geolocation to 1 km or without biomass estimates (i.e., providing only volume) were not included in the assessment of the maps because they are mostly redundant with the SC13-17 plot dataset, which has the advantage to provide plot-level biomass estimates harmonized for biomass definition and pool.

Table 1. Metadata of the NFI plots openly available. In this study, only the NFI plots for Spain and Sweden were used to assess the biomass maps.

Country	N. plots	Reference Years	Plot size (ha)	Variable	Permanent plot	Geolocation
France	50,470	2008-2012	0.071	Volume	No	1 Km
Germany	18,106	2000-2003	Angle-count	Biomass	Yes	1 Km
Italy	7,272	2003-2006	0.053	Biomass	No	1 Km
Spain	59,928	1997-2007	0.196	Biomass	Yes	Plot-level
Sweden	29,178	2007-2018	0.015	Biomass	No	Plot-level
The Netherlands	3,658	2012-2013	0.126	Volume	Yes (50%)	Plot-level

3.3 Harmonization and screening of the field plots

The field plots are used in this study to assess the estimates of the biomass maps at pixel level (Chapter 5 and 6). To perform a proper assessment of the biomass maps, the field plots need to be screened and harmonized with the maps before the comparison. Even though the two plot datasets described above (SC13-17 and NFI plots), are used separately to assess the maps, the procedures to harmonize and select them are the same. Such procedures are aimed to update the plots to match the reference year of the biomass maps (temporal harmonization) and to remove the plots that are not representative of the map pixels (spatial screening).

3.3.1 Temporal harmonization

The temporal harmonization is necessary because the year of acquisition of the plots varies largely between countries, and differs with the reference year of the biomass maps. The temporal harmonization of the plots uses a different approach compared to the temporal harmonization of the reference biomass statistics (Section 2.2). Here, the temporal harmonization follows a two-step process and is performed using growth rates instead than a forest growth model (as for the reference statistics) because of the lack of tree-level data necessary for the modelling approach.

Firstly, the plots are checked with a tree cover change map to detect deforestation or reforestation events. The high-resolution (30 m) Global Forest Change map produced by Maryland University (Hansen et al., 2013) was used to identify and discard the plots located in pixels where tree cover change (loss and gain) occurred between the NFI plot acquisition and the year of the biomass maps. The forest change processes affected a substantial number of plots. Ad example, in the case of the NFI plot dataset, this screening discarded 11% of the available plots, of which 9% were located in pixels with forest loss and 2% in pixels with forest gain.

Secondly, the biomass density of the plots was updated to the reference year of the biomass maps using the IPCC Tier 1 Growth rates (IPCC, 2006). Specifically, the biomass density of each plot was increased or decreased (depending if the plot was measured before or after the maps) of the biomass growth occurred between the year of measurement of the plot and the reference year of the map. Since the IPCC coefficients are provided by continent and ecozone, each plot was related to an ecozone using the FAO Global Ecological Zone map (FAO, 2001). In case the IPCC provided a range of growth rates, the mean value was applied. When the IPCC provided a different rate for forest younger or older than 20 years, the appropriate growth rate for the plot was identified by computing the expected biomass density at 20 years, estimated by multiplying the growth rate of younger forest by an age factor of 20. Then, if the biomass of the plots was lower than the expected biomass at 20 years, the growth rate for young forest was applied, otherwise the growth rate for older forest was used.

3.3.2 Spatial screening

The field plots were screened to assess if they represent the biomass density of the corresponding map pixel. The representative plots were then used to assess the biomass maps. Since the SC13-17 biomass plots were provided with a geolocation approximated to the centre of the 1 km Inspire grid cell, the plots were assessed for representativeness over the 1 km^2 area of the corresponding grid cell. In such case, the biomass maps were resampled to this 1 km grid using bilinear interpolation. Instead, the NFI biomass plots provided with complete geolocation were assessed for representativeness over the pixel of the biomass maps in which they were located. In this case, the screening procedure was also aimed to identify spatial mismatches due to the plot geolocation errors caused by poor GPS recording in the field.

The representativeness of the field plots was assessed based on the tree cover variability over the corresponding grid cell, considering tree cover as a proxy for biomass density. The tree cover statistics of the grid cells were obtained from the 30 m Global Forest Cover dataset (Hansen et al., 2013). The plot screening mostly followed the methodology presented by Avitabile and Camia (2018) and consisted of five steps (Figure 9).

Step 1: the plots with biomass > 0 located in areas with no tree cover were removed. Instead, the plots with no tree cover and no biomass were retained as they represent non-forest areas.

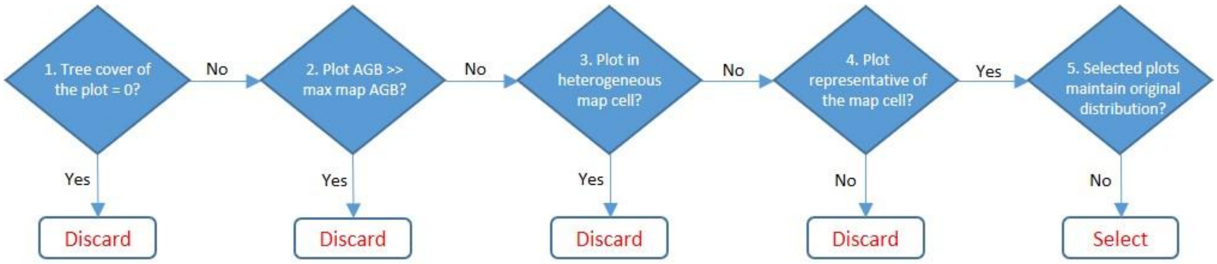
Step 2: the field plots with biomass density substantially higher than the maximum value reached by the biomass maps were removed to reduce the difference of scale between the plots and the pixels. The rationale for this selection lies in the different spatial resolution of the two datasets: the field plots usually have a much smaller size (< 1 ha) than the map pixel (1 - 100 ha) and it is known that the biomass density range depends on the spatial resolution, with lower mean values over larger areas. Hence, the biomass density in dense forest can reach very high values over small areas (i.e., the size of field plots), but it is unlikely that such values occur constantly over the larger map pixels. Therefore, plots with extreme high biomass were considered inappropriate to validate the accuracy of the biomass maps. Using the boxplot distribution of the plots, the threshold value of 600 Mg/ha was defined, which is higher than the maximum value of the biomass maps (511 Mg/ha) and corresponds with the 1.5 inter-quartile range of the upper quartile.

Step 3: the plots located in map cells with heterogeneous tree cover were discarded. This step was based on the assumption that the biomass density varies accordingly with the tree cover and that a small sample plot in a grid cell with heterogeneous forest cover is unlikely to be representative of its biomass. The grid cells were considered heterogeneous when the standard deviation of tree cover was larger than 15%. This threshold was defined by combining visual analysis of Google Earth images, empirical test and sensitivity analysis. For example, it was noted that restricting the threshold from 15% to 10% reduced considerably the amounts of selected plots but did not change the map validation results, which however become less stable due to the small number of selected plots. Instead, increasing the tree cover standard deviation to values higher than 15% resulted in selecting pixels where the tree cover variability, assessed with the visual analysis of high-resolution images on Google Earth, became too large to assume plot representativeness.

Step 4: the plots located in grid cells with homogeneous tree cover (standard deviation < 15%) but not representative of the pixel biomass because of local scale variability were also removed. This procedure aimed to remove the plots located in a small patch of forest within a mainly non-forested pixel, or plots located in a small opening within a forested pixel. The indicator used to identify this local-scale variability was the relation between tree cover and biomass, which tends to increase linearly until the tree cover saturates. The scatterplot between tree cover and biomass was used to identify the plots with a biomass density not related to the tree cover density. The relation between these two variables was modelled using a logarithmic regression model, and the plots with biomass outside of the 75% prediction interval were discarded.

Step 5: the histogram of the selected plots was compared with that of the original plot dataset to assess if the selected plots maintained a similar distribution of biomass values. Since the screening procedure tended to select plots located in areas with dense tree cover and therefore high biomass while removing plots in open forests (inherently characterized by larger spatial variability), the histogram of the selected plots tended to be skewed right in terms of biomass density. To avoid bias in the validation results, the screened plots were further selected to obtain a subset with a histogram representative of the distribution of the original plots. The plots were assessed by biomass bins of 50 Mg/ha each, and when the relative frequency of the screened plots was higher than that of the original dataset for a certain bin, a random sample was taken from the screened plots to match the relative frequency of the original dataset. In case the frequency of the screened plots was smaller, the screened plots were not sampled further. This process was repeated iteratively until the relative difference among the selected and original plots for each biomass bin was smaller than 5%, leading to similar distribution of the two datasets.

Figure 9. Flowchart of the screening procedure for the biomass plots



The five steps of the screening procedure have a very different impact on the number of plots that are discarded at each step. For example, considering the NFI biomass plots, the screening procedure discarded in total as much as 62% of the available plots, and each step contributed as follows:

— Step 1: 16% of the plots were removed because located in grid cells with no tree cover;
— Step 2: 0.01% of the plots were removed because presenting biomass density higher than 600 Mg/ha;
— Step 3: 22% of the plots were removed because located in heterogeneous grid cells;
— Step 4: 11% of the plots were removed because presenting a biomass density not related to the tree cover density of the grid cell;
— Step 5: 2% of the plots were removed to obtain a subset of the plot with a distribution by biomass class similar to that of the complete dataset.

4 Biomass maps

4.1 Description of the biomass maps

Currently, there are six published maps providing forest biomass density for Europe: the datasets of Santoro et al. (2018a), Baccini et al. (2017), Thurner et al. (2014), Barredo et al. (2012), Gallaun et al. (2010) and Kindermann et al. (2008). These maps are hereafter referred to with the name of the first author.

The Santoro map, produced by the ESA GlobBiomass project, is a global-scale, wall-to-wall map of aboveground biomass of woody vegetation at 100 m resolution for the year 2010. The map is based on spaceborne SAR, lidar and optical observations and also uses auxiliary datasets from forest inventories, climatological variables and ecosystems classifications. This product is based on a modelling framework that adapts to different forest and environmental conditions and does not require in situ data for calibration. Remote sensing data were used to estimate the Growing Stock Volume (GSV). The GSV values were then converted to aboveground biomass using wood density estimates and stem-to-total biomass expansion factors, derived from a global data pool of in situ measurements. The biomass definition refers to the oven-dry weight of the woody parts (stem, bark, branches and twigs) of all living trees excluding stump and roots.

The Baccini map is a global-scale, wall-to-wall map of aboveground biomass of woody vegetation at 30 m resolution for the year 2000. This product, provided by Global Forest Watch (2018), expands on the methodology presented in Baccini et al. (2012). This approach first derives a global sample of biomass estimates from the spaceborne Geoscience Laser Altimeter System (GLAS) lidar observations using allometric equations based on lidar-derived canopy metrics. Then, the GLAS biomass estimates are used to train empirical models to predict biomass from spatially continuous data, namely Landsat images, tree canopy cover data, climate variables and Digital Elevation Models (DEMs).

The Thurner map covers the complete northern hemisphere above 30° at the resolution of approximately 1 km for the year 2010. Similarly to the Santoro map, this product is based on a GSV map derived from ENVISAT ASAR images (Santoro et al., 2015), and the volume map is then converted to aboveground biomass using local biomass expansion factors.

The Barredo map provides the aboveground biomass and total (aboveground and belowground) carbon stocks for European forests at 1 km resolution for the year 2010. This map spatializes the IPCC Tier 1 biomass density values per forest type and ecozone using the CORINE land cover map and the FAO Global Ecological Zone (GEZ) map, and further harmonizes the estimates to match the national values reported in the FAO FRA 2010 Report.

The Gallaun map provides growing stock volume at 500 m and forest aboveground biomass density at 10 km resolution for Europe for the year 2000. This map is based on the CORINE land cover map, MODIS images and NFI data from 16 European countries, and further harmonizes the estimates to match the EFISCEN data for the year 2000.

The Kindermann map is a global-scale map of forest aboveground biomass density at approximately 1 km resolution. This map downscales the FAO FRA 2010 national biomass statistics on the basis of the MODIS Net Primary Production (NPP) products and a map of human impact. The map used in this study is a version updated to the year 2010 (Kindermann, pers. comm.) of the original map produced using statistics for the year 2005 (Kindermann et al., 2008).

An overview of the map characteristics is provided in Table 2. The maps present an increasing level of complexity in their modelling approaches. A key difference among the maps is that the Barredo and Kindermann maps essentially spatialize the total national biomass stocks using spatial data (hence, maintaining the correspondence with the total country values) while the Santoro, Baccini, Gallaun and Thurner maps used reference biomass data to calibrate a model based on satellite images without constraining ex-ante the estimates to match the national statistics. However, the Gallaun map was ex-post adjusted to match the regional values provided by the EFISCEN model, for the regions covered by the model.

The maps also differ with regard to their spatial coverage because they used different forest masks. The Santoro and Baccini maps did not use a forest mask but only masked out the areas with no vegetation: the Santoro map used the ESA CCI land cover map to identify and remove the areas classified as urban, bare or water bodies, while the Baccini map used a global tree cover map to identify vegetated areas. The Kindermann and Thurner maps used the forest classes of the GLC2000 map, which applies a minimum canopy cover of 15%. Both maps included the mosaic class where forest covers at least 50% of the pixel area, and the Kindermann map further included the mosaic class with a forest coverage of 20%. Instead, the Barredo and Gallaun maps used the forest area of the CORINE land cover map, which applies a minimum canopy cover of 30%, but the Gallaun map further adjusted the forest cover threshold separately for each country to match the FAO FRA 2000 statistics (Table 2).

Table 2. Main characteristics of the biomass maps for Europe. The acronyms in the table are explained in the List of Abbreviations and Definitions.

Map	Reference data	Spatial data	Auxiliary data	Forest mask	Year	Resolution
Santoro	NFI statistics	ALOS, ASAR, Landsat	Climate, Ecozone, BEF	ESA CCI	2010	0.00089° (~100 m)
Baccini	Field plots	Landsat, GLAS	Ecozone, Climate, DEM	Tree Cover map	2000	0.00025° (~30 m)
Thurner	NFI statistics	ASAR	BEF	GLC2000	2010	0.01° (~1.1 km)
Barredo	IPCC Tier 1	CORINE, GEZ	FAO statistics	CORINE	2010	1 km
Gallaun	NFI plots	MODIS	CORINE, EFISCEN	CORINE, FRA	2000	500 m
Kindermann	FAO statistics	MODIS NPP	Human impact map	GLC2000	2010	0.083° (~1 km)

4.2 Processing of the biomass maps

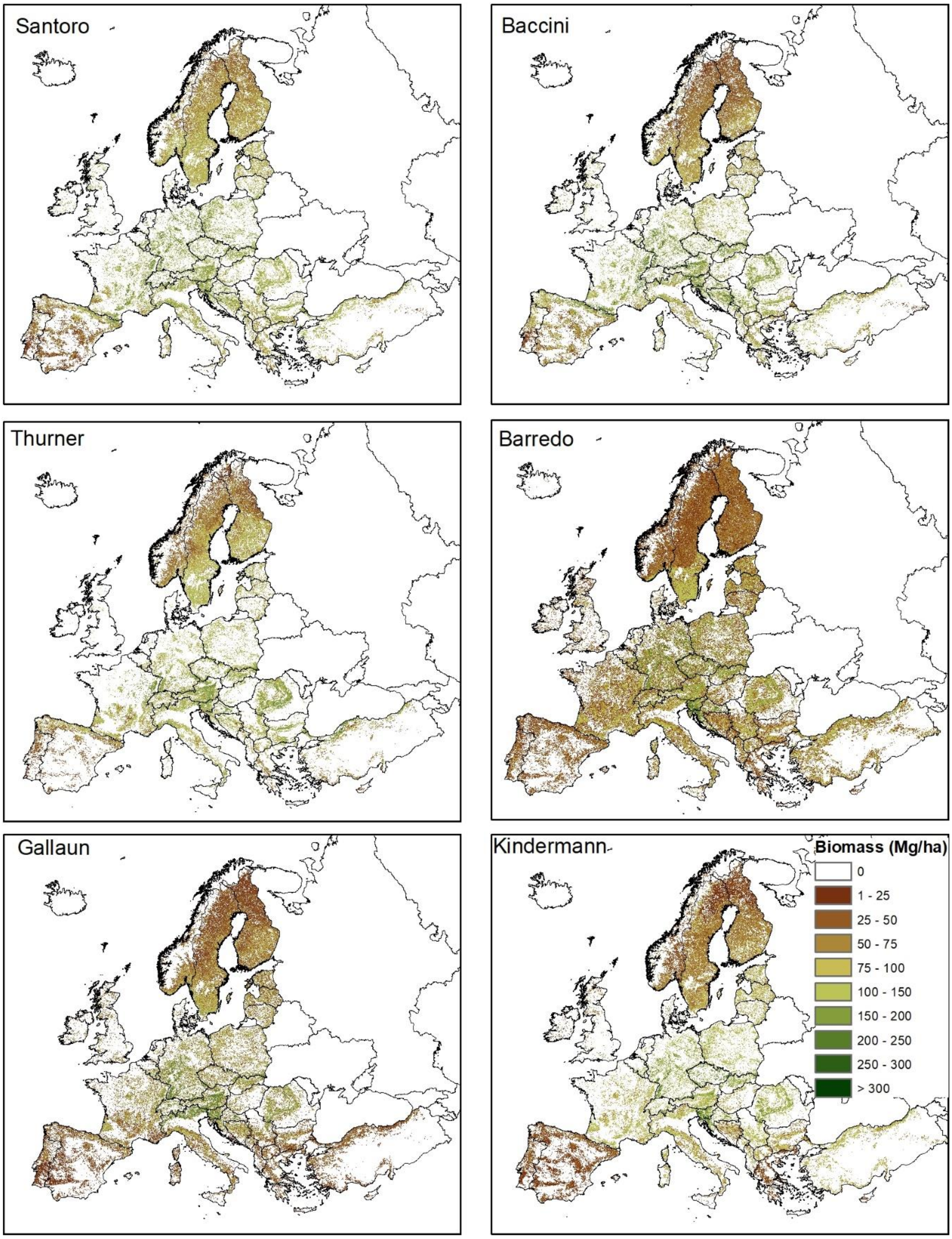
The six biomass maps were harmonized to the same reference system (Lambert Azimuthal Equal Area), study area (Europe), unit (aboveground biomass density in Mg/ha) and spatial resolution (100 m for the Santoro and Baccini maps, 1 Km for the other maps) (Figure 10). Each map required an ad-hoc pre-processing. In particular, the Gallaun map provides the GSV at 500 m and biomass density at 10 km resolution, and it was harmonized using the following procedure: the GSV map was first aggregated to 10 km and compared to the 10 km biomass map to derive biomass expansion and conversion factors for each 10 km cell, which were applied to convert the 500 m GSV map to biomass units, then aggregated to the resolution of 1 km. The Thurner map was provided in unit of carbon obtained using carbon fractions dependent on the leaf-type as mapped by the GLC2000 map, and it was converted back to biomass units using the respective forest types provided by the GLC2000 map.

The biomass maps are not directly comparable among each other and with the reference biomass statistics because they were produced using different forest masks (i.e., forest maps applying different forest definition and spatial resolution) and thus presented substantial differences in the area included, especially in the transitional areas between forest and non forest. The choice of the forest mask is critical also because the biomass maps provide the biomass density relative to the land area and, due to their coarse resolution (100 m - 1 km), the map cells may cover heterogeneous areas with only a fraction of forest cover. Instead, the reference statistics based on the NFI data provide biomass density with regard to the forest area.

Thus, in order to compare the biomass density of the maps and the statistics over the same (or, similar) forest area, the biomass maps were masked using the EFI Forest Map of Europe (Gunia et al., 2012). The EFI map was chosen because, differently from other forest maps, it was calibrated with the NFI statistics on forest area. The EFI map provides the percent forest cover at 1 km resolution and it was converted to a forest – non forest map by selecting the cells with predominance of forest cover (i.e., larger than 50%). Such threshold produced a forest mask that was highly consistent with the forest area reported by the reference statistics. The forest mask was applied by setting to no data the map cells located in non-forest areas.

The maps were also assessed using their native forest mask to take into account that the application of a common mask underestimates the stock of the maps produced with a more stringent forest mask, which excludes areas that are included in the common forest mask. Therefore the assessment of the total stock was performed using the biomass maps with their original extent, and the results incorporate both the biomass estimates and the land area covered. In the case of the Santoro and Baccini maps that masked out only the areas with no vegetation but include also non-forest vegetation, the ESA Copernicus Forest Type map at 100 m resolution for the year 2012 was applied as forest mask because it matched the spatial resolution and presented a high correspondance with the forest area of the reference statistics.

Figure 10. The six biomass maps for Europe harmonized to the same reference system, unit, study area, legend and spatial resolution, but with their original forest mask: the Santoro, Baccini, Barredo, Kindermann, Gallaun and Thurner maps (clockwise, from upper-left).



5 Assessing the biomass maps with harmonized statistics and plots

5.1 Maps assessment with the reference statistics

The six biomass maps were assessed by comparing them with the reference biomass statistics for 37 European countries with regard to mean biomass density and total biomass stock. The comparison was performed at three spatial scales: at European scale, at national scale and at the resolution of the reference statistics (hereafter referred to as “sub-national” scale), which included data at sub-national level for 22 countries and at national level for 15 countries (see Section 2.3). The reference data at sub-national level usually corresponded to the NUTS-2 administrative units, with the exception of few cases where data at NUTS-1 or NUTS-3 level were available. The reference statistics correspond to the reference year of the biomass maps, which is the year 2000 for the Gallaun and Baccini maps and the year 2010 for the Barredo, Kindermannm, Thurner and Santoro maps.

As indicated above (Section 4.2), the assessment of the mean biomass density was performed over the same forest area by applying the EFI Forest Map of Europe to all biomass maps (Section 5.1.1). Instead, the assessment of the total biomass stock was performed using the biomass maps with their native forest mask to consider both the estimates of the biomass maps and their spatial coverage (Section 5.1.2).

The assessment of the total biomass stock and the mean biomass density of the maps was performed using the three validation metrics weighted by the reference forest area of the administrative units: the bias, or the area-weighted mean difference between the maps and the reference data, the area-weighted Root Mean Square Error (RMSE), and the area-weighted relative RMSE, computed as the ratio between the RMSE and the area-weighted mean value of the reference data, and expressed in percentage.

5.1.1 Assessment of biomass density using a common forest mask

The comparison of the mean biomass density at European level (37 countries) using a common forest mask showed that all maps estimated, on average, smaller biomass densities compared to the reference statistics. In particular, the Santoro, Baccini and Thurner maps were closer to the reference statistics while the Barredo, Kindermann and Gallaun maps provided much lower estimates (Table 3). In this analysis the forest area of the maps matched well the statistics because a common forest mask was applied to all maps, besides the Thurner map that presented a much smaller area because it did not include large areas of the common forest mask.

The comparison of the mean biomass density at national scale and at the resolution of the reference data, which included data at national and sub-national scale (hereafter, “sub-national”) and computed using the common forest mask, showed that the Santoro, Baccini and Thurner maps showed a smaller bias and error than the Barredo, Gallaun and Kindermann maps (Table 4, Figure 11). In general, the maps accuracy was higher at national than at sub-national level, most likely because of aggregation effects, meaning that areas with overestimation and underestimation tended to compensate each other with an effect that increased with the size of the area considered.

The lowest relative error was achieved by the Santoro map at national level (22%) and sub-national level (27%), but the differences among the maps were not particularly marked, with the Thurner, Baccini and Barredo maps presenting a relative RMSE ranging 25% - 26% at national level and 29% - 32% at subnational level. Instead, the Kindermann and Gallaun maps showed larger differences, with a relative error of 33% - 35% at national level and 37% - 39% at sub-national level, respectively (Table 4).

The maps presented two types of distribution of the errors: the Barredo, Gallaun and Kindermann presented a constant underestimation of the biomass density while the Baccini, Santoro and Thurner tended to underestimate at lower values and overestimate at higher values (Figure 11). The former error distribution is associated with maps calibrated with national statistics and limited spatial modelling while the latter distribution is typical in maps based on satellite imagery calibrated with empirical models and field plots.

Table 3. Forest area and mean biomass density of the biomass maps and reference statistics for the 37 European countries indicated in Figure 5. The forest area refers to the biomass maps with the EFI forest mask. The biomass density of the reference statistics is provided for the year 2000 (reference year of the Gallaun and Baccini maps) and the year 2010 (reference year for the Barredo, Kindermannm, Thurner and Santoro maps), while the forest area of the statistics includes multiple years (see Section 2.2).

Dataset	Forest area (1,000 ha)	Mean biomass (Mg/ha)
Reference Statistics (2000)	181,318	98.0
Baccini	186,614	92.8
Gallaun	168,753	73.4
Reference Statistics (2010)	182,878	105.8
Barredo	178,301	83.4
Kindermann	185,515	74.7
Santoro	186,618	97.2
Thurner	123,408	94.5

Figure 11: Comparison of the mean biomass density of the reference statistics with the corresponding values of the six biomass maps at sub-national level (i.e., the administrative units of Figure 5). The red lines represent the linear regressions between the two datasets (in the common model form y = ax + b) and the black lines represent the 1:1 line.

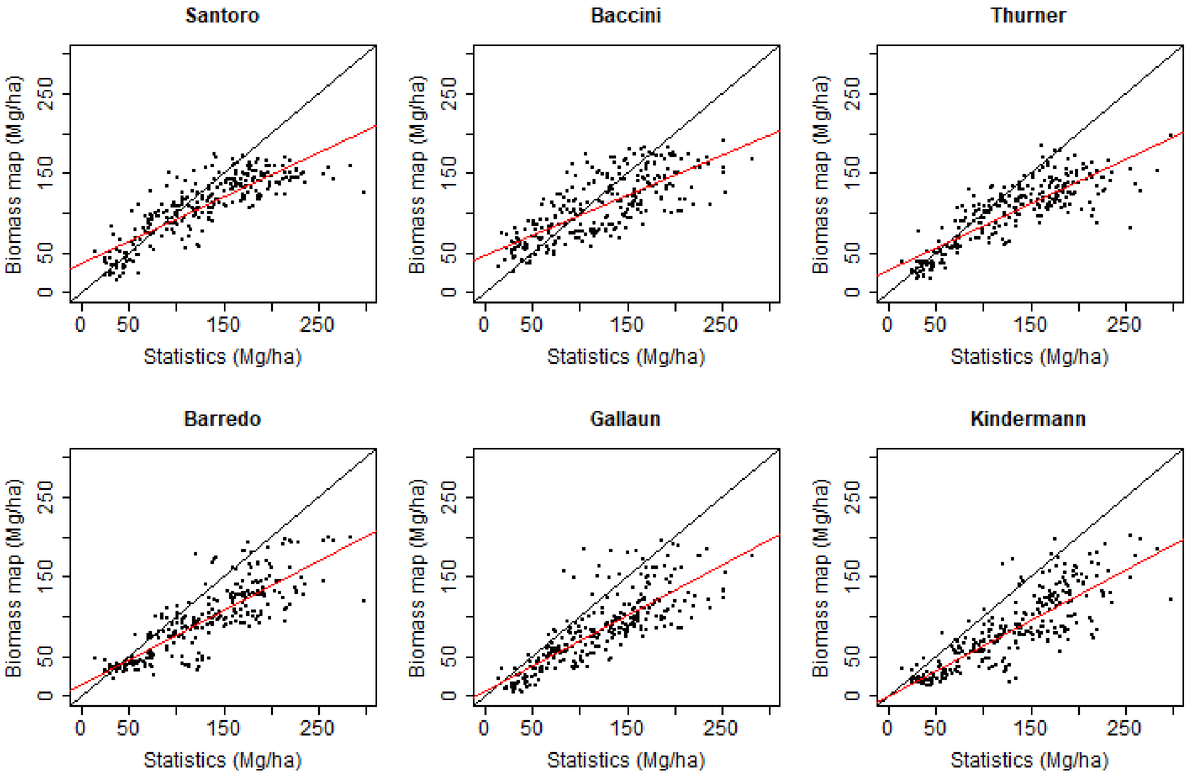


Table 4. Assessment of the mean biomass density estimated by the biomass maps, obtained by comparing the maps with the reference biomass statistics at national scale (left) and at the resolution of the reference data ("sub-national" in the Table), which included data at national and sub-national scale as shown in Figure 5.

	National (n = 37)			Sub-national (n = 274)		
	Bias (Mg/ha)	RMSE (Mg/ha)	Rel. RMSE	Bias (Mg/ha)	RMSE (Mg/ha)	Rel. RMSE
Baccini	-3	25	26%	-3	29	29%
Barredo	-23	27	26%	-22	33	32%
Gallaun	-26	35	35%	-27	38	39%
Kindermann	-30	35	33%	-30	39	37%
Santoro	-7	23	22%	-7	28	27%
Thurner	-11	27	25%	-12	30	29%

5.1.2 Assessment of biomass stock using the native forest mask

The biomass maps assessed with their native forest masks presented substantial differences in their estimates of biomass stock, with most maps having smaller biomass amounts compared to the harmonized reference statistics. The comparison of the total biomass stock at regional level (37 countries) showed that the Santoro, Baccini, Barredo and Kindermann maps were closer to the reference statistics while the Thurner and Gallaun maps provided much lower estimates (Table 5).

Interestingly, the land area covered by the maps varied largely, with the Barredo, Gallaun and Kindermann maps covering a much larger extent compared to the other three maps, which are closer to the forest area of the reference statistics. However, the larger land area did not reflect in larger biomass stocks, because the difference in land area was mainly due to mosaic and transitional areas between forest and non-forest that in some countries cover large areas but present very low biomass density (Table 5).

Ad example, both the Kindermann and the Thurner maps used the GLC2000 land cover map to identify forest areas, where forest is defined as an area with at least 15% of tree canopy cover. However, these two maps covered very different land area because the Thurner map included only grid cells with at least 50% of forest cover (i.e., the GLC2000 class "Mosaic of tree cover and other natural vegetation") while the Kindermann map included also mixed land classes where the forest cover could be as low as 20% of the grid cell (i.e., the GLC2000 class "Mosaic of cropland, tree cover and other natural vegetation").

At national scale and at sub-national scale, the Barredo, Kindermann and Santoro maps matched well the reference statistics, achieving smaller relative errors (14% – 16%) at national level compared to the Baccini, Gallaun and Thurner maps, with the Baccini map performing better than the Barredo at sub-national (Table 6). The errors are heteroscedastic, as they are not constant but tend to increase with the biomass stock, resulting in higher uncertainties in areas with larger biomass stocks (Figure 12).

The close correspondence of the Barredo and Kindermann maps with the reference values was because these maps used the FAO FRA statistics directly to calibrate their estimates, which are closely related to the reference statistics as they are both based on the same NFI data. It is noteworthy that the method used by the Kindermann map to spatialize the total national values hold also at sub-national level, where it achieved good agreement with the reference values.

Table 5. Land area and total biomass stock of the biomass maps and the reference statistics for the 37 European countries indicated in Figure 5. The land area refers to the area covered by the biomass maps with their original forest masks that, in the transitional areas, may include a mosaic of forest and other land cover types. Therefore the results refer to different areas than those in Table 4. The biomass stock of the reference statistics are provided for the year 2000 (reference year of the Gallaun and Baccini maps) and the year 2010 (reference year for the Barredo, Kindermannm, Thurner and Santoro maps), while the land area of the statistics includes multiple years (see Section 2.2).

Dataset	Land area (1,000 ha)	Total stock (Tg)
Reference Statistics (2000)	181,318	18,186
Baccini	188,321	19,704
Gallaun	231,577	14,379
Reference Statistics (2010)	182,878	19,877
Barredo	312,560	19,486
Kindermann	445,543	18,970
Santoro	196,913	20,724
Thurner	165,532	14,963

Figure 12. Comparison of the total biomass stock of the biomass maps with the reference statistics at sub-national level (i.e., the administrative units of Figure 5). For graphical reasons, the graphs are cropped at 600 Tg. The red lines represent the linear regressions between the two datasets (in the common model form y = ax + b) and the black lines represent the 1:1 line.

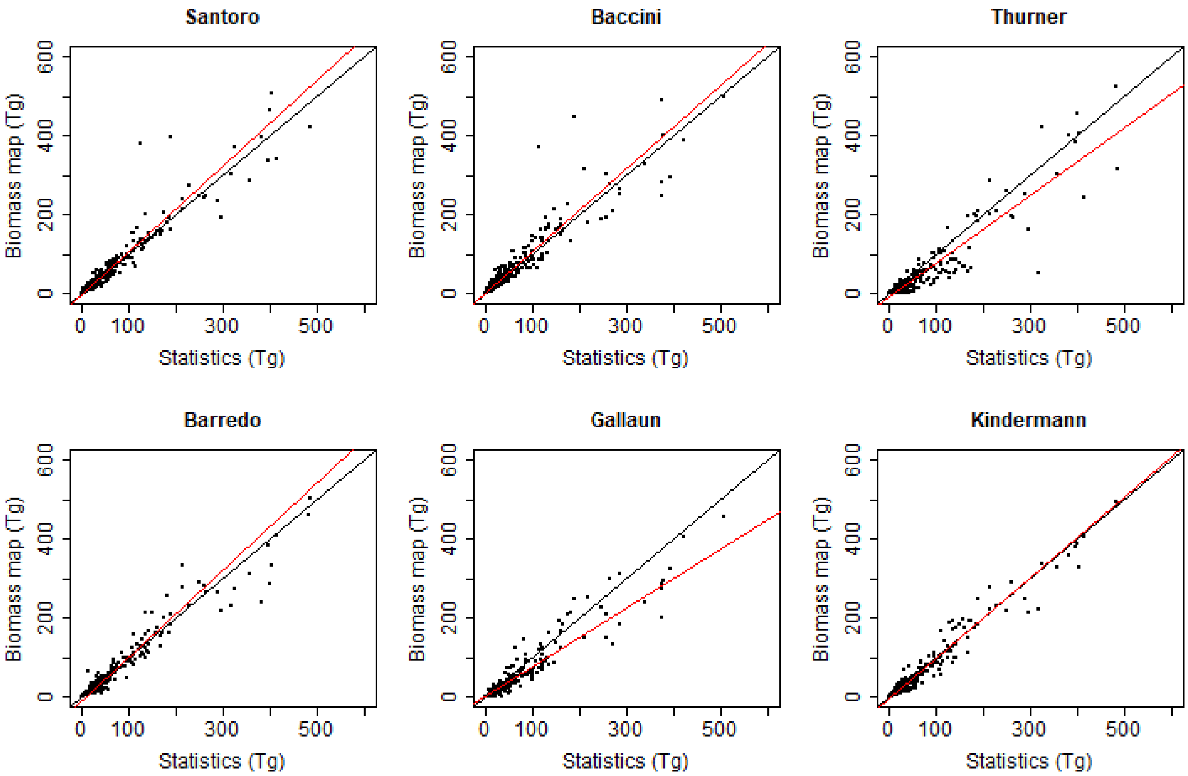


Table 6. Assessment of the total biomass stocks estimated by the biomass maps, obtained by comparing the maps with the harmonized reference biomass statistics at national scale (left) and at the resolution of the reference data ("sub-national" in the Table), which included data at national and sub-national scale as shown in Figure 5.

	National (n = 37)			Sub-national (n = 274)		
	Bias (Tg)	RMSE (Tg)	rel RMSE (%)	Bias (Tg)	RMSE (Tg)	rel RMSE (%)
Baccini	59	317	29%	19	92	36%
Barredo	-26	188	16%	22	114	40%
Gallaun	-198	313	28%	-55	150	59%
Kindermann	-61	167	14%	3	45	16%
Santoro	99	175	15%	45	96	34%
Thurner	-200	430	36%	-24	118	41%

5.2 Maps assessment with the harmonized SC13-17 plots

Besides the comparison at aggregated scales, the biomass maps were also assessed at pixel level because the local estimates and their spatial distribution are the main advantages of a biomass map compared to the reference statistics. The local assessment was performed using the harmonized SC13-17 plots, which provide a reference database of field estimates covering almost all EU countries. Instead, the NFI plots, available only for few countries, were used for the validation of the bias-corrected biomass map (see Chapter 6). Since the SC13-17 plots were provided with geolocation approximated to the centre of the 1 km INSPIRE grid cell, the biomass maps were resampled to the INSPIRE grid using bilinear interpolation before their comparison with the plots.

It is noted that the SC13-17 plot dataset is not homogeneously distributed over Europe but presents higher plot density in the Scandinavian region, which are characterized by lower biomass density than central Europe. To assess the impact of this effect on the validation of the biomass maps, the plots in Scandinavia (Norway, Sweden and Finland) were sub-sampled to adjust their density to the mean plot density computed over the rest of Europe (i.e., 225 Km^2 per plot). Since the comparison with the biomass maps provided very similar results using the complete dataset and the subset (Avitabile and Camia, 2018), all plots were used in this study.

The plots were screened for each reference period of the maps according to the procedures described in Section 3.3. The selected plots were about 5 - 7% of the complete field dataset and ranged from 1,074 plots for the year 2000 to 1,245 plots for the year 2010. Nonetheless the small size, the selected plots represented well the complete dataset both in terms of spatial coverage and frequency distribution of biomass. Hence, even though the plot selection reduced considerably the amount of data available for the map assessment, it also provided more reliable accuracy estimates because it removed the errors due to the spatial mismatch between the plots and the pixels.

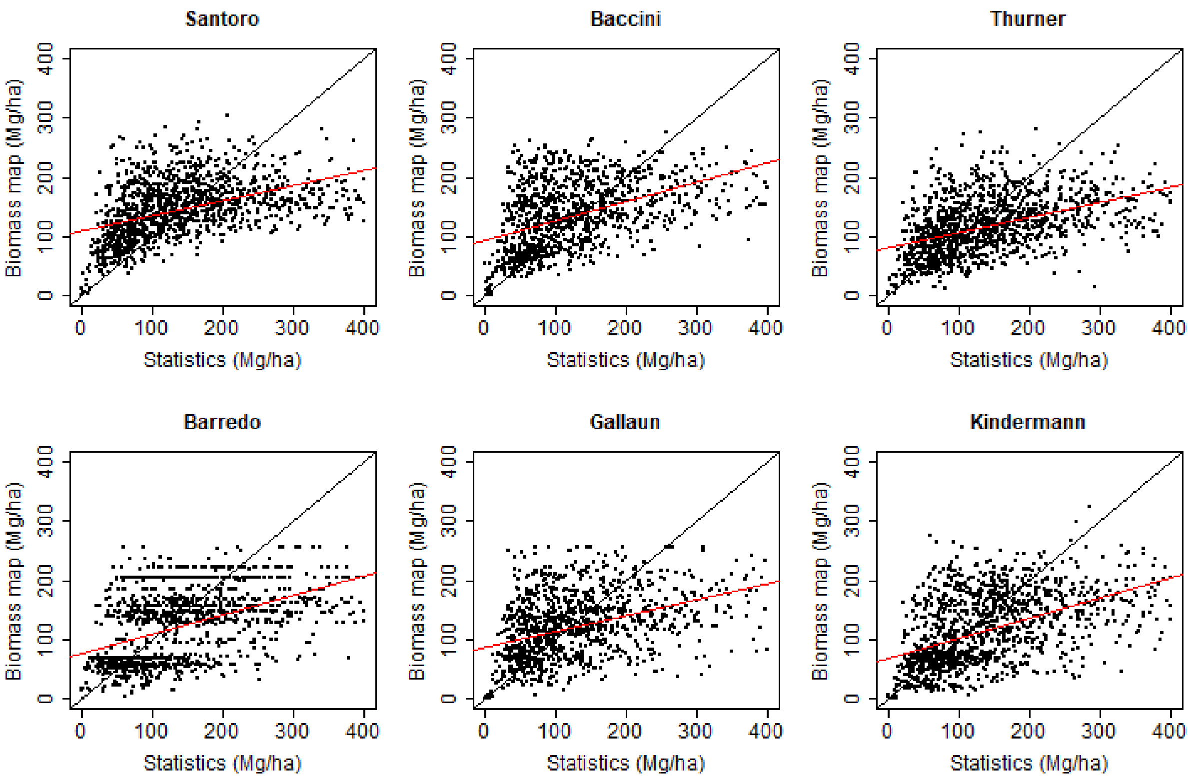
The map estimates at pixel level were assessed relative to the harmonized plot database by computing the bias (defined as the mean difference between the map and the plot values), the RMSE, and the relative RMSE (defined as the RMSE divided by the mean plots value). These statistics were computed for all data pooled and by biomass class using bins of 100 Mg/ha, defined with regard to the plot values. Assessing the error structure by biomass class is very useful for the map users interested in areas or forest types having specific biomass values (e.g., old-growth forest or sparse forest), as a map can be unbiased over the complete biomass range but it can be heavily biased, and with different magnitudes, at certain biomass ranges (Rodríguez-Veiga et al., 2019).

The assessment of the biomass maps using the selected SC13-17 field plots confirmed that, as indicated by the reference statistics, on average the maps tended to underestimate the biomass density in comparison with the harmonized estimates (Table 7, Figure 13). The assessment results were similar among the maps, with the Santoro map presenting slightly lower relative error and absolute error. The maps bias was between -24 and 9 Mg/ha, the RMSE between 77 and 81 Mg/ha and the relative RMSE between 56% and 63%. Hence, at pixel level the bias was slightly smaller but the absolute and relative errors were substantially higher that those reported at national and sub-national levels.

Table 7. Accuracy of the biomass maps obtained using the selected and harmonized SC13-17 field plots.

Map	Bias (Mg/ha)	RMSE (Mg/ha)	Rel. RMSE
Baccini	8.8	76.9	61%
Barredo	-17.4	79.6	57%
Gallaun	-5.4	79.6	63%
Kindermann	-23.4	80.6	57%
Santoro	5.6	78.1	56%
Thurner	-23.5	80.6	57%

Figure 13. Comparison of the biomass maps with the reference SC13-17 field plots. The red lines represent the linear regressions between the two datasets (in the common model form y = ax + b) and the black lines represent the 1:1 line.



The error statistics by biomass range showed that all maps tended to overestimate biomass in the range 0 – 100 Mg/ha and underestimate it at higher values (Table 8). The maps presented lower absolute errors but higher relative errors in the range 0 – 100 Mg/ha. Interestingly, the maps accuracy was highest in the range 100 – 200 Mg/ha, where the maps bias was between -21 and 14 Mg/ha, the RMSE between 49 and 59 Mg/ha and the relative RMSE between 34% and 41%.

Table 8. Accuracy of the biomass maps by biomass range (bins by 100 Mg/ha) obtained using the selected and harmonized SC13-17 field plots.

Map	Biomass range (Mg/ha)	Bias (Mg/ha)	RMSE (Mg/ha)	Rel. RMSE (%)	N. plots
Santoro	0 - 100	56.0	71.3	113.8	496
Baccini		51.4	74.6	125.5	509
Thurner		30.3	51.4	82.0	496
Barredo		27.3	58.7	93.7	496
Gallaun		40.4	64.6	108.7	509
Kindermann		22.7	55.2	88.2	496
Santoro	100 - 200	14.3	49.1	33.5	474
Baccini		4.8	51.5	35.7	375
Thurner		-20.2	53.3	36.4	474
Barredo		-9.7	58.0	39.6	474
Gallaun		-9.0	53.9	37.3	375
Kindermann		-17.9	59.3	40.5	474
Santoro	200 - 300	-72.7	86.7	35.6	201
Baccini		-74.7	88.2	36.4	142
Thurner		-101.8	111.7	45.9	201
Barredo		-86.9	102.2	42.0	201
Gallaun		-99.5	112.8	46.5	142
Kindermann		-92.9	108.4	44.6	201
Santoro	300 - 400	-175.6	181.0	52.4	74
Baccini		-164.1	171.6	49.8	48
Thurner		-192.6	198.7	57.5	74
Barredo		-177.0	183.6	53.2	74
Gallaun		-184.2	192.4	55.9	48
Kindermann		-178.7	185.8	53.8	74

5.3 Discussion on the performance of the maps

There are always multiple and complex factors that influence the comparison of the maps with reference data, and it is not always possible to fully explain the validation results (Duncanson et al., 2019). However, considering the different data and approaches used by the biomass maps, the results may be partly explained by the following considerations.

The Barredo and Kindermann map downscaled national reference data (as reported to the FAO) using spatial maps and therefore the total country stocks were unbiased but their biomass density in dense forest areas was lower than the reference values. The Barredo map was mainly driven by the use of mean reference values by forest type, which likely caused the overestimation at low biomass and the underestimation at high biomass as mean values cannot fully represent the data variability. Instead, the Kindermann map downscaled the national stocks using assumptions aimed to depict the biomass distribution at global scale, which may not fully fit the biomass distribution in Europe. For instance, this map assumed that managed forests store half of the biomass of undisturbed forests, which may underestimate the stocks of central European forests where most managed stands can reach high biomass densities before logging (Neumann et al., 2016).

The Baccini, Gallaun, Santoro and Thurner maps were mainly driven by models based on remote sensing data, and their uncertainty is likely due to the limited sensitivity of satellite sensors to variations in canopy height and tree diameter. More specifically, underestimation may be due to the saturation of the optical and short-wavelength radar sensors used by the maps (i.e., MODIS, Landsat, ALOS and ASAR) at high biomass in dense forest, while overestimation may occur in open forests or young stands having relatively wide or closed canopy but small tree diameter and height (Avitabile et al., 2012; Santoro et al., 2015). Furthermore, the Gallaun map limited the biomass estimates to the maximum value of 250 Mg/ha at 500 m resolution while central European mature forests may reach higher densities. Instead, the Santoro and Baccini maps benefitted from the use of lidar data for the model calibration, which provide information on the vertical structure of the forest that is closely related to its biomass density.

In addition, the maps based on remote sensing are negatively affected by the lack of sensitivity of satellite data to the variation of the wood density of the trees. Wood density is a key factor given that the biomass of a tree is obtained by the product of the tree volume for its wood density. Wood density is species-specific and is also affected by several environmental factors but, in general, it tends to be lower in fast-growing species and higher in slow-growing species. The biomass maps either estimate the tree stem volume from the satellite data and then convert it to biomass density using Biomass Conversion and Expansion Factors (BCEF) (e.g., the Santoro and Thurner maps), or directly calibrate the satellite data to biomass using environmental parameters related to forest types and species distribution (e.g., climate and topographic variables) (e.g., the Baccini and Gallaun maps).

The uncertainty of a map is also related to the spatial resolution of the satellite data. In particular, the estimates of the Barredo, Kindermann, Gallaun and Thurner maps, which have coarser spatial resolution (1 Km), are negatively affected by mixed pixels where a similar signal detected by the satellite may correspond to vegetation types having different biomass density (Avitabile et al., 2016). In addition, it was shown that the map errors tend to increase when the calibration data (i.e., the field plots) have a size that is much smaller than the map cells (Réjou-Méchain et al., 2014). For these reasons, it is likely that the Santoro and Baccini maps present higher precision at pixel level (i.e., when compared to the harmonized plots) also thanks to their higher spatial resolution (100 m).

Similarly, it is noted that the estimates of biomass stocks are affected by the choice of the forest mask because the existing land cover or forest maps differ considerably for forest definition, thematic content and spatial resolution (Seebach et al., 2012). Moreovoer, the land cover maps with moderate resolution (e.g., 1 km) and mixed classes present large mosaic areas with a fractional coverage of forest, which introduce large variability when they are used to estimate the biomass density of a region.

The accuracy reported by the maps producers, when provided, used metrics and spatial scales not compatible with the results presented here but the Gallaun and Thurner maps also reported a small negative bias due their underestimation at high biomass.

Lastly, it is noted that the map assessment results obtained using the reference statistics (Section 5.1), the SC13-17 plots (Section 5.2) and the NFI plots (Section 6.3) are not fully comparable because they are affected by three differences. Firstly, even if the plots, the reference statistics and the biomass maps refer to the same year, the temporal harmonization was performed differently: the statistics were harmonized to the reference year using a modelling approach (Section 2.2) while the plots were updated to the reference year using the IPCC growth factors, which do not take into consideration the specific forest dynamics related to forest management and human disturbances. Secondly, the reference statistics and the SC13-17 plots used a harmonized biomass definition, while the NFI plots used the national biomass definition. Thirdly, nonetheless the spatial screening (Section 3.3.2), it is likely that some spatial mismatches between the plots and pixels remained due to their different sizes and their imprecise geolocation, such as the incorrect GPS recording in the field or artifacts introduced during the map processing and resampling.

5.4 Impact of the harmonization on the assessment results

The harmonization of the reference data had a substantial effect on the assessment of the biomass maps. The effect of each harmonization step on the validation results was quantified by assessing the total biomass stock at national level of the Santoro map using four different levels of harmonization of the reference data, namely using reference data:

- (1) non harmonised;
- (2) harmonized for biomass definition;
- (3) harmonized for biomass definition and aligned in time;
- (4) harmonised for biomass and forest definitions and aligned in time.

This analysis was carried out for the 21 European countries with fully harmonized reference data (see Section 2.3) and using the relative RMSE as measure of map accuracy.

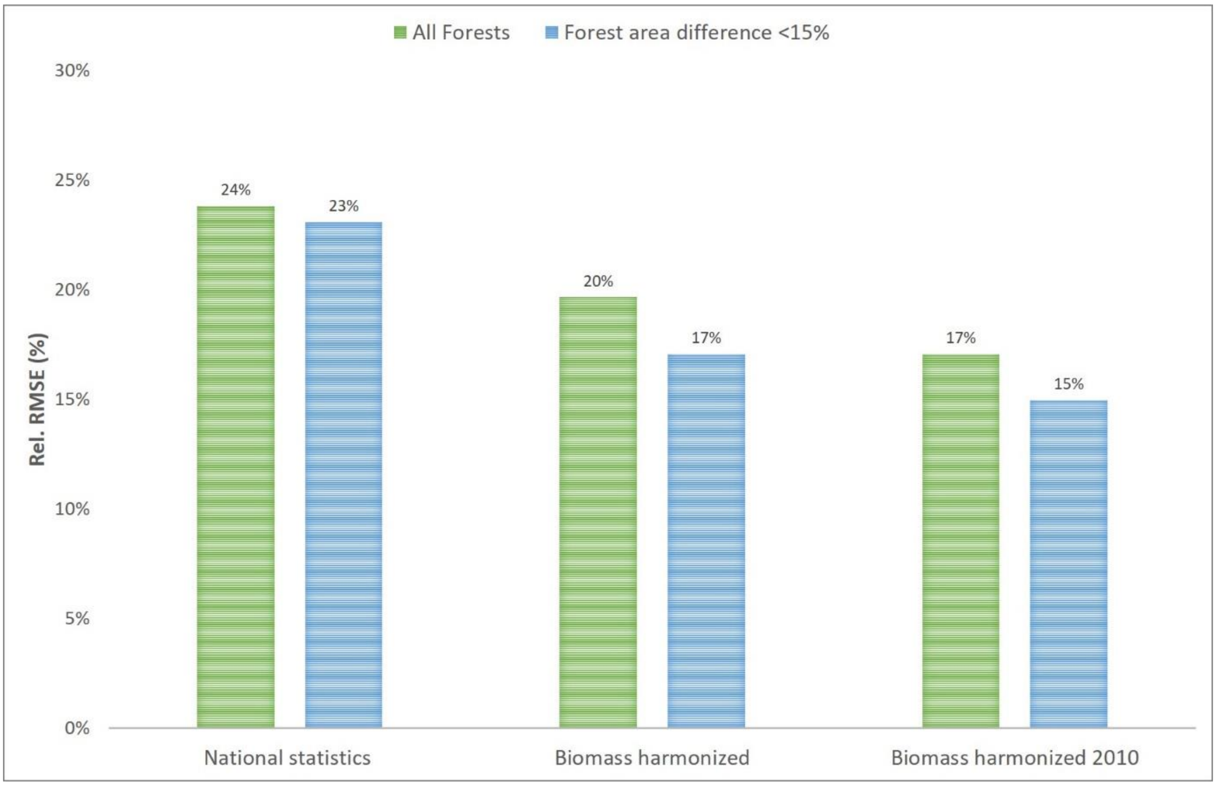
First, the biomass stock estimated by the map was compared with the most recent statistics as provided directly by the NFI, without any harmonization. The NFI reference data use country-specific definitions and parameters, and are not harmonized among themselves and with the map to validate in terms of forest definition, biomass definition, and reference period. Hence, in a second step the validation was performed using the NFI reference statistics harmonized for biomass definition using country-specific biomass correction factors (see Section 2.1).

Then, in a third step the statistics were further harmonized to the reference year of the biomass map (2010) using the Carbon Budget Model as adapted to the specific European conditions (see Section 2.2). Lastly, as fourth step, the previous validations were repeated accounting also for the differences among forest definitions. This was done by applying a forest mask to the biomass map that matched the forest area reported by the statistics.

The Copernicus Forest Map for the year 2012 was used as forest mask because it was the map matching best the NFI statistics on forest area at European level. Nonetheless, in some countries, the difference in forest area between the NFI statistics and the map was still relevant, and thus only the countries (16) where such differences were smaller than 15% were selected, to reduce the impact of different forest areas in the validation results.

The validation results show that the agreement between the reference statistics and the Santoro biomass map increased at each step of the harmonization process, with the relative RMSE decreasing steadily from 24% to 15% when the reference statistics were harmonized for biomass definition, temporal resolution and forest definition (Figure 14). In other words, a substantial part of the difference initially found between the reference statistics and the biomass map was only due to the lack of harmonization and not to "errors" in the biomass map. This analysis shows the importance of the harmonization of the reference data for a fair and accurate assessment of the biomass maps.

Figure 14. Validation results of the Santoro map for the total biomass stock at national level using the original national statistics ("National statistics"), the statistics harmonized for biomass definition ("Biomass harmonized"), the statistics harmonized for biomass definition and for temporal resolution ("Biomass harmonized 2010"), and only for the countries with similar forest area (yellow bars).



6 A new biomass map harmonized with the statistics

The assessment of the existing biomass maps (Chapter 5) has shown that in Europe the maps present substantial uncertainty at sub-national and, in particular, at pixel level, where the relative error is larger than 50%. Considering that the usefulness of the maps for local management and detailed modelling activities lie in their ability to provide accurate spatial estimates at a moderate and high resolution, the existing maps are not very appropriate for such purposes, suggesting the need for an improved product.

The error of a map can be distinguished in two components: the random error and the systematic error (or, bias). Random errors are caused by unknown and unpredictable changes in the measurements or in the environmental conditions, while systematic errors result from a persistent issue and leads to predictable and consistent departures from the true value. In the case of biomass maps, the bias is often due to systematic issues in the calibration data, inaccurate model parameters and in the limited sensitivity of the remote sensing data to biomass variability. Several studies have reported that biomass maps tend to overestimate the stock in areas with low biomass density and underestimate the stock in areas with high biomass density, thus showing that the maps are affected by different systematic errors at different biomass ranges (Avitabile and Camia, 2018; Rejou-Mechain et al., 2019).

Given the availability of harmonized reference statistics at sub-national scale and a set of reference plots distributed across Europe (Chapter 3), such information can be used not only to assess but also to improve the existing maps. While random errors are essentially unavoidable, systematic errors are not. The reference data shall be intended not as error-free data but rather as the best available estimate because, even though affected by the sampling error, they are obtained from a statistical sample and an unbiased estimator. For this reason, the reference statistics can be used to correct the systematic error of a map, by removing the systematic under- or over-estimation of the map estimates for a certain region.

In this study, the Santoro map was corrected for systematic error at national and sub-national scale using the reference statistics, and it was then validated using the reference NFI field plots. Among the six available biomass maps, the Santoro map was selected because of its higher accuracy and spatial resolution compared to the other maps. The Santoro biomass map was matched to the reference statistics both in terms of forest area and biomass density, which required to produce a forest mask matching the forest area statistics.

6.1 Adjustment of forest area

The correction of the bias of a biomass map using reference statistics requires to first match their forest area. In fact, the biomass reference statistics refer to a certain forest area (which is usually estimated from a sample) and a systematic difference between the statistics and a map may be due to the fact that they refer to different areas. The Santoro map, provided without a forest mask, was masked using an adjusted version of the Copernicus 2012 Forest Type map.

The Copernicus map was selected because it presents a good match with the national statistics of forest area and is compatible with the spatial and temporal resolutions of the Santoro map. However, the analysis of the forest area at sub-national scale showed that some spatial units have large differences (> 30%) in forest area between the reference statistics and the Copernicus forest map. In those cases, the validation of the biomass maps is likely affected by the differences in forest area.

In fact, in most cases the reference statistics had lower biomass density than the Santoro map when they represent larger forest area, most likely because they include also sparse forests with low biomass. Conversely, the statistics usually had higher biomass density than the map when they cover a smaller forest area, most likely because they refer to the most dense and high biomass forests. Hence, it is necessary to first match the differences in forest area before correcting the bias of the map.

The forest mask of the biomass map (i.e., the Copernicus 2012 map) was adjusted by matching it to the forest area reported by the statistics using the following approach. When the statistics reported smaller forest area than the map, the forest mask was reduced by removing the forest areas with lower biomass, until the map matches the statistics. When the statistics reported larger forest area than the map, the forest mask was expanded on areas with higher biomass located outside forest. Usually, the forest mask was expanded around the forest edges with high biomass that were not included in the forest map because of edge effect (geolocation mismatches), and then in low-biomass forest areas. The resulting forest mask was applied to the Santoro biomass map.

6.2 Bias correction

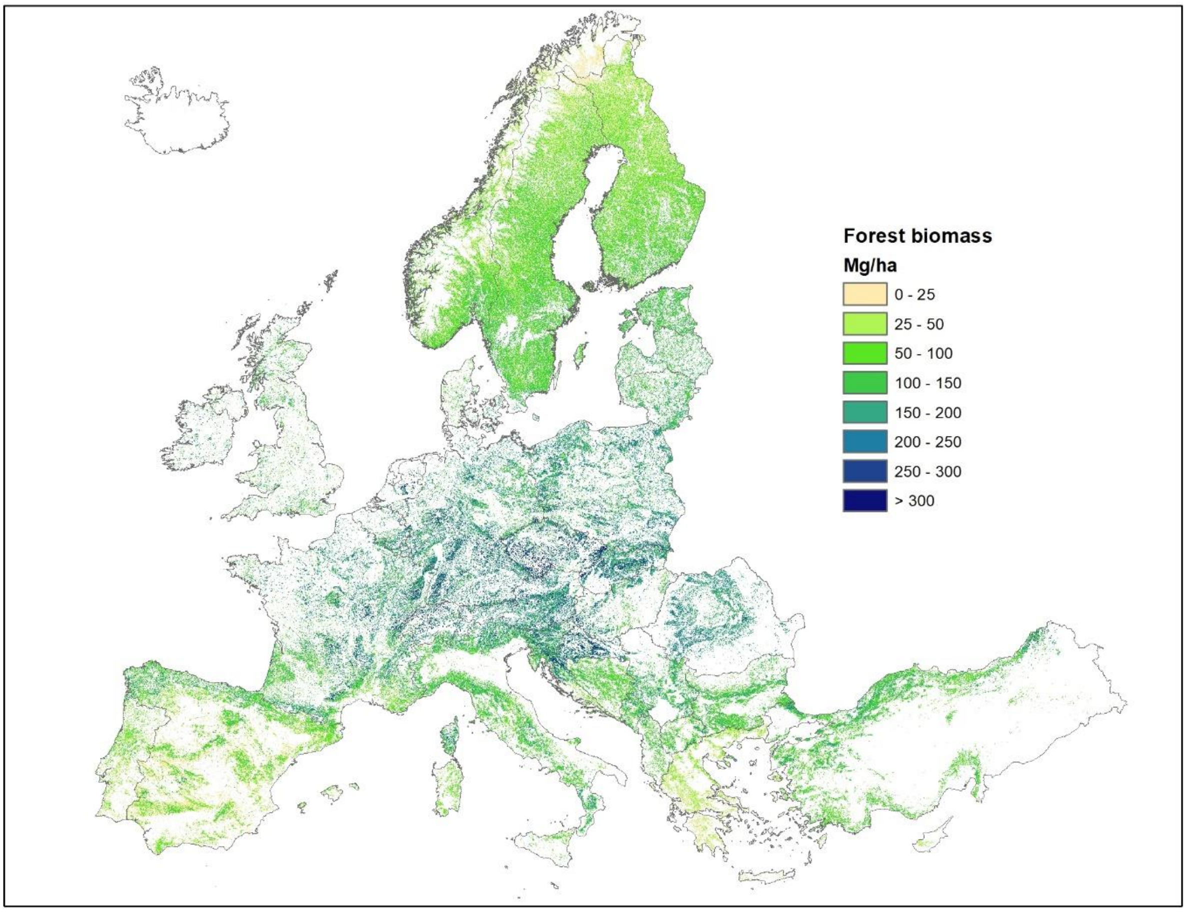
The Santoro map, matched for forest area with the reference data, was then corrected by removing the bias (i.e., the systematic difference) with respect to the reference statistics. The bias was removed using a correction factor, computed as ratio between the biomass density of the reference statistics (AGB^{Ref}) and the mean biomass density of the biomass map (AGB^{Map}) over the same area represented by the reference statistics. The correction factor was computed at the spatial scale of the reference data (i.e., at sub-national scale for 22 countries and at national scale for 15 countries, see Figure 5), and then removed from the biomass map at pixel level. The correction occurs by multiplying the biomass density of each pixel (i) of the map with the correction factor, to match the reference statistics for each spatial unit (k):

$$\text{Map Corrected} = AGB^{Map}{}_{(i)} \times (AGB^{Ref}{}_{(k)} / AGB^{Map}{}_{(k)})$$

The result of the bias correction of the Santoro map is a biomass map of Europe at 100 m spatial resolution for the reference year 2010 that matches the reference statistics in terms of forest area and biomass density (Figure 15). The map is freely available in the JRC Data Catalogue (https://data.jrc.ec.europa.eu/dataset/d1fdf7aa-df33-49af-b7d5-40d226ec0da3).

This biomass map was integrated with the Copernicus 2012 Forest Type map to quantify the biomass stock by forest type. The total biomass stock resulted equally divided between coniferous forests (43%) and broadleaved forests (43%), while mixed forests (i.e., a balance mix of coniferous and broadleaved species) store 14% of the biomass stock. The conifers cover a smaller forest area (38%) and therefore present, on average, a larger biomass density (108 Mg/ha) compared to the broadleaves (89 Mg/ha), which cover 47% of the forest area. Mixed forests, present on 14% of the forest area, have an average biomass density of 97 Mg/ha.

Figure 15. The bias corrected biomass map for Europe, derived from the Santoro et al. (2018) map and adjusted to match the reference statistics in terms of forest area and biomass density.



6.3 Map validation

The bias correction adjusted the Santoro biomass map to match the reference statistics at national or sub-national scale. However, the added value of a map, compared to the statistics, is in the spatial distribution of the estimates, and a correction at sub-national scale does not ensure that the adjusted map achieves a higher accuracy also at pixel level. For this reason, the accuracy of the bias-adjusted biomass map was assessed at pixel level by comparing the pixel estimates with the reference plot data.

As described in Section 3.2, the two available biomass plot datasets are complementary: the SC13-17 plots have the advantage to be harmonized for biomass definition and cover most of Europe but their geolocation is approximated to 1 Km, while the free-access NFI plots with precise geographic location follow the national definitions and are available only in two countries (Sweden and Spain). Since the bias-corrected map presents a spatial resolution of 1 ha (100 m), the SC13-17 plots with approximated geolocation at 1 km were sub-optimal to assess the pixel level accuracy, and the NFI plots with precise geolocation were used for the map validation.

The validation was performed for the three high-resolution biomass maps (Baccini, Santoro and the bias-corrected Santoro map) using the geolocated NFI biomass plots for Sweden and Spain. After the spatial screening and temporal harmonization of the field plots, 28,507 plots were selected for the validation of the maps. The validation was performed using the data in the native reference system of the maps (WGS84) to reduce the errors due to the map resampling to a different reference system.

The validation results for Sweden and Spain show that the bias correction improved the accuracy of the Santoro map, reducing significantly the bias (from 29 to 3 Mg/ha) and achieving a 15% reduction of the relative error (relative RMSE decreased from 81% to 66%) (Table 9). Even though the Santoro and the Baccini maps present similar accuracy results, the scatterplots show that the two maps have different error patterns. The Baccini map tends to group its estimates in two clusters, one centred at 100 Mg/ha and the other at 200 Mg/ha, probably due to the use of a decision tree model (Random Forest) to produce the estimates. Instead, the Santoro map presents a uniform distribution of the estimates with no clustering (Figure 16).

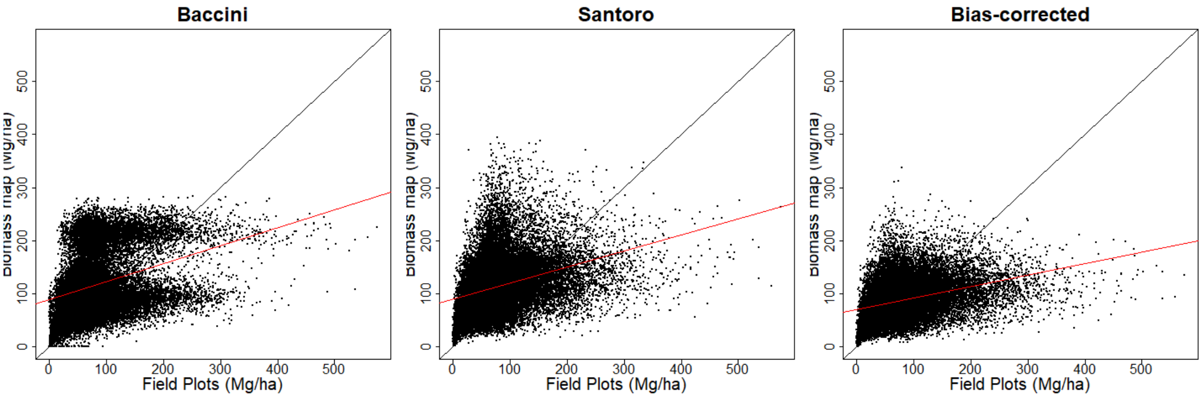
According to the validation results, the bias-corrected map reduces the overestimation of the Santoro map at lower biomass values and it has a much lower systematic and random errors, but still presents substantial uncertainty at pixel level. These results are based on a substantial amount of field plots (28,507) that represent both southern and northern European forests but they are still clustered in two countries (Sweden and Spain), and a more spatially distributed validation dataset would be needed to obtain validation results fully representative of the European forests.

The validation results were also re-computed using more stringent plot selection criteria, such as selecting only the plots with an area larger than 0.1 ha or located within pixels with more homogeneous forest cover (standard deviation of the tree cover smaller than 10% instead than 15%) (see Section 3.3.2). In both cases, and even when using both criteria together (which lead to discard about half of the selected plots), the validation results were almost identical to the results presented above, suggesting that the respective selection criteria ensure robust validation outputs.

Table 9. Validation results of the biomass maps using the NFI biomass plots for Sweden and Spain.

Map	Bias (Mg/ha)	RMSE (Mg/ha)	Rel. RMSE
Baccini	32.0	75.0	86%
Santoro	29.4	70.3	81%
Bias-corrected	2.8	57.1	66%

Figure 16. Comparison of the biomass maps with the geolocated NFI biomass plots for Sweden and Spain. The red lines represent the linear regressions between the two datasets and the black lines represent the 1:1 line.



7 Conclusions

7.1 Status of biomass data in Europe

The present report provides an overview of existing forest biomass data in Europe, namely the biomass statistics produced by the National Forest Inventory (NFI) institutes, the field plots acquired by the NFIs, and the biomass maps produced by research organizations.

The biomass statistics provided by the NFIs are a valuable reference dataset at national scale, but they refer to different definitions, periods and spatial scales, with large variability among countries especially in their temporal frequency. For these reasons, their use for a pan-European assessment of the forest biomass stocks required a substantial harmonization effort, made possible thanks to a wide collaboration with the NFI experts of 26 European countries (Chapter 2 and 3).

In this study, the best available data for each country were collated in a reference database of forest biomass for Europe, which includes statistics and field plots harmonized for biomass definition and reference year. Still, the harmonized statistics remain limited in their spatial and temporal resolutions and cannot support various applications that require spatially-explicit data. For this reason, the availability of a biomass map can provide a substantial added-value, under the condition that its biomass estimates are detailed, updated and accurate.

The six biomass maps available for Europe were assessed using the reference statistics and plots to evaluate their accuracy and to develop strategies to improve the spatial estimation of forest biomass (Chapter 4 and 5). A key part of this analysis consisted on the harmonization of the statistics, plots and maps, which is essential to perform a meaningful comparison. The statistics and the plots were updated to the reference year of the maps using modelling approaches, the plots were screened to remove the samples that were not representative of the map pixels, and the maps were harmonized with the statistics in terms of forest area to compare them over the same forest extent.

The accuracy assessment indicated that the biomass maps present limited accuracy at pixel level, suggesting the need for an improved biomass map for Europe. The reference statistics were used to identify the most accurate biomass map and to correct its systematic error at sub-national scale using a linear bias correction, obtaining a map that matches the biomass statistics at national and sub-national level for forest area and biomass density (Chapter 6). This bias-corrected map was validated using the reference field plots, showing a better accuracy compared to the original map.

The bias-corrected map presented in this study is a first step towards a mapping of forest biomass that supports the detailed assessment of existing biomass resources and the modelling of future biomass availability. To this aim, it is suggested that the biomass map fulfills the following requirements: high spatial resolution (e.g., 100 m), recent and frequently updated (e.g., every 1 – 5 years), absence of systematic error at sub-national scale and for biomass classes (e.g., consistent over-estimation at low biomass ranges and under-estimation at high biomass ranges), and accurate estimates at local (pixel) scale (e.g., relative error < 30%).

The achievement of these characteristics depends not only on improved remote sensing data and modelling approaches, but also on the availability of harmonized reference data at local (i.e., field plots) and regional scale (i.e., statistics) for the proper calibration and validation of the biomass maps. For this reason, the harmonization efforts performed by the European NFIs described in this Report are an important contribution towards a better assessment of the role of forest biomass in the bioeconomy. Furthermore, the reference database presented in this study can be further updated to recent years using a forest growth model to assess and adjust new biomass maps that will be released.

7.2 Biomass monitoring with remote sensing

The use of Earth Observation for forest monitoring has developed substantially in the last years because it can integrate and support ground-based data and statistics with wall-to-wall forest mapping over large areas in a frequent, consistent and independent way. Remote sensing of forest can facilitate early warnings and timely policy responses to forest disturbances (Ceccherini et al., 2020), support the implementation of forest and climate policies (Grassi et al., 2017) or trade-off analysis of different ecosystem services (Verkerk et al., 2014), and improve the monitoring of forest dynamics such as in the upcoming EU Observatory on changes in the world's forest (European Commission, 2019).

In the bioeconomy context, Earth Observation allows a better assessment of the potential supply of biomass from the forest sector through the detailed mapping of the standing stocks and other environmental properties. The availability of forest biomass for the bioeconomy is highly dependent on several factors besides the amount of standing biomass, such as the type of forest management and related restrictions, the trade-offs with other ecosystem services, the forest accessibility and the cost of biomass extraction, or the type and quality of the wood assortments. For this reason, a biomass map with sufficient spatial resolution (e.g., 1 ha) and its integration with other spatial data may allow to perform a spatially-explicit analytical assessment of different management strategies and cost-supply curves, as well as the geospatial modelling of the ecosystem services, harvesting costs or restrictions to biomass availability (Mubareka et al., 2018).

Until recently, remote sensing data and biomass maps have not often been used for the country assessment of forest biomass because of the limited sensitivity to biomass shown by the available sensors and the lack of complete uncertainty information of the biomass maps, making it difficult to assess their accuracy. In addition, the field data usually acquired by the NFIs follow a sampling scheme not designed to relate with satellite data, with spatial and temporal mismatches that make it difficult to use the ground plots for the calibration and validation of the biomass maps (Réjou-Méchain et al., 2014).

Earth Observation data are being increasingly introduced in the NFI systems especially for the frequent and detailed mapping of forest cover. In particular, the ESA Copernicus Sentinels mission and the NASA Landsat program currently provide an unprecedented amount of open-access, frequent and high-resolution satellite data for forest monitoring (Zhu et al., 2019). The combination of large data availability and cloud computing platforms makes it now possible to produce temporally consistent and spatially detailed maps of forest cover, forest change and forest properties over large areas, such as the Copernicus pan-European High-Resolution Forest layers (Buchhorn et al., 2020).

These satellite images have also been used as direct biomass predictors, even though the Sentinel and Landsat sensors are not designed for biomass detection but provide information on canopy characteristics that can be related to biomass density, or to produce forest maps that are valuable inputs in the biomass models for (e.g.) a better stratification of forest types (Tyukavina et al., 2015; Zarin et al., 2016; Santoro et al., 2018a).

7.3 Upcoming developments of biomass remote sensing

The field of biomass mapping is rapidly evolving thanks to recent and upcoming satellite missions and dedicated projects. Two global biomass products are currently being produced using different approaches and data sources, and two new satellite missions highly relevant to biomass mapping are planned for launch by 2022.

The NASA Global Ecosystem Dynamics Investigation (GEDI) mission has installed the first high resolution lidar sensor on the International Space Station on December 2018 (https://gedi.umd.edu/). The GEDI lidar instrument has acquired data on forest structure with a dense sampling scheme for the years 2019 and 2020, providing metrics of forest canopy cover, height and structure from which aboveground biomass can be estimated with high accuracy. The GEDI products are expected to improve the knowledge of the spatial distribution of forest biomass at global scale. However, due to the orbit characteristics of the ISS, GEDI will acquire data on the Earth's surface only until the latitude of 51.6° N and therefore it will not provide data on Northern Europe.

The ESA Climate Change Initiative (CCI) Biomass project currently ongoing aims to produce by the year 2021 global biomass maps for three epochs (2010, 2017 and 2018) using an unprecedented multiplicity of satellite data (optical, radar and lidar) combined with an advanced modelling approach (http://cci.esa.int/biomass). The maps will have a complete global coverage and will be produced in a consistent way to support direct quantification of biomass change.

The ESA BIOMASS mission will bring in space by the year 2022 for the first time a P-band radar sensor, which has an enhanced sensitivity to forest vertical structure and biomass compared to other satellite sensors, with no saturation effect (https://earth.esa.int/eogateway/missions/biomass?text=BIOMASS). Thanks to these characteristics, this satellite is expected to map also very high biomass forests with high accuracy. Unfortunately, due to communication restrictions in the P-band wavelength, the sensors will not be allowed to operate and acquire data over Europe and North America (Carreiras et al., 2017).

The NASA-ISRO Synthetic Aperture Radar (NISAR) mission, planned for launch in 2022, will use advanced radar imaging to map various land properties and their changes with high spatial and temporal resolutions (https://nisar.jpl.nasa.gov/). This satellite will have full coverage over Europe but will employ a L-band radar sensor that has limited sensitivity to high biomass, and therefore it will be mainly useful to improve the mapping of low biomass forests (e.g., southern and northern Europe) and the monitoring of their changes.

Besides better satellites, new remote sensing technologies such as airborne and terrestrial lidar are highly promising for the acquisition of high-quality biomass reference data from local to sub-national scale (Morton et al., 2016). Compared to the spaceborne lidar, the airborne lidar has a much higher point density that provide a detailed analysis of the forest vertical structure and biomass distribution (Asner et al., 2014). In turn, the terrestrial lidar acquires extremely dense three-dimensional measurements of the forest canopy from the ground that allow to estimate tree biomass with very high accuracy, comparable to that of destructive measurements (Disney, 2019; Calders et al., 2015). The terrestrial lidar can also be used to construct new allometric models and therefore improve the biomass estimates derived from the tree parameters acquired in the traditional field plots (Lau et al., 2019).

7.4 Biomass monitoring in Europe: a way forward

On the basis of the current status and upcoming developments of the remote sensing technology and data processing capabilities, Earth Observation is expected to play an increasing role in the field of monitoring forest biomass in the near future. As indicated above, the remote sensing of biomass is rapidly evolving thanks to new dedicated satellite missions with global coverage (Herold et al., 2019), the increasing use of airborne laser sensors for forest monitoring at national and sub-national scale (Zhao et al., 2018), the promising results of the terrestrial laser sensors for high-quality ground reference data (Disney et al., 2019) and a better understanding of how to collect and relate plot data with satellite data (Réjou-Méchain et al., 2019).

These new technologies present enhanced sensitivity to woody biomass and, as they are rapidly maturing and becoming operational, they are expected to substantially improve the knowledge of the spatial distribution and temporal dynamics of forest biomass. In the European context, where the biomass assessment is mostly based on extensive ground plots, remote sensing can increase the monitoring frequency with consistent and spatially explicit data, and help to reduce the cost of field sampling.

Considering the high diversity of European forests in terms of ecological conditions and dynamics, and the mentioned coverage limitations for Europe of some satellites, it is foreseen that there will not be a single optimal data source for all forest types but rather the way towards a better monitoring in Europe will be through the skilful integration of the existing and upcoming satellite data with airborne and terrestrial lidar measurements and traditional ground plots. The synergic use of these data can allow the accurate, consistent, timely estimation of the biomass stocks and their changes of European forests, and ultimately support a better assessment of the forest resources and their potential role in the bioeconomy.

For example, a cost-effective strategy for the European countries may integrate satellite data, which provide freely available frequent coverage over large areas, with selected airborne lidar flights acquired according to a sampling strategy, which provide high-quality biomass estimates for satellite calibration and biomass mapping at sub-national scale, and with terrestrial lidar plots, which provide accurate reference data at local scale for the proper calibration and validation of airborne and satellite data.

In addition to remote sensing data, the availability of extensive forest inventory plots that are harmonized, well distributed over the European forests and with a sampling design that facilitates the integration with remote sensing data will be critical for the calibration and validation of the remote sensing maps. Moreover, the forest inventory plots will continue to produce independent and statistically robust sample-based statistics of the forest biomass stock at national and sub-national scale, which represent the reference values for the assessment of the maps accuracy at regional scale and the evaluation of the quality and usability of the maps for various applications.

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List of abbreviations and definitions

AGB	Aboveground biomass
ALOS	Advanced Land Observing Satellite
ASAR	Advanced Synthetic Aperture Radar
BCEF	Biomass Conversion and Expansion Factor
BEF	Biomass Expansion Factor
CBM	Carbon Budget Model
CCI	Climate Change Initiative
CORINE	Coordination of Information on the Environment
DEM	Digital Elevation Model
EFDAC	European Forest Data Centre
EFI	European Forest Institute
EFISCEN	European Forest Information SCENario
ESA	European Space Agency
EU	European Union
FAO	Food and Agricolture Organization
FRA	Forest Resource Assessment
GEDI	Global Ecosystem Dynamics Investigation
GEZ	Global Ecological Zone
GLAS	Geoscience Laser Altimeter System
GLC2000	Global Land Cover 2000
GSV	Growing Stock Volume
JRC	Joint Research Centre
INSPIRE	Infrastructure for Spatial Information in Europe
IPCC	Intergovernmental Panel on Climate Change
ISS	International Space Station
LIDAR	Light Detection and Ranging
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NFI	National Forest Inventory
NISAR	NASA-ISRO Synthetic Aperture Radar
NUTS	Nomenclature of Units for Territorial Statistics
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SC	Specific Contract
SoEF	State of Europe’s Forests

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