Doctoral Dissertation

UNIVERSITÄT FÜR BODENKULTUR WIEN
University of Natural Resources
and Life Sciences, Vienna

Assessment of Europe's potential wood supply

submitted by

Christoph PUCHER, MSc

in partial fulfilment of the requirements for the academic degree

Doktor der Bodenkultur (Dr.nat.techn.)

Vienna, March 2023

Supervisor:

Univ.Prof. Dipl.-Ing. Dr.nat.techn. DDr.h.c. Hubert Hasenauer
Institute of Silviculture
Department of Forest- and Soil Sciences

Affidavit

I hereby declare that I have authored this dissertation independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included. Any contribution from colleagues is explicitly stated in the authorship statement of the published papers.

I further declare that this dissertation has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 1 March 2023 Christoph PUCHER *(manu propria)*

Acknowledgements

The work leading to this thesis was funded by Bio-Based Industries Joint Undertaking under the European Union’s Horizon 2020 research and innovation program, TECH4EFFECT—Techniques and Technologies or EffectiveWood Procurement project [Grant Number 720757]. Additional financial support came from the «GIS and Remote Sensing for Sustainable Forestry and Ecology (SUFOGIS)» project funded with support from the EU ERASMUS+ program.

I acknowledge the open data policies by European forest inventory agencies, that made this analysis possible. Parts of the used inventory data were obtained from the previous project ‘FORest management strategies to enhance the MITigation potential of European forests’ (FORMIT), which received funding from the European Union Seventh Framework Programme under grant agreement n°311970.

This work would have also been impossible without the work of those people who produce publicly available gridded data sets and the open data policies of the NASA and the European Union’s Earth Observation Programme.

I want to thank my colleagues at BOKU DI MMag. Benno Eberhard, DI Dr. Gernot Erber, Christian Hochauer, DI Mathias Leiter, DI Dr. Elisabeth Pötzelsberger, my colleagues from the TECH4EFFECT project Dr. Rasmus Astrup, Dr. Robert Prinz and Dr. Johanna Routa, my supervisor Univ.Prof. DI DR. DDr.h.c. Hubert Hasenauer, and my advisory team Univ.Prof DI Dr. Manfred Lexer and Ass.Prof. DI Dr. Mathias Neumann who supported me in various ways throughout my PhD study.

Finally, I want to thank my family for their support throughout my academic education.

Table of content

List of publications

Publications that comprise the main part of this cumulative dissertation

1. Pucher, C.; Neumann, M.; Hasenauer, H. An Improved Forest Structure Data Set for Europe. Remote Sens. 2022, 14, 395, doi:10.3390/rs14020395.

2. Pucher, C.; Erber, G.; Hasenauer, H. Europe' s Potential Wood Supply by Harvesting System. Forests **2023**, 14(2), 398, doi: 10.3390/f14020398

The papers in full text are available in the Appendix at the end of this doctoral dissertation.

Please cite the thesis as Pucher, C., 2023. Assessment of Europe's potential wood supply, Dissertation, University of Natural Resources and Life Sciences, Vienna, p.85, or by citing the individual papers.

Additional contributions

Cruz-Alonso, V.; Pucher, C.; Ratcliffe, S.; Ruiz-Benito, P.; Astigarraga, J.; Neumann, M.; Hasenauer, H.; Rodríguez-Sánchez, F. The Easyclimate R Package: Easy Access to High-Resolution Daily Climate Data for Europe. Environ. Model. Softw. 2023, 161, 1–8, doi:10.1016/j.envsoft.2023.105627.

Pucher, C; Erber, G; Neumann, M; Hasenauer, H. (2022): Reconciling timber harvesting systems with forest structure data to assess the harvesting options of European forests. [Poster]; All-IUFRO Conference 2022, 21.09.2022 - 23.09.2022, A-1030 Vienna, Vordere Zollamtsstraße 7

Pucher, C. (2020): Combining remote sensing and national forest inventory data for large scale forest structure assessment. SUFOGIS Zoom dissemination conference "Forest ecosystems in the conditions of climate change: biological productivity and remote sensing", SEP 15-16, 2020, Zoom Meeting, Online

Erber, G; Spinelli, R; Ottaviani Aalmo, G; Jaeger, D; Schönauer, M; Hoffmann, S; Talbot, B; Stampfer, K; Pucher, C. (2019): Flat and wet: Cable yarding on sensitive soils in Europe - motivations, challenges and potential. [52 nd International Symposium on Forestry Mechanization (FORMEC) 42 nd Edition of the Council on Forest Engineering (COFE), Forchtenstein, Austria, 06.10.2019 - 10.10.2019] In: Czupy, I; University of Sopron Press, Sopron, Hungary 2019 (Hrsg.), Exceeding the Vision: Forest Mechanisation of the Future. Proceedings of the 52 nd International Symposium on Forestry Mechanization. , e-book 651 p.; ISBN: 978-963-334-343-2

Abstract

Around 1/3 of Europe's land area is covered with forests. Forest ecosystems are vital for a society as they provide numerous goods and services and play a key role in tackling the major challenges of our time, such as climate change or the energy crisis. Supranational strategies for tackling these issues (i.e. Europe's forest strategy) need to be supported by consistent and comprehensible forest reporting. Europe still lacks a uniform, harmonized forest reporting system. Figures for the "forest available for wood supply" (FAWS) in Europe are reported in a bottom-up approach, where the considered environmental, economic and social restrictions vary by country. Consistent reporting of the growing stock in FAWS is key to evaluate if wood supply can be ensured in a bioeconomy promoting the sustainable use of wood. This thesis provides a consistent assessment of Europe's potential wood supply. The assessment is executed in a top-down approach which applies the same environmental and economic restrictions all over Europe. The consistent European forest data needed for such an assessment is produced by harmonizing national forest inventory data from 16 European countries and applying a gap-filling algorithm to fill the gaps left by countries where no inventory data could be gathered. The resulting forest characteristics are then combined with other data to assess Europe's potential wood supply. The assessment of FAWS considers environmental (protection status) and economic (slope of the terrain, soil, forest road network) restrictions based on the technical and economic operation range of eight mechanized harvesting systems. The assessment shows that 74.9% of Europe's forest area can be considered FAWS with the potential to be economically harvested. Around 80% of the harvestable forest area and growing stock can potentially be harvested by the fully mechanized harvesting systems (i) harvester and forwarder and (ii) winch-assisted harvester and winch-assisted forwarder.

Kurzfassung

In Europa ist ungefähr 1/3 der Landfläche mit Wäldern bedeckt. Waldökosysteme sind unverzichtbar für eine Gesellschaft, da sie wichtige Güter und Dienstleistungen bereitstellen und eine wichtige Rolle in der Bewältigung der Klima- und Energiekrisen spielen. Um die Umsetzung entsprechender Europäischer Strategien (z.B. Waldstrategie) zu unterstützen, sind konsistente und verständliche Europäische Waldzustandsberichte notwendig. In Europa gibt es allerdings nach wie vor kein einheitliches, harmonisiertes Waldberichtssystem. Bei der Bewertung des wirtschaftlich nutzbaren Waldes unterscheiden sich beispielsweise die berücksichtigten umwelttechnischen, ökonomischen und sozialen Beschränkungen von Land zu Land. Konsistente Abschätzung des Holzvorrates im wirtschaftlich nutzbaren Wald ist in einer Bioökonomie, in der die nachhalte Nutzung von Holz gefördert wird, von besonderem Interesse. In dieser Arbeit wird die potentielle Holzversorgung in Europa anhand einer konstanten Methodik, welche in allen Ländern dieselben Beschränkungen anwendet, abgeschätzt. Für die Produktion konsistenter Europäischer Walddaten werden zuerst Waldinventurdaten aus 16 Europäischen Ländern harmonisiert. Danach wird ein gap-filling Algorithmus angewandt um Länder zu füllen, für die keine Inventurdaten gesammelt werden konnten. Die resultierenden Europäischen Walddaten werden dann mit anderen Daten kombiniert und wirtschaftlich nutzbare Wälder anhand umwelttechnischer (Schutzstatus) und ökonomischer (Geländeneigung, Bodenbedingungen, Forststraßennetz) Einschränkungen und den Einsatzbereichen von acht mechanisierten Holzerntesystemen identifiziert. Die Abschätzung zeigt, dass 74.9 % der Europäischen Waldfläche als wirtschaftlich nutzbar angesehen werden können. Ungefähr 80 % des wirtschaftlich nutzbaren Vorrats kann potentiell mit dem voll mechanisierten Harvester und Forwarder Holzerntesystem (ggf. unter Zuhilfenahme von Traktionswinden) geerntet werden.

1. Introduction

Europe's forest area has experienced an increase of 19.3 million ha during the last 30 years (FOREST EUROPE, 2020). Currently, over 1/3 of Europe's total land area is covered with forests (FOREST EUROPE, 2020). Forest ecosystems are important for society, providing numerous ecosystem services such as timber production, provision of non-wood products, protection of infrastructure, protection of soil, water supply, biodiversity, recreation and well-fare. Forests are instrumental for climate change mitigation by sequestering carbon from the atmosphere and storing it in above- and belowground biomass (FOREST EUROPE, 2020). The provided renewable material wood can be used to substitute fossil fuels and other non-renewable and emission-intensive materials such as concrete. Long-lived wood products will be an integral part of a bio-based economy (bioeconomy) (European Commission - Directorate-General for Research and Innovation, 2018) aiming to reduce greenhouse gas emissions (Eyvindson et al., 2018).

Climate change mitigation, the establishment of a bioeconomy and the provision of key ecosystem services cannot be tackled solely on a national level but need a supranational effort. This is reflected in EU strategies such as the forest strategy for 2030 (European Commission, 2021), the biodiversity strategy for 2030 (European Commission, 2020) and the bioeconomy strategy (European Commission - Directorate-General for Research and Innovation, 2018). The bioeconomy strategy aims (i) to manage natural resources sustainably and (ii) to reduce the dependence on non-renewable, unsustainable resources. Likewise, the EU forest strategy for 2030 wants to promote the sustainable forest bioeconomy for long-lived wood products and ensure the sustainable use of wood-based resources for bioenergy. As a consequence, the demand for the renewable raw material wood is likely to rise. This leads to the question, if the European forestry sector is able to meet this demand, especially as forests not only contribute to climate change mitigation but are themselves threatened by changing growing conditions (e.g. temperature, precipitation patterns, drought) (Dyderski et al., 2018; Hanewinkel et al., 2013; Hlásny et al., 2017) and an increase in natural disturbances (e.g. wind throw, forest fires) (Neumann et al., 2017; Seidl et al., 2017; Senf and Seidl, 2021). This suggests that an assessment of the potential wood supply in Europe is needed.

In Europe, forest assessments commonly rely on national forest inventories (NFI) providing systematic, repeated measurements of tree characteristics (Tomppo et al., 2010). Two different NFI approaches are in place and differ by country: (i) aggregated stand-level inventories resulting from surveying and (ii) statistical point sampling based on a systematic grid design across the country (Tomppo et al., 2010). Stand-level inventories were initially conducted for stand management purposes and forest planning (Tomppo et al., 2010). With the increasing demand for forest data to inform national forest policy decision making, many countries changed and implemented a statistical sampling approach which also estimates sampling error (Tomppo et al., 2010).

Nowadays, the majority of countries (e.g. 25 out of the EU27) use a probability-based statistical sampling design. However, the actual sampling design still varies substantially between countries, with differences in grid spacing between plots or clusters, the number of plots per cluster, the proportion of permanent plots, the length of inventory cycles, or the approximate forest area represented by each field plot (Tomppo et al., 2010).

Apart from the differences in the sampling design and forest area estimation (e.g. based on field plots, photo interpretation, or a combination), even basic definitions like forest (e.g. minimum area, width and crown cover) or growing stock (e.g. minimum diameter at breast height, inclusion of stumps, branches or deadwood) vary between countries (Tomppo et al., 2010; Tomppo and Schadauer, 2012). While there are ongoing efforts to harmonize definitions and to establish a uniform inventory design to allow easier comparison and consistent reporting, the comparison of forest data across countries is thus still challenging (Alberdi et al., 2016; Gschwantner et al., 2022; McRoberts et al., 2012; Tomppo et al., 2010; Tomppo and Schadauer, 2012; Vidal et al., 2016). This limits any analysis or assessment on the European level due to the lack of data accessibility and consistency (Vidal et al., 2016).

Consequently, the forest reporting in Europe is based on a bottom-up approach, where individual countries report their figures based on their own calculations which are then aggregated to the European level (Vidal et al., 2016). An example is the State of Europe's Forests (FOREST EUROPE, 2020) which reports forest attributes for Europe based on country reports.

The State of Europe's Forests (SOEF) reports figures for forest area of and growing stock in areas considered 'forest available for wood supply' (FAWS). While a reference definition for FAWS has been established (see Alberdi et al., 2016), the considered environmental, social or economic restrictions and threshold values (e.g. maximum extraction distance, steepness of terrain) vary between countries, introducing further inconsistencies. In addition to SOEF, several studies provide estimations for the biomass available for wood supply at a regional (NUTS) or country and European level. These estimations are commonly based on modelling approaches, e.g. using an inventory-based large scale forest resource model (Verkerk et al., 2019, 2011), an inventory-based yield data driven carbon budget model (Nabuurs et al., 2018) or a global forest model based on empirical growth functions (Di Fulvio et al., 2016).

Beside an assessment of forests available for wood supply, the wood mobilization needs to be considered. Wood provision is mainly driven by the cost-efficiency of harvesting, which depends on the growing stock and the productivity of the work force and the land owner. Since the demand for wood will likely increase and the increased demand needs to be met on less area of forest available for wood supply, as more forests will be protected, mechanized, cost-efficient harvesting will be important to secure wood supply (Samset, 1985; Silversides, 1997). Mechanized harvesting also increases work safety (e.g. Holzfeind et al., 2020), making forestry jobs more attractive, which is important considering that the European forest sector experiences a decline in man power due to aging (Payn, 2018). Potential operational areas of mechanized harvesting systems are largely defined by the technical requirements at the harvesting site (e.g. slope of the terrain, soil conditions, tree species and dimensions) and its accessibility, as defined by the forest road network (Nordfjell et al., 2004). GIS-based decision support systems have been used for identifying potential operation areas and selecting the most suitable harvesting systems at the regional level (Becker et al., 2018; Berendt et al., 2017; Bont et al., 2022; Kühmaier and Stampfer, 2010; Marčeta et al., 2020; Piragnolo et al., 2019). Di Fulvio et al. (2016) assessed the roundwood and logging residue availability and costs for the EU28, applying ten different harvesting systems but does not present potential operation areas of the harvesting systems or the amount potentially harvested by system. The potential operation areas of harvesting systems and the potential for mechanized harvesting at the European level are therefore currently unknown.

2. Vision and objectives

The vision of this thesis is to provide a consistent estimate of wood supply by harvesting system for the forest in Europe. A prerequisite for such an assessment are forest characteristics data at the European level. Since such data across Europe do not exist we first need to develop a consistent European forest characteristics data set, which is based on 16 gridded national forest inventory data in combination with remote sensing information to fill missing country information. This data set is then used to assess and evaluate the potential for mechanized harvesting in Europe. Assessment of the potential wood supply is based on the protection status of forested areas and the technical and economic (e.g. slope of the terrain, extraction distance) limitations of eight mechanized harvesting systems.

The objectives are:

- Production of an improved version of the European forest characteristics data (Paper 1)
- Assessment of Europe’s potential wood supply by harvesting system (Paper 2)

3. Data

For the assessment of Europe's potential wood supply, various data sets about the forest, terrain and site conditions, protection status, or climate were obtained (Table 1). The majority of the data was publicly available. Since the data sets vary in measurement type (ground-based in situ vs. remote), spatial (e.g. point or raster) and temporal scaling, pre-processing was needed to ensure the consistency.

Data processing, i.e. projecting, aligning or resampling of the data, was performed using the statistical software R (R Core Team, 2020) and ESRI ArcGIS 10.2.1 (Redlands, 2011). Usage of data and information are now discussed in more detail based on the thematic groups (i) Inventory, (ii) Remote sensing, (iii) Climate, and (vi) Other data.

Table 1: Overview of the data inputs and in which paper they are used.

Input	Group	Description	Paper
Forest inventory	Inventory	Plot based point inventory data. Used for producing the gridded forest structure data.	1
Tree species maps of European forests	Inventory	Tree species maps for European forests providing the dominant tree species and the share of 20 tree species.	2
Forest structure	Inventory	Gridded forest structure data for ten forest stand characteristics. Produced in Paper 1.	1,2
MODIS_EURO net primary production	Remote Sensing	European remote sensing net primary production (NPP) data based on the MODIS MOD17 algorithm.	1
Canopy height	Remote Sensing	Global canopy height data produced from space borne LiDAR (light detection and ranging data).	1
MODIS land cover	Remote Sensing	MODIS MCD12Q1 land cover data based on MODIS reflectance data.	1
COPERNICUS forest type	Remote Sensing	COPERNICUS Forest Type 2018 product based on SENTINEL reflectance data.	2
EU-DEM digital elevation model	Remote Sensing	Digital elevation model based on SRTM and ASTER remote sensing instruments.	2
Downscaled European climate	Climate	Daily downscaled European climate data generated by downscaling coarse E-Obs climate data with finer-resolution WorldClim data.	1
Climate limitation index	Climate	Product of normalized average growing season length, average annual short-wave solar radiation and average vapor pressure deficit.	1
Conservation status	Other	Common Database on Designated Areas (CDDA) information about the conservation status of areas.	2
Road network	Other	OpenStreetMap (OSM) road network data.	2
Soil	Other	European Soil Database (ESDB) soil data.	2
Auxiliary	Other	Shapefiles of the country borders and the biogeographical regions of Europe.	1, 2

3.1. Inventory

3.1.1. Forest inventory

Plot based regional and national forest inventories provide in situ (ground-based) systematic tree measurements and are traditionally used in many (but not all) European countries to derive forest stand characteristics such as mean height of trees, mean diameter at breast height, volume or age structure (Tomppo et al., 2010). This thesis uses plot inventory data from 16 European countries (Albania, Austria, Belgium, Croatia, Estonia, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Poland, Romania, Spain, Sweden), representing over 350,000 inventory plots. These countries have a gridded systematic point sampling inventory design and provided the following plot-level forest information with some information missing in some countries (e.g. height not reported in Romania): carbon content, biomass for individual compartments (stem, branch, foliage, root), volume, height, diameter at breast height (DBH), stem number, basal area, stand density index, age class, and tree species group.

Each forest inventory has its own definitions and methods (Tomppo et al., 2010). Therefore, harmonization is needed to make the estimations of the individual forest inventories comparable (Alberdi et al., 2016; Gabler et al., 2012; Gschwantner et al., 2022; Neumann et al., 2016a; Ståhl et al., 2012; Tomppo and Schadauer, 2012; Vidal et al., 2008). For the inventory data used in this thesis, harmonization was done according to age classes, tree species groups, and partly to volume and biomass definitions. The inventory data was used to produce gridded forest structure data (Paper 1).

3.1.2. Tree species maps of European forests

Tree species is an important factor for the selection of a harvesting system. We obtained tree species maps from Brus et al. (2012). The maps were produced using spatial interpolation of national inventory data from 18 countries. For areas where no inventory data was available, a regression model calibrated on ICP-Forests-Level-I plot data was used for mapping (Brus et al., 2012). They provide maps for the dominant tree species and the share of 20 tree species at 1 x 1 km resolution. In this thesis, we utilized the dominant tree species map in the assessment of the potential wood supply by harvesting system (Paper 2).

3.2. Remote sensing

Remote sensing provides consistent, spatially-explicit data for large areas. When integrated with in situ forest data (e.g. from national forest inventories) it (i) can improve the accuracy of describing forested areas and (ii) allows us to obtain spatially-explicit products (Tomppo et al., 2008). In this thesis, remotely sensed net primary production, canopy height and land cover data were used to produce gap-filled forest characteristics maps based on the point inventory data (Paper 1). Remote sensing was also used to identify forested areas and to calculate the slope of harvesting sites for the selection of the harvesting system (Paper 2).

3.2.1. MODIS_EURO net primary production

Net primary production (NPP) quantifies the uptake of atmospheric CO_2 and its conversion into plant biomass (Running et al., 2004). It is the difference between gross primary production (GPP), which quantifies the total uptake of atmospheric CO_2, and plant autotrophic respiration. NPP is an indicator for the productivity of ecosystems, like the potential supply of biomass in forest ecosystems (Neumann et al., 2016b). Ecophysiological modelling allows the calculation of NPP from satellite reflectance and climate data (Running et al., 2004). The MOD17 algorithm estimates NPP based on the normalized difference vegetation index (NDVI) derived from remote sensing reflectance data of the MODerate resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra and Aqua satellites (Running et al., 2004). In this thesis we used the MODIS_EURO data provided by Neumann et al. (2016b). MODIS_EURO uses the original MOD17 algorithm with a European regional climate dataset (Moreno and Hasenauer, 2015) to provide improved NPP estimations for Europe at 0.00833° (~1 km) resolution for the years 2000 to 2010. NPP was used as a co-variate in the gap-filling algorithm producing the gridded forest characteristics data (Paper 1).

3.2.2. Canopy height

Light detection and ranging (LiDAR) determines range based on the traveling time of emitted and reflected light pulses. The waveform produced by the returned signals can be used to derive vegetation height based on the first (canopy top) and last (ground) Gaussian peak within the waveform (Brenner et al., 2003; Simard et al., 2011).

Global space borne LiDAR data are available from the GLAS sensor onboard the ICESat satellite. Simard et al. (2011) used this data to produce a global wall-to-wall canopy height map at 0.00833° (~ 1km resolution). Gaps in the ICESat data were filled using a regression tree based gap-filling algorithm which utilizes various global ancillary variables providing information about the climate, elevation, tree cover and protection status (Simard et al., 2011). Canopy height was used in this thesis to produce gridded forest structure data (Paper 1).

3.2.3. Land cover

Satellite images are commonly used to produce land cover maps. The maps are generated either by photo interpretation or by classifying features within the remotely sensed image according to their different reflection characteristics (Aplin, 2004). In this thesis, two different land cover products were used: (i) MODIS MCD12Q1 Version 6, and (ii) COPERNICUS Forest Type 2018. The land cover products differ in the sensor used to gather the reflectance data, the spatial and temporal resolution and coverage, and the land cover classes.

3.2.3.1. MODIS land cover

The MODIS MCD12Q1 Version 6 uses reflectance data of the MODIS sensor to provide global land cover data at yearly intervals from 2001 to 2020 at 500 m resolution for six different land cover classifications (Friedl and Sulla-Menashe, 2019). In this thesis, land cover data for the year 2005 and the University of Maryland (UMD) classification, which consists of 17 different land cover classes, was used. This classification distinguishes five different forest types: (i) Evergreen Needleleaf Forests, (ii) Evergreen Broadleaf Forests, (iii) Deciduous Needleleaf Forests, (iv) Deciduous Broadleaf Forests, and (v) Mixed Forests. In addition, we also considered the three land cover classes (i) Woody Savannas, (ii) Savannas, and (iii) Cropland/Natural Vegetation Mosaics as partly forested. A MODIS based forest mask at 500 m resolution was generated, where each forested cell contributes a forest area ranging from 1.25 ha (barely forested) to 25 ha (fully forested), depending on the land cover class. The MODIS land cover data was used to produce the gridded forest structure data and for the calculation of the total growing stock per country (Paper 1).

3.2.3.2. COPERNICUS forest type

The COPERNICUS Forest Type 2018 product of the Copernicus Land Monitoring Service is provided by the European Environment Agency (EEA) (EEA, 2020). Reflectance data collected by the MultiSpectral Instrument on board the SENTINEL-2A+B satellites were used to derive the dominant leaf type which in turn is the basis for the forest type product. The forest type product covers the EEA members and cooperating countries (EEA39) and distinguishes (i) non-forest areas, (ii) broadleaved forest, and (iii) coniferous forest at 10 m spatial resolution and a Minimum Mapping Unit (MMU) of 0.5 ha. Following the FAO forest definition, tree covered areas in agricultural and urban contexts are excluded. The forest type product is available either in its 10 m original resolution or at an aggregated 100 m resolution, where a 100 x 100 m grid cell is considered forested if at least 50 % of its enclosed 10 m cells are forested. Based on the aggregated version, a COPERNICUS forest mask was generated, where each 100 m cell identified as forest is considered fully forested and contributes 1 ha of forest area. The data was then aggregated to 500 x 500 m resolution and used in the assessment of current harvesting options in Europe (Paper 2).

3.2.4. EU-DEM digital elevation model

Slope information was needed for the selection of the harvesting system as the operation range of different harvesting systems (e.g. ground-based, winch-assisted, cable yarding) is limited by the slope of the terrain.

Digital elevation models (DEMs) can be used to calculate the slope. Global digital elevation models have been produced from remote sensing data by studying the interference patterns caused by combining two sets of radar signals. In this thesis, we obtained the EU-DEM (EEA, 2017) which was created by merging the data gathered by the SRTM (Shuttle Radar Topography Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instruments. Later, the EU-DEM was improved using SPOT 2011 imagery and ICESat data. The EU-DEM covers Europe at a horizontal spatial resolution of 25 m and a vertical accuracy of +/- 7 metres RMSE (root mean squared error).

The DEM was used to calculate the slope in percent for each 25 m x 25 m cell based on its eight neighbouring cells using the raster package (Hijmans, 2021) in R (R Core Team, 2020). We then assigned each 25 m slope cell to one of three slope classes: (i) < 30 %, (ii) 30 to 60 %, and (iii) ≥ 60 %. Finally, the slope class for each 500 m x 500 m cell was derived by combining slope class shares and the mean slope of the 500 m cell. This information was then used for harvesting system selection (Paper 2).

3.3. Climate

3.3.1. Downscaled European climate

The downscaled European climate data (Moreno and Hasenauer, 2015) provides daily precipitation, minimum temperature and maximum temperate at 0.0083° x 0.0083° resolution for the years 1951 to 2012. For the production of the climate data, finer-resolution (0.0083°) WorldClim (Cornes et al., 2018) data was used to downscale the coarse (0.25°) daily E-Obs (Cornes et al., 2018) climate data. This was done by applying a spatial delta method with a monotone cubic interpolation of anomalies (Moreno and Hasenauer, 2015; Mosier et al., 2014). WorldClim provides global long-term monthly averages of climatic variables. E-Obs provides gridded daily climate data for Europe by interpolating weather station data. Since its original release, the downscaled climate data has been updated, with the current Version 3 now covering the period 1951 to 2020 (Pucher and Neumann, 2022; Rammer et al., 2022). In addition, an R package for easily accessing the climate data has been developed (Cruz-Alonso et al., 2023). The original downscaled European climate data was used to produce the NPP data (see 3.2.1 MODIS_EURO net primary production) and climate limitation index used in this thesis (Paper 1).

3.3.2. Climate limitation index

The climate limitation index is the product of a normalized average growing season length, average annual short-wave solar radiation (SWRAD) and average vapour pressure deficit (VPD) (Moreno and Hasenauer, 2015). Both SWRAD and VPD are calculated using the MtClim algorithm, with the downscaled climate data and a digital elevation model as inputs (McRoberts et al., 2002; Moreno and Hasenauer, 2015). Average growing season length is estimated using the onset of the increase of leaf area index (LAI) in spring and the end of the decrease in LAI in autumn using MODIS Leaf Area Index data (Myneni et al., 2002). Both NPP and climate limitation index were not calculated as part of this thesis as they were still available from previous studies carried out by Neumann et al. (2016b) and Moreno et al. (2017). The climate limitation index was used as a co-variate in the gap-filling algorithm producing the gridded forest characteristics data (Paper 1).

3.4. Other data

3.4.1. Conservations status

The Common Database on Designated Areas provided by the European Environment Agency (EEA) provides shapefiles with information about the conservation status and the availability of forested areas for harvesting. The International Union for Conservation of Nature (IUCN) categories “Ia - strict nature reserve”, “Ib - wilderness area”, and “II - national park” which correspond to the MCPFE (Pan-European Ministerial Conference on the Protection of Forests in Europe) classes “1.1 No active intervention” and “1.2 Minimum Intervention” are considered unavailable for harvesting activities (Frank et al., 2005). Conservation status was used to assess the current potential wood supply in Europe (Paper 2).

3.4.2. Road network

Freely available OpenStreetMap (OSM) road network data was used to calculate road density as a proxy for extraction distance. OSM road shapefiles were obtained from Geofabrik (www.geofabrik.de) and cover the period between January and April 2019. Only road types relevant to forestry operations (i.e. secondary, tertiary, unclassified and track) were used in the calculation. Road density was calculated for the four radii (i) 100 m, (ii) 300 m, (iii) 600 m and (iv) 1000 m which correspond to the maximum extraction distance of different harvesting systems (see Table 2 below). This information was used for harvesting system selection (Paper 2).

3.4.3. Soil

Soil bearing capacity gives an indication for the trafficability of a soil. Bearing capacity depends on the soil type, soil texture and soil moisture content. Since bearing capacity in general decreases with increasing moisture content, the use of heavy machinery on soils with groundwater access is limited to very dry or frozen periods to minimize soil damage (Allman et al., 2017; Cambi et al., 2015; Goltsev and Lopatin, 2013). In this thesis, the European Soil Database (ESDB) v2 (Panagos, 2006) of the European Soil Data Centre (Panagos et al., 2012) was used to identify soil types influenced by groundwater: (i) gleyic and stagnic Albeluvisol, (ii) gleyic and fluvic Cambisol, (iii) gleyic Fluvisol, (iv) Gleysol,(v) gleyic Luvisol, (vi) Phaeozem, (vii) Planosol, (viii) gleyic Podzol and (ix) Umbrisol (IUSS Working Group WRB, 2015). Soil trafficability was used for harvesting system selection (Paper 2).

4. Analysis and methods

Forests will play a key role in overcoming the climate and energy crisis. In Europe, consistent forest assessment is limited by the lack of a common forest reporting system. The majority, but not all, of European countries have established a national forest inventory (NFI). NFIs systematically collect forest data which are then used for forest resource assessment and reporting. The problem of forest reporting in Europe is that, as of yet, attempts to harmonize the individual NFIs have been unsuccessful. This means that NFIs of individual countries use their own sampling design, definitions and calculation methods. Across country analysis and comparison are further complicated by data policies often limiting the access to the forest inventory data, with only regional or country statistics publicly available. Europe's forest reporting is consequently based on a bottom-up approach, with each country reporting their own figures based on their own methodology and calculations.

Forest reporting in Europe would greatly benefit from publicly accessible, harmonized, consistent, and spatially-explicit forest data covering all of Europe. Given the current situation of Europe's forest inventory system as outlined above, the following steps are necessary to produce such data: (i) harmonization of the different NFIs as far as possible (ii) filling of gaps where no inventory data is available. This thesis provides the methodology to produce partly harmonized, consistent, and spatially-explicit European forest data. The usefulness of the data is then demonstrated based on one of many possible application cases, specifically the estimation of Europe's potential wood supply by harvesting system.

4.1. General workflow

For the production of consistent, spatially-explicit European forest data, it is, first, pivotal to gather point forest inventory data from all over Europe. This ensures that the variety of European forest, spanning from the Mediterranean region in the South to the Boreal region in the North and passing the mountainous Alpine region between them, is sufficiently represented in the data. In a first step, the data coming from different countries with different inventory systems are harmonized. After harmonization, gaps that are still present either because a country still lacks an inventory system or the inventory data could not be obtained are filled. For this purpose, a gap-filling algorithm is applied. Areas without inventory data are filled by identifying similar (according to climate and remote sensing data) areas with data. The gap-filled maps then provide consistent and spatially-explicit forest characteristics data for Europe (Paper 1).

The forest characteristics data are then applied in the assessment of Europe's potential wood supply by harvesting system. A huge benefit of the forest characteristics data is its spatially-explicit nature, which allows for its combination with other spatially-explicit European data (e.g. forest mask, conversation, slope, soil). We assess Europe's potential wood supply by harvesting system by combining the forest characteristics data with other European spatial data and applying a set of eight mechanized harvesting systems. The 'forest available for wood supply' (FAWS) is identified based on the protection status, and the terrain (slope and soil), road network, and stand (tree species and dimensions) conditions using a top-down approach with consistent methodology all over Europe. The result is a European assessment of forest area of and growing stock in FAWS by harvesting system (Paper 2).

Figure 1 shows the workflow for the production of the improved forest characteristics data and their application in assessing Europe's potential wood supply by harvesting system.

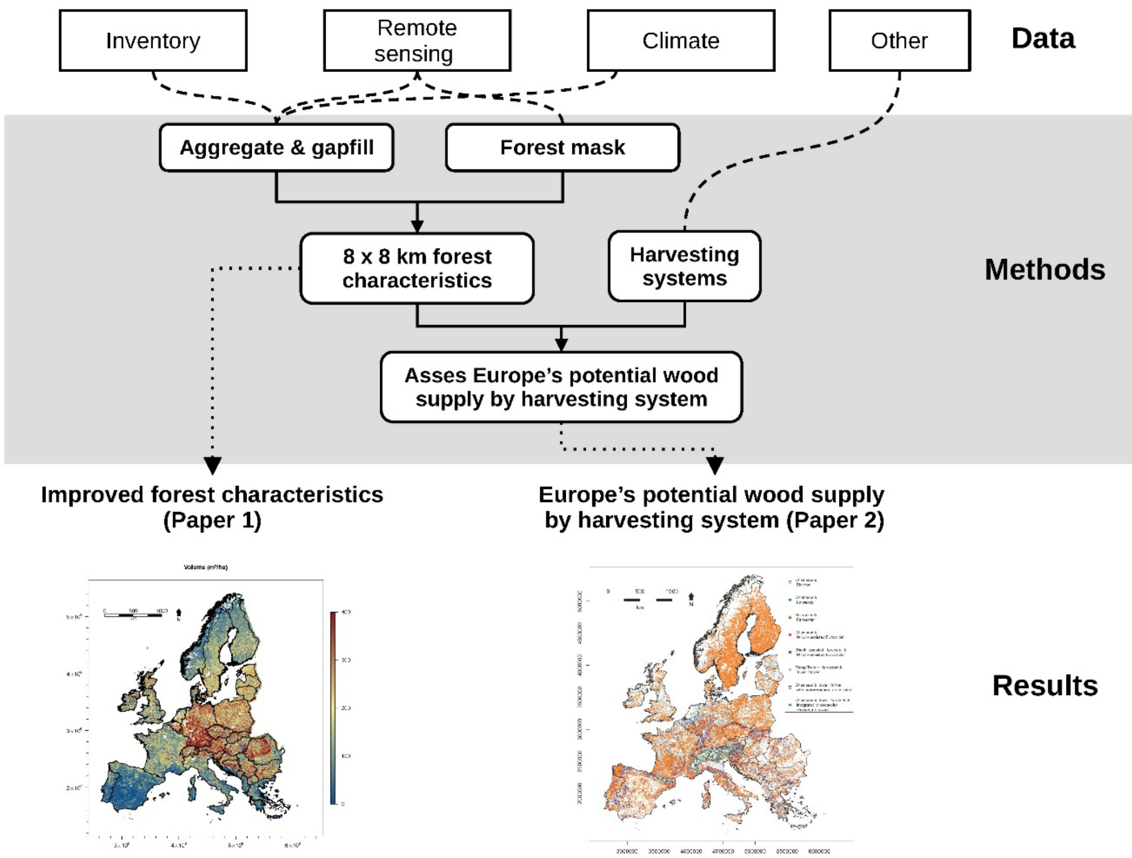


Figure 1: Workflow showing the inputs and methods used in and the results of the thesis.

4.2. Gridded forest characteristics

For this study, point forest inventory data from 16 European countries (Albania, Austria, Belgium, Croatia, Estonia, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Poland, Romania, Spain, Sweden) were obtained (Figure 2). Data from the different national forest inventories were harmonized according to age class, tree species group and partly volume and biomass definitions as described in Neumann et al. (2016b). For a European forest resource assessment, the gaps where no inventory data exists or could not be obtained needed to be filled. For this purpose, we applied a gap-filling algorithm to produce wall-to-wall European forest characteristics data.

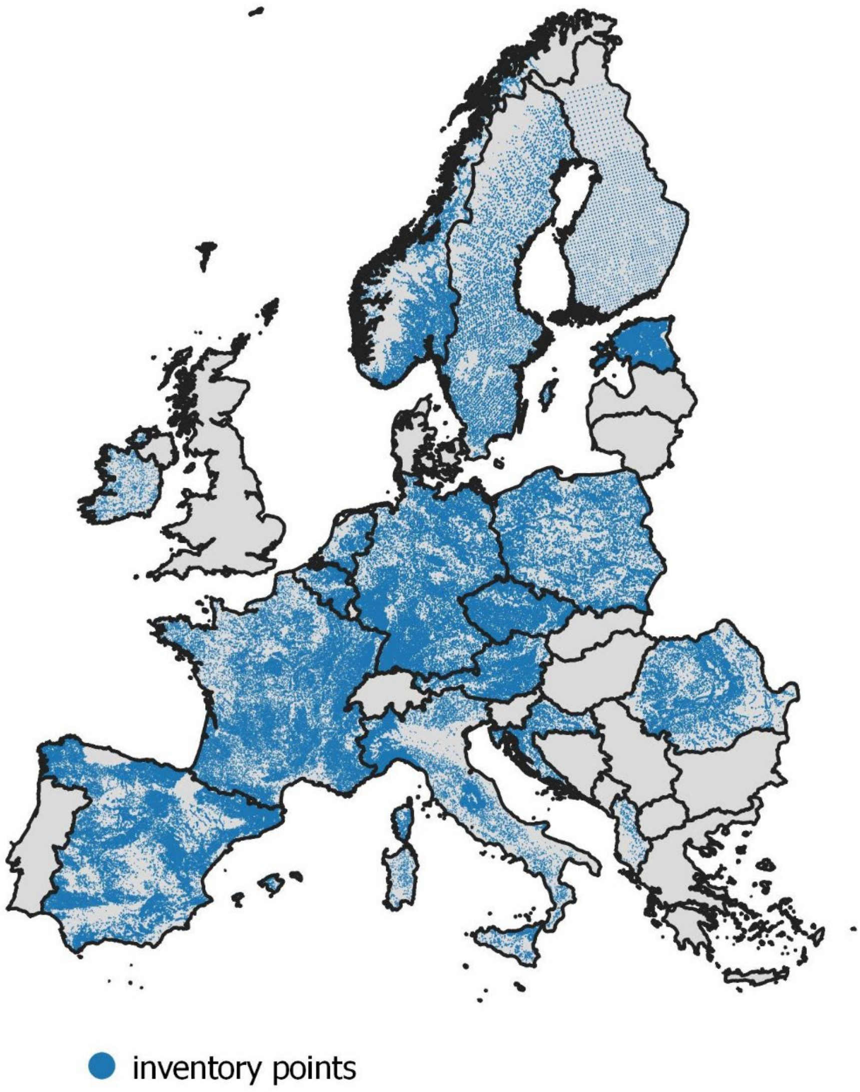


Figure 2: Map showing the gathered point inventory data.

4.2.1. Aggregate & gap-fill

First, the point inventory data were aggregated to 8 x 8 km resolution by averaging the metric variables (e.g. height and volume) and calculating the proportion and most frequent values for nominal values (age class, tree species group). Aggregation to 8 x 8 km was performed to ensure enough inventory points are within a cell to have statistical confidence in the derived cell values (Moreno et al., 2016).

In a next step, a two-step gap-filling algorithm was applied to fill areas where no inventory data could be obtained: (i) cells were clustered by similarity and (ii) a k-Nearest Neighbor (kNN) algorithm was used to assign each cell with missing gridded inventory data its nearest neighbor with inventory data belonging to the same cluster. The kNN non-parametric approach makes predictions for an object with unobserved values based on the k most similar objects with observed values, with the similarity of objects being based on the distance between the objects in a user-defined co-variate space (McRoberts et al., 2002).

In our case, clustering by similarity was based on the MODIS MCD12Q1 land cover type and biogeographical region of the cell. For the kNN algorithm, the co-variates NPP, NPP trend, canopy height and climate limitation index were used. This follows the procedure given by Moreno et al. (2017): The climate limitation index matches forests with similar productivity curves, and canopy height acts as a proxy for the forest development stage. NPP and NPP trend determine the position along the productivity curve (Moreno et al., 2017).

The resulting aggregated and gap-filled data at 8 x 8 km resolution provides mean forest stand characteristics like mean volume per cubic metre, mean diameter at breast height or share of mixture types. We did not use the forest inventory data for forest area estimation, but based our forest area estimations on remotely sensed forest masks.

4.2.2. Forest masks

The produced mean forest stand characteristics are independent of the forest area within an 8 x 8 km cell and can therefore be combined with any forest mask providing forest area information. Further, the resolution of the forest mask is not limited to the 8 x 8 km resolution, allowing the use of higher resolution data better able to delineate forested and non-forested areas. In this thesis we produced two different spatially-explicit forest masks based on two different remotely sensed land cover data: (i) MODIS and (ii) COPERNICUS (see also 3.2.3. Land cover).

4.3. Harvesting systems

Profitable provision of wood depends on the growing stock and the productivity of harvesting operations. Mechanized harvesting systems commonly have a high productivity, allowing cost-efficient harvesting as well as an increase in harvesting safety (Holzfeind et al., 2020; Silversides, 1997). Applicability of a harvesting system depends largely on the general accessibility of and the technical requirements at the harvesting site as defined by the slope of the terrain, soil bearing capacity, road network density, tree dimensions, and species composition (Nordfjell et al., 2004).

In this thesis, we applied a set of eight mechanized harvesting systems differing in harvesting method, technology and level of mechanization (see Table 2). Each harvesting system has a technical operation range which can be matched with the parameters (i) slope, (ii) soil conditions, (iii) extraction distance, (iv) tree species, and (v) diameter at breast height (DBH) to see if a harvesting system is suitable. The harvesting systems were used to identify ‘forest available for wood supply’ and assess the potential wood supply in Europe (see Paper 2).

Table 2: Overview of the eight defined harvesting systems. Each harvesting system is characterized by its limitations regarding terrain (slope, soil), road infrastructure (extraction distance) and stand conditions (species, DBH - diameter at breast height).

	Harvesting System	Technical Limitations				
		Slope	Soil	Extraction Distance	Tree Species	DBH
1	**Chainsaw and skidder** Harvesting method: tree length Level of mechanization: Partially mechanized	< 30 %	-	≤ 100 m	-	-
2	**Chainsaw and forwarder** Harvesting method: cut-to length method Level of mechanization: Partially mechanized	< 30 %	Limited	≤ 1000 m	-	-
3	**Harvester and forwarder** Harvesting method: cut-to length method Level of mechanization: Fully mechanized	< 30 %	Limited	≤ 1000 m	limited	tree species specific
4	**Chainsaw and winch-assisted forwarder** Harvesting method: cut-to length method Level of mechanization: Partially mechanized	< 60 %	Limited	≤ 300 m	-	-
5	**Winch-assisted harvester and winch-assisted forwarder** Harvesting method: cut-to length method Level of mechanization: Fully mechanized	< 60 %	Limited	≤ 300 m	limited	tree species specific
6	**Steep terrain harvester and tower yarder** Harvesting method: cut-to-length method Level of mechanization: Fully mechanized	< 60 %	Limited	≤ 600 m	limited	tree species specific
7	**Chainsaw and tower yarder** Harvesting method: cut-to-length method Level of mechanization: Partially mechanized	< 100 %	-	≤ 600 m	-	-
8	**Chainsaw and tower yarder with integrated or excavator-based processor** Harvesting method: whole tree method Level of mechanization: Highly mechanized	< 100 %	-	≤ 600 m	limited	tree species specific

5. Results

5.1. Improved forest characteristics (Paper 1)

For the production of the European, spatially-explicit gridded forest characteristics dataset, point inventory data from 16 European countries were used (see Figure 2). The data were aggregated to 8 x 8 km resolution and the two-step gap-filling algorithm was used to fill areas where no inventory data could be obtained (see 4.2.1 Aggregate & gap-fill). The result of the gap-filling are wall-to-wall, gridded forest characteristics maps for Europe (Figure 3).

The gridded forest structure maps provide the following, forest area independent, mean forest characteristics at 8 x 8 km resolution (Figure 3): carbon content (tC/ha), biomass for individual compartments (stem, branch, foliage, root) (t/ha), volume (m^3/ha), height (m), diameter at breast height (cm), stem number (stems/ha), basal area (m^2/ha), age class (%), the tree species group (%), and stand density index.

In order to validate the data and demonstrate how the data can be used to describe the current forest state, the total growing stock per country was calculated and compared with the reported values of the State of Europe's Forest 2015 (FOREST EUROPE, 2015). Country totals were calculated by multiplying the growing stock in m^3 per hectare obtained from the forest characteristics maps with the forest area in hectare for each 500 x 500 m cell from the MODIS forest mask (Figure 4a). Country values are the summary of the cell values within the country.

The comparison with the reported values (Figure 4b) showed that while some countries might be over- or underestimated, the forest structure maps can provide realistic estimations at the European level. More importantly, the methodology was able to provide realistic estimations for many of the countries where no national forest inventory data was available, such as Czech Republic (CZ), Hungary (HU), Latvia (LV), Slovenia (SI), and the United Kingdom (UK). However, especially in the South-East region, a slight tendency of overestimating countries where no inventory data were available (Figure 4b) could be observed (e.g. BA Bosnia, BG Bulgaria, SK Slovakia, RS Serbia).

The ability to provide realistic estimations at the European level was an important precondition for assessing Europe's potential wood supply.

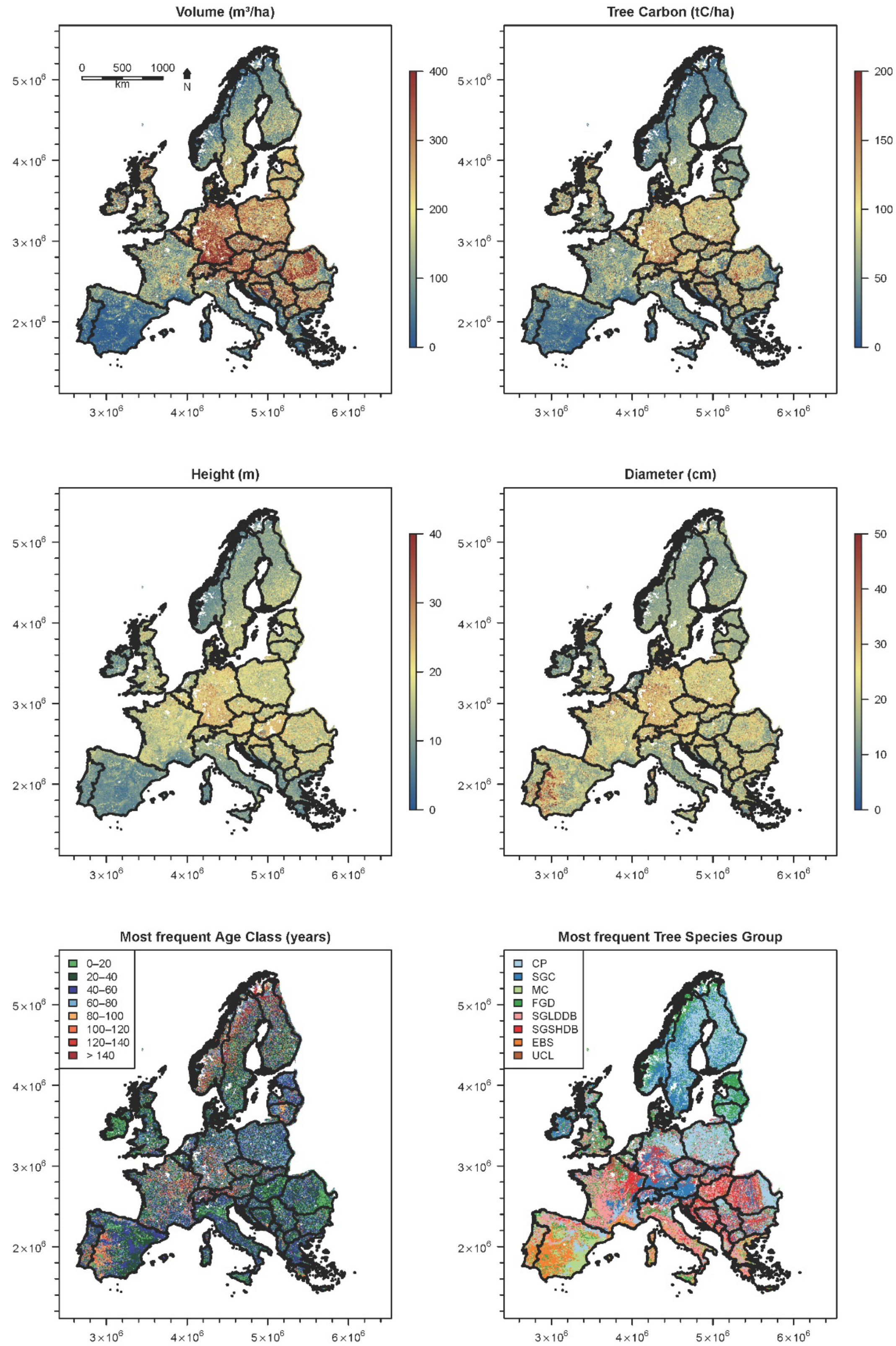
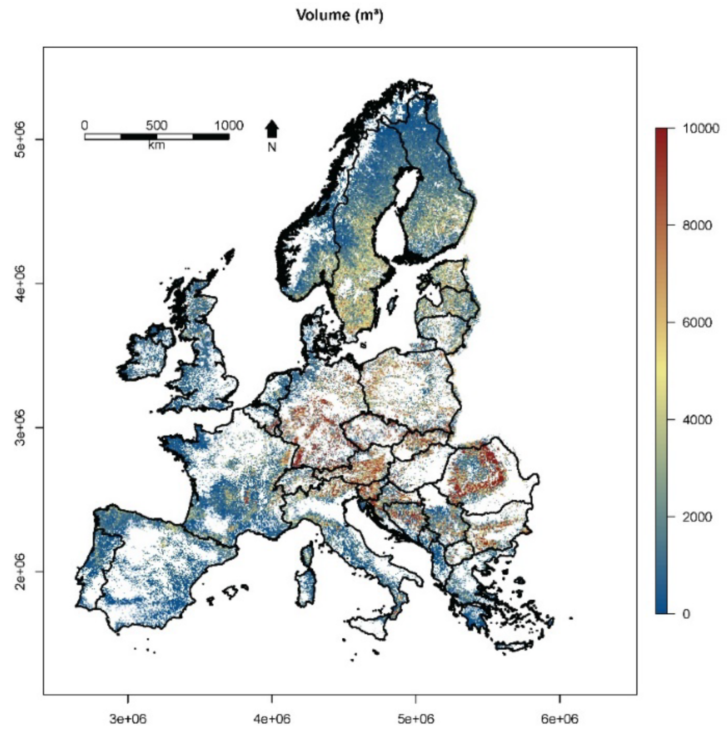
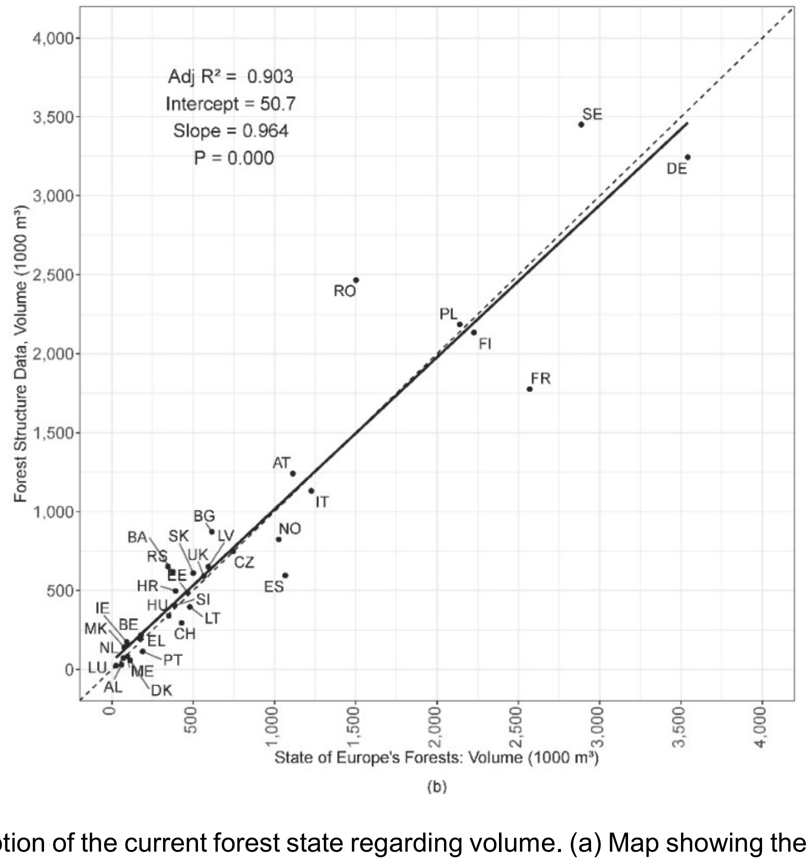


Figure 3: Gridded forest structure maps for Europe at 8 x 8 km resolution. Here the maps for mean volume, mean tree carbon, mean height, mean diameter at breast height, most frequent age class and most frequent tree species group are shown. Maps for biomass by compartment, stem number, basal area and stand density index are not shown.



(a)



(b)

Figure 4: Description of the current forest state regarding volume. (a) Map showing the absolute volume in m³ for each 500 x 500 m cell. The map is produced by combining the gridded forest characteristics map at 8 x 8 km resolution with the MODIS forest mask at 500 x 500 m resolution. Based on this map the total volume per country can be calculated. (b) Comparison of the total volume per country calculated using the map and the total volume per country as reported by State of Europe's Forests 2015.

5.2. Assessing Europe’s potential wood supply (Paper 2)

Since parts of Europe’s forest is not available for sustainable harvesting, the Food and Agriculture Organization of the United Nations (FAO) distinguishes between (i) ‘forest available for wood supply’ (FAWS) and (ii) ‘forest not available for wood supply’ (FNAWS) (Alberdi et al., 2016). FAWS have no environmental, social or economic restrictions, while FNAWS includes forest in protected areas not available for harvesting (e.g. national parks or nature conservation) as well as forests where harvesting may not be feasible due to inaccessibility of the forest area, lack of profitability or low yield productivity (Alberdi et al., 2020). The first step in assessing Europe’s potential wood supply was therefore to identify ‘forest available for wood supply’.

Although efforts have been made to harmonize the assessment of ‘forest available for wood supply’ (FAWS), assessment on the European level is currently based on individual country reports with the definition of FAWS varying by country (Alberdi et al., 2020, 2016). In our assessment of FAWS we chose a top-down approach with consistent definition and methodology all over Europe. Such an analysis needs consistent, spatially-explicit data covering the whole study area, i.e. Europe. Spaceborne remote sensing can provide such data (e.g. digital elevation models or land cover maps), but its ability to map forest resources (e.g. biomass or volume) are currently still limited (Zhao et al., 2016). This gap is filled with the produced improved forest characteristics for Europe (see Results 5.1 Improved forest characteristics) which enable a consistent forest resource assessment at the European level.

5.2.1. Forest available for wood supply

The forest characteristics data were combined with other spatial explicit European data (conservation, land cover, road network, slope, soil, tree species, see chapter 3. Data) to identify the ‘forest available for wood supply’ (FAWS).

First, the COPERNICUS forest mask at 500 m resolution was blended with the conservation data to exclude forest where harvesting is prohibited. Following the suggestion by Alberdi et al. (2020) we consider forest areas belonging to the MCPFE classes “1.1 No active intervention” and “1.2 Minimum Intervention” as not available for wood supply. For the remaining forest cells, profitability of a harvesting operations was assessed by applying a set of eight different harvesting systems which differ in harvesting method and level of mechanization (see 4.3 Harvesting systems).

Applicability of a harvesting system and profitability of a harvesting operation were limited by (i) slope of the terrain, (ii) soil conditions, (iii) extraction distance, (iv) tree species, and (v) tree dimensions. These factors were evaluated using the slope, soil, road network, tree species, and forest characteristics data (see 3. Data). As the selection of a harvesting system is largely driven by the terrain (slope and soil) and road network situation at the harvesting site, and the respective data was available at a higher resolution compared to the 8 x 8 km resolution of the forest characteristics data, a 500 m x 500 m resolution was chosen for identifying the potential harvesting system. If at least one of the eight harvesting systems could be applied the respective forest cell was considered as 'forest available for wood supply' (FAWS) (Figure 5a). If none of the eight harvesting systems was applicable, the forest area was considered to have a "limited accessibility".

The assessment showed that in Europe, the 34 countries considered in our analysis, 74.9 % (137.4 Million ha) of the total forest area (183.4 Million ha) are 'forest available for wood supply' (FAWS) (Table 3). From the area of 'forest not available for wood supply' (FNAWS), 4.3 % are not available due to the protection status and another 20.8 % due to having a limited accessibility.

The share of FAWS and FNAWS varies between geographic regions. While in Central-West-Europe 90 % of the area is FAWS, its share is only 62.2 % in South-East Europe where 34.9 % of the area have a "limited accessibility" (Table 3). North Europe has, at 7.1 %, the highest share of protected area, while the share is only 1.1 % in Central-West Europe.

We were also interested in the growing stock in FAWS. The growing stock in each 500 m cell of FAWS was calculated by multiplying the mean volume per hectare obtained from the forest characteristics data with the forest area provided by the COPERNICUS forest mask. The total growing stock in FAWS amounts to 25 billion m³ (Table 4).

5.2.2. Harvestable area and growing stock by harvesting system

Over two thirds of the area (70.8 %) of and growing stock (66.7 %) in 'forest available for wood supply' (FAWS) can be potentially harvested by the fully mechanized harvester and forwarder (HFW) system (Figure 5b and Tables 3 and 4). An additional 15 % of the area and growing stock can be potentially harvested by the fully mechanized harvesting systems winch-assisted harvester and winch-assisted forwarder (WHWF) and steep terrain harvester and tower yarder (SHTY). Only around 6 % of the growing stock in FAWS can solely be harvested with chainsaw and tower yarder systems (Table 4). This shows a high potential for mechanized harvesting in Europe.

In North Europe, over 95 % of the area of and growing stock in FAWS can be harvested by fully mechanized harvesting systems (HFW, WHWF, and SHTY), with HWF being the dominant system (Tables 3 and 4). In comparison, in South-East Europe, the HFW is only suitable for 45.8 % of the area of and 42.7 % of the growing stock in FAWS. Together with WHWF and SHTY, over 75 % of the area and growing stock in South-East Europe remains harvestable by fully mechanized harvesting systems. Central-West Europe has the lowest potential for mechanization, but still 78.1 % of the area of and 74.9 % of the growing stock in FAWS are harvestable by a fully mechanized harvesting system.

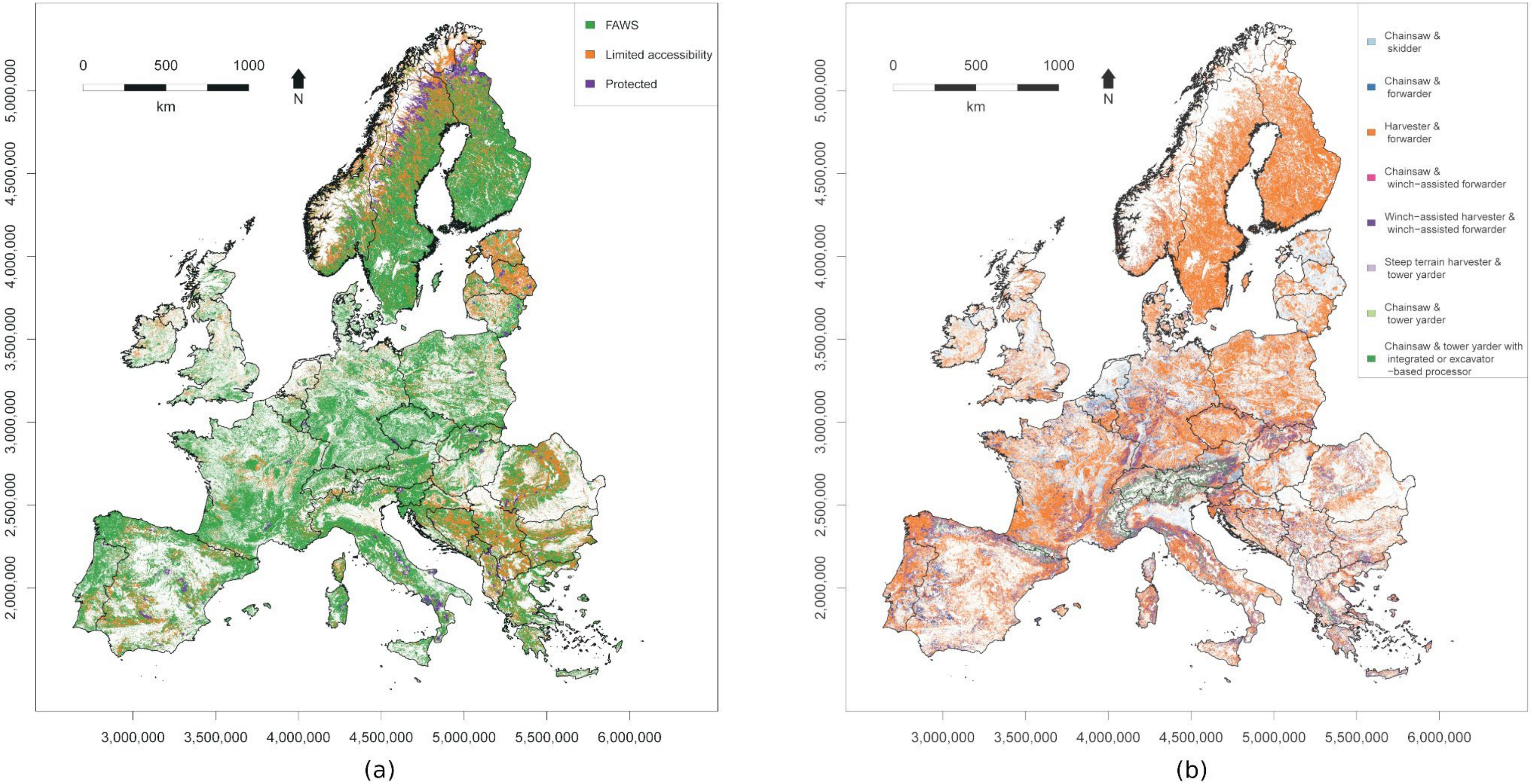


Figure 5: Assessment of the ‘forest available for wood supply’ (FAWS) in Europe at 500 m resolution. (a) European forest area categorized into FAWS (green) and ‘forest not available for wood supply’ (FNAWS). FNAWS is further separated into protected areas (purple) and areas with limited accessibility (orange). (b) Map showing the harvesting system with the highest level of mechanization suitable for each 500 m cell of FAWS. Harvesting systems: (i) Chainsaw and skidder (light blue), (ii) Chainsaw and forwarder (dark blue), (iii) Harvester and forwarder (orange), (v) Chainsaw and winch-assisted forwarder (pink), (v) Winch-assisted harvester and winch-assisted forwarder (dark purple), (vi) Steep terrain harvester and tower yarder (light purple), (vii) Chainsaw and tower yarder (light green), (viii) Chainsaw and tower yarder with integrated or excavator-based processor (dark green).

Table 3: Summary of the forest area in Europe (all 34 countries considered) and the share of area of 'forest available for wood supply' (FAWS) by harvesting system for Europe and five European regions. 'Forest not available for wood supply' (FNAWS) comprises protected forest where commercial harvesting is prohibited as well as forest areas where commercial harvesting is allowed but is non-profitable due to limited accessibility. All other forest areas are considered as 'forest available for wood supply' (FAWS). The regions are defined according to the State of Europe's Forests (FOREST EUROPE, 2020) and include the following countries: (i) Europe: all of the 34 countries mentioned; (ii) North Europe: Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden; (iii) Central-West Europe: Austria, Belgium, France, Germany, Ireland, Lichtenstein, Luxembourg, Netherlands, Switzerland, United Kingdom; (iv) Central-East Europe: Czech Republic, Hungary, Poland, Romania, Slovakia; (v) South-West Europe: Italy, Portugal, Spain; (vi) South-East Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Montenegro, North Macedonia, Serbia, Slovenia.

	Europe	North Europe	Central-West Europe	Central-East Europe	South-West Europe	South-East Europe
Total (Million ha)	183.4	66.7	38.1	26.6	29.3	22.7
Protected (%)	4.3	7.1	1.1	2.5	4.8	2.9
Limited accessibility (%)	20.8	25.8	8.9	20.2	14.6	34.9
FAWS (Million ha)	137.4	44.8	34.3	20.5	23.6	14.1
(%)	74.9	67.1	90.0	77.3	80.6	62.2
	Distribution of FAWS among Harvesting Systems (in %)					
Chainsaw and skidder	2.6	1.7	5.2	3.7	0.6	1.1
Chainsaw and forwarder	4.7	0.4	8.0	4.1	7.1	6.8
Harvester and forwarder	70.8	94.7	61.7	74.7	50.5	45.8
Chainsaw and winch-assisted forwarder	1.0	0.0	1.3	1.5	1.2	2.2
Winch-assisted harvester and winch-assisted forwarder	11.7	1.4	14.3	9.1	23.4	22.9
Steep terrain harvester and tower yarder	4.2	1.2	2.1	4.2	7.8	13.2
Chainsaw and tower yarder	0.6	0.0	0.6	1.1	0.8	1.9
Chainsaw and tower yarder with integrated or excavator-based processor	4.3	0.7	6.8	1.6	8.7	6.1

Table 4: Share of growing stock in ‘forest available for wood supply’ (FAWS) per harvesting system for Europe, the five European regions and their countries. FAWS corresponds to forest where harvesting is allowed from a legal perspective and is profitable. Harvesting Systems: CSK Chainsaw and skidder, CFW Chainsaw and forwarder, HFW Harvester and forwarder, CWF Chainsaw and winch-assisted forwarder, WHWF Winch-assisted harvester and winch-assisted forwarder, SHTY Steep terrain harvester and tower yarder, CTY Chainsaw and tower yarder, CTYP Chainsaw and tower yarder with integrated or excavator-based processor.

	Volume	Distribution among Harvesting Systems							
	FAWS	CSK	CFW	HFW	CWF	WHWF	SHTY	CTY	CTYP
	Million m³	%	%	%	%	%	%	%	%
Europe	25119.0	3.2	6.1	66.7	1.7	12.2	3.9	1.1	5.1
North Europe	6307.9	2.4	0.8	94.5	0.0	1.0	0.9	0.0	0.5
Denmark	117.7	3.5	22.0	74.5	0.0	0.0	0.0	0.0	0.0
Estonia	183.6	29.7	0.0	70.3	0.0	0.0	0.0	0.0	0.0
Finland	1991.8	0.3	0.4	99.3	0.0	0.0	0.0	0.0	0.0
Latvia	261.7	18.4	0.0	81.6	0.0	0.0	0.0	0.0	0.0
Lithuania	301.8	9.9	1.6	88.5	0.0	0.0	0.0	0.0	0.0
Norway	662.0	0.8	0.1	78.0	0.0	9.1	7.3	0.0	4.6
Sweden	2789.3	0.1	0.3	99.3	0.0	0.2	0.2	0.0	0.0
Central-West Europe	7979.3	5.2	9.9	58.3	1.7	15.1	1.5	0.7	7.7
Austria	1124.9	5.5	2.1	23.3	1.9	35.7	1.9	1.8	27.9
Belgium	211.1	6.0	17.7	73.1	0.3	2.8	0.1	0.0	0.0
France	2200.5	3.8	8.8	61.0	1.1	15.5	3.3	0.8	5.7
Germany	3619.6	5.2	13.3	67.8	2.0	9.8	0.2	0.1	1.6
Ireland	89.3	13.9	1.9	79.3	0.1	3.3	0.9	0.0	0.5
Lichtenstein	1.2	1.5	4.4	11.7	18.1	7.1	0.0	51.2	6.0
Luxemburg	14.2	7.1	5.8	74.9	3.2	7.9	0.4	0.4	0.5
Netherlands	45.6	49.9	1.1	49.0	0.0	0.0	0.0	0.0	0.0
Switzerland	312.6	2.6	2.7	23.2	4.6	24.7	2.1	4.6	35.5
United Kingdom	360.3	6.6	11.6	72.6	0.5	5.1	2.0	0.2	1.3
Central-East Europe	5713.5	3.3	5.5	70.8	2.3	9.7	4.7	1.8	1.8
Czech Republic	856.2	0.8	3.8	82.1	0.6	11.0	1.3	0.1	0.3
Hungary	466.8	9.2	3.3	81.0	0.0	5.0	0.9	0.0	0.6
Poland	2474.4	5.0	4.4	86.7	0.6	2.2	0.7	0.3	0.1
Romania	1403.0	0.7	7.1	45.1	5.4	16.4	13.8	6.0	5.5
Slovakia	513.1	1.5	11.1	36.2	7.2	29.2	8.5	2.4	3.8
South-West Europe	2211.0	0.7	3.0	38.6	2.0	29.5	8.3	1.6	16.3
Italy	1282.3	1.1	2.2	27.2	2.3	32.7	8.2	2.0	24.2
Portugal	150.8	0.4	5.5	69.8	0.6	18.5	4.4	0.2	0.6
Spain	777.9	0.1	3.8	51.3	1.8	26.3	9.3	1.1	6.4
South-East Europe	2907.5	1.4	10.7	42.7	3.6	20.9	12.3	3.0	5.6
Albania	43.6	0.5	5.7	18.3	7.9	26.4	18.7	10.0	12.6
Bosnia and Herzegovina	404.1	0.1	9.9	47.8	1.8	19.1	14.8	1.6	5.0
Bulgaria	695.4	1.2	9.2	46.5	3.4	18.7	13.3	3.5	4.3
Croatia	407.0	4.5	17.8	53.8	3.6	11.5	5.6	2.0	1.2
Greece	314.0	0.0	5.1	30.5	2.8	34.1	14.3	2.5	10.7
Montenegro	76.2	0.0	3.8	31.5	3.5	29.4	17.9	4.0	9.9
North Macedonia	95.8	0.0	8.5	33.0	5.9	21.4	19.8	7.1	4.3
Serbia	511.4	1.3	13.8	42.3	3.6	18.1	14.8	3.3	2.7
Slovenia	360.0	1.6	9.4	36.1	5.3	27.5	5.5	2.9	11.7

6. Discussion

Pressing issues like climate change mitigation or securing wood supply require supranational efforts and cannot be tackled on the national level. In support of these efforts, common forest reporting systems producing comparable estimations and allowing consistent analysis across country borders are needed. Europe still lacks such a forest reporting system. The produced gridded forest characteristics data are one important step towards consistent forest reporting and resource assessment in Europe. It provides mean forest characteristics including volume, biomass, tree dimensions (height and diameter), age class, basal area and tree species group at 8 x 8 km for Europe (Figure 3). For its production, national forest inventory data from 16 European countries were harmonized according to age class, tree species group, and partly biomass and volume definitions. The produced forest characteristics data are publicly available, allowing large scale forest analysis in Europe, usually limited by availability and accessibility of European forest data.

Confidence in the produced forest characteristics data is given by the cross-validation results, showing that the methodology is robust and accurate (see Appendix 9.1 Paper 1). Comparison with FAO statistics revealed that, at a country level, the estimated growing stock can notably differ from reported figures, even for countries where inventory data was obtained (Figure 4). These differences could partly be explained with differences in forest area estimation, problems with the harmonization of definitions and variables, and comparison of different time periods (see Appendix 9.1 Paper 1). For countries where no inventory data could be obtained, the quality of the gap-filling relies on the ability of the gathered inventory data from the 16 European countries to accurately describe the forest conditions in these countries. In South-East Europe, where the gap-filling relied on limited data from Albania and Croatia, a bias towards overestimating the growing stock could be observed (Figure 4). At that time, it was not possible to gather additional data in the region but it was identified as an important step for future improved versions. Besides these differences for some countries, it was shown that the forest characteristics data can be used to produce realistic and unbiased growing stock estimations for the European forest (Figure 4). This was an important prerequisite for assessing Europe's potential wood supply.

The spatially-explicit nature and European coverage of the gridded forest characteristics data allowed a top-down assessment of the 'forest available for wood supply' (FAWS) in Europe (Figure 5). The chosen methodology, for the first time, allowed to apply the same environmental (protection status) and economic (accessibility, slope of terrain, soil conditions, and to some extent profitability) restrictions and threshold values all over Europe. So far, figures for FAWS in Europe (e.g. FOREST EUROPE, 2020) were reported based on a bottom-up approach, with restrictions and threshold values varying by country. The estimated area of and growing stock in FAWS for the 34 European countries considered in our study, are, at 137 million ha and 25 billion m³, around 12 million ha and 1.9 billion m³ lower compared to the figures reported in the State of Europe's forest (FOREST EUROPE, 2020). This difference can be attributed to the different calculation methods (top-down vs. bottom-up). Around 4.3 % or 8 million ha of forest are protected according to the MCPFE classes "1.1 No active intervention" and "1.2 Minimum Intervention" (Figure 5 and Table 3). Additional areas might not be available for wood supply due to national regulations which are not considered in our analysis. Around 21 % or 38 million ha of Europe's forest is not available for wood supply due to a limited accessibility with current mechanized harvesting systems (Figure 5 and Table 3). A low road density was identified as the most limiting factor for the application of mechanized harvesting systems (see Appendix 9.2 Paper 2). Especially in North and South-East-Europe a better forest road infrastructure could increase the share of FAWS.

This study evaluates, for the first time, the potential for mechanized harvesting of European forests by suggesting a high mechanization potential for Europe (Figure 5). Around 80 % of the forest area of and growing stock in 'forest available for wood supply' (FAWS) can be harvested by a fully mechanized harvesting system (Figure 5 and Tables 3 and 4). The study revealed a high potential for mechanized harvesting in all five European regions considered in the study. Even in the region with the lowest potential for mechanized harvesting, Central-West Europe, around 3/4 of the area of and growing stock in FAWS can be harvested by fully mechanized systems (Tables 3 and 4). Here it is important to note, that the study might tend to overestimate the area and growing stock harvestable by fully mechanized harvesting systems, as the forest characteristics data levels the actual diameter at breast height (DBH) distribution in an area and higher DBHs might limit the use of harvester or cable yarder with processor (see Appendix 9.2 Paper 2).

The potential for mechanized harvesting in Europe assessed in this study can be different to the observed level of mechanization (Lundbäck et al., 2021). Differences can be attributed to social and economic factors influencing the willingness to harvest and the selection of harvesting systems: the forest ownership structure (e.g. the share of privately and publicly owned forest land), the implemented silvicultural system, the economic condition of forest owners, the availability and price of equipment and workforce, or the prioritization of other ecosystem services (e.g. protection of soil or infrastructure) (Lundbäck et al., 2021). These factors are not considered in our analysis, since we only looked into the technical/economic (e.g. extraction distance, slope of the terrain) and environmental (protection status) restrictions, which would rule out the use of a specific harvesting system, before even considering other factors like the economic condition or the availability of the equipment.

7. Conclusions

Forest resource assessment in Europe is often limited by the inconsistency and inaccessibility of forest information. This problem was solved by producing an openly accessible, spatially-explicit, gridded forest characteristics data set at 8 x 8 km resolution for Europe. The data were produced based on partly harmonized inventory data from 16 European countries and by applying a gap-filling algorithm to fill areas where no inventory data could be obtained. With these forest characteristics data the "forest available for wood supply" (FAWS) in Europe was determined using a top-down approach, which applied the same environmental (protection status) and economic (accessibility, slope of terrain, soil conditions, and to some extent profitability) restrictions and threshold values (e.g. maximum slope, maximum extraction distance) in all countries. Applying eight mechanized harvesting systems to identify FAWS allowed an assessment for mechanized harvesting potential in Europe.

The assessment of FAWS and potential for mechanized harvesting is of high relevance as forest, biodiversity, and economy strategies in Europe will likely lead to (i) the promotion of using wood in long-lived wood products and an expected increase in the demand for wood and (ii) the need to meet this demand on a decreasing area for harvesting as more forest areas will be protected and taken out of management. The potential operational area of mechanized harvesting systems should encourage the promotion of mechanized harvesting in Europe to ensure wood supply. It should also encourage the development of mechanized harvesting systems to minimize the negative impact on the forest site and to be prepared for future harvesting conditions (e.g. shift in tree species composition to a higher share of broadleaved tree species, change in harvesting season) (Berendt et al., 2017; Marchi et al., 2018; Schweier et al., 2019).

Assessment of Europe's potential wood supply is only one of many possible applications for the produced gridded forest characteristics data. Other applications are quantifying the carbon stored in Europe's forest threatened by invasive alien pests (Seidl et al., 2018), or assessing the impact of conservation policies (Moreno et al., 2019).

The produced forest characteristics are an important step towards a harmonized European forest resource assessment but also highlights information needs in Europe: (i) the lack of a uniform and harmonized inventory system and (ii) the unavailability or inaccessibility of high-resolution European data (e.g. forest or soil information). For both the establishment of a common forest inventory system, as well as an open data policy the United States of America (US) can serve as a role model. In the 1990s, the US transitioned from state-wide and regional forest inventories to a standardized forest inventory across the country, with common plot configuration, sampling design, measurement protocols, estimation formulae, and reporting standards (Tomppo et al., 2010). Great parts to the data gathered by the Forest Inventory and Analysis National Program are openly available on their website.

8. References

Alberdi, I., Bender, S., Riedel, T., Avitable, V., Boriaud, O., Bosela, M., Camia, A., Cañellas, I., Castro Rego, F., Fischer, C., Freudenschuß, A., Fridman, J., Gasparini, P., Gschwantner, T., Guerrero, S., Kjartansson, B.T., Kucera, M., Lanz, A., Marin, G., Mubareka, S., Notarangelo, M., Nunes, L., Pesty, B., Pikula, T., Redmond, J., Rizzo, M., Seben, V., Snorrason, A., Tomter, S., Hernández, L., 2020. Assessing forest availability for wood supply in Europe. For. Policy Econ. 111, 102032. https://doi.org/10.1016/j.forpol.2019.102032

Alberdi, I., Michalak, R., Fischer, C., Gasparini, P., Brändli, U.-B., Tomter, S.M., Kuliesis, A., Snorrason, A., Redmond, J., Hernández, L., Lanz, A., Vidondo, B., Stoyanov, N., Stoyanova, M., Vestman, M., Barreiro, S., Marin, G., Cañellas, I., Vidal, C., 2016. Towards harmonized assessment of European forest availability for wood supply in Europe. For. Policy Econ. 70, 20–29. https://doi.org/10.1016/j.forpol.2016.05.014

Allman, M., Jankovský, M., Messingerová, V., Allmanová, Z., 2017. Soil moisture content as a predictor of soil disturbance caused by wheeled forest harvesting machines on soils of the Western Carpathians. J. For. Res. 28, 283–289. https://doi.org/10.1007/s11676-016-0326-y

Aplin, P., 2004. Remote sensing: Land cover. Prog. Phys. Geogr. 28, 283–293. https://doi.org/10.1191/0309133304pp413pr

Becker, R.M., Keefe, R.F., Anderson, N.M., Eitel, J.U.H., 2018. Use of lidar-derived landscape parameters to characterize alternative harvest system options in the Inland Northwest. Int. J. For. Eng. 29, 179–191. https://doi.org/10.1080/14942119.2018.1497255

Berendt, F., Fortin, M., Jaeger, D., Schweier, J., 2017. How Climate Change Will Affect Forest Composition and Forest Operations in Baden-Württemberg—A GIS-Based Case Study Approach. Forests 8, 298. https://doi.org/10.3390/f8080298

Bont, L.G., Fraefel, M., Frutig, F., Holm, S., Ginzler, C., Fischer, C., 2022. Improving forest management by implementing best suitable timber harvesting methods. J. Environ. Manage. 302, 114099. https://doi.org/10.1016/j.jenvman.2021.114099

Brenner, A.C., Zwally, H.J., Bentley, C.R., Csathó, B.M., Harding, D.J., Hofton, M.A., Minster, J., Roberts, L., Saba, J.L., Robert, H., Yi, D., 2003. Geoscience Laser Altimeter System (GLAS): Derivation of Range and Range Distributions From Laser Pulse Waveform Analysis for Surface Elevations , Roughness , Slope , and Vegetation Heights, Algorithm Theoretical Basis Document-Version 4.

Brus, D.J., Hengeveld, G.M., Walvoort, D.J.J., Goedhart, P.W., Heidema, A.H., Nabuurs, G.J., Gunia, K., 2012. Statistical mapping of tree species over Europe. Eur. J. For. Res. 131, 145–157. https://doi.org/10.1007/s10342-011-0513-5

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015. The impact of heavy traffic on forest soils: A review. For. Ecol. Manage. 338, 124–138. https://doi.org/10.1016/j.foreco.2014.11.022

Cornes, R.C., van der Schrier, G., van den Besselaar, E.J.M., Jones, P.D., 2018. An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. J. Geophys. Res. Atmos. 123, 9391–9409. https://doi.org/10.1029/2017JD028200

Cruz-Alonso, V., Pucher, C., Ratcliffe, S., Ruiz-Benito, P., Astigarraga, J., Neumann, M., Hasenauer, H., Rodríguez-Sánchez, F., 2023. The easyclimate R package: Easy access to high-resolution daily climate data for Europe. Environ. Model. Softw. 161, 1–8. https://doi.org/10.1016/j.envsoft.2023.105627

Di Fulvio, F., Forsell, N., Lindroos, O., Korosuo, A., Gusti, M., 2016. Spatially explicit assessment of roundwood and logging residues availability and costs for the EU28. Scand. J. For. Res. 31, 691–707. https://doi.org/10.1080/02827581.2016.1221128

Dyderski, M.K., Paź, S., Frelich, L.E., Jagodziński, A.M., 2018. How much does climate change threaten European forest tree species distributions? Glob. Chang. Biol. 24, 1150–1163. https://doi.org/10.1111/gcb.13925

EEA, 2020. © European Union, Copernicus Land Monitoring Service - High Resolution Layer: Forest Type (FTY) 2018 [WWW Document]. URL https://land.copernicus.eu/pan-european/high-resolution-layers/forests/forest-type-1/status-maps/forest-type-2018 (accessed 11.7.22).

EEA, 2017. © European Union, Copernicus Land Monitoring Service - EU-DEM [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem (accessed 11.18.22).

European Commission, 2021. New EU forest strategy for 2030 [WWW Document]. URL https://environment.ec.europa.eu/strategy/forest-strategy_en (accessed 11.4.22).

European Commission, 2020. Biodiversity strategy for 2030 [WWW Document]. URL https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en (accessed 11.4.22).

European Commission - Directorate-General for Research and Innovation, 2018. A sustainable bioeconomy for Europe : strengthening the connection between economy, society and the environment : updated bioeconomy strategy. Publications Office. https://doi.org/doi/10.2777/792130

Eyvindson, K., Repo, A., Mönkkönen, M., 2018. Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. For. Policy Econ. 92, 119–127. https://doi.org/10.1016/j.forpol.2018.04.009

FOREST EUROPE, 2020. State of Europe's Forests 2020.

FOREST EUROPE, 2015. State of Europe's Forests 2015.

Frank, G., Latham, J., Declan, L., Parviainen, J., Schuck, A., Vandekerkhove, K., Little, D., Parviainen, J., Schuck, A., Vandekerkhove, K., 2005. Analysis of Protected Forest Areas in Europe - Provisional Results of COST Action E27 PROFOR, in: Commarmot, B.; Hamor, F. D. (Eds): Natural Forests in the Temperate Zone of Euroope - Values and Utilisation. pp. 377–386.

Friedl, M., Sulla-Menashe, D., 2019. MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [WWW Document]. URL https://lpdaac.usgs.gov/products/mcd12q1v006/ (accessed 11.7.22).

Gabler, K., Schadauer, K., Tomppo, E., Vidal, C., Bonhomme, C., McRoberts, R.E., Gschwantner, T., 2012. An enquiry on forest areas reported to the Global forest resources assessment-is harmonization needed? For. Sci. 58, 201–213. https://doi.org/10.5849/forsci.10-060

Goltsev, V., Lopatin, E., 2013. The impact of climate change on the technical accessibility of forests in the Tikhvin District of the Leningrad Region of Russia. Int. J. For. Eng. 24, 148–160. https://doi.org/10.1080/19132220.2013.792150

Gschwantner, T., Alberdi, I., Bauwens, S., Bender, S., Borota, D., Bosela, M., Bouriaud, O., Breidenbach, J., Donis, J., Fischer, C., Gasparini, P., Heffernan, L., Hervé, J.-C., Kolozs, L., Korhonen, K.T., Koutsias, N., Kovácsevics, P., Kučera, M., Kulbokas, G., Kuliešis, A., Lanz, A., Lejeune, P., Lind, T., Marin, G., Morneau, F., Nord-Larsen, T., Nunes, L., Pantić, D., Redmond, J., Rego, F.C., Riedel, T., Šebeň, V., Sims, A., Skudnik, M., Tomter, S.M., 2022. Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation. For. Ecol. Manage. 505, 119868.

https://doi.org/10.1016/j.foreco.2021.119868

Hanewinkel, M., Cullmann, D.A., Schelhaas, M.-J., Nabuurs, G.-J., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Chang. 3, 203–207. https://doi.org/10.1038/nclimate1687

Hijmans, R.J., 2021. raster: Geographic Data Analysis and Modeling. R package version 3.4-13 [WWW Document]. URL https://cran.r-project.org/package=raster

Hlásny, T., Trombik, J., Bošeľa, M., Merganič, J., Marušák, R., Šebeň, V., Štěpánek, P., Kubišta, J., Trnka, M., 2017. Climatic drivers of forest productivity in Central Europe. Agric. For. Meteorol. 234–235, 258–273. https://doi.org/10.1016/j.agrformet.2016.12.024

Holzfeind, T., Visser, R., Chung, W., Holzleitner, F., Erber, G., 2020. Development and Benefits of Winch-Assist Harvesting. Curr. For. Reports 6, 201–209. https://doi.org/10.1007/s40725-020-00121-8

Kühmaier, M., Stampfer, K., 2010. Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. Croat. J. For. Eng. 31, 75–88.

Lundbäck, M., Häggström, C., Nordfjell, T., 2021. Worldwide trends in methods for harvesting and extracting industrial roundwood. Int. J. For. Eng. 00, 1–14. https://doi.org/10.1080/14942119.2021.1906617

Marčeta, D., Petković, V., Ljubojević, D., Potočnik, I., 2020. Harvesting System Suitability as Decision Support in Selection Cutting Forest Management in Northwest Bosnia and Herzegovina. Croat. J. For. Eng. 41, 251–265. https://doi.org/10.5552/crojfe.2020.744

Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P.S., McEwan, A., Brink, M., Laschi, A., 2018. Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. Sci. Total Environ. 634, 1385–1397. https://doi.org/10.1016/j.scitotenv.2018.04.084

McRoberts, R.E., Nelson, M.D., Wendt, D.G., 2002. Stratified estimation of forest area using satellite imagery, inventory data, and the k-Nearest Neighbors technique. Remote Sens. Environ. 82, 457–468. https://doi.org/10.1016/S0034-4257(02)00064-0

McRoberts, R.E., Tomppo, E.O., Schadauer, K., Ståhl, G., 2012. Harmonizing national forest inventories. For. Sci. 58, 189–190. https://doi.org/10.5849/forsci.12-042

Moreno, A., Hasenauer, H., 2015. Spatial downscaling of European climate data. Int. J. Climatol. 36, 1444–1458. https://doi.org/10.1007/s11856-016-1427-1

Moreno, A., Neumann, M., Hasenauer, H., 2017. Forest structures across Europe. Geosci. Data J. 4, 17–28. https://doi.org/10.1002/gdj3.45

Moreno, A., Neumann, M., Hasenauer, H., 2016. Optimal resolution for linking remotely sensed and forest inventory data in Europe. Remote Sens. Environ. 183, 109–119. https://doi.org/10.1016/j.rse.2016.05.021

Moreno, A., Neumann, M., Mohebalian, P.M., Thurnher, C., Hasenauer, H., 2019. The Continental Impact of European Forest Conservation Policy and Management on Productivity Stability. Remote Sens. 11, 1–15. https://doi.org/10.3390/rs11010087

Mosier, T.M., Hill, D.F., Sharp, K. V., 2014. 30-Arcsecond monthly climate surfaces with global land coverage. Int. J. Climatol. 34, 2175–2188. https://doi.org/10.1002/joc.3829

Myneni, R.B., Hoffman, S., Knyazikhin, Y., Privette, J.L., Glassy, J., Tian, Y., Wang, Y., Song, X., Zhang, Y., Smith, G.R., Lotsch, A., Friedl, M., Morisette, J.T., Votava, P., Nemani, R.R., Running, S.W., 2002. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. Remote Sens. Environ. 83, 214–231. https://doi.org/10.1016/S0034-4257(02)00074-3

Nabuurs, G.-J., Arets, E.J.M.M., Schelhaas, M.-J., 2018. Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU. Carbon Balance Manag. 13, 18. https://doi.org/10.1186/s13021-018-0107-3

Neumann, M., Moreno, A., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Achten, W.M.J., Thivolle-Cazat, A., Bronisz, K., Merganič, J., Decuyper, M., Alberdi, I., Astrup, R., Mohren, F., Hasenauer, H., 2016a. Comparison of carbon estimation methods for European forests. For. Ecol. Manage. 361, 397–420. https://doi.org/10.1016/j.foreco.2015.11.016

Neumann, M., Moreno, A., Thurnher, C., Mues, V., Härkönen, S., Mura, M., Bouriaud, O., Lang, M., Cardellini, G., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Alberdi, I., Astrup, R., Mohren, F., Zhao, M., Hasenauer, H., 2016b. Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests. Remote Sens. 8, 554. https://doi.org/10.3390/rs8070554

Neumann, M., Mues, V., Moreno, A., Hasenauer, H., Seidl, R., 2017. Climate variability drives recent tree mortality in Europe. Glob. Chang. Biol. 23, 4788–4797. https://doi.org/10.1111/gcb.13724

Nordfjell, T., Bacher, M., Eriksson, L., Kadlec, J., Stampfer, K., Suadicani, K., Suwala, M., Talbot, B., 2004. Operational Factors Influencing the Efficiency in Conversion, in: Spiecker, H., J. Hansen, E. Klimo, J.P. Skovsgaard, H. Sterba, and K. v. Teufel (Eds.), Norway Spruce Conversion - Options and Consequences, European Forest Institute Research Report, 18. Brill, Leiden - Boston, Netherlands, pp. 197–223.

Panagos, P., 2006. The European soil database. GEO Connex. 5, 32–33.

Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: Response to European policy support and public data requirements. Land use policy 29, 329–338. https://doi.org/10.1016/j.landusepol.2011.07.003

Payn, T., 2018. Future environmental challenges and New Zealand's planted forests. New Zeal. J. For. 63, 14–20.

Piragnolo, M., Grigolato, S., Pirotti, F., 2019. PLANNING HARVESTING OPERATIONS IN FOREST ENVIRONMENT: REMOTE SENSING FOR DECISION SUPPORT. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. IV-3/W1, 33–40. https://doi.org/10.5194/isprs-annals-IV-3-W1-33-2019

Pucher, C., Neumann, M., 2022. Description and Evaluation of Downscaled Daily Climate Data Version 3. https://doi.org/https://doi.org/10.6084/m9.figshare.19070162.v1

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. [WWW Document]. URL https://www.r-project.org/ (accessed 2.15.23).

Rammer, W., Pucher, C., Neumann, M., 2022. Description, Evaluation and Validation of Downscaled Daily Climate Data Version 2. https://doi.org/10.6084/m9.figshare.19063892.v1

Redlands, C.E.S.R.I., 2011. ArcGIS Desktop: Release 10.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., Hashimoto, H., 2004. A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. Bioscience 54, 547. https://doi.org/10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2

Samset, I., 1985. Winch and cable systems. Martinus Nijhoff/Dr. W. Junk Publishers, Dordrecht, The Netherlands.

Schweier, J., Magagnotti, N., Labelle, E.R., Athanassiadis, D., 2019. Sustainability Impact Assessment of Forest Operations: a Review. Curr. For. Reports 5, 101–113. https://doi.org/10.1007/s40725-019-00091-6

Seidl, R., Klonner, G., Rammer, W., Essl, F., Moreno, A., Neumann, M., Dullinger, S., 2018. Invasive alien pests threaten the carbon stored in Europe's forests. Nat. Commun. 9, 1–10. https://doi.org/10.1038/s41467-018-04096-w

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nat. Clim. Chang. 7, 395–402. https://doi.org/10.1038/nclimate3303

Senf, C., Seidl, R., 2021. Storm and fire disturbances in Europe: Distribution and trends. Glob. Chang. Biol. 27, 3605–3619. https://doi.org/10.1111/gcb.15679

Silversides, C.R., 1997. Broadaxe to flying shear: the mechanization of forest harvesting east of the Rockies. Transformation Series no. 6. National Museum of Science and Technology, Ottawa, Canada.

Simard, M., Pinto, N., Fisher, J.B., Baccini, A., 2011. Mapping forest canopy height globally with spaceborne lidar. J. Geophys. Res. 116, G04021. https://doi.org/10.1029/2011JG001708

Ståhl, G., Cienciala, E., Chirici, G., Lanz, A., Vidal, C., Winter, S., McRoberts, R.E., Rondeux, J., Schadauer, K., Tomppo, E., 2012. Bridging national and reference definitions for harmonizing forest statistics. For. Sci. 58, 214–223. https://doi.org/10.5849/forsci.10-067

Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., 2010. National Forest Inventories, National Forest Inventories: Pathways for Common Reporting. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-90-481-3233-1

Tomppo, E., Olsson, H., Ståhl, G., Nilsson, M., Hagner, O., Katila, M., 2008. Combining national forest inventory field plots and remote sensing data for forest databases. Remote Sens. Environ. 112, 1982–1999. https://doi.org/10.1016/j.rse.2007.03.032

Tomppo, E.O., Schadauer, K., 2012. Harmonization of national forest inventories in Europe: Advances under Cost Action E43. For. Sci. 58, 191–200. https://doi.org/10.5849/forsci.10-091

Verkerk, P.J., Anttila, P., Eggers, J., Lindner, M., Asikainen, A., 2011. The realisable potential supply of woody biomass from forests in the European Union. For. Ecol. Manage. 261, 2007–2015. https://doi.org/10.1016/j.foreco.2011.02.027

Verkerk, P.J., Fitzgerald, J.B., Datta, P., Dees, M., Hengeveld, G.M., Lindner, M., Zudin, S., 2019. Spatial distribution of the potential forest biomass availability in Europe. For. Ecosyst. 6, 5. https://doi.org/10.1186/s40663-019-0163-5

Vidal, C., Alberdi, I., Redmond, J., Vestman, M., Lanz, A., Schadauer, K., 2016. The role of European National Forest Inventories for international forestry reporting. Ann. For. Sci. 73, 793–806. https://doi.org/10.1007/s13595-016-0545-6

Vidal, C., Lanz, A., Tomppo, E., Schadauer, K., Gschwantner, T., Di Cosmo, L., Robert, N., 2008. Establishing forest inventory reference definitions for forest and growing stock: A study towards common reporting. Silva Fenn. 42, 247–266. https://doi.org/10.14214/sf.255

Zhao, P., Lu, D., Wang, G., Wu, C., Huang, Y., Yu, S., 2016. Examining spectral reflectance saturation in landsat imagery and corresponding solutions to improve forest aboveground biomass estimation. Remote Sens. 8. https://doi.org/10.3390/rs8060469

9. Appendix

9.1. Paper 1

Pucher, C.; Neumann, M.; Hasenauer, H. An Improved Forest Structure Data Set for Europe. Remote Sens. 2022, 14, 395, doi:10.3390/rs14020395.

remote sensing

Article
An Improved Forest Structure Data Set for Europe

Christoph Pucher *, Mathias Neumann and Hubert Hasenauer

Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences, Peter Jordan Strasse 82, A-1190 Vienna, Austria; mathias.neumann@boku.ac.at (M.N.); hubert.hasenauer@boku.ac.at (H.H.)
* Correspondence: christoph.pucher@boku.ac.at

Abstract: Today, European forests face many challenges but also offer opportunities, such as climate change mitigation, provision of renewable resources, energy and other ecosystem services. Large-scale analyses to assess these opportunities are hindered by the lack of a consistent, spatial and accessible forest structure data. This study presents a freely available pan-European forest structure data set. Building on our previous work, we used data from six additional countries and consider now ten key forest stand variables. Harmonized inventory data from 16 European countries were used in combination with remote sensing data and a gap-filling algorithm to produce this consistent and comparable forest structure data set across European forests. We showed how land cover data can be used to scale inventory data to a higher resolution which in turn ensures a consistent data structure across sub-regional, country and European forest assessments. Cross validation and comparison with published country statistics of the Food and Agriculture Organization (FAO) indicate that the chosen methodology is able to produce robust and accurate forest structure data across Europe, even for areas where no inventory data were available.

Keywords: modelling; bioeconomy; carbon sequestration; biodiversity; forest management; conservation; national forest inventory; monitoring

check for updates

Citation: Pucher, C.; Neumann, M.; Hasenauer, H. An Improved Forest Structure Data Set for Europe. *Remote Sens.* **2022**, *14*, 395. https://doi.org/10.3390/rs14020395

Academic Editor: Carlos Alberto Silva

Received: 1 December 2021
Accepted: 12 January 2022
Published: 15 January 2022

1. Introduction

Since the pre-industrial period, the anthropogenic greenhouse gas emissions including carbon dioxide (CO_2) have steadily increased and will have important impacts on human and natural systems [1]. Forests play an important role within the global carbon cycle because they store a large amount of carbon and mitigate climate change affects [2]. The reduction of greenhouse gas emissions by replacing fossil material and energy with renewable resources, such as biomass, is important to avoid the further increase in atmospheric CO_2 concentration. Thus, the use of wood products is expected to increase since wood is important for a bio-based economy, aiming for a reduction in emissions from the combustion of fossil fuels. In addition, forests provide other important valuable ecosystem services such as the protection of infrastructure in mountainous areas, habitat for wildlife and recreation areas especially near large cities [3].

Forest ecosystems mitigate climate change effects, but they are also directly affected by climate change through changing growing conditions (e.g., temperature, precipitation and length of drought periods). Forest adaptation to changing environmental conditions takes time due to the long lifespan of trees [4,5]. Climate change is often associated with an increase in weather extremes such as drought or storm events followed by wildfires, wind throw and bark beetle infections [6,7]. This is an additional challenge to the forestry sector because the demanded ecosystem services need to be provided and secured for the future [8,9].

European forests cover about 33% of Europe's total land area [3] and extend from the Mediterranean in the south to the Boreal regions in the north. They grow in elevations from sea level to high mountainous areas. These differences in the regional growing conditions have led to distinct ecosystems which are additionally shaped by the long-lasting historic management history in Europe [10]. Therefore, climate change, as an additional driver for forests, will also have distinct regional affects due to the geomorphological and climatic conditions [11–13]. Forest ecosystems and the belonging tree species are characterized by their eco-physiological heritage plus their land management history, both important for the adaptation potential of forest ecosystems [14,15].

Assessing the mitigation and adaptation potential of European forests requires consistent forest data across Europe. Such information may come from national forest reports or the Global Forest Resource Assessment (FRA) published by the United Nations Food and Agricultural Organization (FAO). These reports are often based on forest inventory data [16–18].

In Europe, National Forest Inventories (NFI) are commonly used to provide information for forest ecosystem service assessments [17]. However, it is important to note that the forest inventory monitoring system differs by country which leads to difficulties in comparing the results across countries and within Europe [19,20] since no consistent data collection system across Europe is in place. Each country has its own forest inventory system with its own methodology ranging from gridded sampling designs to forest surveys and/or a combination of remote sensing data with terrestrial forest information [17]. The FAO had some success in harmonizing definitions for their reports; however, only country totals such as aboveground biomass or deadwood are published [3,16]. Efforts to harmonize the different inventory systems or even establish a consistent forest monitoring system across Europe have proven to be a challenge [17,20–23].

The European Forest Information Scenario Model (EFIScen) uses and provides a freely available database for 32 European countries based on aggregated data at the county level [24]. These data are derived from information provided by the National Forest Inventories from each country and grouped by "forest types". Since the size of the counties differ, the spatial boundaries are unknown, and the level of detail may vary between countries. Various gridded datasets were generated using the EFIScen data [25–27]. However, they only provide a limited set of forest attributes.

In response to the need for consistent spatial forest data across Europe, Moreno et al. [28] developed the first freely accessible pan-European spatially explicit gridded forest structure dataset using forest inventory data from countries with a systematic NFI system, that allowed data access. To our knowledge, few countries in Europe have no systematic plot-based forest inventory (such as Hungary, Bulgaria and Lithuania), some countries have a combination of satellite and terrestrial driven forest inventory (e.g., Italy) and the majority of countries have a systematic gridded permanent plot-level NFI in place. Moreno et al. [28] applied a gap-filling algorithm using remotely sensed net primary production (NPP), canopy height and climate data to produce a consistent gridded forest structure data set across Europe which allows analysis by countries, climatic and/or any other regional gradients. The data have been used for improving climate-sensitive models [29,30], for assessing climate limitations on forest structure and the mitigation potential of European forests [31,32]. Furthermore the data have been used for studies on the impact of conservation policies [33] and for quantifying the live tree carbon threatened by invasive alien pests [34].

The goal of this paper is to provide an improved version of this gridded forest structure data using the methodology of [28]. Based on the experiences of working with the previous data set, we added additional forest inventory data from four countries and for two regions previously not covered, included additional plot-level forest structure variables and further improved the resolution and the accuracy of this spatial forest data set. The objectives of our study are:

1. to provide an improved gridded forest structure data set on 8 × 8 km resolution across Europe,
2. to assess the error components of the new forest structure data,
3. to obtain land cover information to generate consistent gridded forest structure maps at 500 m resolution enabling upscaling to regions and/or countries, and

4. to evaluate the provided higher resolution maps by calculating country totals and compare these data to the original NFI data and the FAO statistics.

2. Materials and Methods

The principal approach of our study is to only use point sampled National Forest Inventory (NFI) data covering 16 different countries and apply a gap-filling algorithm for countries and regions where no such data are available. The R statistical software is used for data preparation, statistical analysis and data visualization [35]. The gap-filling is done using the Python script written and made publicly available by Moreno et al. [28]. Figure 1 provides the workflow and the used data including the methodological steps:

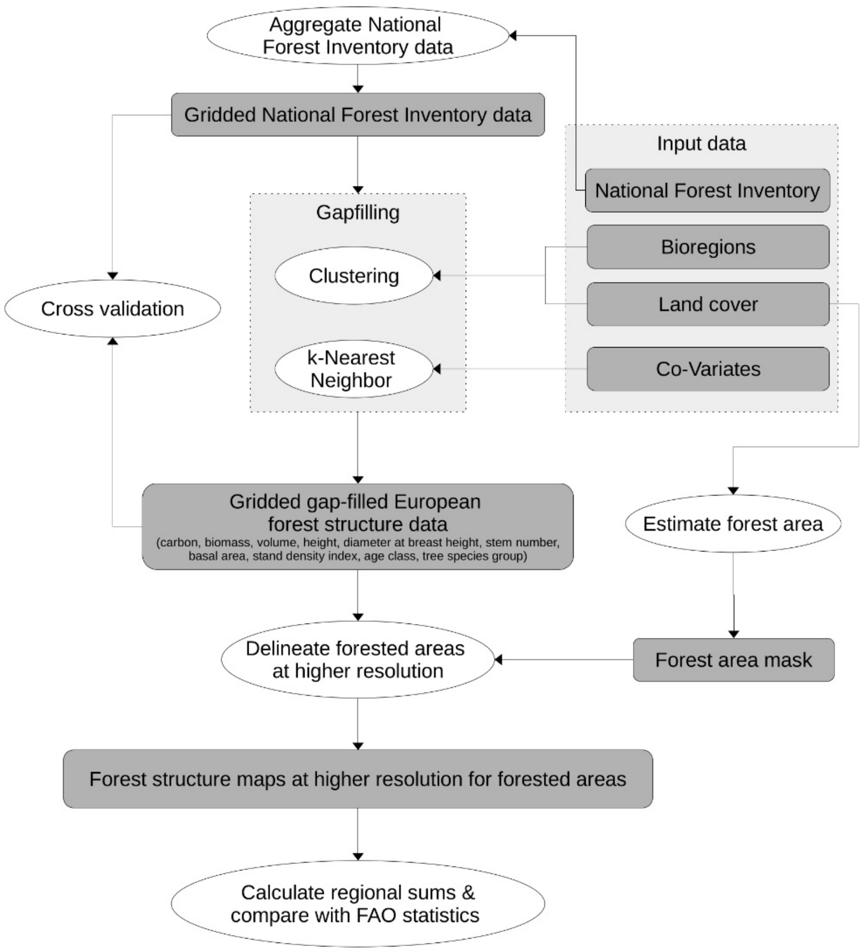


Figure 1. Flow-chart for the methodology to derive a gridded gap-filled forest structure dataset from individual NFI plot tree data across Europe. Grey, round-edged boxes represent input and output data and ellipses calculation steps. Light grey, dotted boxes summarize grouping of the input data and the two-step gap-filling algorithm.

2.1. National Forest Inventory Data

The National Forest Inventory (NFI) data are obtained from 16 European countries and consist of recorded tree information from 350.489 inventory plots (Table 1). All selected countries maintain a gridded systematic point sampling National Forest Inventory. Data for 12 countries were available from a previous study by Moreno et al. [28] with additional details available in [36]. Data from the Czech Republic, used by Moreno et al. [28] were not used in our study. We obtained data from four additional countries, Albania, Croatia [37], Ireland [38] and the Netherlands [39]. We complemented the data from Italy [40,41] (now covering the whole country) and Belgium (now including also the region Wallonie). Overall, about 90.000 additional plot data were gathered. Each country has its own inventory system and sampling design (see Table 1) and use their own definitions and methods. All countries provided plot-level data based on their inventory system. The data were gathered, processed and harmonized as described in Neumann et al. [36]. Harmonization was done according to tree species groups, age classes and as far as possible for biomass and volume definitions (for details see [19,36]). However, basic definitions of volumes (e.g., inclusion of branches or measuring over or under bark) and sampling designs (e.g., diameter thresholds) cannot be changed which makes harmonization difficult [20–22]. The resulting data comprise a full set of plot-level forest variables derived from the recorded tree information on each plot and cover information such as the carbon content, biomass for individual compartments (stem, branch, foliage, root), volume, height, diameter at breast height, stem number, basal area, stand density index, age class and the tree species group. In the previous study [28], only six variables (carbon for whole tree, volume, basal area, diameter at breast height, height, age) were considered, while we extend the forest stand characteristics data to ten variables.

The plot-level inventory data are aggregated to 8 × 8 km grid by averaging the metric variables. For the nominal values (age class and tree species group), we calculate the proportion and most frequent value within an 8 × 8 km grid-cell based on the number of inventory points belonging to each class or group. At 8 × 8 km resolution, on average eight inventory plots are within a cell to ensure statistical confidence in the cell values [42]. It is important to note that Moreno et al. [28] used 0.133 × 0.133 degree resolution and WGS84 projection leading to a varying cell size from approximately 111 × 89 km at 37° latitude (e.g., southern Spain) to 111 × 43.5 km at 67° latitude (e.g., northern Finland). In this study, we use the ETRS89-LAEA projection with a fixed cell size of 8 × 8 km across latitude, providing consistent cell size and resolution in the whole study area (Figure 2).

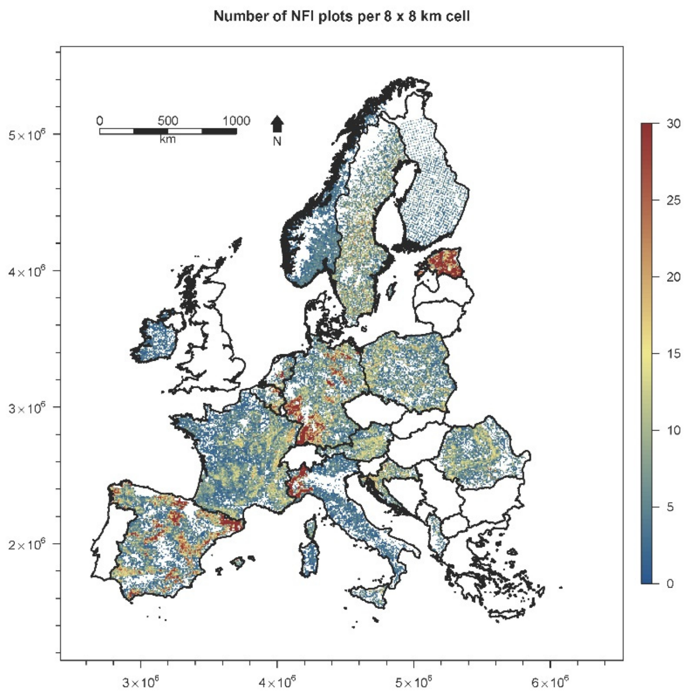


Figure 2. Number of National Forest Inventory (NFI) plots within a given 8 × 8 km cell. In this figure, values higher than 30 plots/cell are truncated for display reasons. Gaps (white regions) indicate regions or countries without NFI data.

Table 1. Summary of the 16 used National Forest Inventory (NFI) datasets. Fixed Area Plots (FAP) and Angle Count Sampling (ACS) [43]. For ACS we provide the basal area factor, while for FAP we show plot area. Min. DBH is the minimum diameter at breast height (DBH) required for each tree to be included in the sample. Sampling Date Range provide information about the observation period by country. Arrangement of sample plots indicates whether the inventory plots are arranged as single plots or within clusters.

Country	Sampling Method	Basal Area Factor (m^2/ha)	Plot Area (m^2)	Min. DBH (cm)	Number of Plots	Sampling Date Range	Arrangement of Sample Plots	Distance between Plots (km)
Albania	FAP	-	25, 200 and 400	7	911	2003	Clusters of 5 plots	1 × 1
Austria	ACS + FAP	4	21.2	5	9562	2000–2009	Clusters of 4 plots	3.889 × 3.889
Belgium	FAP	-	15.9–1017.9	7	5091	1996–2014	Single plots	1 × 0.5
Croatia	FAP	-	38.5–1256.6	5	7136	2005–2009	Clusters of 4 plots	4 × 4 on avg.
Estonia	Survey	-	Undefined	0	19,836	2000–2010	Random	Random
Finland	ACS	2 (south) 1.5 (north)	-	0	6806	1996–2008	Clusters of 14–18	6–8 (south) 6–11 (north)
France	FAP	-	113–706	7.48	48,182	2005–2013	Single plots	2 × 2
Germany	ACS	4	-	7	56,295	2001–2012	Clusters of 4 plots	4 × 4 or 8 × 8
Ireland	FAP	-	500	7	1597	2016	Single plots	2 × 2
Italy	FAP	-	50 and 530	5	21,958	2000–2009	Single plots	Random
Netherlands	FAP	-	50–1256	5	3966	1998–2013	Single plots	Random
Norway	FAP	-	250	5	9200	2002–2011	Single plots	3 × 3
Poland	FAP	-	200–500	7	28,158	2005–2013	Cluster of 5 plots	4 × 4
Romania	FAP	-	200–500	5.6	18,784	2008–2012	Cluster of 4 plots	4 × 4 or 2 × 2
Spain	FAP	-	78.5–1963.5	7.5	69,483	1997–2007	Single plots	1 × 1
Sweden	FAP	-	154	0	37,225	2000–2013	Cluster of 12 plots	10 × 10
					350,489	1996–2016		

2.2. Land Cover and Bioregions for Clustering

Following Moreno et al. [28], we use a bioregion map with six different regions: (i) Alpine, (ii) Atlantic, (iii) Boreal (including Boreal, Arctic and Norwegian Alpine), (iv) Continental (including Continental, Black Sea and Steppe), (v) Mediterranean and (vi) Pannonia. For land cover information, we use version 6 of the MODIS MCD12Q1 product with the University of Maryland (UMD) classification [44] representing land cover conditions of 2005. Spatial aggregation from 500 m to the 8 km resolution was needed to determine the most frequent land cover type within the 8 km grid cell. Only cells dominated by a vegetation land cover type are used for the gap-filling, while cells that are dominated by urban and other non-vegetated land are excluded.

2.3. Co-Variates for Gap-Filling

We use the following variables as co-variates in the gap-filling algorithm: Net primary production, net primary production trend, canopy height and a climate limitation index.

Net Primary Production (NPP) at 0.0083° resolution is derived using the original MOD17 algorithm for global calculations in combination with a European climate dataset which has improved the NPP estimations for European forests [45,46]. For net primary production trend, a linear regression line is fitted to the annual NPP values of 2000 to 2012 at the original 0.0083° resolution. The trend is given by the slope of the regression line.

Tree canopy height is obtained from a global spaceborne lidar data forest canopy height map at 0.0083° resolution [47]. The climate limitation index is the product of three normalized climate datasets: relative growing season length, average annual short-wave solar radiation and average annual vapor pressure deficit. Average growing season length is estimated by using the average time between the onset of the increasing leaf area index (LAI) in spring and the end of the decreasing LAI in autumn using the MODIS Leaf Area Index data [48]. Both short-wave solar radiation and vapor pressure deficit are calculated using the MtClim algorithm which uses climate data and a digital elevation model as inputs [46,49]. Therefore, by using the climate limitation index the elevational gradient is also considered. The climate limitation index was still available from the previous work carried out by Moreno et al. [28]. All data are aggregated to 8 km resolution by calculating the average value within the cell.

2.4. K-Means Clustering and k-Nearest Neighbor Gap-Filling

We apply the landcover and bioregion data and the above-mentioned co-variates in a two-step gap-filling algorithm which (i) clusters cells by similarity and (ii) uses a k-Nearest Neighbor algorithm to fill empty cells. In step number one, cells are grouped according to their land cover and related biogeographical region using a k-means clustering algorithm for assigning all grid cells to their corresponding cluster. In step number two, each cell with missing gridded inventory data is assigned to its nearest neighbor with inventory data belonging to the same cluster using a k-Nearest Neighbor (kNN) algorithm. The kNN method is a non-parametric approach used to predict the values of variables by finding the k most similar objects with observed values within a user-defined co-variate space [49]. Similarity is based on the (Euclidean) distance between the objects in the co-variate space [50]. Following Moreno et al. [28], two k-means cluster and one nearest neighbor are applied. Thus, each cell without NFI data is provided with NFI data from the cell which (i) has NFI data, (ii) belongs to the same cluster as the cell with missing data and (iii) is from all cells fulfilling these two conditions, its nearest neighbor in the co-variate space formed by NPP, NPP trend, canopy height and climate limitation index.

2.5. Forest Area Mask

We use the MODIS land cover data and UMD classification to produce a forest area mask at 500 × 500 m resolution. The UMD land cover classification is among other things based on tree cover and canopy height. We use this information to assign a forest area to a land cover class. Each forest land cover class, (i) Evergreen Needleleaf, (ii) Evergreen

Broadleaf, (iii) Deciduous Needleleaf, (iv) Deciduous Broadleaf, (v) Mixed, are defined by a tree cover > 60% and a canopy height > 2 m. In our forest area mask, cells belonging to these classes are assumed to be fully forested and contribute 25 ha (500 m $\times$ 500 m) of forest area. Woody Savannas have by definition a tree coverage of 30%–60% and we therefore define a factor of 0.45 for calculating the forest area for such cells, meaning that each cell contributes 11.25 ha. For Savannas, we defined a factor of 0.15 (3.75 ha) and for Cropland/Natural Vegetation Mosaics a factor of 0.05 (1.25 ha) is used. All other land cover classes (e.g., Closed/Open Shrublands, Grasslands, Croplands) are assumed to be non-forested.

2.6. Calculation of Country Sums and Comparison with FAO Statistics

The forest area mask (ha) is combined with the gap-filled volume map (m^3/ha) to produce a total volume (m^3) map at 500 m resolution. The values of this map are summarized by country and compared with the mean volumes for the years 2000 to 2010 as reported in the State of Europe's Forest 2015 (FAO) [3]. The period 2000 to 2010 is chosen as it best coincides with the inventory data we used for the gap-filling (Table 1). Linear regression is used to determine goodness-of-fit and bias of our estimations.

3. Results

3.1. An Improved Gridded Forest Structure Data

Even though the collected NFI data covers large forest areas in Europe, there are still regions where no systematic grid-sampled forest inventory data were available (see Figure 2). Another issue is the fact that due to differences in the data recording system and the grid raster by country, differences between countries may occur. The missing forest inventory information from countries where no data were available is filled with the two-step gap-filling algorithm by identifying for every cell where no forest inventory data are available, its most similar cell that does provide such data.

After applying the gap-filling algorithm, a full set of pan-European gridded data comprising volume, carbon content, biomass by compartment, height, diameter at breast height, stem number, basal area, stand density index, age class and tree species group is generated. Volume, carbon content, biomass, stem number and basal area given in per hectare values. All other variables represent the mean average characteristics by cell independent of the forest area of this cell. The results by cell for selected variables are given as maps in Figures 3–6 and include grid-cells with low tree cover such as mixed forest-agriculture cells or small forests in urban areas.

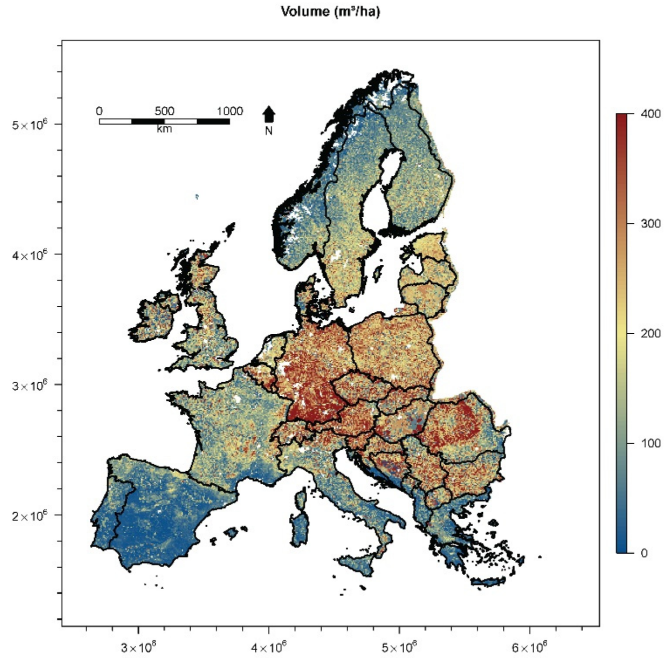


Figure 3. Mean volume per forest area (m^3/ha) by vegetated 8 × 8 km cell. Note that within each cell we made no distinction between forested or non-forested area and a forest area mask is needed to quantify extent of forests (see Figure 7). In this figure, values higher than 400 m^3/ha are truncated for display reasons.

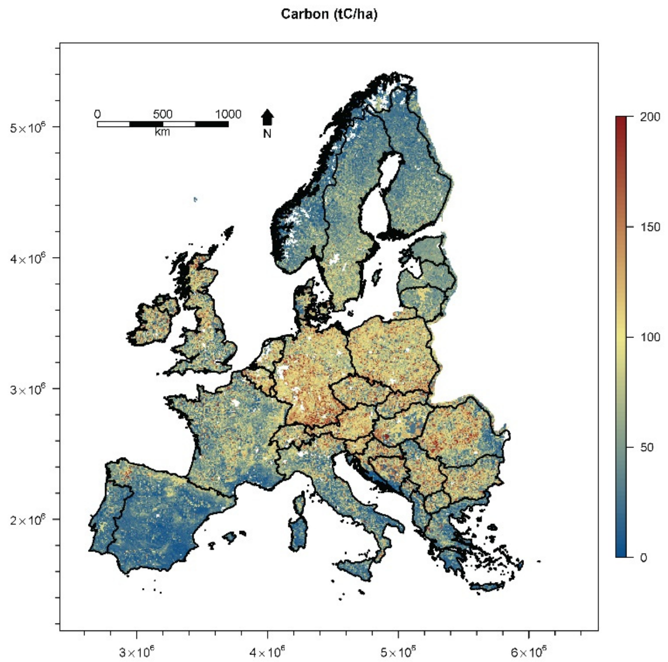


Figure 4. Tree Volume (m^3/ha) only for 500 × 500 m cells with a minimum tree cover of at least 5% (1.25 ha) according to the MODIS land cover classification. We combined this map with MODIS land cover data to calculate total volume (m^3) for each 500 × 500 m cell. Summing up cell values, total volume at regional or country level are estimated. In this figure, values higher than 400 m^3/ha are truncated for display reasons.

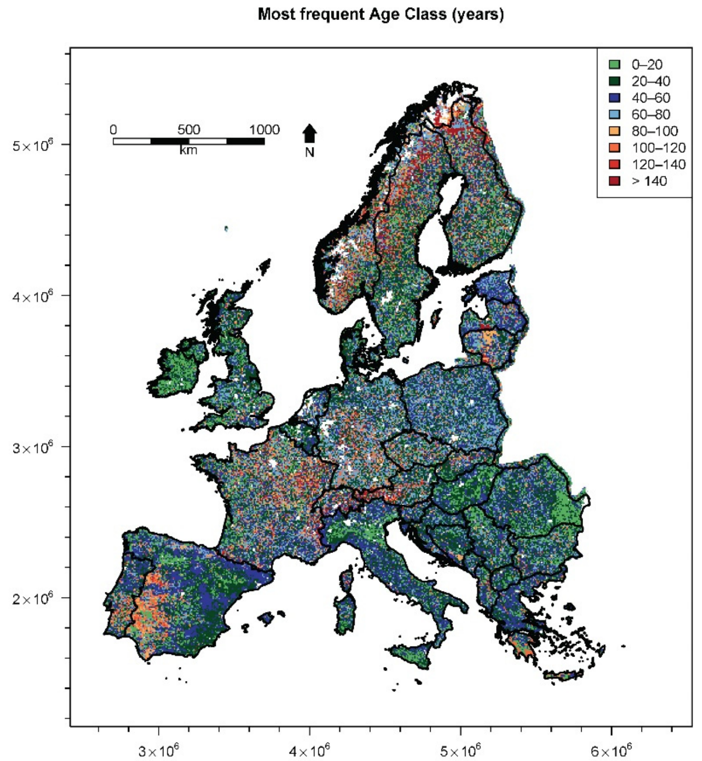


Figure 5. Mean carbon content per forested area (tC/ha) for vegetated 8 × 8 km cells. In this figure, values higher than 200 tC/ha are truncated for display reasons. For details, see Figure 3.

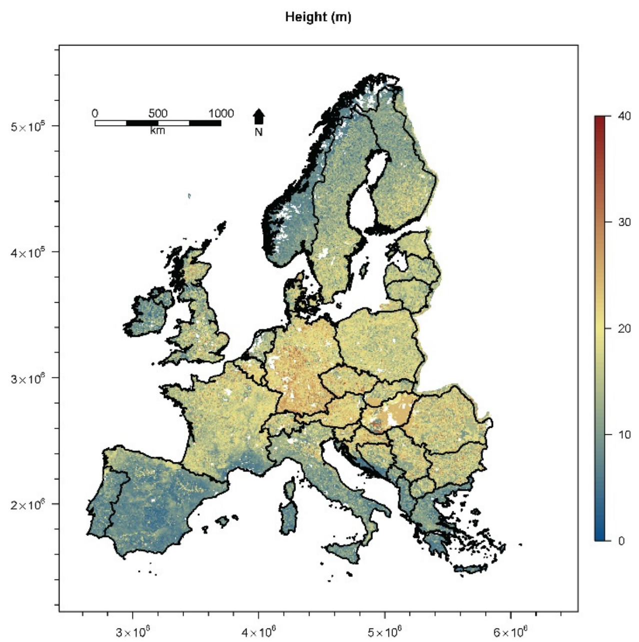


Figure 6. Map showing the most frequent age class for vegetated 8 × 8 km cells. For details, see Figure 3.

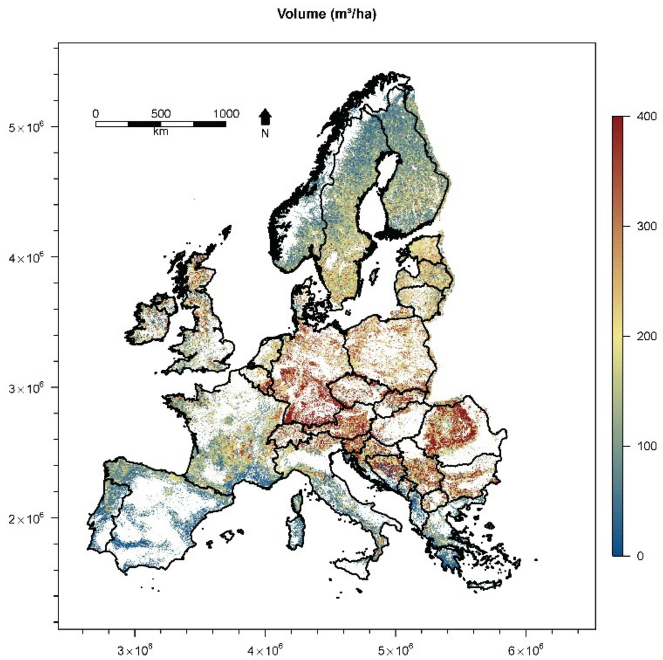


Figure 7. Mean tree height (m) for vegetated 8 × 8 km cells. For details, see Figure 3.

3.2. Accuracy of the Improved Data Set

An important issue with data is its accuracy. Thus, we next assess the error range of the gap-filling algorithm by executing 'leave-one-out' and 'country-wise' cross validations. The 'leave-one-out' cross validation is performed by iteratively removing data from one cell and gap-fill this cell using the data of all other cells. The 'country-wise' cross validation is performed by iteratively removing the entire data from a country and filling all cells within that country only with data from all other countries. We calculate the mean value and the standard deviation (SD) of the gap-filled data sets as well as the mean bias error (MBE), the mean absolute error (MAE) and the root mean square error (RMSE). These measures are compared with the mean value, SD and confidence interval (CI, $\alpha = 0.05$) of the original inventory data.

The mean and SD of the gap-filled data is nearly the same as in the original data in the case of the 'leave-one-out' cross validation and shows, depending on the variable considered, no or only little bias (Table 2). The 'country-wise' cross validation shows negative bias for all variables, leading to lower mean values, while the SD is slightly higher than, but still comparable to, the SD of the original data. MAE and RMSE are close to the CI for the 'leave-one-out' cross validation. The 'country-wise' cross validation shows higher values for the MAE and RMSE, with the MAE still being comparable to the SD.

Table 2. Results of the leave-one-out and country-wise cross validation versus gridded NFI data for entire Europe. N is the total number of 8 × 8 km cells evaluated which may differ by variables since tree height and stand age were not reported by all countries. Aggregated NFI data refers to the aggregated National Forest Inventory (NFI) plots, for which the mean value, standard deviation (SD) and confidence interval (CI) are shown. For leave-one-out and country-wise cross validation the mean value, SD, mean bias error (MBE), mean absolute error (MAE) and root mean squared error (RMSE) are shown. Not Available (NA) indicate that this metric cannot be calculated.

		Aggregated NFI Data			Leave-One-Out					Country-Wise				
Variable	**N**	**Mean**	**SD**	**CI**	**Mean**	**SD**	**MBE**	**MAE**	**RMSE**	**Mean**	**SD**	**MBE**	**MAE**	**RMSE**
Carbon (tC/ha)	38,987	69.7	45.1	33.1	69.9	45.1	0.2	32.4	46.8	63.6	53.0	−6.1	40.1	57.3
Volume (m^3/ha)	38,962	176.9	132.0	86.5	177.2	131.8	0.4	86.1	126.5	163.9	150.6	−13.0	109.3	159.9
Height (m)	36,320	14.7	5.8	3.4	14.7	5.8	0.0	3.7	4.9	12.9	7.7	−1.7	5.8	7.6
Diameter at breast height (cm)	38,967	21.9	8.7	6.6	21.9	8.7	0.0	6.9	9.8	18.9	11.2	−3.0	9.8	13.4
Most frequent Age class (-)	37,118	3.1	1.6	NA	3.1	1.6	0.0	1.5	2.1	2.6	1.8	−0.5	1.8	2.4
Basal Area (m^2/ha)	38,987	20.9	11.1	8.6	20.9	11.0	0.0	8.2	11.5	18.8	13.9	−2.1	10.6	15.2
Stand Density Index (-)	38,967	559.8	543.6	284.2	560.3	522.4	0.4	270.6	619.5	465.4	567.0	−94.4	356.6	780.8

Table 3. Cross validation results by country. We show here the median of the percentage relative difference to the input gridded terrestrial data values for carbon content in tons of live tree carbon per hectare (Carbon), volume in m^3/ha, height in m, diameter in breast height (DBH) in cm, basal area (BA) in m^2/ha and stand density index (SDI). Age class (Age) is given as the mean of the absolute most frequent age class difference between cross validation and gridded terrestrial values. Negative values indicate an underestimation in the algorithm. For full names and units of forest structure variables, see Table 2. NA indicates that these data are missing for this country.

	Leave-One-Out							Country-Wise						
Country	**Carbon**	**Volume**	**Height**	**DBH**	**BA**	**SDI**	**Age**	**Carbon**	**Volume**	**Height**	**DBH**	**BA**	**SDI**	**Age**
Albania	−2.1	45.1	14.0	−6.6	37.9	48.0	1.5	16.5	126.2	27.7	−6.6	104.1	128.6	1.6
Austria	−2.1	−0.7	−1.9	−1.1	−3.2	−3.7	1.9	−3.9	−1.6	−9.4	−4.9	−6.1	−7.9	1.9
Belgium	−13.5	−14.0	−7.5	−12.3	−7.1	−5.4	1.3	−19.9	−18.9	−8.7	−16.3	−9.2	−6.2	1.6
Croatia	8.9	11.0	0.9	−0.1	13.6	1.7	NA	24.3	28.3	−3.1	0.9	25.7	4.7	NA
Estonia	−0.5	−4.4	−3.5	−0.8	−0.1	0.3	1.0	−9.1	−39.4	−30.6	−6.3	−6.5	−2.6	1.6
Finland	7.0	0.1	−3.1	1.4	1.6	24.6	1.9	12.5	2.3	−8.7	1.2	0.8	93.5	2.0
France	8.5	7.8	1.4	0.2	5.5	5.4	1.8	7.8	−3.2	−13.0	−16.0	1.1	4.4	2.0
Germany	−5.5	−9.8	−6.0	−5.2	−6.9	−5.5	1.6	−17.4	−28.8	−16.8	−15.3	−23.0	−19.5	1.6
Ireland	3.0	−0.5	4.9	3.6	−0.9	−1.7	0.8	−47.2	−46.6	0.8	−14.2	−56.6	−60.1	1.3
Italy	9.0	7.9	6.2	13.6	4.9	0.9	1.0	12.6	8.6	15.1	32.5	5.4	−5.4	1.3
Netherlands	−1.0	12.3	13.1	73.1	76.0	62.2	1.3	−5.0	16.9	25.1	114.4	111.0	96.4	1.4
Norway	3.3	4.6	4.5	0.9	2.2	9.2	2.1	−15.5	−6.8	30.5	−6.5	−13.3	7.1	2.6
Poland	−5.3	−2.9	2.4	−1.3	−3.7	−1.9	1.2	−17.3	−7.2	10.7	−3.1	−10.1	−5.8	1.4
Romania	3.5	−0.8	NA	5.0	2.8	3.4	1.1	2.2	−9.2	NA	10.9	1.1	4.5	1.3
Spain	−2.2	0.8	−0.1	−0.8	−0.8	0.3	1.1	−60.8	−54.1	−26.1	−40.0	−46.3	−38.4	1.8
Sweden	−2.4	0.0	−0.7	−0.2	−0.9	−15.0	1.9	−27.6	−23.9	−15.4	−10.7	−18.7	−69.1	2.1
EU	0.2	−0.2	0.1	0.1	−0.1	0.1	1.5	−13.9	−16.2	−8.8	−8.6	−11.8	−14.0	1.8

At country level, the error is expressed as the median of the relative difference in percent between the aggregated inventory data versus the gap-filled data (see Table 3). Our results of the cross validation on the country level exhibit for the 'country-wise' cross validation a higher error than 'leave-one-out.' No pattern is evident, suggesting that regions, latitude or longitude, are associated with higher errors. At the EU level, the median of the percentage relative difference is close to zero for 'leave-one-out', while for the county vise validation it is around 10% and is evident for all produced variables except the most frequent age class (see Table 3).

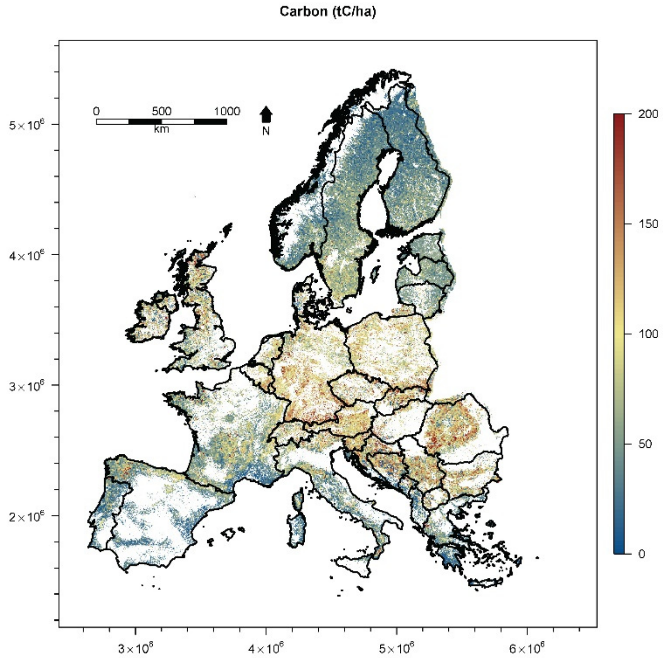


Figure 8. Map showing carbon content (tC/ha) only for 500 × 500 m cells with a with a minimum tree cover of at least 5% (1.25 ha) according to the MODIS land cover classification. This map can be combined with MODIS land cover data to calculate total carbon content (tC) for each 500 × 500 m cell. By summing up cell values, total biomass at regional or country level can be estimated. In this figure, values higher than 200 tC/ha area truncated for display reasons.

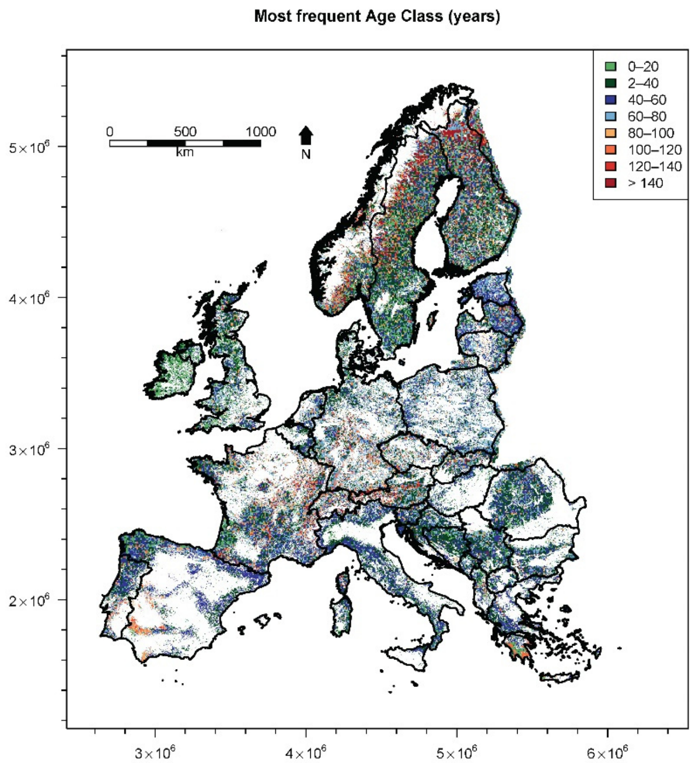


Figure 9. Most frequent age class (years) only for 500 × 500 m cells with a minimum tree cover of at least 5% (1.25 ha) according to the MODIS land cover classification.

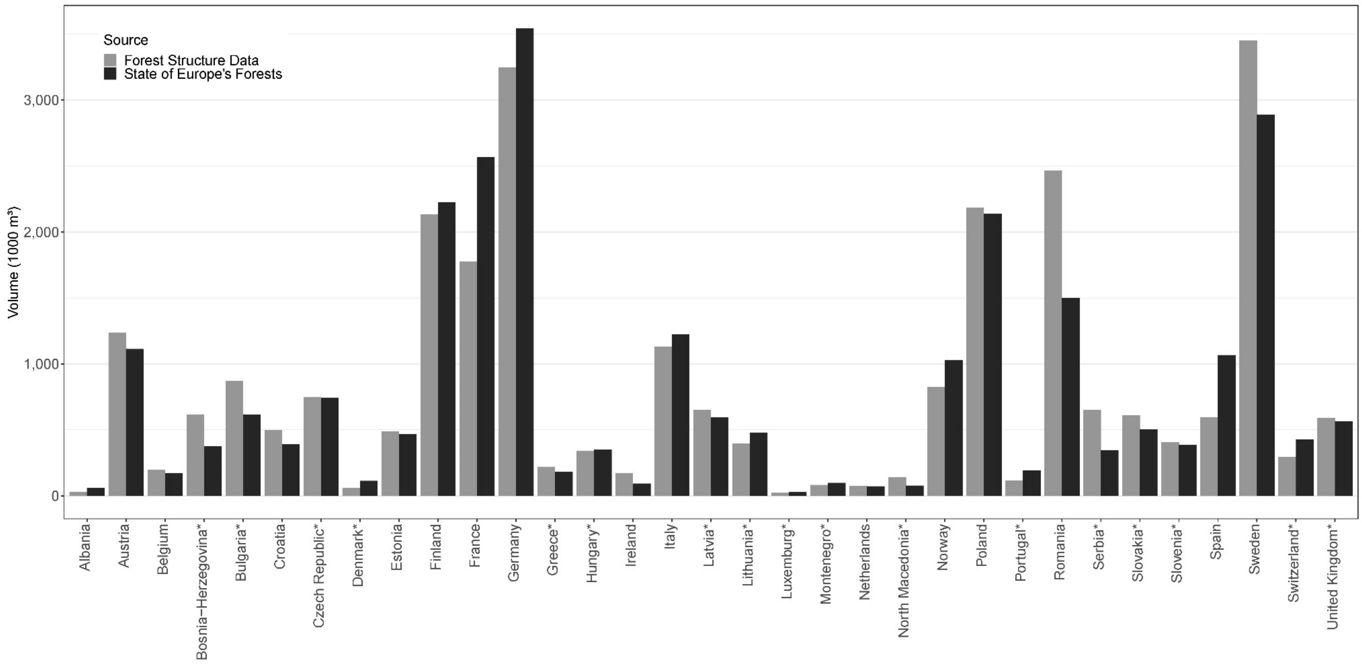


Figure 10. Comparison of the volume by country derived from our Forest Structure Data versus the mean of the volumes for the period 2000 to 2010 as reported in State of Europe's Forest 2015 [3] (Ind 1.2B Change in growing stock on forests). Forest Structure Data refers to the values calculated by combining the gap−filled maps with land cover information to calculate country totals. Countries where no inventory data was available are marked with an asterisk.

3.3. Upscaling Data

An important part of this study is to deliver consistent European forest data across countries and regions at any spatial resolution. For the upscaling, we use the forest area mask derived from MODIS land cover data at a 500 × 500 m resolution. By combining the forest area mask with the 8 × 8 km gap-filled maps, we produce maps at 500 × 500 m resolution which better reflect the possible heterogeneity of the landscape within an 8 × 8 km grid cell (Figures 7–9). An 8 × 8 km cell may only be partly forested and also contain urban areas, water bodies or agricultural land. These maps can then be used in combination with other data available at a similar resolution to study certain aspects of European forests, such as the legal or technical accessibility of forest resources.

3.4. Evaluate the Results Using FAO Statistics

Important for this study is comparing our derived information with other available data such as the State of Europe's Forests (FAO) statistics [3], as this allows to assess the quality of the gap-filling algorithm in countries, where no NFI data were available. In general, a high agreement between our produced volume estimates versus the reported values (Adj R^2 = 0.903) are evident (Figures 10 and 11). When looking at the European scale, almost no bias (Slope = 0.964) is present. However, some countries (e.g., Bulgaria, France, Romania, Spain) do show substantial overestimation or underestimation (Figures 10 and 11). When only looking at countries where no inventory information was available, there is also an overall good agreement (Adj R^2 = 0.787) between our estimations and the reported values (Figure 11b). In this case, the estimates in general tend to be higher than the reported values (Slope = 1.12). Individual countries can be overestimated or underestimated, in some cases substantially (e.g., Bosnia-Herzegovina, Bulgaria, Serbia). Estimations are close to the reported values for some countries where we had inventory information (Austria, Belgium, Estonia, Finland, Italy, Netherlands, Poland) as well as countries without that information (Czech Republic, Greece, Hungary, Latvia, Montenegro, Slovenia, United Kingdom) (Figures 10 and 11).

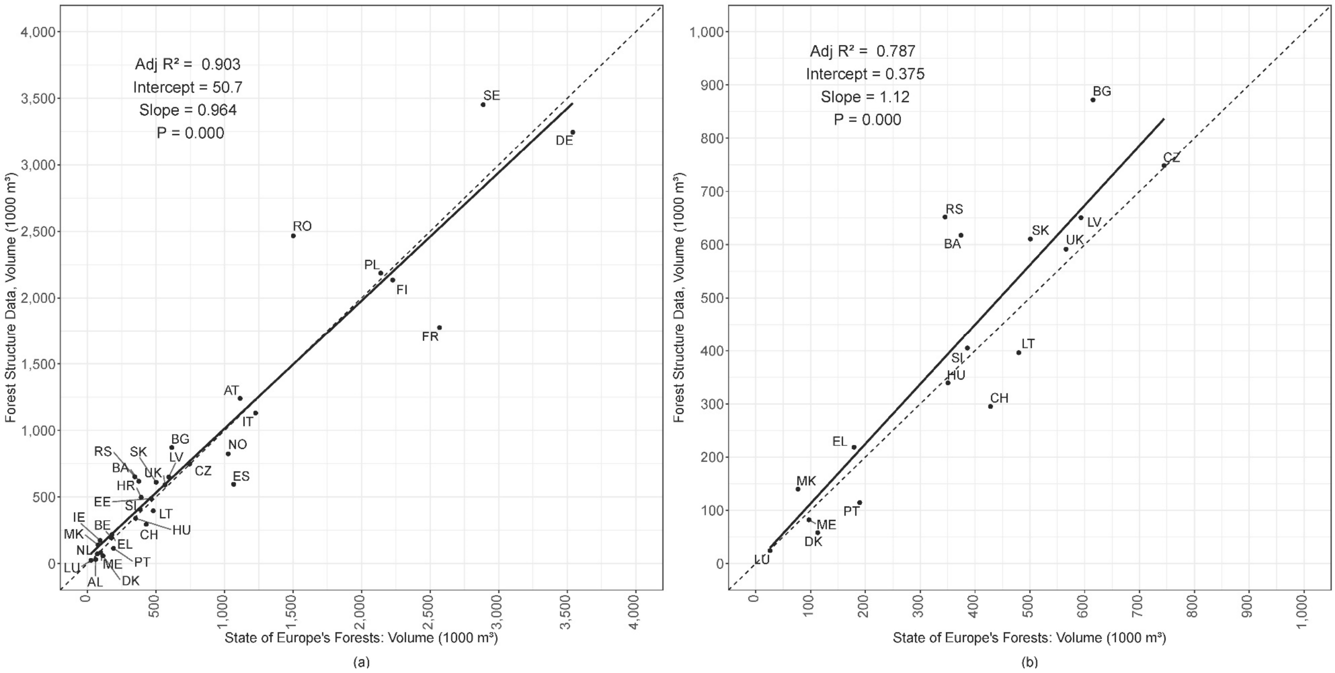


Figure 11. Comparison of the volume calculated from our Forest Structure Data versus the mean of the volumes for the period 2000 to 2010 as reported in State of Europe's Forest 2015 [3] (Ind 1.2B Change in growing stock on forests). Forest Structure Data refers to the values calculated by combining the gap-filled maps with land cover information to calculate country totals (see Figure 7). Linear regression results R^2 (Adj R^2), Intercept, Slope and $p-$Value (P) are shown. (**a**) Shows results when using all countries, irrespective if National Forest Inventory (NFI) data were available. (**b**) Shows the results only for countries where no NFI data were available. Country codes are: AL = Albania, AT = Austria, BA = Bosnia−Herzegovina*, BE = Belgium, BG = Bulgaria*, CZ = Czech Republic*, CH = Switzerland*, DE = Germany, DK = Denmark*, EE = Estonia, EL = Greece*, ES = Spain, FI = Finland, FR = France, HR = Croatia, HU = Hungary*, IE = Ireland, IT = Italy, LT = Lithuania*, LU = Luxemburg*, LV = Latvia*, ME = Montenegro*, MK = North Macedonia*, NL = Netherlands, NO = Norway, PL = Poland, PT = Portugal*, RO = Romania, RS = Serbia*, SE = Sweden, SI = Slovenia*, SK = Slovakia*, UK = United Kingdom*; Countries where no inventory data were present are marked with an asterisk.

4. Discussion

Lack of a consistent and accessible European forest inventory data makes detailed analysis at the European level difficult or even impossible [17,19]. With this study, we provide and produce a pan-European gridded forest structure dataset based on an extensive collection of point sampled National Forest Inventory data, remote sensing information and a gap-filling algorithm for those areas where no gridded data were collected or gridded inventory data were not available. With these data, we are able to depict forest structure differences at the regional and sub-regional levels which allows detailed forest analysis across Europe (Figures 3–6).

Cross validation is used to assess the quality and accuracy of the data. The results show that the chosen methodology is robust and accurate which gives confidence in the produced data. The gap-filling algorithm relies on the regional distribution of the input inventory data and how well it covers the latitudinal and elevational gradients, climatic conditions and bioregions in Europe. Only high coverage of the relevant conditions ensures that the nearest object determined by the kNN algorithm really bears similarity with the object which variable values need to be predicted. This limitation is evident when looking at the 'country−wise' cross validation results. When removing the entire data from a country where prevailing conditions (e.g., climatic, management history) are not well covered by the remaining data of all the other countries, the uncertainty tends to be higher. This can be observed for Spain on the Iberian Peninsula, Ireland on the British Isles, as well as Albania and Croatia in the north-eastern Mediterranean. This may also be evident for the Netherlands, where our produced inventory volume and DBH values are lower compared to the neighboring countries Belgium and Germany, which are likely to be used for gap-filling.

When removing data from an entire country and the growing conditions are well covered by the remaining data from the neighboring countries, the error tends to be lower, e.g., Austria, France or Germany. Being aware of these limitations, in this study we specifically added data from Albania, Croatia and Ireland to better cover these regions.

Differences in the sampling design or calculation method among countries, such as the minimum diameter at breast height required for a tree to be included or biomass function used, could also explain high errors. For instance, when removing the entire data from Sweden, it is likely that it will be filled with data coming from the two other Scandinavian countries. However, Sweden uses fixed area plots with no minimum diameter requirement, while Norway, although also using fixed area plots, requires trees to have a minimum diameter at breast height of 5 cm and Finland uses angle count sampling, which is a different plot design altogether.

4.1. Comparison with FAO Statistics

Comparison with FAO statistics gives further confidence in the chosen methodology and produced data, especially on the European scale where agreement between calculated and reported values is high. This high agreement was expected when only looking at countries were we did gather inventory data, as also the FAO statistics are mainly based on national inventories [18]. However, for some of these countries substantial overestimation or underestimation can still be observed. The reasons can be manifold.

In Romania, reported growing stock for the years 2000, 2005 and 2010 are estimated using a relationship between forest area and a mean growing stock by unit of area based on the Forest Inventory in 1985, while the estimation for 2015 is based on the National Forest Inventory 2012, the same inventory our data for Romania comes from. The growing stock reported for 2015 is substantially higher than the previous reported values (2222 million m^3 in 2015 versus 1378 million m^3 in 2010) and closer to our estimations [51]. However, in our study, we only compare with the mean of the values reported for the period 2000 to 2010, as this period overall coincides best with our gathered inventory data. In general, different time periods can affect the comparison as we considered the mean of the reported values for the period 2000 to 2010 for all countries, although the inventory data in individual countries do not cover this whole period (Table 1).

In Sweden, a different minimum diameter requirement for trees to be considered between FAO report (minimum of 10 cm) and NFI data (no minimum requirement) may contribute to overestimation [52]. In general, problems with the harmonization of variables and definitions such as stem volume [22], growing stock [20], forest available for wood supply or even forest in general [18,21] could partly explain some of the observed differences.

These differences in the definitions of forest and forest available for wood supply lead to different forest area estimations which can be another reason for overestimation or underestimation [53]. The FAO defines forest as, "land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use" [54]. In addition to the presence of trees the definition is also land-use based, meaning that temporarily unstocked areas intended for forestry or conservation use are included [54,55]. In our study, a forest area mask is generated using MODIS land cover data, which relies on the presence or absence of tree cover to identify forests and cannot account for intended land use [55]. The coarse resolution of 500 × 500 m (25 ha) also means that not only the Forest or Woody Savanna land cover types contain forest as basically every cell irrespective of the land cover class can contain forest as defined by the FAO, i.e., a land spanning more than 0.5 ha with trees higher than 5 meters and a canopy cover of more than 10%. We partly considered this in our forest area mask by assuming all Forest land cover cells to be fully forested, compensating for small forest areas in cells with land cover classes which did not contribute to forest area in our study. We also introduced forest area factors for selected other land cover classes, such as Woody Savannas, Savannas or Cropland/Natural Vegetation Mosaic. Differences between reported global forest cover change in the Global Forest Resources Assessment 2015 (FRA 2015) and global remote sensing estimations by Hansen et al. [56,57] could also possibly be explained by the used tree cover threshold of 25% and also by the coarse resolution of the MODIS images used in the earlier of the two studies [55]. We also explored the usage of the high-resolution 25 × 25 m CORINE land cover data to estimate forest area (Appendix A) [58]. Underestimation of forest area might be the main reason for the substantial underestimation of volume in France and Spain. In both countries, the share of 500 m cells belonging to one of the Forest MODIS land cover classes are low compared to other countries. As savannas and shrublands cover large areas in these countries, our approach may be unable to account for all the small forest areas in cells belonging to these and other classes. This could be improved by using a different approach based on forest cover data or using different land cover data such as CORINE [59,60]. However, detailed analysis of all possible reasons for overestimating or underestimating and optimizing our estimations were not the aim and scope of our study. Furthermore, when using the gap-filled data, one is not limited to the forest area mask proposed in this study but can use any other forest area mask.

In countries where no inventory data were obtained, overestimation or underestimation can, in addition to the reasons already mentioned, also be related to the inventory data not covering the prevalent conditions in these countries well enough (see also Section 4.1). In south-east Europe, we were only able to gather data from Albania and Croatia, which might not be sufficient to accurately describe the situation in other countries belonging to this region, as suggested by the observed overestimation in many of these countries (Bosnia and Herzegovina (BA), Bulgaria (BG), Greece (EL), the Republic of North Macedonia (MK) and Serbia (RS)). As a consequence, although we were able to add the data from Albania and Croatia for this study, additional data from that region are likely needed to improve the forest structure data.

4.2. Potential Applications

A big advantage of high-quality spatial explicit gridded forest structure data is the ability to combine it with other spatial explicit information, such as soil information, conservation status, land cover, climate data or terrain data. This allows for detailed analysis which can contribute to solving and providing relevant questions related to the carbon mitigation potential of European forests, the impact of conservation policies or how forest resources are threatened by changing disturbance regimes [31–34]. A most recent example is the assessment of the harvestable forest area and stocking volume in Europe [61]. The study combines the Forest Structure data with conservation status, slope, soil and road infrastructure data to quantify the legal and technical accessibility of forest resources for mechanized harvesting. The availability of wood resources is an important question in regard to the potential of using wood products to substitute non−renewable fossil products. Another application is initializing large-scale, climate-sensitive bio-geochemical-mechanistic forest simulation models. All these studies can support decision makers during the transition towards a bio-based economy.

4.3. Room for Improvement

The lack of a common inventory system across European forests with standardized definitions as well as sampling designs and measurement methods, make a comparison of even basic forest variables, such as forest area or growing stock difficult in Europe.

Our harmonization of the different national forest inventory data with the improved data sources and methodology is important part for consistent pan-European forest studies. If a common inventory system as well as a common forest area mask could be established, the methods described in this study could be used to support countries in official reporting of key forest variables. The results of this study are an important attempt to provide consistent forest structure data to the scientific community.

Author Contributions: Conceptualization, C.P. and H.H.; methodology, C.P.; software, C.P.; validation, C.P.; formal analysis, C.P.; investigation, C.P. and M.N.; resources, C.P.; data curation, C.P. and M.N.; writing—original draft preparation, C.P. writing—review and editing, M.N. and H.H.; visualization, C.P.; supervision, H.H.; project administration, H.H.; funding acquisition, H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program, TECH4EFFECT—Techniques and Technologies or Effective Wood Procurement project [Grant Number 720757]. Additional financial support came from the «GIS and Remote Sensing for Sustainable Forestry and Ecology (SUFOGIS)» project funded with support from the EU ERASMUS+ program. The European Commission support for the production of this publication does not constitute an endorsement of the contents, which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Data Availability Statement: The produced forest structure data set are (will be) openly available at: ftp://palantir.boku.ac.at/Public/ImprovedForestCharacteristics/ (accessed on 30 November 2021).

Acknowledgments: We acknowledge the open data policies by European forest inventory agencies, that made this analysis possible. Parts of the used inventory data were gathered as part of the collaborative project 'FORest management strategies to enhance the MITigation potential of European forests' (FORMIT), which received funding from the European Union Seventh Framework Programme under grant agreement n° 311970. We would like to thank John Redmond and Luke Heffernan and the Department of Agriculture, Food and the Marine for providing national forest inventory data for Ireland. The data used for Ireland are the property of the Department of Agriculture, Food and the Marine, Ireland. We appreciate the help of Huguez Lecomte and Andre Thibaut (Service Public de Wallonie) and Sebastien Bauwens (University of Liege) for their support with the Wallonian forest inventory. The data used for Wallonia are the property of SPW−DGARNE. We thank Elvin Toromani (University of Tirana) for his support analyzing the Albanian forest inventory. We further extend our gratitude to Jura Cavlovic (University of Zagreb, Croatia) and Goran Videc (Ministry of Agriculture, Croatia) for their support with the Croatian forest inventory. The data used for Croatia are the property of the Croatian Ministry of Agriculture. We acknowledge the open access to national forest inventory data from Italy and Netherlands.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

During the course of our study, we also explored the usage of CORINE land cover data for the production of the forest area mask. The higher resolution 25 × 25 m data is better able to detect small forested areas which might be overlooked when using the coarse 500 × 500 m MODIS land cover data (see Section 4.1). For the CORINE forest area mask, each cell belonging to a Forest land cover class contributed 0.0625 ha (25 × 25 m) of forest area, while cells belonging to other land cover classes did not contribute any forest area.

In some countries such as Finland, France, Norway or Spain, difference in estimated forest area is substantial, while in other countries (e.g., Austria, Bulgaria, Romania) the difference is only minor (Figure A1). Especially in France and Spain, the forest area estimated with the CORINE data is likely way closer to the true value compared to the estimations based on the MODIS data. However, although overall the model estimations better fitted the reported values (Figure A2a), this was not true when only looking at countries where we did not have inventory data (Figure A2b). Therefore, we decided to still use the MODIS land cover data for forest area estimation as this data set are already used in the gap-filling algorithm. It is important to stress that the gap-filled maps can be combined with any other forest area mask and using forest area mask with higher resolution is encouraged. In this study, we simply provide one way of creating a forest area mask using MODIS land cover data, which was sufficient for our needs. It was not the aim of the study to provide the best possible forest area mask.

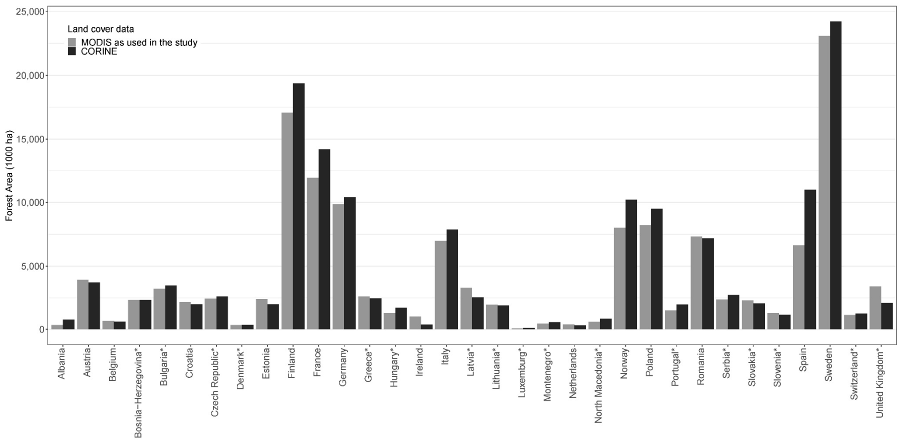


Figure A1. Comparison of the forest area estimations based on MODIS [44] and CORINE [58] land cover data sets. MODIS refers to the forest area mask as used in this study (see Section 2.5) while CORINE refers to a forest area mask based on CORINE land cover data which was not used in the study (see Appendix A). Countries where no inventory data were available are marked with an asterisk.

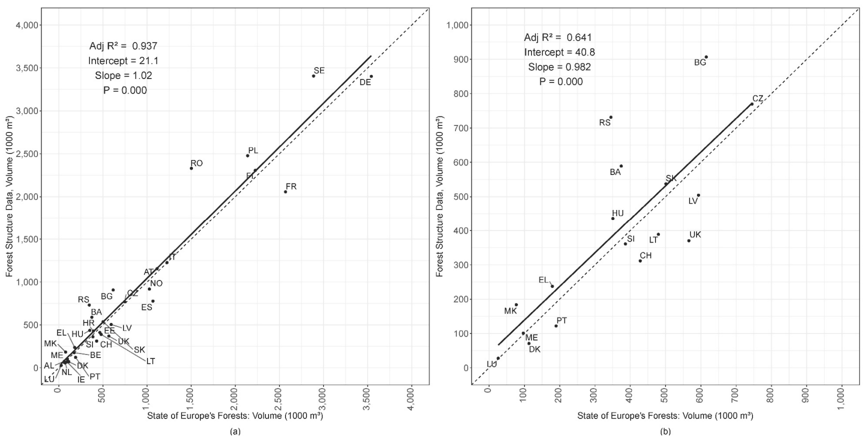


Figure A2. Comparison of the volume calculated from our Forest Structure Data versus the mean of the volumes for the period 2000 to 2010 as reported in State of Europe's Forest 2015 [3] (Ind 1.2B Change in growing stock on forests). Forest Structure Data refers to the values calculated by combining the gap-filled maps with land cover information to calculate country totals (see Figure 7). In this case, underlying forest area estimations are based on CORINE land cover data, compared to Figure 11 where forest area estimations are based an MODIS land cover data as used in the study. Linear regression results R^2 (Adj R^2), Intercept, Slope and $p-$Value (P) are shown. (**a**) Shows results when using all countries, irrespective if National Forest Inventory (NFI) data were available. (**b**) Shows the results only for countries where no NFI data were available. Country codes are: AL = Albania, AT = Austria, BA = Bosnia−Herzegovina*, BE = Belgium, BG = Bulgaria*, CZ = Czech Republic*, CH = Switzerland*, DE = Germany, DK = Denmark*, EE = Estonia, EL = Greece*, ES = Spain, FI = Finland, FR = France, HR = Croatia, HU = Hungary*, IE = Ireland, IT = Italy, LT = Lithuania*, LU = Luxemburg*, LV = Latvia*, ME = Montenegro*, MK = North Macedonia*, NL = Netherlands, NO = Norway, PL = Poland, PT = Portugal*, RO = Romania, RS = Serbia*, SE = Sweden, SI = Slovenia*, SK = Slovakia*, UK = United Kingdom*; Countries where no inventory data were present are marked with an asterisk.

References

1. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014; ISBN 9789291691432.
2. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; et al. A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993. [CrossRef]
3. Forest Europe. *State of Europe's Forests 2015*; Forest Europe: Madrid, Spain, 2015.
4. Lindner, M.; Maroschek, M.; Netherer, S.; Kremer, A.; Barbati, A.; Garcia-Gonzalo, J.; Seidl, R.; Delzon, S.; Corona, P.; Kolström, M.; et al. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *For. Ecol. Manag.* **2010**, *259*, 698–709. [CrossRef]
5. Lindner, M.; Fitzgerald, J.B.; Zimmermann, N.E.; Reyer, C.; Delzon, S.; van der Maaten, E.; Schelhaas, M.J.; Lasch, P.; Eggers, J.; van der Maaten-Theunissen, M.; et al. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manag.* **2014**, *146*, 69–83. [CrossRef]
6. Senf, C.; Pflugmacher, D.; Zhiqiang, Y.; Sebald, J.; Knorn, J.; Neumann, M.; Hostert, P.; Seidl, R. Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nat. Commun.* **2018**, *9*, 4978. [CrossRef] [PubMed]
7. Seidl, R.; Schelhaas, M.J.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806–810. [CrossRef] [PubMed]
8. Dyderski, M.K.; Paź, S.; Frelich, L.E.; Jagodziński, A.M. How much does climate change threaten European forest tree species distributions? *Glob. Chang. Biol.* **2018**, *24*, 1150–1163. [CrossRef] [PubMed]
9. Hanewinkel, M.; Cullmann, D.A.; Schelhaas, M.-J.; Nabuurs, G.-J.; Zimmermann, N.E. Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Chang.* **2013**, *3*, 203–207. [CrossRef]
10. McGrath, M.J.; Luyssaert, S.; Meyfroidt, P.; Kaplan, J.O.; Bürgi, M.; Chen, Y.; Erb, K.; Gimmi, U.; McInerney, D.; Naudts, K.; et al. Reconstructing European forest management from 1600 to 2010. *Biogeosciences* **2015**, *12*, 4291–4316. [CrossRef]
11. Anderson-Teixeira, K.J.; Herrmann, V.; Rollinson, C.R.; Gonzalez, B.; Gonzalez-Akre, E.B.; Pederson, N.; Alexander, M.R.; Allen, C.D.; Alfaro-Sánchez, R.; Awada, T.; et al. Joint effects of climate, tree size, and year on annual tree growth derived from tree-ring records of ten globally distributed forests. *Glob. Chang. Biol.* **2022**, *28*, 245–266. [CrossRef] [PubMed]
12. Latte, N.; Perin, J.; Kint, V.; Lebourgeois, F.; Claessens, H. ajor changes in growth rate and growth variability of beech (*Fagus sylvatica* L.) related to soil alteration and climate change in Belgium. *Forests* **2016**, *7*, 174. [CrossRef]
13. Pretzsch, H.; Biber, P.; Schütze, G.; Uhl, E.; Rötzer, T. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nat. Commun.* **2014**, *5*, 4967. [CrossRef] [PubMed]
14. Kulakowski, D.; Seidl, R.; Holeksa, J.; Kuuluvainen, T.; Nagel, T.A.; Panayotov, M.; Svoboda, M.; Thorn, S.; Vacchiano, G.; Whitlock, C.; et al. A walk on the wild side: Disturbance dynamics and the conservation and management of European mountain forest ecosystems. *For. Ecol. Manag.* **2017**, *388*, 120–131. [CrossRef] [PubMed]
15. Kolström, M.; Lindner, M.; Vilén, T.; Maroschek, M.; Seidl, R.; Lexer, M.J.; Netherer, S.; Kremer, A.; Delzon, S.; Barbati, A.; et al. Reviewing the science and implementation of climate change adaptation measures in European forestry. *Forests* **2011**, *2*, 961–982. [CrossRef]
16. FAO. *Global Forest Resources Assessment 2015*; Elsevier B.V.: Rome, Italy, 2015; ISBN 978-92-5-108826-5.
17. Tomppo, E.; Gschwantner, T.; Lawrence, M.; McRoberts, R.E. (Eds.) *National Forest Inventories*; Springer: Dordrecht, The Netherlands, 2010; ISBN 978-90-481-3232-4.
18. Vidal, C.; Alberdi, I.; Redmond, J.; Vestman, M.; Lanz, A.; Schadauer, K. The role of European National Forest Inventories for international forestry reporting. *Ann. For. Sci.* **2016**, *73*, 793–806. [CrossRef]
19. Neumann, M.; Moreno, A.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Achten, W.M.J.; Thivolle-Cazat, A.; Bronisz, K.; et al. Comparison of carbon estimation methods for European forests. *For. Ecol. Manag.* **2016**, *361*, 397–420. [CrossRef]
20. Gschwantner, T.; Alberdi, I.; Bauwens, S.; Bender, S.; Borota, D.; Bosela, M.; Bouriaud, O.; Breidenbach, J.; Donis, J.; Fischer, C.; et al. Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation. *For. Ecol. Manag.* **2022**, *505*, 119868. [CrossRef]
21. Vidal, C.; Lanz, A.; Tomppo, E.; Schadauer, K.; Gschwantner, T.; Di Cosmo, L.; Robert, N. Establishing forest inventory reference definitions for forest and growing stock: A study towards common reporting. *Silva Fenn.* **2008**, *42*, 247–266. [CrossRef]
22. Gschwantner, T.; Alberdi, I.; Balázs, A.; Bauwens, S.; Bender, S.; Borota, D.; Bosela, M.; Bouriaud, O.; Donis, J.; Gschwantner, T.; et al. Harmonisation of stem volume estimates in European National Forest Inventories. *Ann. For. Sci.* **2019**, *76*, 24. [CrossRef]
23. Tomppo, E.O.; Schadauer, K. Harmonization of national forest inventories in Europe: Advances under Cost Action E43. *For. Sci.* **2012**, *58*, 191–200. [CrossRef]
24. Schelhaas, M.J.; Varis, S.; Schuck, A.; Nabuurs, G.J. *EFISCEN Inventory Database*; European Forest Institute: Joensuu, Finland, 2006.
25. Vilén, T.; Gunia, K.; Verkerk, P.J.; Seidl, R.; Schelhaas, M.J.; Lindner, M.; Bellassen, V. Reconstructed forest age structure in Europe 1950–2010. *For. Ecol. Manag.* **2012**, *286*, 203–218. [CrossRef]
26. Gallaun, H.; Zanchi, G.; Nabuurs, G.J.; Hengeveld, G.; Schardt, M.; Verkerk, P.J. EU-wide maps of growing stock and above-ground biomass in forests based on remote sensing and field measurements. *For. Ecol. Manag.* **2010**, *260*, 252–261. [CrossRef]

27. Verkerk, P.J.; Fitzgerald, J.B.; Datta, P.; Dees, M.; Hengeveld, G.M.; Lindner, M.; Zudin, S. Spatial distribution of the potential forest biomass availability in europe. *For. Ecosyst.* **2019**, *6*, 5. [CrossRef]
28. Moreno, A.; Neumann, M.; Hasenauer, H. Forest structures across Europe. *Geosci. Data J.* **2017**, *4*, 17–28. [CrossRef]
29. Härkönen, S.; Neumann, M.; Mues, V.; Berninger, F.; Bronisz, K.; Cardellini, G.; Chirici, G.; Hasenauer, H.; Koehl, M.; Lang, M.; et al. A climate-sensitive forest model for assessing impacts of forest management in Europe. *Environ. Model. Softw.* **2019**, *115*, 128–143. [CrossRef]
30. Neumann, M.; Godbold, D.L.; Hirano, Y.; Finér, L. Improving models of fine root carbon stocks and fluxes in European forests. *J. Ecol.* **2020**, *108*, 496–514. [CrossRef]
31. Hasenauer, H.; Neumann, M.; Moreno, A.; Running, S. Assessing the resources and mitigation potential of European forests. *Energy Procedia* **2017**, *125*, 372–378. [CrossRef]
32. Moreno, A.; Neumann, M.; Hasenauer, H. Climate limits on European forest structure across space and time. *Glob. Planet. Chang.* **2018**, *169*, 168–178. [CrossRef]
33. Moreno, A.; Neumann, M.; Mohebalian, P.M.; Thurnher, C.; Hasenauer, H. The Continental Impact of European Forest Conservation Policy and Management on Productivity Stability. *Remote Sens.* **2019**, *11*, 87. [CrossRef]
34. Seidl, R.; Klonner, G.; Rammer, W.; Essl, F.; Moreno, A.; Neumann, M.; Dullinger, S. Invasive alien pests threaten the carbon stored in Europe's forests. *Nat. Commun.* **2018**, *9*, 1626. [CrossRef]
35. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
36. Neumann, M.; Moreno, A.; Thurnher, C.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Cardellini, G.; Thivolle-Cazat, A.; et al. Creating a regional MODIS satellite-driven net primary production dataset for european forests. *Remote Sens.* **2016**, *8*, 554. [CrossRef]
37. Vidal, C.; Alberdi, I.A.; Hernández Mateo, L.; Redmond, J.J. (Eds.) *National Forest Inventories*; Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-44014-9.
38. Department of Agriculture, Food and the Marine. *Ireland's National Forest Inventory 2017 Field Procedures and Methodology*; Department of Agriculture, Food and the Marine: Dublin, Ireland, 2017; ISBN 9781406429800.
39. Schelhaas, M.J.; Clerkx, A.P.P.M.; Daamen, W.P.; Oldenburger, J.F.; Velema, G.; Schnitger, P.; Schoonderwoerd, H.; Kramer, H. *Zesde Nederlandse Bosinventarisatie: Methoden en Basisresultaten*; Alterra-Rapport 2545; Alterra Wageningen UR (University & Research Centre): Wageningen, The Netherlands, 2014.
40. Gasparini, P.; Tabacchi, G. L'Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. In *Secondo inventario forestale nazionale italiano. Metodi e risultati. Ministero delle Politiche Agricole, Alimentari e Forestali*; Corpo Forestale dello Stato; Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per il Monitoraggio e la Pianificazione Forestale, Edagricole: Milano, Italy, 2011; p. 650. Available online: https://shop.newbusinessmedia.it/collections/edagricole/products/l-inventario-nazionale-delle-foreste-e-dei-serbatoi-forestali-di (accessed on 30 November 2021).
41. Gasparini, P.; Di Cosmo, L.; Floris, A.; Notarangelo, G.; Rizzo, M.; Guida per i Rilievi in Campo. *INFC2015—Terzo Inventario Forestale Nazionale. Consiglio per la Ricerca in Agricoltura e L'analisi Dell'economia Agraria, Unità di Ricerca per il Monitoraggio e la Pianificazione Forestale (CREA-MPF)*; Corpo Forestale dello Stato, Ministero per le Politiche Agricole, Alimentari e Forestali: Agordo, Italy, 2016; ISBN 9788899595449. Available online: https://www.inventarioforestale.org/it/node/82 (accessed on 30 November 2021).
42. Moreno, A.; Neumann, M.; Hasenauer, H. Optimal resolution for linking remotely sensed and forest inventory data in Europe. *Remote Sens. Environ.* **2016**, *183*, 109–119. [CrossRef]
43. Hasenauer, H.; Eastaugh, C.S. Assessing Forest Production Using Terrestrial Monitoring Data. *Int. J. For. Res.* **2012**, *2012*, 961576. [CrossRef]
44. Friedl, M.; Sulla-Menashe, D. MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500 m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. 2019. Available online: https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD12Q1/#data-availability (accessed on 4 September 2019).
45. Running, S.W.; Nemani, R.R.; Heinsch, F.A.; Zhao, M.; Reeves, M.; Hashimoto, H. A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. *Bioscience* **2004**, *54*, 547–560. [CrossRef]
46. Moreno, A.; Hasenauer, H. Spatial downscaling of European climate data. *Int. J. Climatol.* **2015**, *36*, 1444–1458. [CrossRef]
47. Simard, M.; Pinto, N.; Fisher, J.B.; Baccini, A. Mapping forest canopy height globally with spaceborne lidar. *J. Geophys. Res. Biogeosci.* **2011**, *116*, 1–12. [CrossRef]
48. Myneni, R.B.; Hoffman, S.; Knyazikhin, Y.; Privette, J.L.; Glassy, J.; Tian, Y.; Wang, Y.; Song, X.; Zhang, Y.; Smith, G.R.; et al. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sens. Environ.* **2002**, *83*, 214–231. [CrossRef]
49. McRoberts, R.E.; Nelson, M.D.; Wendt, D.G. Stratified estimation of forest area using satellite imagery, inventory data, and the k-Nearest Neighbors technique. *Remote Sens. Environ.* **2002**, *82*, 457–468. [CrossRef]
50. Manning, C.D.; Schütze, H. Foundations of Statistical Natural Language Processing. *SIGMOD Rec.* **2002**, *31*, 37–38. [CrossRef]
51. FAO. *Global Forest Resources Assessment 2015 Country Report Romania*; FAO: Rome, Italy, 2014.
52. FAO. *Global Forest Resources Assessment 2015 Country Report Sweden*; FAO: Rome, Italy, 2014.
53. Gabler, K.; Schadauer, K.; Tomppo, E.; Vidal, C.; Bonhomme, C.; McRoberts, R.E.; Gschwantner, T. An enquiry on forest areas reported to the Global forest resources assessment-is harmonization needed? *For. Sci.* **2012**, *58*, 201–213. [CrossRef]

54. FAO. *FRA 2015 Terms and Definitions*; FAO: Rome, Italy, 2012.
55. Keenan, R.J.; Reams, G.A.; Achard, F.; de Freitas, J.V.; Grainger, A.; Lindquist, E. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *For. Ecol. Manag.* **2015**, *352*, 9–20. [CrossRef]
56. Hansen, M.C.; Stehman, S.V.; Potapov, P.V. Quantification of global gross forest cover loss. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 8650–8655. [CrossRef] [PubMed]
57. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **2013**, *342*, 850–853. [CrossRef]
58. European Environment Agency. *Corine Land Cover*; European Environment Agency: Copenhagen, Denmark, 2019.
59. Pérez-Hoyos, A.; García-Haro, F.J.; San-Miguel-Ayanz, J. Conventional and fuzzy comparisons of large scale land cover products: Application to CORINE, GLC2000, MODIS and GlobCover in Europe. *ISPRS J. Photogramm. Remote Sens.* **2012**, *74*, 185–201. [CrossRef]
60. Congalton, R.G.; Gu, J.; Yadav, K.; Thenkabail, P.; Ozdogan, M. Global land cover mapping: A review and uncertainty analysis. *Remote Sens.* **2014**, *6*, 12070–12093. [CrossRef]
61. Pucher, C.; Erber, G.; Hasenauer, H. Assessment of the European forest area and stocking volume harvestable according to level of harvesting mechanization. manuscript in preperation, 2022.

9.2. Paper 2

Pucher, C.; Erber, G.; Hasenauer, H. Europe' s Potential Wood Supply by Harvesting System. Forests **2023**, 14(2), 398, doi: 10.3390/f14020398

forests

Article

Europe's Potential Wood Supply by Harvesting System

Christoph Pucher [1,*], Gernot Erber [2] and Hubert Hasenauer [1]

[1] Institute of Silviculture, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Peter Jordan Strasse 82, A-1190 Vienna, Austria
[2] Institute of Forest Engineering, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences, Peter Jordan Strasse 82, A-1190 Vienna, Austria
* Correspondence: christoph.pucher@boku.ac.at

Abstract: Forests cover about 1/3 of Europe's land area and are an important source in providing goods and services such as timber, drinking water, biodiversity, and carbon storage. They are important for a bioeconomy to mitigate climate change effects by reducing greenhouse gas emissions from the combustion of fossil fuels. The purpose of this paper is to assess Europe's potential wood supply by harvesting system. Gridded forest characteristics data are combined with other European spatially-explicit data. A set of eight mechanized harvesting systems is applied to assess the "forest available for wood supply" (FAWS) in Europe. The results show that 74.9% of the total forest area in Europe can be considered FAWS and has the potential to be harvested under the current economic and technical harvesting conditions. The remaining forest area is under legal protection (4.3%) or has limited accessibility with the current mechanized harvesting systems (20.8%). Around 79% of the FAWS can be accessed with ground-based machinery, and another 16% if their operation range is extended using special attachments (e.g., chains or band) or winch-assisted systems. Around 5% of the FAWS is only accessible by cable yarding machinery. With the fully mechanized harvesting systems (i) harvester and forwarder and (ii) winch-assisted harvester and winch-assisted forwarder, about 80% of the harvestable forest area and growing stock can potentially be utilized.

Keywords: harvesting systems; European forest data; bioeconomy; harvestable forest; FAWS

Citation: Pucher, C.; Erber, G.; Hasenauer, H. Europe's Potential Wood Supply by Harvesting System. *Forests* **2023**, *14*, 398. https://doi.org/10.3390/f14020398

Academic Editor: Raffaele Cavalli

Received: 19 January 2023
Revised: 13 February 2023
Accepted: 14 February 2023
Published: 16 February 2023

1. Introduction

While a severe decline in forest cover is evident in large parts of the world, Europe is the only continent with a continuous increase in forest area during the last 100 years [1]. Currently, more than 1/3, or 227 million ha, of Europe's total land area is covered with forests [1]. Forests in Europe provide a variety of ecosystem services, such as timber production, water supply, biodiversity, protection of infrastructure, as well as recreation and welfare. Further, they are of increasing importance in mitigating climate change effects due to their carbon storage potential.

In achieving the climate targets of Europe, the transformation towards a sustainable forest bioeconomy is necessary [2]. Renewable wood from sustainable forest management will be an integral part of it, with a focus on the promotion of long-lived wood products [3,4]. It is expected that the importance of sustainable forest management will increase.

Europe's forest area can be distinguished into forest areas available for sustainable harvesting versus protected forests not available for harvesting, e.g., national parks and nature conservation [5]. According to the State of Europe's Forests 2020 report, about 50 million ha, or 23.6% of the forests in Europe, are in protected areas [1]. In most of these areas, limited harvesting is allowed if the other services, such as conservation of biodiversity, the protection of the forest soil or infrastructure, the provision of non-wood products (e.g., drinking water) or recreation near urban areas, is secured. Only in 5% of Europe's forest area no harvesting is allowed due to its legal protection status [1]. However, with the EU aiming to protect and restore already degraded ecosystems [6], this share is expected to rise.

Even if no legal harvesting restrictions exist, timber harvesting may not be feasible due to low yield productivity, inaccessibility of the forest area, or lack of profitability. Therefore, the Food and Agriculture Organization of the United Nations (FAO) distinguishes forest areas into (i) *'forest available for wood supply' (FAWS)* and (ii) *'forest not available for wood supply' (FNAWS)* [5]. FAWS include forests with no environmental, social or economic restrictions, while FNAWS cover forest areas with legal restrictions on timber harvesting but also those forest areas which lack profitability. According to the State of Europe's Forests 2020, around 77% of Europe's forest can be considered FAWS and the remaining 23% FNAWS.

Commonly, information about the forest area, as well as the stocking biomass, is available at the country and sub-country level (NUTS—Nomenclature of territorial units for statistics) (see [7–9]). It includes the harvesting possibilities according to different regulations for Land Use as well as Land Use Change and Forestry (EU-LULUCF) [10].

The provision of wood as raw material depends on the growing stock and the work force for cost-efficient harvesting. Since the European forest sector faces a severe decline in man power due to aging [11] and the forest area available for wood supply will decline if more forest areas are protected [6], cost-efficient, mechanized harvesting systems are of increasing importance to secure the provision of wood [12,13]. Mechanized harvesting additionally increases harvesting safety [14] and makes forestry jobs more attractive. A recent example is the increased use of winch-assisted systems for mechanized timber harvesting operations on steep terrain [14,15].

The implementation of a timber harvesting system depends largely on the technical requirements at the harvesting site (e.g., slope, soil bearing capacity, tree dimension, and species), and the accessibility of the forest area defined by the road network density [16]. In general, from all applicable harvesting systems at a harvesting site, the most mechanized harvesting systems is the most cost-efficient. The cost relationship between harvesting systems can, however, change depending on local factors such as the silvicultural system (e.g., clearfell, group, or selection system) or the price and availability of the work force [17–19]. GIS-based spatial solutions have been used at the regional level to select the most suitable timber harvesting system [19–25]. Di Fulvio et al. [26] assessed the availability, costs of roundwood, and the logging residues on a European level using the G4M computer model [27] and by defining 10 different harvesting options according to felling, extraction, and storage method.

The purpose of this study is to provide an estimate of the forest area and growing stock potentially available for mechanized harvesting in Europe. We obtain gridded forest characteristics data, combine this data with other European spatially-explicit information, and apply a set of eight different mechanized harvesting systems. The 'forest available for wood supply' (FAWS) is estimated using a top-down approach, which applies the same restrictions and threshold values across European forests.

We are interested in:

- Quantifying the area of 'forest available for wood supply' (FAWS) versus the 'forest not available for wood supply' (FNAWS)—The harvestable forest area;
- Delineating the area of and growing stock in FAWS by harvesting system for Europe, European geographic region, and country—Harvestable area and growing stock by harvesting system.

2. Materials and Methods

We assess the harvesting options in Europe's forest by combining forest characteristics [28] and other spatial data (e.g., slope, soil, road network; see next chapter) with the technical limitations of different harvesting systems. We use the Geographic Information System (GIS), ESRI® ArcGIS (Version 10.2.1, Redlands, CA, USA) [29] for initial data processing (e.g., re-projecting data) and handling the OpenStreetMap road data (see 2.1.5 Road network below). The statistical software R (Version 4.1.2, Vienna, Austria) [30] is used for further data processing (e.g., aggregation), the analysis of the data (e.g., identifying the harvesting systems), and the creation of the maps. The harvesting system analysis is conducted on a 500 m × 500 m-grid using the ETRS89-LAEA (European Terrestrial Reference System 89-Lambert Azimuthal Equal-Area) projection. The workflow of our analysis, including the input data, is shown in Figure 1.

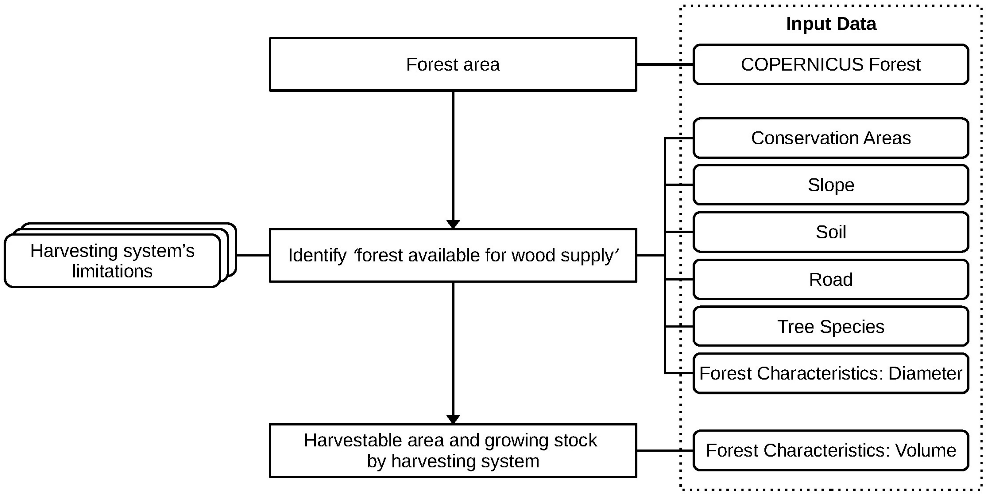


Figure 1. General workflow of the analysis. COPERNICUS forest data are used for generating a forest area mask. 'Forest available for wood supply' is the forest area where harvesting is legally allowed as well as profitable. Conservation areas data are used to identify protected forest where harvesting is prohibited. The defined harvesting systems are used to identify areas where economically profitable harvesting is feasible. Harvestable forest area and growing stock are cumulated by the harvesting system and are provided at a European and regional level.

2.1. Input Data

2.1.1. COPERNICUS Forest

Forested areas are identified using the Forest Type 2018 product of the Copernicus Land Monitoring Service, provided by the European Environment Agency [31]. The data are available either at the original 10 m resolution or aggregated at a 100 m resolution. In our analysis, we use the aggregated forest type product where a 100 m × 100 m grid cell (1 hectare) is considered a forest cell if at least 50% of the enclosed 10 m cells are covered with forests. The forest area for each 500 m cell is derived as the sum of the forested 100 m cells and ranges between 0 and 25 ha of the forest land.

2.1.2. Conservation Areas

According to the State of Europe's Forest 2020, about 5% of the forested area is legally protected and no active or only minimum interventions are allowed [1]. Protected areas are identified from the Common Database on Designated Areas for the year 2021 (Version 19) shapefile, provided by the United Nations Environment Program World Conservation Monitoring Centre (UNEP-WCMC) in collaboration with the European Environment Agency (EEA) [32]. Areas belonging to the International Union for Conservation of Nature (IUCN) categories "Ia" (strict nature reserve), "Ib" (wilderness area) and "II" (national park) are considered as not available for harvesting activities. These categories correspond to the MCPFE (Pan-European Ministerial Conference on the Protection of Forests in Europe) classes "1.1 No Active Intervention" and "1.2 Minimum Intervention" [33]. Using these categories follows the suggestion by Alberdi et al. [9] for estimating the protected areas belonging to "forest not available for wood supply" (FNAWS). A forest area mask is created, which defines the total forested area and its proportion of "protected" versus potentially "harvestable" area.

2.1.3. Slope

The European Union Digital Elevation model [34] with a 25 m resolution is used to derive the slope in percent for each 25 m × 25 m cell. The calculation of the slope is based on 8 neighboring cells using the raster package provided by [35] in the statistical software R (Version 4.1.2, Vienna, Austria) [30]. Each 25 m cell is assigned to one of three slope classes: (i) <30% (ii) 30 to 60%, and (iii) ≥60%. The three slope classes correspond to the operation range of different harvesting systems (see Section 2.2 Harvesting Systems below). The slope class for each 500 m grid cell is derived by combining the slope class share and the mean slope of the 500 m cell.

2.1.4. Soil

Soil bearing capacity is an indicator for trafficability and is strongly affected by soil type, soil texture, and soil moisture content. In general, bearing capacity decreases with an increasing moisture content [36,37]. Particularly, soils with groundwater access cannot be traversed by heavy machinery or traffic is limited to frozen or very dry periods [38].

We use soil data at a 1 km × 1 km resolution from the European Soil Database v2 (ESDB) [39] of the European Soil Data Centre [40] to identify soil types influenced by groundwater. Combining the AGLIM1, AGLIM2, PEAT, FAO85-FULL, FAO85-LEV1 and WRB-LEV1 attributes, the following soil types influenced by groundwater are considered: (i) gleyic and stagnic Albeluvisol, (ii) gleyic and fluvic Cambisol, (iii) gleyic Fluvisol, (iv) Gleysol, (v) gleyic Luvisol, (vi) Phaeozem, (vii) Planosol, (viii) gleyic Podzol, and (ix) Umbrisol [41]. Terrain roughness (microtopography) may further limit the use of wheeled and tracked machinery [22]. However, as no data are available at the required level of detail, ground roughness is not considered in our analysis.

2.1.5. Road Network

Freely available road network data from the OpenStreetMap (OSM) community project are used to calculate road density as a proxy for the extraction distance. OSM road data for each country are obtained as shapefiles from Geofabrik (www.geofabrik.de (accessed on 10 April 2019)) and cover the period between January and April 2019. Key-value pairs are used to extract road types relevant to forestry operations, i.e., secondary, tertiary, unclassified, and track. All other road types (e.g., motorway, trunk, primary, or residential) were considered not relevant to forestry operations (see https://wiki.openstreetmap.org/wiki/Key:highway (accessed on 10 February 2023) for details regarding the different road types). For each 500 m cell, road density is derived using the line density tool in the ArcGIS toolbox with 100 m, 300 m, 600 m and 1000 m radii and radius and cell centers aligned. The four radii correspond to the maximum extraction distance of the different harvesting systems, as explained below. The maximum extraction distance for a cell is then determined by the lowest radius with which a road density of at least 1 m/ha is detected. Mean road density for each 500 m cell (25 ha) is calculated using a radius of 282 m, which results in a corresponding circular area of 25 ha.

2.1.6. Forest Characteristics and Tree Species

Forest characteristics are obtained from the latest European forest structure data set [28] in combination with tree species distribution data from the European tree species maps [42]. The forest characteristics data (8 km × 8 km resolution) are based on 350,489 point samples of National Forest Inventory (NFI) data from 16 countries (Albania, Austria, Belgium, Croatia, Estonia, Finland, France, Germany, Ireland, Italy, The Netherlands, Norway, Poland, Romania, Spain, Sweden) covering the years 1996 to 2016. For details of the recorded inventory data by country we refer to [28].

The inventory data are aggregated to 8 km × 8 km grid cells by averaging the metric variables (e.g., height or diameter) and calculating the proportion for nominal values (e.g., age class and tree species group) based on the inventory plots within one cell. The 8 km × 8 km resolution follows the suggestion by Moreno et al. [43], who could show that on average a good balance between spatial resolution and accuracy of the forest characteristics by cell exists.

For countries and regions where no inventory data were available, a two-step gap-filling algorithm which (i) clusters cells by similarity and (ii) fills empty cells using a k-nearest neighbor (kNN) algorithm, is applied. The clustering is based on biogeographical regions [44] and MODIS MCD12Q1 land cover [45] information. For the kNN gap filling, the co-variates MODIS EURO net primary production (NPP) [46], NPP trend, spaceborne LiDAR based canopy height [47], and a climate limitation index are used to match forests with a similar productivity curve and development stage [48]. Pucher et al. [28] showed that gap-filled data provide realistic and unbiased estimates of the growing stock at the European level.

The forest characteristics data provide at an 8 km × 8 km the mean forest information such as biomass, volume, height, diameter at breast height, stem number, stand density index, age class, and tree species group. Thus, all forested 500 m cells within an 8 km grid cell share the same forest characteristics. The diameter at breast height (DBH) is used for selecting the harvesting system, while the volume provides the potentially harvestable growing stock by harvesting system.

Tree species are important for selecting the harvesting system. The forest characteristics data distinguish eight different tree species groups (e.g., coniferous pioneers, slow growing coniferous). However, for our analysis, we use the more detailed (1 km × 1 km) European tree species maps, which provide the dominant tree species and the share of 20 tree species [42]. The dominant tree species identified for a given cell is used for selecting the harvesting system and to distinguish forests dominated by coniferous versus broad-leaved tree species.

2.2. Harvesting Systems

Eight mechanized harvesting systems, which differ in harvesting method, technology and level of mechanization (Table 1) are considered. The harvesting systems are adopted from an earlier study [20], in which a multi-attribute decision support system for selecting timber harvesting systems on a regional level was developed. The harvesting system "tracked harvester and cable-forwarder" [20] is replaced by "winch-assisted harvester and winch-assisted forwarder" to reflect the technical improvements during the last decade [14].

Next, we determine which of the eight harvesting systems is suitable for a given cell by matching the technical operation ranges with (i) slope, (ii) soil conditions, (iii) the extraction distance, (iv) tree species, and (v) DBH. If there is more than one harvesting system applicable, the one with the highest level of mechanization is attributed to a given cell.

2.2.1. Terrain Parameters

The slope limit for ground-based harvesting systems varies with soil bearing capacity [49] and may range between 30% to 40% to avoid excessive soil damage [50]. The operation range of ground-based machinery can be extended by special attachments (e.g., chains, bands) or winch-assisted systems [51]. Similar to Kühmaier and Stampfer [20], we use a slope limit of 30% for all ground-based harvesting systems, except for the steep terrain harvester and winch-assisted harvester and forwarder, where the limit is set to 60% [14,50] (Table 1).

Ground-based harvesting systems may have negative impacts on sensitive soils [37,52]. Thus, on groundwater-affected soils, no ground-based harvesting systems are selected except for harvesting by chainsaw and skidder, since we assume that the skidder operates on a pre-defined skidding road. Harvesting with a chainsaw and cable yarding is not limited by the soil since this method is particularly suitable for extraction on sensitive soils [13,53].

Table 1. Overview of the eight defined harvesting systems. Each harvesting system is characterized by its limitations regarding terrain (slope, soil), road infrastructure (extraction distance) and stand conditions (species, DBH—diameter at breast height). For the tree species-specific DBH limits, see Table A1 in Appendix A.

	Harvesting System	Technical Limitations				
		Slope	Soil	Extraction Distance	Tree Species	DBH
1	Chainsaw and skidder Harvesting method: tree length Level of mechanization: Partially mechanized	<30%	-	≤100 m	-	-
2	Chainsaw and forwarder Harvesting method: cut-to length method Level of mechanization: Partially mechanized	<30%	Limited	≤1000 m	-	-
3	Harvester and forwarder Harvesting method: cut-to length method Level of mechanization: Fully mechanized	<30%	Limited	≤1000 m	limited	tree species specific
4	Chainsaw and winch-assisted forwarder Harvesting method: cut-to length method Level of mechanization: Partially mechanized	<60%	Limited	≤300 m	-	-
5	Winch-assisted harvester and winch-assisted forwarder Harvesting method: cut-to length method Level of mechanization: Fully mechanized	<60%	Limited	≤300 m	limited	tree species specific
6	Steep terrain harvester and tower yarder Harvesting method: cut-to-length method Level of mechanization: Fully mechanized	<60%	Limited	≤600 m	limited	tree species specific
7	Chainsaw and tower yarder Harvesting method: cut-to-length method Level of mechanization: Partially mechanized	<100%	-	≤600 m	-	-
8	Chainsaw and tower yarder with integrated or excavator-based processor Harvesting method: whole tree method Level of mechanization: Highly mechanized	<100%	-	≤600 m	limited	tree species specific

2.2.2. Road Network

In general, harvesting systems are limited by an economically feasible extraction distance, while cable harvesting systems are additionally limited by the length of the cable. In this study, we use a maximum extraction distance of (i) 1000 m for forwarder [54], (ii) 600 m for tower yarder [55], (iii) 300 m for winch-assisted forwarder [56,57] and (iv) 100 m for a skidder with winch [20]. Only road types relevant to forest operations were considered in the calculations (see Section 2.1.5 Road network). While extraction on temporary winter roads or by floating timber along lakes and rivers is possible, these extraction methods are not considered in this study.

2.2.3. Forest Characteristics

Mechanized felling is limited by the maximum cutting diameter of the employed harvester head or processor. Today's harvester heads are mostly designed for a felling diameter between 50 and 70 cm, even though there are some heads that can cut diameters of up to 100 cm [58].

For coniferous trees, we follow the suggestion by Kühmaier and Stampfer [20] and use a more conservative DBH limit of 40 cm for felling by harvester. For cable yarders with integrated or excavator-based processors, this limit is set to 50 cm, because we assume that the butt flare is prepared by chainsaw and therefore is no longer a limiting factor.

For broad-leaved trees, the mechanized processing can be hampered by the branch diameter, forks, crooks, and sweeps, as well as the wood density [59,60]. The diameter of the branches, which usually increases with DBH, limits the machinability with harvester head and processor. We set the DBH limit for mechanized felling and processing equal to 30 cm for all broad-leaved species, except for alder, birch, and eucalyptus, which are usually easy to debranch. Finally, poplar is considered unsuitable for mechanized felling and processing because of its large dimension. A table showing the tree species-specific limits is provided in Appendix A (Table A1).

2.3. Forest Available for Wood Supply

Forests in Europe can be distinguished into 'forest available for wood supply' (FAWS) and 'forest not available for wood supply' (FNAWS) [5]. FNAWS include forest areas under legal protection and forest areas, which are economically unsuitable for harvesting. We use the COPERNICUS Forest Type 2018 product to determine the total forest area and combine it with the Common Database on Designated Areas for the year 2021 EEA categories "Ia" (strict nature reserve), "Ib" (wilderness area) and "II" (national park) to identify the forest area under legal protection in Europe.

FNAWS also include forest areas where harvesting is economically not feasible with the current technical standards. In our analysis, we address this by using threshold values for the extraction distance and the tree species-specific DBH for processing (see Table 1). We combine terrain, road, and forest stand data with the operation range of the different harvesting systems presented in Table 1 to identify forest areas accessible with the current mechanized harvesting systems. These areas have the potential for economically profitable harvesting. Areas where none of the defined harvesting systems are applicable are considered "areas with limited accessibility" and added to the FNAWS area.

2.4. Harvestable Volume by Harvesting System

For each forest cell identified as 'forest available for wood supply' (FAWS), we (i) identify the suitable harvesting systems and (ii) select the harvesting system with the highest level of mechanization. For instance, if both (i) the chainsaw and forwarder and (ii) the harvester and forwarder system were applicable, the cell and its associated forest area and growing stock are attributed to the harvester and forwarder harvesting system.

The growing stock for each 500 m cell is calculated by multiplying the forest area within a cell (derived from the COPERNICUS Forest Type data) with the volume per hectare obtained from the forest characteristics data [28].

3. Results

3.1. Forest Area in Europe

The forest area of the 34 countries of our study covers 183.4 million ha, or 1/3 of the total land area (Table 2). About 7.8 million ha, or 4.3%, are under legal protection, while another 38.2 million ha, or 20.8% (Table 2, Figure 2), are considered as areas with limited accessibility with the current mechanized harvesting systems. Thus, 46.0 million hectares (7.8 and 38.2), or 25.1%, are 'forest not available for wood supply' (FNAWS). The remaining 137.4 million ha or 74.9% of the forest are 'forest available for wood supply' (FAWS), and represent the "harvestable forest area" of the 34 countries.

As shown in Table 2, the share of FNAWS versus FAWS varies largely by country and major geographic region. In Central-West Europe, 90% of the forest land is FAWS, while only 62% in South-East Europe is available for harvesting. The forest area under legal protection ranges from 1.1% in Central-West Europe to 7.1% in North Europe. At the country level, the variation between FNAWS and FAWS is even more pronounced and, for FAWS, ranges from less than 50% in Estonia, Latvia, Albania, and North Macedonia to over 90% in Denmark, Austria, Belgium, Germany, and the Czech Republic (see Table 2).

Table 2. Summary of the forest area in Europe (all 34 countries considered) and distinguished by geographic regions and countries. The regions are defined according to the State of Europe's Forests (FOREST EUROPE, 2020). 'Forest not available for wood supply' (FNAWS) comprises protected forest where commercial harvesting is prohibited as well as forest areas with limited accessibility (Lim. Accessibility). All other forest areas are considered as 'forest available for wood supply' (FAWS).

	Total	**Protected**		**Lim. Accessibility**		**FAWS**	
	1000 ha	**1000 ha**	**%**	**1000 ha**	**%**	**1000 ha**	**%**
Europe	183,424.9	7864.7	4.3	38,187.6	20.8	137,372.6	74.9
North Europe	66,724.1	4713.5	7.1	17,226.6	25.8	44,784.0	67.1
Denmark	591.8	1.8	0.3	31.5	5.3	558.5	94.4
Estonia	2256.2	71.7	3.2	1321.2	58.6	863.3	38.3
Finland	21,037.8	1562.5	7.4	3417.3	16.2	16,058.0	76.3
Latvia	3388.2	213.5	6.3	1857.5	54.8	1317.2	38.9
Lithuania	2310.9	115.1	5.0	732.1	31.7	1463.7	63.3
Norway	10,965.6	577.6	5.3	4248.5	38.7	6139.5	56.0
Sweden	26,173.5	2171.2	8.3	5618.4	21.5	18,383.9	70.2
Central-West Europe	38,115.7	428.0	1.1	3390.8	8.9	34,296.9	90.0
Austria	3868.2	42.2	1.1	239.9	6.2	3586.0	92.7
Belgium	768.8	1.2	0.2	50.4	6.6	717.3	93.3
France	17,071.8	168.6	1.0	1576.6	9.2	15,326.6	89.8
Germany	11,398.4	132.0	1.2	599.6	5.3	10,666.8	93.6
Ireland	719.3	0.0	0.0	228.1	31.7	491.1	68.3
Lichtenstein	7.3	1.0	13.1	0.7	9.3	5.7	77.6
Luxembourg	92.6	41.6	44.9	1.8	1.9	49.2	53.2
The Netherlands	350.4	35.2	10.0	90.9	25.9	224.4	64.0
Switzerland	1363.1	6.2	0.5	154.7	11.4	1202.1	88.2
United Kingdom	2475.9	0.0	0.0	448.1	18.1	2027.8	81.9
Central-East Europe	26,575.7	652.5	2.5	5375.7	20.2	20,547.5	77.3
Czech Republic	3009.9	74.5	2.5	42.5	1.4	2892.8	96.1
Hungary	2228.2	75.4	3.4	364.0	16.3	1788.8	80.3
Poland	10,685.7	141.5	1.3	1156.8	10.8	9387.4	87.8
Romania	8375.8	266.5	3.2	3572.6	42.7	4536.8	54.2
Slovakia	2276.2	94.6	4.2	239.8	10.5	1941.8	85.3
South-West Europe	29,312.6	1411.4	4.8	4281.7	14.6	23,619.5	80.6
Italy	10,894.9	859.4	7.9	1016.4	9.3	9019.1	82.8
Portugal	2867.1	10.8	0.4	341.2	11.9	2515.0	87.7
Spain	15,550.7	541.2	3.5	2924.1	18.8	12,085.4	77.7
South-East Europe	22,696.8	659.4	2.9	7912.8	34.9	14,124.7	62.2
Albania	1063.2	119.5	11.2	449.6	42.3	494.1	46.5
Bosnia and Herzegovina	2939.4	49.2	1.7	1231.5	41.9	1658.6	56.4
Bulgaria	4755.0	125.3	2.6	1933.4	40.7	2696.3	56.7
Croatia	2401.3	0.1	0.0	582.3	24.2	1818.9	75.7
Greece	4525.9	53.2	1.2	1006.9	22.2	3465.9	76.6
Montenegro	752.2	41.3	5.5	246.2	32.7	464.7	61.8
North Macedonia	1213.0	67.5	5.6	698.8	57.6	446.8	36.8
Serbia	3760.6	149.2	4.0	1672.7	44.5	1938.7	51.6
Slovenia	1286.1	53.9	4.2	91.5	7.1	1140.7	88.7

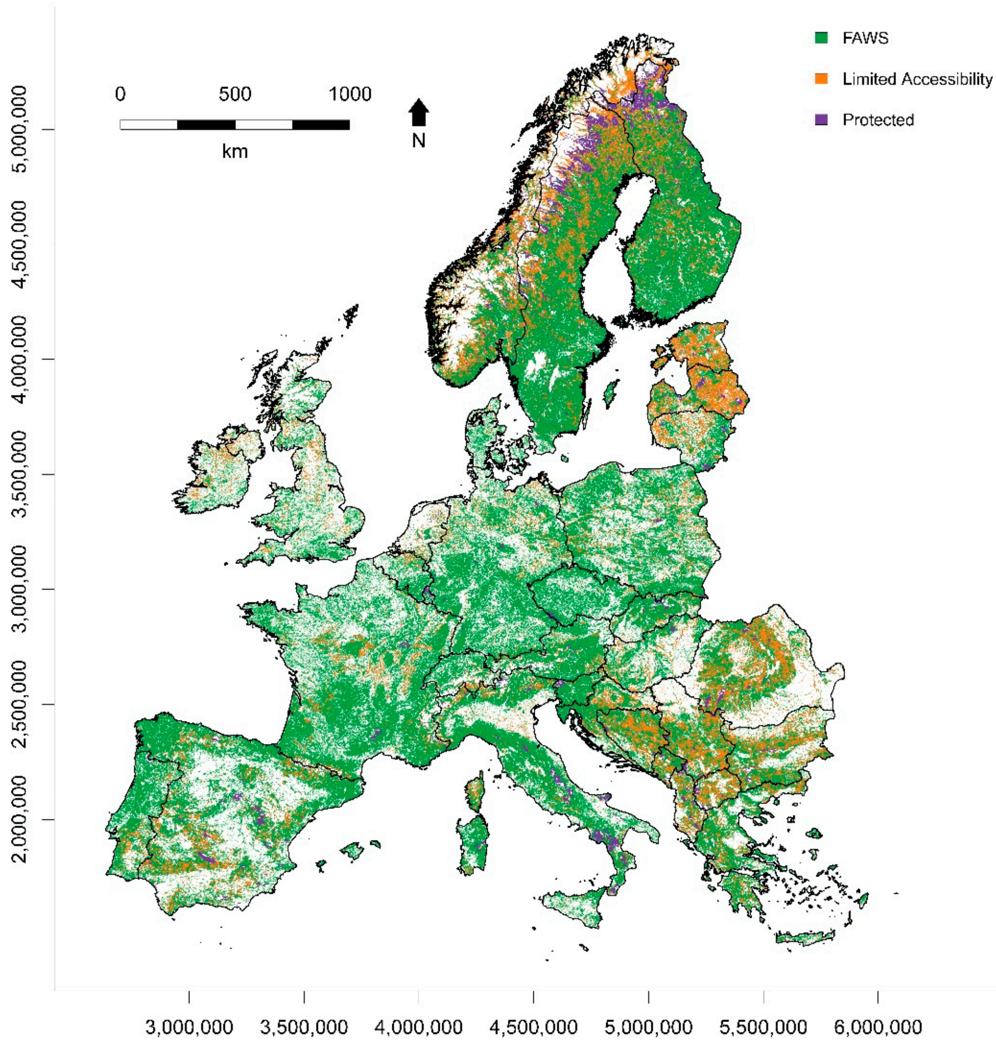


Figure 2. 'Forest available for wood supply' (FAWS, green) as well as 'forest not available for wood supply' (FNAWS) at 500 m × 500 m resolution. FNAWS is further separated into legally protected areas (purple) or areas with limited accessibility (orange). Forested areas are identified using COPERNICUS data at 100 m × 100 m resolution.

The Harvestable Forest Area

Harvesting operations are usually conducted if economically profitable. Profitability—among other factors—depends mostly on (i) forest stand characteristics, (ii) the species type (coniferous vs. broad-leaved), (iii) the slope, (iv) the road density or extraction distance, and (v) if ground water affects the soil, indicating sensitive harvesting conditions.

In Europe, about 2/3 of the harvestable forest area is dominated by coniferous and 1/3 by broad-leaved species (Table 3). In addition, 78.1% of the harvestable forest area is located on slopes < 30%, while the shares of slopes from 30 to 60%, and >60%, are 18% and 4%, respectively (Table 3). Higher forest road densities result in shorter extraction distances and allow the selection of less cost-intensive harvesting systems. Our analysis shows that 68.0% of the harvestable forest area is located within 300 m of the next forest road and only 8.1% of the forests revealed an extraction distance of >600 m. In addition, 2.9% of the harvestable forest area is located on soils affected by groundwater, where harvesting operations are limited to frozen soil conditions during the winter to avoid excessive soil damage (Table 3).

Table 3. The area of 'forest available for wood supply' (FAWS), the average road density and area of FAWS, according to dominant tree species type, slope, soil and road infrastructure conditions, are given for Europe and by region. Dominant tree species type was provided by the tree species maps for European forests [42]. Note that only the dominant tree species is considered and that a forest area dominated by coniferous tree species need not necessarily be a coniferous forest. Regions: (i) Europe: all of the 34 countries mentioned; (ii) North Europe: Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden; (iii) Central-West Europe: Austria, Belgium, France, Germany, Ireland, Lichtenstein, Luxembourg, The Netherlands, Switzerland, United Kingdom; (iv) Central-East Europe: Czech Republic, Hungary, Poland, Romania, Slovakia; (v) South-West Europe: Italy, Portugal, Spain; and (vi) South-East Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Montenegro, North Macedonia, Serbia, Slovenia.

	Europe	North Europe	Central-West Europe	Central-East Europe	South-West Europe	South-East Europe
FAWS (million ha)	137.4	44.8	34.3	20.5	23.6	14.1
Average road density (m/ha)	17.9	9.0	30.2	17.7	19.5	11.0
	% within region					
Dominated by coniferous tree species	62.1	85.6	55.8	73.0	43.3	18.6
Dominated by broad-leaved tree species	34.9	7.3	43.2	26.6	55.0	80.4
Dominated by undefined tree species	3.0	7.1	1.0	0.4	1.7	1.0
Slope class 0–30%	78.1	96.8	74.9	82.5	58.2	53.7
Slope class 30–60%	17.6	2.6	18.4	16.1	32.9	40.0
Slope class 60–100%	4.2	0.6	6.7	1.5	8.8	6.2
Road within 100 m	34.0	22.3	52.1	35.8	33.9	25.2
Road within 100 m and 300 m	34.0	32.4	34.0	35.6	36.2	33.4
Road within 300 m and 600 m	23.9	30.2	12.5	22.6	24.2	32.6
Road within 1000 m	8.1	15.1	1.5	6.0	5.7	8.8
Soil affected by groundwater	2.9	1.6	5.9	4.0	0.8	1.5

As expected, there are distinct differences between geographic regions and countries within Europe. In North Europe, 85.6% of the forest area is dominated by coniferous tree species and 96.8% of the harvestable forest area is located on flat terrain. With an average road density of 9 m/ha and an average extraction distance > 300 m for 45% of the harvestable forest area, it is the region with the lowest road infrastructure (Table 3). In Central-West Europe, 3/4 of the FAWS are located on flat terrain, with 55.8% dominated by coniferous and 43.2% by broad-leaved species. With a road density of 30.2 m/ha and 50% of the harvestable forest area within a distance of <100 m from the next forest road, it is the region with the best developed road infrastructure. Central-East Europe is similar to North Europe, where the majority of FAWS are located on flat terrain and most of the area (around 3/4) is dominated by coniferous species. Compared to North Europe, Central-East Europe has a better road infrastructure, with on average 17.7 m/ha. With 5.9% and 4.0%, Central-West and Central-East Europe have the highest share of FAWS on soil affected by groundwater (Table 3).

The FAWS (forest available for wood supply) in South-West and South-East Europe are dominated by broad-leaved species (55.0% and 80.4%) and 32.9% in South-West and 40% in South-East are located on slopes ranging from 30% to 60%. Only 8.8% and 6.2% (South-West and South-East) are on slopes > 60%. The road infrastructure, with an average of 11 m/ha in South-East Europe, is similar to North Europe (9 m/ha), while South-West Europe, with 19.5 m/ha, exhibits the second highest road density of all five geographic regions (Table 3).

3.2. Harvestable Area and Volume by Harvesting System

Next, we were interested in the spatial distribution (Figure 3) of the eight mechanized harvesting systems. Note that if more than one harvesting system is possible, the most mechanized one is chosen, assuming that it is the most cost-efficient, and thus preferred harvesting system. In addition, 70.8% of the harvestable forest area and 66.7% of the growing stock can be utilized with harvester and forwarder (HFW) (Tables 4 and 5). Winch-assisted harvester and winch-assisted forwarder (WHWF), as well as the steep terrain harvester and tower yarder (SHTY), both fully mechanized harvesting systems, are suitable on 11.7% and 4.2% of the forest area, as well as 12.2% and 3.9% of the growing stock (Tables 4 and 5).

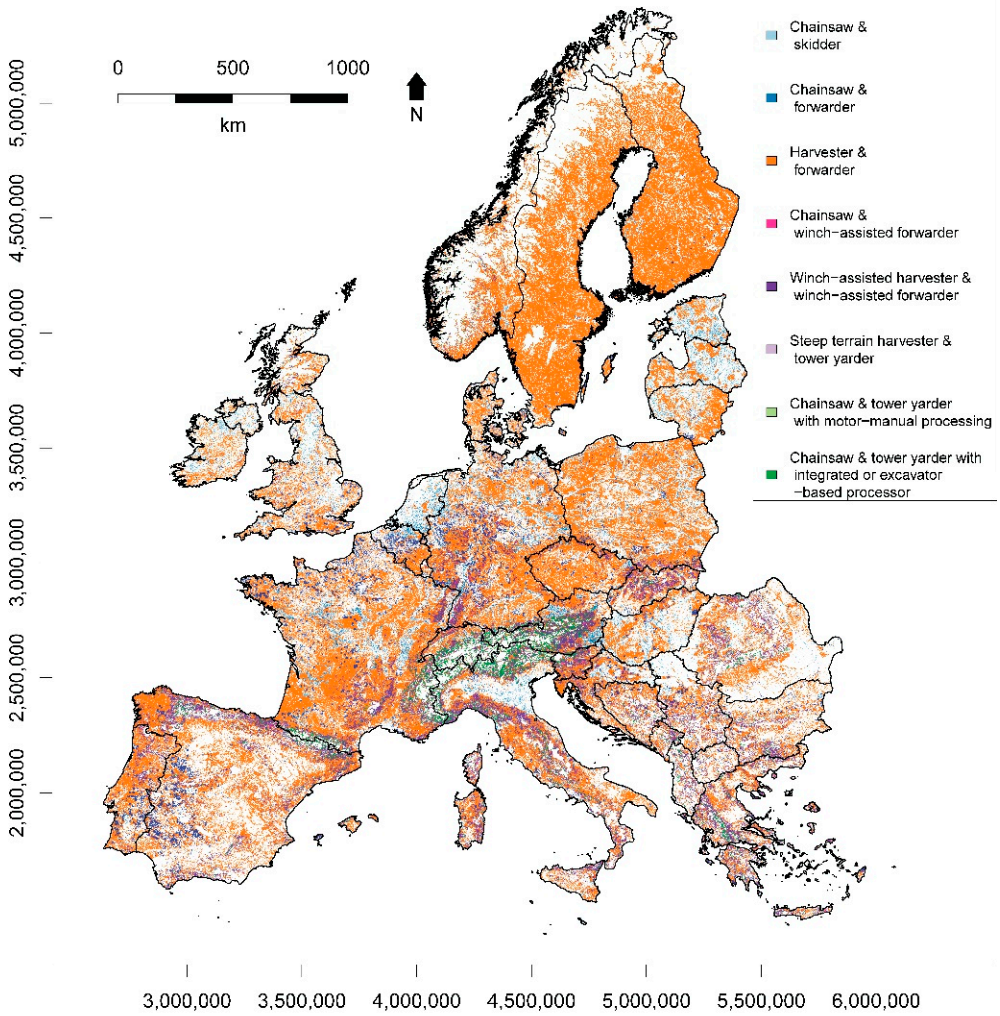


Figure 3. Harvesting systems map at 500 m × 500 m resolution. The harvesting systems shown for each 500 m cell are identified by comparing the harvesting systems technical limitations (see Table 1) with the terrain, infrastructure and stand conditions of the cell. If more than one harvesting system is applicable for an area, only the harvesting system with the highest degree of mechanization is shown. The harvesting systems are: (i) chainsaw and skidder (light blue), (ii) chainsaw and forwarder (dark blue), (iii) harvester and forwarder (orange), (v) chainsaw and winch-assisted forwarder (pink), (v) winch-assisted harvester and winch-assisted forwarder (dark purple), (vi) steep terrain harvester and tower yarder (light purple), (vii) chainsaw and tower yarder with motor-manual processing (light green), and (viii) chainsaw and tower yarder with integrated or excavator-based processor (dark green).

Table 4. Share of area of 'forest available for wood supply' (FAWS) by harvesting system for Europe and the five European regions and countries. FAWS corresponds to forest where harvesting is allowed from a legal perspective and is profitable. Harvesting Systems: CSK—chainsaw and skidder, CFW—chainsaw and forwarder, HFW—harvester and forwarder, CWF—chainsaw and winch-assisted forwarder, WHWF—winch-assisted harvester and winch-assisted forwarder, SHTY—steep terrain harvester and tower yarder, CTY—chainsaw and tower yarder, CTYP—chainsaw and tower yarder with integrated or excavator-based processor.

		Distribution among Harvesting Systems							
	FAWS 1000 ha	**CSK** %	**CFW** %	**HFW** %	**CWF** %	**WHWF** %	**SHTY** %	**CTY** %	**CTYP** %
Europe	137,372.6	2.6	4.7	70.8	1.0	11.7	4.2	0.6	4.3
North Europe	44,784.0	1.7	0.4	94.7	0.0	1.4	1.2	0.0	0.7
Denmark	558.5	3.4	13.2	83.3	0.0	0.0	0.0	0.0	0.0
Estonia	863.3	28.4	0.0	71.6	0.0	0.0	0.0	0.0	0.0
Finland	16,058.0	0.3	0.4	99.3	0.0	0.0	0.0	0.0	0.0
Latvia	1317.2	18.3	0.0	81.7	0.0	0.0	0.0	0.0	0.0
Lithuania	1463.7	9.4	2.1	88.4	0.0	0.0	0.0	0.0	0.0
Norway	6139.5	0.6	0.0	77.1	0.0	9.3	8.0	0.0	5.0
Sweden	18,383.9	0.1	0.1	99.4	0.0	0.2	0.2	0.0	0.0
Central-West Europe	34,296.9	5.2	8.0	61.7	1.3	14.3	2.1	0.6	6.8
Austria	3586.0	5.3	2.1	24.1	1.9	35.6	1.9	1.7	27.4
Belgium	717.3	7.6	18.4	70.9	0.3	2.6	0.1	0.0	0.1
France	15,326.6	3.8	6.9	64.9	0.8	14.5	3.6	0.6	5.0
Germany	10,666.8	5.8	12.0	69.8	1.8	8.9	0.2	0.1	1.3
Ireland	491.1	13.2	1.0	81.3	0.1	3.2	0.8	0.0	0.4
Lichtenstein	5.7	1.0	3.1	8.0	22.0	4.7	0.0	57.0	4.2
Luxembourg	49.2	8.0	4.3	76.3	2.3	8.0	0.3	0.3	0.5
The Netherlands	224.4	51.1	1.0	47.9	0.0	0.0	0.0	0.0	0.0
Switzerland	1202.1	2.9	1.9	24.8	3.4	25.7	2.2	3.4	35.7
United Kingdom	2027.8	6.6	8.6	75.6	0.3	5.5	2.1	0.1	1.2
Central-East Europe	20,547.5	3.7	4.1	74.7	1.5	9.1	4.2	1.1	1.6
Czech Republic	2892.8	0.8	3.1	84.0	0.4	10.2	1.1	0.1	0.3
Hungary	1788.8	9.4	3.3	81.4	0.0	4.6	0.8	0.0	0.6
Poland	9387.4	5.2	3.2	88.4	0.4	1.9	0.6	0.2	0.0
Romania	4536.8	0.9	5.1	52.7	3.4	15.9	13.1	3.7	5.1
Slovakia	1941.8	1.6	8.6	39.7	5.0	30.9	8.8	1.7	3.7
South-West Europe	23,619.5	0.6	7.1	50.5	1.2	23.4	7.8	0.8	8.7
Italy	9019.1	1.3	1.9	36.8	1.4	32.0	8.7	1.0	17.0
Portugal	2515.0	0.9	14.6	67.8	0.6	12.1	3.3	0.2	0.5
Spain	12,085.4	0.1	9.4	57.2	1.1	19.2	8.0	0.7	4.2
South-East Europe	14,124.7	1.1	6.8	45.8	2.2	22.9	13.2	1.9	6.1
Albania	494.1	0.7	2.5	23.2	3.4	30.0	23.0	4.5	12.7
Bosnia and Herzegovina	1658.6	0.2	6.5	52.0	1.0	19.1	15.0	1.0	5.3
Bulgaria	2696.3	1.2	6.7	51.9	2.3	18.4	13.0	2.4	4.1
Croatia	1818.9	3.9	12.1	61.3	2.1	11.8	6.2	1.2	1.4
Greece	3465.9	0.0	3.4	36.7	1.6	33.1	14.5	1.1	9.6
Montenegro	464.7	0.0	2.1	38.6	1.8	27.7	17.4	2.2	10.2
North Macedonia	446.8	0.0	6.6	36.5	3.6	22.4	21.1	4.5	5.2
Serbia	1938.7	1.5	9.8	47.6	2.5	18.3	15.1	2.3	2.9
Slovenia	1140.7	1.6	8.4	38.3	4.8	28.3	5.8	2.6	10.2

Table 5. Share of growing stock in 'forest available for wood supply' (FAWS) per harvesting system for Europe and the five European regions and countries. FAWS corresponds to forest where harvesting is allowed from a legal perspective, and is profitable. Harvesting systems: CSK—chainsaw and skidder, CFW—chainsaw and forwarder, HFW—harvester and rorwarder, CWF—chainsaw and winch-assisted Forwarder, WHWF—winch-assisted harvester and winch-assisted forwarder, SHTY—steep terrain harvester and tower yarder, CTY—chainsaw and tower yarder, CTYP—chainsaw and tower yarder with integrated or excavator-based processor.

		Distribution among Harvesting Systems							
	FAWS Million m^3	CSK %	CFW %	HFW %	CWF %	WHWF %	SHTY %	CTY %	CTYP %
Europe	25,119.0	3.2	6.1	66.7	1.7	12.2	3.9	1.1	5.1
North Europe	6307.9	2.4	0.8	94.5	0.0	1.0	0.9	0.0	0.5
Denmark	117.7	3.5	22.0	74.5	0.0	0.0	0.0	0.0	0.0
Estonia	183.6	29.7	0.0	70.3	0.0	0.0	0.0	0.0	0.0
Finland	1991.8	0.3	0.4	99.3	0.0	0.0	0.0	0.0	0.0
Latvia	261.7	18.4	0.0	81.6	0.0	0.0	0.0	0.0	0.0
Lithuania	301.8	9.9	1.6	88.5	0.0	0.0	0.0	0.0	0.0
Norway	662.0	0.8	0.1	78.0	0.0	9.1	7.3	0.0	4.6
Sweden	2789.3	0.1	0.3	99.3	0.0	0.2	0.2	0.0	0.0
Central-West Europe	7979.3	5.2	9.9	58.3	1.7	15.1	1.5	0.7	7.7
Austria	1124.9	5.5	2.1	23.3	1.9	35.7	1.9	1.8	27.9
Belgium	211.1	6.0	17.7	73.1	0.3	2.8	0.1	0.0	0.0
France	2200.5	3.8	8.8	61.0	1.1	15.5	3.3	0.8	5.7
Germany	3619.6	5.2	13.3	67.8	2.0	9.8	0.2	0.1	1.6
Ireland	89.3	13.9	1.9	79.3	0.1	3.3	0.9	0.0	0.5
Lichtenstein	1.2	1.5	4.4	11.7	18.1	7.1	0.0	51.2	6.0
Luxembourg	14.2	7.1	5.8	74.9	3.2	7.9	0.4	0.4	0.5
The Netherlands	45.6	49.9	1.1	49.0	0.0	0.0	0.0	0.0	0.0
Switzerland	312.6	2.6	2.7	23.2	4.6	24.7	2.1	4.6	35.5
United Kingdom	360.3	6.6	11.6	72.6	0.5	5.1	2.0	0.2	1.3
Central-East Europe	5713.5	3.3	5.5	70.8	2.3	9.7	4.7	1.8	1.8
Czech Republic	856.2	0.8	3.8	82.1	0.6	11.0	1.3	0.1	0.3
Hungary	466.8	9.2	3.3	81.0	0.0	5.0	0.9	0.0	0.6
Poland	2474.4	5.0	4.4	86.7	0.6	2.2	0.7	0.3	0.1
Romania	1403.0	0.7	7.1	45.1	5.4	16.4	13.8	6.0	5.5
Slovakia	513.1	1.5	11.1	36.2	7.2	29.2	8.5	2.4	3.8
South-West Europe	2211.0	0.7	3.0	38.6	2.0	29.5	8.3	1.6	16.3
Italy	1282.3	1.1	2.2	27.2	2.3	32.7	8.2	2.0	24.2
Portugal	150.8	0.4	5.5	69.8	0.6	18.5	4.4	0.2	0.6
Spain	777.9	0.1	3.8	51.3	1.8	26.3	9.3	1.1	6.4
South-East Europe	2907.5	1.4	10.7	42.7	3.6	20.9	12.3	3.0	5.6
Albania	43.6	0.5	5.7	18.3	7.9	26.4	18.7	10.0	12.6
Bosnia and Herzegovina	404.1	0.1	9.9	47.8	1.8	19.1	14.8	1.6	5.0
Bulgaria	695.4	1.2	9.2	46.5	3.4	18.7	13.3	3.5	4.3
Croatia	407.0	4.5	17.8	53.8	3.6	11.5	5.6	2.0	1.2
Greece	314.0	0.0	5.1	30.5	2.8	34.1	14.3	2.5	10.7
Montenegro	76.2	0.0	3.8	31.5	3.5	29.4	17.9	4.0	9.9
North Macedonia	95.8	0.0	8.5	33.0	5.9	21.4	19.8	7.1	4.3
Serbia	511.4	1.3	13.8	42.3	3.6	18.1	14.8	3.3	2.7
Slovenia	360.0	1.6	9.4	36.1	5.3	27.5	5.5	2.9	11.7

Chainsaw and tower yarder with integrated or excavator-based processor (CTYP) are potentially suitable on 4.3% of the forest area and 5.1% of the growing stock. On the remaining 8.9% of the forest area and 12.1% of the growing area, mechanization is only partly possible by employing chainsaw and skidder (CSK), chainsaw and forwarder (CFW), chainsaw and winch-assisted forwarder (CWF), and chainsaw and tower yarder (CTY) for harvesting.

In North Europe, over 95% of the forest area and growing stock are potentially harvestable with fully mechanized systems. Within the region, HFW is the dominant harvesting system (94.7% of the harvestable forest area and 94.5% of the growing stock), while in South-East Europe this system is suitable for less than half of the harvestable area and growing stock (45.8% and 42.7%) (Tables 4 and 5). Since WHWF and SHTY are both suitable for around 1/3 of the forest area and growing stock in South-East Europe, a total of about 3/4 of the forest area and growing stock are harvestable with fully mechanized systems.

Central-West Europe has the lowest potential for mechanization. Nevertheless, 3/4 of the forest area and about 3/4 of the growing stock are suitable for fully mechanized harvesting systems, with HFW being suitable for 60% and the WHWF for around 15% of the forest area and growing stock. South-West Europe is the region with the highest shares (9.5% of the area and 17.9% of the growing stock) of partially and highly mechanized harvesting systems using cable yarding (chainsaw and tower yarder (CTY) and chainsaw and tower yarder with integrated or excavator-based processor (CTYP)), while in North Europe, cable yarding harvesting systems are almost neglectable (see Tables 4 and 5).

At the country level, the variation is even more evident. For instance, while in North Europe, chainsaw and skidder (CSK) is the most suitable harvesting system only on <3% of the forest area and growing stock, it is quite important for Estonia where it is the most suitable harvesting system on almost 30% of the forest area. In the Netherlands, the CSK has a high share with around 50% for both forest area and growing stock because of the groundwater-affected soil conditions, which limit the use of mechanized harvesting systems.

While the chainsaw and tower yarder (CTY) and chainsaw and tower yarder, with integrated or excavator-based processor (CTYP) cable yarding systems, are only important on around 5% of the European forest area and 6% of the growing stock, they are highly relevant systems in countries such as Switzerland, with 35% CTYP. Similarly, the winch-assisted harvester and winch-assisted forwarder (WHWF) are important for Austria, Slovakia, Italy or Albania, where around 30% of the forest area and growing stock are harvested with this system.

Finland, Norway, Sweden, and the Czech Republic revealed the highest potential for mechanization, since the fully mechanized harvesting systems area is suitable for 95% of the forest area and growing stock. The lowest mechanization options are evident for Lichtenstein, where only 12.7% of the forest area and 18.7% of the growing stock are suitable for fully mechanized harvesting, followed by the Netherlands with 47.9% and 49%, respectively.

4. Discussion

The 34 European countries in our study exhibit an estimated growing stock in 'forest available for wood supply' (FAWS) of 25 billion m^3 (Table 5). This number is similar to the State of Europe's Forest (SOEF) report [1], which estimate a growing stock of 26.9 billion m^3, covering the same countries. The 7% difference in growing stock is mainly due to the fact that in our study, the identified area of FAWS is 12 million ha lower versus the SOEF report (137 million ha vs. 149 million ha), while the total forest area with 183 million ha is similar in both studies [1].

The difference in FAWS was expected, since the calculation methods differ. The SOEF report provides the sum of individual country reports, which may differ (i) by country-specific differences in collecting national forest inventory data, ranging from point sampling information to surveying or combinations of remote sensing and terrestrial data, (ii) by different threshold definitions (e.g., maximum extraction distance, slope classes, forest area definitions), as well as (iii) different country-specific environmental, economic, and social factors [5,9].

When estimating the protected areas belonging to "forest not available for wood supply" (FNAWS), we followed the suggestion by Alberdi et al. [9] and considered the Ministerial Conference on the Protection of Forests in the Europe (MCPFE) categories "No

Active Intervention" and "Minimum Intervention". Other areas that are not available for wood supply due to national regulations are not considered in our analysis.

Our results show a high mechanization potential for harvesting in large parts of Europe (Tables 4 and 5), while [61] provide an estimate of the current mechanization level for selected countries. For most of North Europe (Estonia, Finland, Latvia) and parts of Central-West (Germany, Ireland, UK) and South-West (Italy) Europe, the current and potential mechanized harvesting level are similar (see [61]), while for other countries within these regions (Lithuania, Austria, France, Spain), the gap between potential and observed mechanization is higher. In Central-East (Czech Republic, Poland, Romania, Slovakia) and South-East (Bulgaria) Europe, the current level of mechanization is, in general, still relatively low [61,62]. This gap between potential and observed mechanization may be explained by forest ownership structure (e.g., share of publicly owned forest land), financial means of individual forest owners, economic condition of the country, the implemented silvicultural system, simply personal preference, or the availability of equipment and workforce [18,61,62]. These factors influence the selection of a harvesting system and the willingness to harvest.

The suitability of a harvesting system strongly depends on the regional road density, the slope, the soil water conditions, and the dominant tree species at the harvesting site (Table 3). We use road density as a proxy for the extraction distance and rather conservative values for the extraction distances by the harvesting system to address that within a 500 m cell, the forest distribution and any obstacles (e.g., waterbodies, creeks) are unknown.

Most of Europe's landscape can be categorized as flat or hilly with a slope of <30° (see also [63]). Thus, harvester and forwarder (HFW), with its recent technological improvements, including the winch-assisted harvester and winch-assisted forwarder (WHWF), is the most important harvesting system. Extraction distance is not a limiting factor for WHWF if the road network is well-developed. However, the low average road density in South-East Europe (11 m/h) limits the use of WHWF and other harvesting systems on moderate to steep slopes, resulting in around 35% of the forest area having limited accessibility. In addition, in North Europe, ground-based machinery on flat terrain is limited by the low average road density (9 m/ha).

In our analysis we use Open Street Map (OSM) data. These data result from a community project and may underestimate the forest road density in remote areas. Therefore, a low average road density can reflect the actual infrastructure as well as an inactivity of the mapping community. In addition, temporary winter roads are not considered in our analysis.

According to the European Soil Data Base (ESDB) [39], limits in trafficability due to groundwater are mainly found in the Baltic region, the British Isles, and the Netherlands. In these areas, large-scale sensitive soil features such as wetlands exist. Small-scale soil features which might also limit the use of harvester and forwarder on a local level were not considered in our analysis due to the data limitations of the ESDB [39].

Our study suggests that tree dimension limits, only in exceptional cases, the use of harvester and forwarder (HFW), winch-assisted harvester and winch-assisted forwarder (WHWF), and chainsaw and tower yarder with integrated or excavator-based processor (CTYP). One of the reasons for this result may be the fact that we obtained the average diameter at breast height (DBH) from the forest characteristics data with a given 8 km × 8 km resolution [28]. This levels the actual DBH distribution, which may lead to a tendency of to overestimate the growing stock available for processing by a harvester or processor. We address this effect by choosing conservative maximum DBH values which can be processed: (i) For conifers, a DBH = 40 cm in case of harvester and a DBH = 50 cm in case of processor, and (ii) for selected broad-leaved species, a DBH = 30 cm for both harvester and processor. Note that, in general, harvester heads can also process thicker trees but maximum productivity is reached at a certain diameter after which it decreases again [58,60,64].

The applicability of harvesting systems mostly depends on slope and accessibility (soil, road) of the terrain. As these data were available at a higher resolution, the selection of the mechanized harvesting system was perfomed using a 500 m × 500 m grid.

The estimated forest area of and growing stock in 'forest available for wood supply' (FAWS) is accessible and feasible for economically profitable harvesting with current mechanized harvesting techniques. Forest ownership, which often affects the willingness to harvest, and prioritization of other ecosystem services, such as protection of soil or infrastructure, may further reduce the availability of potentially harvestable timber.

In this study, we assess the current harvesting situation in Europe's forests without considering potential climate change effects such as changes in tree species composition or the harvesting season, especially on sensitive soils [22]. Any increase of protected forest areas will decrease the 'forest available for wood supply'. However, technical innovations or an extension of the road network system may increase 'forests available for wood supply'. With the methodology presented in this study, any of these changes and how they affect the mechanized harvesting potential can be addressed easily, given that suitable data are available.

5. Conclusions

The forest of the 34 European countries of our study covers 183 million ha, where 4.3%, or 7.8 million ha, are protected by legal regulations, and 20.8%, or 38 million ha, have a limited accessibility. This results in an area of 137 million ha, or 74.9%, of 'forest available for wood supply' (FAWS). According to our results, a low road density is the most limiting factor for mechanized harvesting. Especially in North and South-East Europe, the share of FAWS could be improved by establishing additional forest roads. It is also important to note that the areas with limited accessibility can still be feasible for a profitable forest management. However, further data and/or increased care and planning might be needed when harvesting these areas. Harvester and forwarder (HFW) is by far the most important harvesting system since it is suitable for 2/3 of the area of 'forest available for wood supply' (FAWS) in Europe. Together with winch-assisted harvester and winch-assisted forwarder (WHWF), about 80% of the area and growing stock of FAWS in Europe can be harvested by fully mechanized harvesting systems.

Our analysis suggests a high potential for mechanized harvesting in Europe. We think that in the context of ensuring wood supply, this is a promising result, but also want to stress that, even though a harvesting system may be considered applicable to a certain forest site, thorough planning and execution of forest operations are key to limit undesired environmental impacts such as soil compaction, soil erosion, or stand damage [65,66] to avoid a negative impact on forest growth [52].

Author Contributions: Conceptualization, C.P., G.E. and H.H.; methodology, C.P., G.E. and H.H.; software, C.P.; validation, C.P.; formal analysis, C.P.; investigation, C.P.; resources, C.P.; data curation, C.P.; writing—original draft preparation, C.P., G.E. and H.H.; writing—review and editing, G.E. and H.H.; visualization, C.P.; supervision, H.H.; project administration, H.H.; funding acquisition, H.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program, TECH4EFFECT—Techniques and Technologies or Effective Wood Procurement project [Grant Number 720757]. The European Commission support for the production of this publication does not constitute an endorsement of the contents, which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data produced in this study are available on request from the corresponding author. Third party data used in this study are publicly available from different sources (see references).

Acknowledgments: We acknowledge the open data policies by European forest inventory agencies, which enabled the creation of the Improved Forest Structures across Europe dataset used in this analysis, and thank Benno Eberhard, Martin Kühmaier, and Mathias Neumann for their input.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Diameter at breast height (DBH) limitations for different tree species and harvesting systems. Tree species ID and name according to the tree species maps for European forests [42]. Poplar (*Populus* spp.) is considered unsuitable for mechanized felling and processing. Harvester refers to harvesting systems using harvester, winch-assisted harvester or steep terrain harvester. Processor refers to the chainsaw and tower yarder with integrated or excavator-based processor harvesting system.

		DBH Limit (cm)	
ID	**Name**	**Harvester**	**Processor**
1	*Abies* spp.	40	50
2	*Alnus* spp.	40	50
3	*Betula* spp.	40	50
4	*Carpinus* spp.	30	30
5	*Castanea* spp.	30	30
6	*Eucalyptus* spp.	40	50
7	*Fagus* spp.	30	30
8	*Fraxinus* spp.	30	30
9	*Larix* spp.	40	50
10	Broadleaved misc	30	30
11	Conifers misc	40	50
12	Pinus misc	40	50
13	Quercus misc	30	30
14	*Picea* spp.	40	50
15	*Pinus pinaster* Aiton	40	50
16	*Pinus sylvestris* L.	40	50
17	*Populus* spp.	-	-
18	*Pseudotsuga menziesii* (Mirb.) Franco	40	50
19	*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.	30	30
20	*Robinia* spp.	30	30

References

1. FOREST EUROPE. State of Europe's Forests 2020. Available online: https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf (accessed on 15 January 2023).
2. European Commission. *Directorate-General for Research and Innovation A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment: Updated Bioeconomy Strategy*; Publications Office: Luxembourg, 2018.
3. Eyvindson, K.; Repo, A.; Mönkkönen, M. Mitigating Forest Biodiversity and Ecosystem Service Losses in the Era of Bio-Based Economy. *For. Policy Econ.* **2018**, *92*, 119–127. [CrossRef]
4. European Commission. New EU Forest Strategy for 2030. Available online: https://environment.ec.europa.eu/strategy/forest-strategy_en (accessed on 4 November 2022).
5. Alberdi, I.; Michalak, R.; Fischer, C.; Gasparini, P.; Brändli, U.-B.; Tomter, S.M.; Kuliesis, A.; Snorrason, A.; Redmond, J.; Hernández, L.; et al. Towards Harmonized Assessment of European Forest Availability for Wood Supply in Europe. *For. Policy Econ.* **2016**, *70*, 20–29. [CrossRef]
6. European Commission. Biodiversity Strategy for 2030. Available online: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en (accessed on 4 November 2022).
7. Verkerk, P.J.; Anttila, P.; Eggers, J.; Lindner, M.; Asikainen, A. The Realisable Potential Supply of Woody Biomass from Forests in the European Union. *For. Ecol. Manag.* **2011**, *261*, 2007–2015. [CrossRef]
8. Verkerk, P.J.; Fitzgerald, J.B.; Datta, P.; Dees, M.; Hengeveld, G.M.; Lindner, M.; Zudin, S. Spatial Distribution of the Potential Forest Biomass Availability in Europe. *For. Ecosyst.* **2019**, *6*, 5. [CrossRef]
9. Alberdi, I.; Bender, S.; Riedel, T.; Avitable, V.; Boriaud, O.; Bosela, M.; Camia, A.; Cañellas, I.; Castro Rego, F.; Fischer, C.; et al. Assessing Forest Availability for Wood Supply in Europe. *For. Policy Econ.* **2020**, *111*, 102032. [CrossRef]

10. Nabuurs, G.-J.; Arets, E.J.M.M.; Schelhaas, M.-J. Understanding the Implications of the EU-LULUCF Regulation for the Wood Supply from EU Forests to the EU. *Carbon Balance Manag.* **2018**, *13*, 18. [CrossRef]
11. Payn, T. Future Environmental Challenges and New Zealand's Planted Forests. *N. Z. J. For.* **2018**, *63*, 14–20.
12. Silversides, C.R. *Broadaxe to Flying Shear: The Mechanization of Forest Harvesting East of the Rockies*; Transformation Series No. 6; National Museum of Science and Technology: Ottawa, ON, Canada, 1997; ISBN 0660159805.
13. Samset, I. *Winch and Cable Systems*; Martinus Nijhoff/Dr. W. Junk Publishers: Dordrecht, The Netherlands, 1985; ISBN 978-94-017-3684-8.
14. Holzfeind, T.; Visser, R.; Chung, W.; Holzleitner, F.; Erber, G. Development and Benefits of Winch-Assist Harvesting. *Curr. For. Reports* **2020**, *6*, 201–209. [CrossRef]
15. Visser, R.; Harrill, H. Cable Yarding in North America and New Zealand: A Review of Developments and Practices. *Croat. J. For. Eng.* **2017**, *38*, 209–217.
16. Nordfjell, T.; Bacher, M.; Eriksson, L.; Kadlec, J.; Stampfer, K.; Suadicani, K.; Suwala, M.; Talbot, B. Operational Factors Influencing the Efficiency in Conversion. In *Norway Spruce Conversion—Options and Consequences, European Forest Institute Research Report*, *18*; Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H., Eds.; Brill: Leiden, The Netherlands; Boston, MA, USA, 2004; pp. 197–223.
17. Mason, W.L.; Diaci, J.; Carvalho, J.; Valkonen, S. Continuous Cover Forestry in Europe: Usage and the Knowledge Gaps and Challenges to Wider Adoption. *Forestry* **2022**, *95*, 1–12. [CrossRef]
18. Purser, P.; Ó'tuama, P.; Vítková, L.; Dhubháin, Á.N. Factors Affecting the Economic Assessment of Continuous Cover Forestry Compared with Rotation Based Management. *Irish For.* **2015**, *72*, 150–165.
19. Bont, L.G.; Fraefel, M.; Frutig, F.; Holm, S.; Ginzler, C.; Fischer, C. Improving Forest Management by Implementing Best Suitable Timber Harvesting Methods. *J. Environ. Manag.* **2022**, *302*, 114099. [CrossRef] [PubMed]
20. Kühmaier, M.; Stampfer, K. Development of a Multi-Attribute Spatial Decision Support System in Selecting Timber Harvesting Systems. *Croat. J. For. Eng.* **2010**, *31*, 75–88.
21. Becker, R.M.; Keefe, R.F.; Anderson, N.M.; Eitel, J.U.H. Use of Lidar-Derived Landscape Parameters to Characterize Alternative Harvest System Options in the Inland Northwest. *Int. J. For. Eng.* **2018**, *29*, 179–191. [CrossRef]
22. Berendt, F.; Fortin, M.; Jaeger, D.; Schweier, J. How Climate Change Will Affect Forest Composition and Forest Operations in Baden-Württemberg—A GIS-Based Case Study Approach. *Forests* **2017**, *8*, 298. [CrossRef]
23. Marčeta, D.; Petković, V.; Ljubojević, D.; Potočnik, I. Harvesting System Suitability as Decision Support in Selection Cutting Forest Management in Northwest Bosnia and Herzegovina. *Croat. J. For. Eng.* **2020**, *41*, 251–265. [CrossRef]
24. Piragnolo, M.; Grigolato, S.; Pirotti, F. Planning Harvesting Operations in Forest Environment: Remote Sensing for Decision Support. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *4*, 33–40. [CrossRef]
25. Gülci, N.; Akay, A.E.; Erdaş, O.; Gülci, S. Üretim Işlerinin Planlanmasında RTK-GPS Tabanlı Sayısal Yükseklik Modelinin Kullanılması. *İstanbul Üniv. Orman Fakültesi Derg.* **2015**, *65*, 60. [CrossRef]
26. Di Fulvio, F.; Forsell, N.; Lindroos, O.; Korosuo, A.; Gusti, M. Spatially Explicit Assessment of Roundwood and Logging Residues Availability and Costs for the EU28. *Scand. J. For. Res.* **2016**, *31*, 691–707. [CrossRef]
27. Kindermann, G.E.; Schörghuber, S.; Linkosalo, T.; Sanchez, A.; Rammer, W.; Seidl, R.; Lexer, M.J. Potential Stocks and Increments of Woody Biomass in the European Union under Different Management and Climate Scenarios. *Carbon Balance Manag.* **2013**, *8*, 2. [CrossRef]
28. Pucher, C.; Neumann, M.; Hasenauer, H. An Improved Forest Structure Data Set for Europe. *Remote Sens.* **2022**, *14*, 395. [CrossRef]
29. E.S.R.I. *ArcGIS Desktop: Release 10 2011*; Environmental Systems Research Institute: Redlands, CA, USA, 2011.
30. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. Available online: https://www.r-project.org/ (accessed on 15 January 2023).
31. EEA European Union. Copernicus Land Monitoring Service—High Resolution Layer: Forest Type (FTY). 2018. Available online: https://land.copernicus.eu/pan-european/high-resolution-layers/forests/forest-type-1/status-maps/forest-type-2018 (accessed on 7 November 2022).
32. EEA. Nationally Designated Areas (CDDA) V19. Available online: https://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-16 (accessed on 18 November 2022).
33. Frank, G.; Latham, J.; Declan, L.; Parviainen, J.; Schuck, A.; Vandekerkhove, K.; Little, D.; Parviainen, J.; Schuck, A.; Vandekerkhove, K. Analysis of Protected Forest Areas in Europe—Provisional Results of COST Action E27 PROFOR. In Proceedings of the Natural Forests in the Temperate Zone of Euroope—Values and Utilisation, Mukachevo, Ukraine, 13–17 October 2003; Commarmot, B., Hamor, F.D., Eds.; pp. 377–386.
34. EEA. European Union, Copernicus Land Monitoring Service—EU-DEM. Available online: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem (accessed on 18 November 2022).
35. Hijmans, R.J. Raster: Geographic Data Analysis and Modeling. R Package Version 3.4-13. Available online: https://cran.r-project.org/package=raster (accessed on 15 January 2023).
36. Allman, M.; Jankovský, M.; Messingerová, V.; Allmanová, Z. Soil Moisture Content as a Predictor of Soil Disturbance Caused by Wheeled Forest Harvesting Machines on Soils of the Western Carpathians. *J. For. Res.* **2017**, *28*, 283–289. [CrossRef]
37. Cambi, M.; Certini, G.; Neri, F.; Marchi, E. The Impact of Heavy Traffic on Forest Soils: A Review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]

38. Goltsev, V.; Lopatin, E. The Impact of Climate Change on the Technical Accessibility of Forests in the Tikhvin District of the Leningrad Region of Russia. *Int. J. For. Eng.* **2013**, *24*, 148–160. [CrossRef]
39. Panagos, P. The European Soil Database. *GEO Connex.* **2006**, *5*, 32–33.
40. Panagos, P.; Van Liedekerke, M.; Jones, A.; Montanarella, L. European Soil Data Centre: Response to European Policy Support and Public Data Requirements. *Land Use Policy* **2012**, *29*, 329–338. [CrossRef]
41. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015.
42. Brus, D.J.; Hengeveld, G.M.; Walvoort, D.J.J.; Goedhart, P.W.; Heidema, A.H.; Nabuurs, G.J.; Gunia, K. Statistical Mapping of Tree Species over Europe. *Eur. J. For. Res.* **2012**, *131*, 145–157. [CrossRef]
43. Moreno, A.; Neumann, M.; Hasenauer, H. Optimal Resolution for Linking Remotely Sensed and Forest Inventory Data in Europe. *Remote Sens. Environ.* **2016**, *183*, 109–119. [CrossRef]
44. EEA Biogeographical Regions. Available online: https://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-3 (accessed on 7 November 2022).
45. Friedl, M.; Sulla-Menashe, D. MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006. Available online: https://lpdaac.usgs.gov/products/mcd12q1v006/ (accessed on 7 November 2022).
46. Neumann, M.; Moreno, A.; Thurnher, C.; Mues, V.; Härkönen, S.; Mura, M.; Bouriaud, O.; Lang, M.; Cardellini, G.; Thivolle-Cazat, A.; et al. Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests. *Remote Sens.* **2016**, *8*, 554. [CrossRef]
47. Simard, M.; Pinto, N.; Fisher, J.B.; Baccini, A. Mapping Forest Canopy Height Globally with Spaceborne Lidar. *J. Geophys. Res.* **2011**, *116*, G04021. [CrossRef]
48. Moreno, A.; Neumann, M.; Hasenauer, H. Forest Structures across Europe. *Geosci. Data J.* **2017**, *4*, 17–28. [CrossRef]
49. Heinimann, H.R. Forest Operations under Mountainous Conditions. In *Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000. Task Force on Forests in Sustainable Mountain Development*; CABI Publishing: Wallingford, UK, 2000; pp. 224–234.
50. Visser, R.; Stampfer, K. Expanding Ground-Based Harvesting onto Steep Terrain: A Review. *Croat. J. For. Eng.* **2015**, *36*, 321–331.
51. Enache, A.; Kühmaier, M.; Visser, R.; Stampfer, K. Forestry Operations in the European Mountains: A Study of Current Practices and Efficiency Gaps. *Scand. J. For. Res.* **2016**, *31*, 412–427. [CrossRef]
52. Gebauer, R.; Neruda, J.; Ulrich, R.; Martinkov, M. Soil Compaction—Impact of Harvesters' and Forwarders' Passages on Plant Growth. In *Sustainable Forest Management—Current Research*; InTech: London, UK, 2012.
53. Erber, G.; Spinelli, R. Timber Extraction by Cable Yarding on Flat and Wet Terrain: A Survey of Cable Yarder Manufacturer's Experience. *Silva Fenn.* **2020**, *54*, 2. [CrossRef]
54. Spinelli, R.; Owende, P.; Ward, S.; Tornero, M. Comparison of Short-Wood Forwarding Systems Used in Iberia. *Silva Fenn.* **2004**, *38*, 437. [CrossRef]
55. Wassermann, C.; Kühmaier, M.; Stampfer, K. Marktübersicht—Europäische Mastseilgeräte. *Osterr. Forstztg.* **2019**, 1–8.
56. Holzfeind, T.; Stampfer, K.; Holzleitner, F. Productivity, Setup Time and Costs of a Winch-Assisted Forwarder. *J. For. Res.* **2018**, *23*, 196–203. [CrossRef]
57. Holzfeind, T.; Kanzian, C.; Stampfer, K.; Holzleitner, F. Assessing Cable Tensile Forces and Machine Tilt of Winch-Assisted Forwarders on Steep Terrain under Real Working Conditions. *Croat. J. For. Eng.* **2019**, *40*, 281–296. [CrossRef]
58. Leszczyński, N.; Tomczak, A.; Kowalczuk, J.; Zarajczyk, J.; Węgrzyn, A.; Kocira, S.; Depo, K. The Relationship between the Mass of the Harvester Head and Its Maximum Cutting Diameter. *J. Res. Appl. Agric. Eng.* **2016**, *61*, 50–54.
59. Labelle, E.; Breinig, L.; Sycheva, E. Exploring the Use of Harvesters in Large-Diameter Hardwood-Dominated Stands. *Forests* **2018**, *9*, 424. [CrossRef]
60. Mederski, P.S.; Schweier, J.; Đuka, A.; Tsioras, P.; Bont, L.G.; Bembenek, M. Mechanised Harvesting of Broadleaved Tree Species in Europe. *Curr. For. Rep.* **2022**, *8*, 1–19. [CrossRef]
61. Lundbäck, M.; Häggström, C.; Nordfjell, T. Worldwide Trends in Methods for Harvesting and Extracting Industrial Roundwood. *Int. J. For. Eng.* **2021**, *32*, 202–215. [CrossRef]
62. Moskalik, T.; Borz, S.A.; Dvořák, J.; Ferencik, M.; Glushkov, S.; Muiste, P.; Lazdiņš, A.; Styranivsky, O. Timber Harvesting Methods in Eastern European Countries: A Review. *Croat. J. For. Eng.* **2017**, *38*, 231–241.
63. Lundbäck, M.; Persson, H.; Häggström, C.; Nordfjell, T. Global Analysis of the Slope of Forest Land. *Forestry* **2021**, *94*, 54–69. [CrossRef]
64. Ackerman, S.A.; Talbot, B.; Astrup, R. The Effect of Tree and Harvester Size on Productivity and Harvester Investment Decisions. *Int. J. For. Eng.* **2022**, *33*, 22–32. [CrossRef]

65. Marchi, E.; Chung, W.; Visser, R.; Abbas, D.; Nordfjell, T.; Mederski, P.S.; McEwan, A.; Brink, M.; Laschi, A. Sustainable Forest Operations (SFO): A New Paradigm in a Changing World and Climate. *Sci. Total Environ.* **2018**, *634*, 1385–1397. [CrossRef]
66. Schweier, J.; Magagnotti, N.; Labelle, E.R.; Athanassiadis, D. Sustainability Impact Assessment of Forest Operations: A Review. *Curr. For. Rep.* **2019**, *5*, 101–113. [CrossRef]