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Growing stock monitoring by European National Forest Inventories: Historical origins, current methods and harmonisation

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In memory: Our work-package leader, colleague and dear friend Jean-Christophe Hervé passed away during the project period. He greatly supported and significantly contributed to the harmonisation activities of our group, and to the scientific work of ENFIN. We remember his scientific expertise and dedication, his visionary spirit and warm personality.

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A B S T R A C T

Wood resources have been essential for human welfare throughout history. Also nowadays, the volume of growing stock (GS) is considered one of the most important forest attributes monitored by National Forest Inventories (NFIs) to inform policy decisions and forest management planning. The origins of forest inventories closely relate to times of early wood shortage in Europe causing the need to explore and plan the utilisation of GS in the catchment areas of mines, saltworks and settlements. Over time, forest surveys became more detailed and their scope turned to larger areas, although they were still conceived as stand-wise inventories. In the 1920s, the first sample-based NFIs were introduced in the northern European countries. Since the earliest beginnings, GS monitoring approaches have considerably evolved. Current NFI methods differ due to country-specific conditions, inventory traditions, and information needs. Consequently, GS estimates were lacking international comparability and were therefore subject to recent harmonisation efforts to meet the increasing demand for consistent forest resource information at European level. As primary large-area monitoring programmes in most European countries, NFIs assess a multitude of variables, describing various aspects of sustainable forest management, including for example wood supply, carbon sequestration, and biodiversity. Many of these contemporary subject matters involve considerations about GS and its changes, at different geographic levels and time frames from past to future developments according to scenario simulations. Due to its historical, continued and currently increasing importance, we provide an up-to-date review focussing on large-area GS monitoring where we i) describe the origins and historical development of European NFIs, ii) address the terminology and present GS definitions of NFIs, iii) summarise the current methods of 23 European NFIs including sampling methods, tree measurements, volume models, estimators, uncertainty components, and the use of air- and space-borne data sources, iv) present the recent progress in NFI harmonisation in Europe, and v) provide an outlook under changing climate and forest-based bioeconomy objectives.

1. Introduction

Throughout European history, wood resources have been essential for human welfare due to the versatile use of wood as construction and manufacturing material and as energy source (e.g. Perlin, 1989; Radkau, 2018). In the late Middle Ages, wood shortage necessitated the exploration of forest resources and the planning of their utilisation in the catchment areas of mines, salt works, construction- and shipyards, and settlements (Loetsch and Haller, 1964; Zöhrer, 1980; Susmel, 1994; Gabler and Schadauer, 2007). Similarly, but on larger areas, in the 20th century, the main motivations for introducing sample-based National Forest Inventories (NFIs) were concerns about overexploitation, a lack of information, and the need to plan the sustainable utilisation of forest resources (e.g. Alberdi Asensio et al., 2010; Fridman and Westerlund, 2016; Breidenbach et al., 2020a). Also nowadays, the volume of growing stock (GS) is considered one of the most important forest attributes monitored by NFIs to quantify and describe the status and change of wood resources (Spurr, 1952; Zöhrer, 1980; Köhl et al., 2006; Vidal et al., 2016a).

In addition to GS estimates, European NFIs provide many other results on a regular basis to supply national and international information needs (Tomppo et al., 2010a; Vidal et al., 2016a). As the key forest monitoring programme in most European countries, NFIs assess a multitude of variables on their sample plots to describe the state and change of forest ecosystems. Ongoing innovation in NFIs integrates data from remote sensing products, digital maps, and various models to allow for comprehensive information supply on a broad range of forest-related topics and at different geographical scales (e.g. Tomppo et al., 2008; Fridman et al., 2014; Fischer and Traub, 2019). As economically important information, GS is frequently the target variable in such multi-source applications (e.g. Hollaus et al., 2009; Nord-Larsen and Schumacher, 2012; McRoberts et al., 2013; Steinmann et al., 2013; Saarela et al., 2015; Astrup et al., 2019).

Apart from economic relevance, GS monitoring relates to many other contemporary topics. Simulation studies about forest resources development, wood supply and carbon storage imply considerations on sustainable GS under different management and climate scenarios (e.g. Schmid et al., 2006; Lundmark et al., 2014; Sievänen et al., 2014; Barreiro et al., 2016; Braun et al., 2016; Heinonen et al., 2017). GS and its development are used to evaluate climate change impact, and to assess adaptation and mitigation strategies (Santopuoli et al., 2020). In terms of biodiversity, GS can serve as structural indicator (e.g. Uotila et al., 2002; Geburek et al., 2010; McRoberts et al., 2012b) and is considered relevant for assessing the forest naturalness through the deviation from natural GS levels (EC, 2003). Besides, non-wood forest products are related to the amount of GS as for example honey yield from honeydew-producing tree species (Prešern et al., 2019).

International reporting obligations such as the Forest Resources Assessment (FRA) of the United Nations Food and Agriculture Organisation (e.g. FAO, 2015, 2020) and the State of Europe's Forest report (SoEF) (e.g. Forest Europe, 2015, 2020) require countries to report on their forest resources at regular time periods of 5 years (Fig. 1). Information on GS serves as indicator for the maintenance and enhancement of European forest resources and their contribution to global carbon cycles (Forest Europe, 2020). For the purpose of greenhouse gas reporting (United Nations, 1992, 1998; IPCC, 2006; European Parliament and Council of the European Union, 2018), GS is converted and expanded to above-ground and below-ground biomass and its carbon contents (e.g. Di Cosmo et al., 2016; Drexhage and Colin, 2001; Lehtonen et al., 2004; Longuetaud et al., 2013; Nord-Larsen et al., 2017; Repola, 2009; Ruiz-Peinado et al., 2011, 2012; Van de Walle et al., 2005; Marklund, 1988; Tomé et al., 2007a; Weiss, 2006).

The limited international comparability of forest resource information reported by countries has been repeatedly pointed out (e.g. Päivinen and Köhl, 2005; McRoberts et al., 2009; Tomppo and Schadauer, 2012; Vidal et al., 2016b). The deviations originate from different historical NFI developments in European countries and reflect country-specific conditions and information needs (McRoberts et al., 2009, 2010). Lawrence et al. (2010) compared over 30 NFIs and concluded that the sampling designs and GS definitions vary considerably. With the aim to minimize the deviations, a harmonisation process was initiated in the late 1990s (EFICS, 1997) and received strong impulse by the foundation of the European National Forest Inventory Network in 2003 (ENFIN, 2021). Recent harmonisation provides comparable GS estimates from European NFIs (Gschwantner et al., 2019; Alberdi et al., 2020).

In summary, GS monitoring has one of the longest histories in natural resource assessment, remains a central subject matter in NFIs, and at the same time increasingly regains relevance at European level in terms of sustainable wood supply and bioeconomy (e.g. UNECE/FAO, 2011; EC, 2013; EC, 2018a). From among the many forest resource indicators existing today that describe the state and production of forests (e.g. FRA, Forest Europe), we devote this comprehensive, up-to-date review to GS monitoring by European NFIs because of its historical, continued, and currently increasing importance. The study is based on a standardised enquiry among NFIs during the Horizon 2020 project DIABOLO (2015) and a complementary review of sources. It is structured to address the following key areas: First, we outline the evolution of European NFIs based on available sources from their very origin to the first documented surveys until modern multipurpose NFIs. Second, we consider the establishment of the GS terminology and the definitions in use by 23 European NFIs. Third, we give an up-to-date overview about monitoring options by summarising the GS estimation methods of the NFIs in Austria (AT), Belgium (BE), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Norway (NO), Portugal (PT), Romania (RO), Serbia (RS), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE) and Switzerland (CH). Fourth, we present the recent harmonisation progress to improve the comparability of GS at European level. And finally, we provide an outlook on GS monitoring under changing climate and bioeconomy objectives.

2. Historical origins of European NFIs

2.1. Earliest forest surveys

The late Middle Ages are regarded as origin of forest surveys when wood shortage had developed in the catchment areas of mines, salt-works, and settlements, and caused the need to explore and plan the utilisation of wood resources (Loetsch and Haller, 1964; Zöhrer, 1980). However, recent literature suggests that forest surveys may have an even longer history. Ancient wood shortage and trade relations indicate the early need for exploring and assessing forest resources (Appendix A). Youngs (2009) mentions that "*From the earliest times, the use of wood involved consideration of quality, cost and availability, …*". According to Valbuena-Carabaña et al. (2010), *Pliny the elder* (23 – 79 AD) has reviewed the timber resources of the Mediterranean basin. The writings of Roman land surveyors (1st – 6th century) contain advice for assessing woodlands to "… *establish what age the trees are, if their age is appropriate for felling, …*" (Campbell, 2000). Hennius (2018) found archeological evidence of intensified tar production and export from Sweden in the 8th century, concluding an emphasised need to plan wood resource utilisation on larger areas. However, the oldest preserved woodland descriptions we are aware of date from the 14th century. Zöhrer (1980) mentions two examples from Erfurt and Nürnberg in Germany. About at the same time *El Libro de la Monteria* from Spain (Alfonso de Castilla, 1877) and similarly the *Livro da Montaria* from Portugal (Pereira, 1918) compiled data on the types and location of forests suitable for hunting. The Venetian Republic *La Serenissima* started the first *catastici forestali* in Veneto, Friuli and Istria in 1489 (Susmel, 1994; Viola, 2011). *Fief books* from the feudal times of the Livonian Confederation contain woodland descriptions from the 15th century (Vasilevskis, 2007). In Central Europe the oldest predecessors were named *Waldbeschreibungen*, *Waldbeschaue*, or *Waldbereitungen* and provided rough visual estimates of forest area (Loetsch and Haller, 1964), amount of stocking wood, tree species, development stage, and hauling expenses (Johann, 1983; Gabler and Schadauer, 2007). The amount of stocking wood was estimated apparently depending on local requirements, e.g. in obtainable barrels of charcoal, or the wood amount needed for a saline pot (Koller, 1970). In Central Slovakia, the chamber forests of Kremnica and Banská Bystrica were surveyed in 1563 (Barták, 1929), and an early woodland description in Tyrol dates from 1459 (Trubrig, 1896). The description of main woodlands together with passages of wild animals in Lithuania (Volovič, 1559) indicates the early beginning of multifunctional forest assessments. Forest surveys were soon recognised as valuable sources of information and planning instrument. Johann (1983) lists over 150 woodland descriptions in former Austria from the 15th up to the 19th century, and according to Gabler and Schadauer (2007), in some cases they were even carried out periodically.

2.2. Stand-wise forest surveys

A division of forests into area sub-units is reported already for the 14th century for the two previously mentioned examples from Erfurt and Nürnberg in Germany (von Gadow, 2005). The purpose of such classifications was to obtain the yearly harvestable area that represented a certain amount of GS (Fig. 2A). Mapping of forest estates and area registers for forest management became widely used at the beginning of the 19th century, and were rather detailed in Central Europe (Loetsch and Haller, 1964). The *German Classical School of Forestry*, in particular the developments in forest mensuration and taxation by Hartig (1795), Cotta (1804), König (1813) and Hundeshagen (1826), mark the beginning of modern forest management planning and introduced a sustained area structure in forests. Forest estates were divided into compartments and stands as sub-units became the basic management unit and served as units for forest assessments (Fig. 2B). Visual GS estimation was frequently

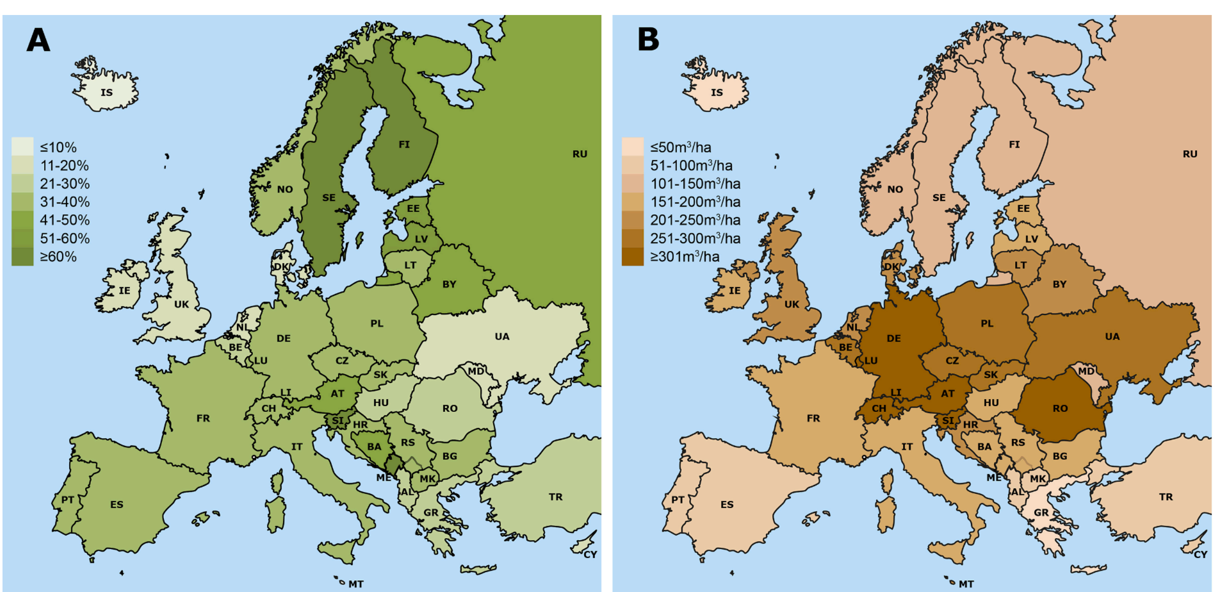

Fig. 1. Forest resources according to the latest SoEF report of Forest Europe (2020): A) Forest area in percent of country land area; B) Average growing stock per hectare of forest available for wood supply.

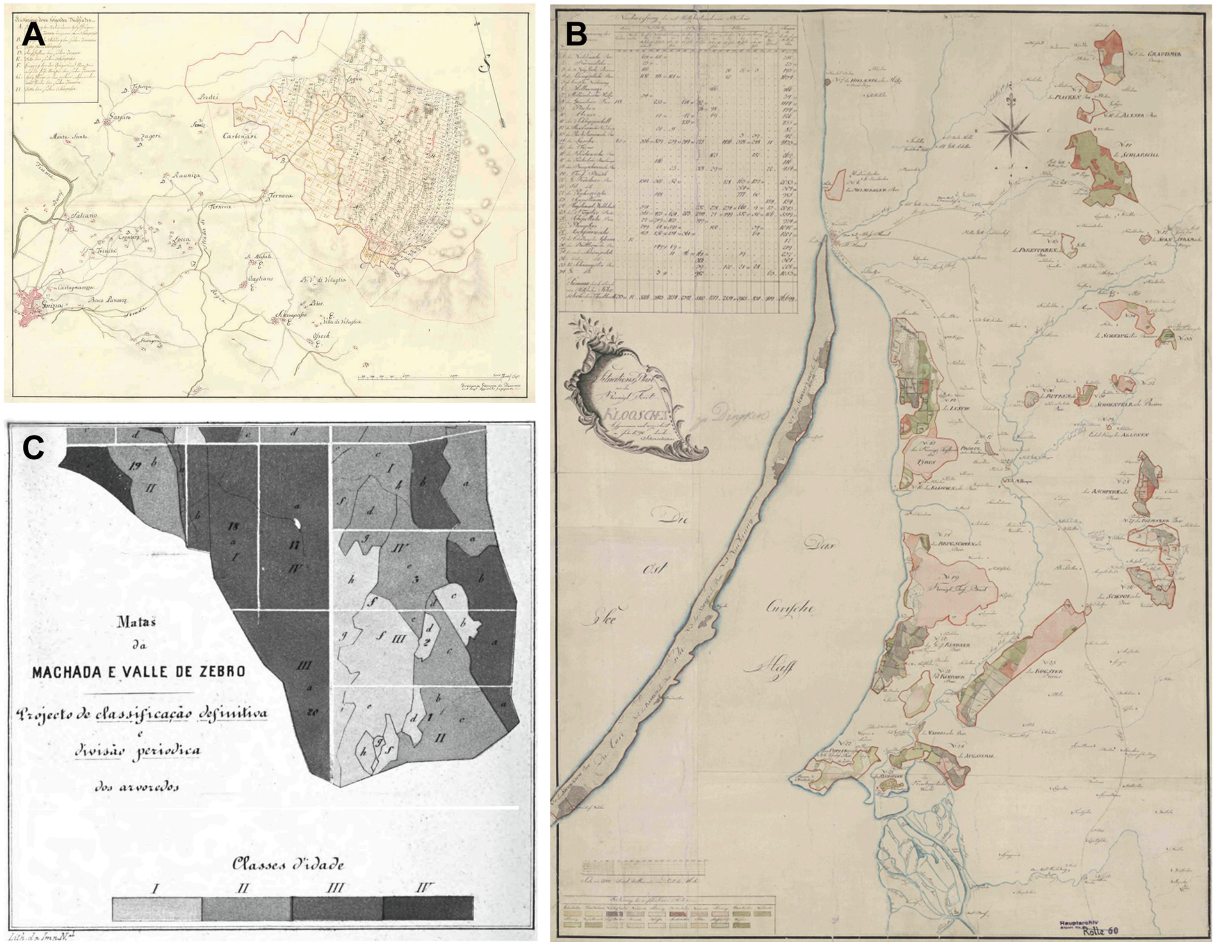

Fig. 2. Early forest maps and management plans from Slovenia, Lithuania and Portugal: A) Trnovo forest 1769: Sub-units are numerated by the year of planned harvest (Source: Perko et al., 2014/SFI); B) Kliošių Royal Forest administrative unit from 1790: Land use categories, tree species and age classes are marked by different colours and signs (Source: Deltuvas, 2019/VMUAA); C) Machada e valle de Zebro: Compartments and stands are delineated and age-classes distinguished by different colours (Source: Gomes, 1865/CEABN).

used and gradually perfected and stand estimates were aggregated for groups of stands or higher-level management units. The production shift from fuel wood to timber during the industrialisation (Appendix A) required information about single trees and led to the development and continuous improvement of measurement techniques. Sample plots were recognised already in the early 18th century as cost-efficient alternative to full tree census (Schwappach, 1886) and were at least occasionally used to obtain GS estimates for stands (Prodan, 1965). The Central European stand-wise approach influenced the survey methods in many countries. For instance, in Slovakia and Lithuania the first stand-level surveys started in the late 18th or early 19th century (Brukas et al., 2002; Szarka and Bavlšík, 2011; Deltuvas, 2019) and the oldest local forest management plans in Serbia, Romania and Portugal (Fig. 2C) date back to the mid or second half of the 19th century (Stinghe and Sburlan, 1941; Rego, 2001; Medarević, 2006). In the early 20th century stand-wise surveys were also performed on larger areas in several countries, e.g. in Estonia (Etverk, 1998), the state forests of Finland (Koivuniemi and Korhonen, 2006), Latvia (Vasilevskis, 2007), Lithuania (Kuliešis et al., 2010b), and Romania (Stinghe and Sburlan, 1941). Country-wide forest management planning after World War II furthered the large-area implementation of stand-wise inventories in many East-European countries (Tomppo et al., 2010a) and the *compilation-method* to obtain country-level results of GS (Loetsch and Haller, 1964).

2.3. Towards large-area forest information

The desire for large-area information is most clearly manifested in the history of cartography (Harley and Woodward, 1987) and the manifold purposes of maps including orientation, exploration and exploitation of resources, state administration and taxation, warfare, or self-representation of a state's wealth. Also, the earliest large-area forest representations for state territories in Europe are cartographic works or registers of forest lands that reach back to the early modern era. Most examples feature forest area mapping and more or less detailed descriptions of forests, but we can also recognise characteristics of modern multi-source NFIs such as regular reporting and integration of various information sources (Table 1). In Sweden for instance, local governors had to report on the forest situation in their counties from 1740 onwards to the central administration (Anonymous, 1914). Wessely (1853) in Austria and similarly von Berg (1859) in Finland based their forest statistics on various information sources including travel observations, own work experience, published material, and personal communication. The first attempt of country-level GS estimation from Sweden is reported for the year 1840 and was conducted by *A.I. af Ström*. Subsequent assessments followed in 1882 by *J.O. Zellén* and in 1905 by *U. Wallmo* (Anonymous, 1914). But, large-area estimation of GS remained methodically challenging and led particularly in Northern Europe to the search for new approaches, while in other countries forest mapping, census or stand-wise approaches remained prevalent (e.g. Milizia Nazionale Forestale, 1936; Lietuvos miškų statistika, 1939; BMLF and FBVA, 1960).

2.4. Sample-based NFIs

In the Northern European countries, vast and widely unsurveyed

Table 1
Examples of historical large-area forest resource information until the early 20th century.

Year	Description	Reference
1517	*Descripción y cosmografía de España* by *H. Colón*, a collection of catastral information together with woodland and terrain description along the itinary to prepare a cartography of Spain.	Colón (1988)
1559	Register of woodlands and passages of game animals on the lands of Grand Dukedom of Lithuania.	Volovič (1559)
1655 – 1659	Mapping of Ireland following the Cromwellian conquest, assessment of townlands and their value, including woodlands and boundaries of properties.	Simington (1953)
1737–1746	Mapping and description of Norway's forests by the brothers *J.G.* and *F.P. von Langen*.	Fryjordet (1992)
~1740	Reporting of local governors in Sweden on the forest situation in their counties to the central administration.	Anonymous (1914)
1772	Land survey and forest area statistics on the territory of nowadays Latvia.	Vasilevskis (2007)
1770–1778	Mapping of the Austrian Netherlands and the Prince-Bishopric of Liège in actual Belgium.	Lemoine-Isabeau (1984), De Coene et al. (2012)
1780–1820	Landscape survey in Denmark and mapping of forest area.	Bradshaw (2004)
1805	Countrywide census and maps of wood for ship building in the French forests.	Brenac (1984)
1817–1861	*Franziszeischer Kataster* of the Habsburg Empire, a complete estate cadastre with distinction of forest land, based on the earlier land register *Josefinisches Lagebuch* (1786–1788).	Fuhrmann (2007), Stockmann (2016)
1840	First estimation of GS, increment and timber consumption for entire Sweden and subsequent assessments of Swedish forest recources in 1882 and in 1905.	Anonymous (1914)
1853	Compilation of forest statistics for the Austrian alpine crown lands including forest area, average stand volume and growth.	Wessely (1853)
1858	Report on the forest resources of Finland including a rough map on the condition of forest resources.	von Berg (1859)
1867	First reliable land use area assessment including forests in Portugal.	Ribeiro and Delgado (1868)
1874	Statistical yearbook founded by the Austrian Ministry of Agriculture containing agricultural and forest statistics.	Braun (1974)
1878	First forest census on forest area based on combinations of official statistics covering the entire area of the German Empire, periodically repeated and developed further, with most detailed information provided in 1937 including ownership, forest types, condition and yield.	Schmitz et al. (2006)
1881	Forest census and compilation of national statistics on forest area and tree species distribution in Denmark.	Bastrup-Birk et al. (2010)
1878–1889	Survey of mainly public forests in France and preparation of 85 forest maps based upon the existing military maps.	Brenac (1984)
1887 – 1902	Assessments for producing the *Carta Agrícola e Florestal* of Portugal.	Basto (1936)
1907	First official statistics in Norway on forest area obtained by the Census of Agriculture.	Det Statistiske Centralbyraa (1910), Fryjordet (1962)
1912	First complete forest statistics in France containing forest area at canton level by property, tree species and silvicultural management.	Daubrée (1912)

forests and sparse road networks (e.g. Michelsen, 1995) required an alternative approach to the stand-wise surveys in Central Europe and spurred the idea of using representative samples in large-area forest inventories. The first line-sampling survey was made by *A.I. af Ström* in the 1840s in the Swedish province of Norrland (Loetsch and Haller, 1964; Zöhrer, 1980). This technique was used in Finland first in 1885, and in 1911–1912 in the municipalities of Sahalahti and Kuhmalahti (Ilvessalo, 1923). In 1907–1909, an inventory was conducted in the municipality of Åmot in Norway, where sample plots and sample strips were used (Vevstad, 1994). A trial inventory was undertaken in 1910–1911 in Värmland to develop the methods for a country-wide NFI in Sweden. For the inventory of the vast state-owned coniferous forests located predominantly in northern Norway, a line sampling design was used as of 1914 (Breidenbach et al., 2020a). As the first country in the world, Norway commenced a sample-based NFI by counties in 1919 and the first report was published for the county Østfold in the following year (Landsskogtakseringen, 1920). Further county-reports were released yearly until the completion of the first NFI in 1930 (Landsskogtakseringen, 1933). The first Finnish NFI started in 1921, was completed in 1924 and preliminary results were published the same year (Ilvessalo, 1924). Sweden's first NFI began in 1923 and was completed in 1929 (Fridman et al., 2014). The GS assessments of the first NFIs were carried out by measuring trees on parallel belts (Fig. 3) at a particular compass bearing across the country (Axelsson et al., 2010; Tomter et al., 2010; Breidenbach et al., 2020a), or by visual assessment of the stands intersecting with parallel survey lines in combination with plot measurements to calibrate and correct the visual estimates (Ilvessalo, 1927). Traversing the country on parallel belts or lines also served the purpose of mapping land uses, timber distribution, forest types, and topography (Kangas and Maltamo, 2006).

In the 1950s, the road networks and transportation infrastructure had been extended in the Northern European countries. Belt and line sampling became less efficient and sampling designs changed towards cluster plots (Fridman et al., 2014; Korhonen, 2016; Tomter, 2016; Breidenbach et al., 2020a). The subsequently emerging NFIs in Europe were based on single or cluster plots to obtain the sample tree measurements for GS estimation. However, it was not before the 1960s that further countries also introduced sample-based NFIs (Fig. 4). Additional countries followed in the 1980s and 1990s and in the two recent decades most countries in Europe had established sample-based NFIs to obtain the required periodical information about the state and change of forest resources, efficiently and representatively, and according to reliable statistical principles (Fisher, 1950). The introduction of regularly re-measured permanent sample plots facilitated the observation of change components, i.e. fellings, natural losses, surviving trees, and new trees (Kuliešis et al., 2016; Tomter et al., 2016). First implemented in the 1980s by Austria, Switzerland, Sweden, Germany, Norway and Spain, today most NFIs rely on permanent plots or on a combination of permanent and temporary plots (Sections 4.1 and 4.2).

3. Terminology and definitions

3.1. Establishment of the term growing stock

The term *growing stock* originates from the Anglophone countries and in regard to forestry describes the amount of wood volume stored by the trees on a certain forest area. Evelyn (1760) in his influential work *Sylva* used the term *stock of timber* already in this sense. Towards the early 20th century, the term *growing stock* apparently became more widely used, for example through the forest mensuration textbooks by Schenck (1905) and Graves (1906) and the forest terminology by the Society of American Foresters (1916). Alternatively, in the earliest reports on world forest resources by Zon (1910) and Zon and Sparhawk (1923) this statistical quantity is denoted as *present stand* or *stand of timber*. The first world forest resources survey by the FAO (1948) used the term *volume of growing stock* and argued the great diversity in the statistics available from countries. Recommendations for standardising the use of symbols and abbreviations of terms in forest mensuration were made by IUFRO (1959), and Päivinen et al. (1994) developed guidelines for the compatible collection and reporting of forest monitoring data. The first homogeneous set of terms and definitions was achieved in the global Forest Resources Assessment FRA 2000 and its contribution on

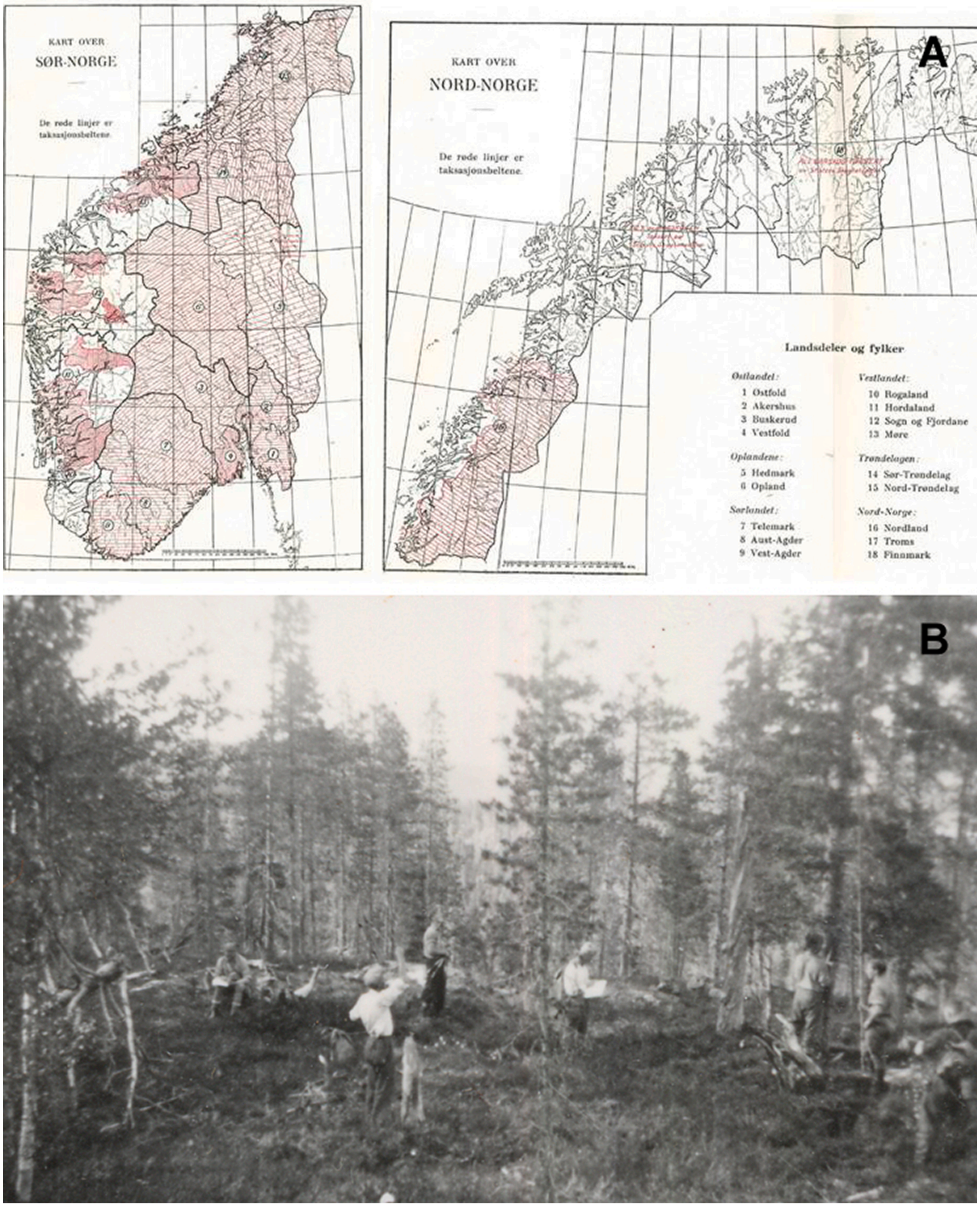

Fig. 3. The early NFIs in Norway and Sweden: A) Coverage and density of sampling strips in Southern and Northern Norway; numbers indicate counties as delineated inventory areas, parallel red lines are the inventory strips (Source: Landsskogtakseringen, 1933/NIBIO); B) Field work of the Swedish NFI in 1939 (© SLU).

temperate and boreal forests TBFRA (FAO, 1998; UNECE/FAO, 2000; FAO, 2001). In the subsequent FRAs the GS definition was revised (FAO 2004, 2010, 2012, 2018) and also other international reporting programmes included GS in their glossaries (IPCC, 2003, 2006; Forest Europe, 2015). Other sources of GS definitions are forestry dictionaries and similar collections (e.g. Helms, 1998; Delijska and Manoilov, 2004; IUFRO, 2021).

3.2. Terms and definitions for growing stock in European NFIs

In other European languages comparable terms for *growing stock* are *Zásoba dříví* (Czech), *Stående vedmasse* (Danish), *Kasvava metsa tagavara* (Estonian), *Puuston tilavuus* (Finnish), *Matériel sur pied* (French), *Stehender Holzvorrat* (German), *ξυλαπόθεμα* (transcribed *ksilapothema*, Greek), *Élöfakészlet* (Hungarian), *Provvigione legnosa* (Italian), *Krāja or masa* (Latvian), *Medyno tūris* (Lithuanian), *Stående volum* (Norwegian), *Volume em crescimento* (Portuguese), *Volumul de lemn pe picior* (Romanian), *Запас древостоя* (transcribed *Zapas drevostoja*, Russian), *Dubeća drvna zapremina* (Serbian), *Zásoba dreva* (Slovak), *Lesna zaloga* (Slovenian), *Volumen en pie* (Spanish), *Virkesförråd* (Swedish). These terms are defined in European NFIs by similarly composed definitions that specify the minimum dbh, the tree parts included, and the living and standing status of perennial woody plants taken into account in GS estimation (Vidal et al., 2008). However, national definitions reflect the specific historical development and information needs and hence vary between countries. For example, the dbh-thresholds range between 0 and 12 cm and also the included tree parts indicate considerable variation (Fig. 5) as well as the associated thresholds for stump height, top diameter and branch diameter (Gschwantner et al., 2019). A unified GS definition was established by the European NFIs for the purpose of harmonised

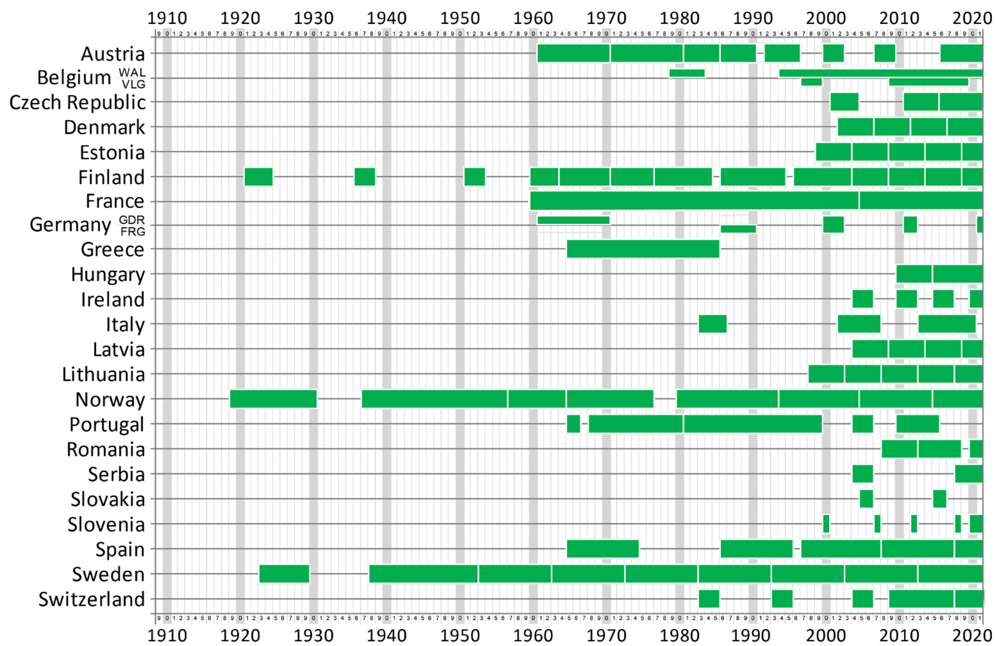

Fig. 4. Sample-based NFIs in 23 European countries over time. Remark: The inventories in France were conducted at Département-level from 1960 to 2004, resulting in overlapping NFI cycles. Abbreviations: WAL Wallonia, VLG Flanders, GDR German Democratic Republic, FRG Federal Republic of Germany.

international reporting (Section 5).

4. Current methods of European NFIs

4.1. Overall sampling schemes

For monitoring the status and development of GS, European countries have implemented national sampling frames. A sampling frame is defined by the area from which the sample elements are selected. The sample elements are a number of sample plots. In the infinite population approach the population is the infinite number of potential sample plots in the area (Mandallaz, 2008). Sample plots located on forest land are determined by a forest definition and associated thresholds for minimum crown cover, area, width, and potential or actual tree height (Schreuder et al., 1993; Köhl et al., 2006; Vidal et al., 2008; Lanz et al., 2019b). The sample plots have a specific arrangement, shape and size and defined sample tree inclusion probabilities (Section 4.3). Fig. 6 gives an overview on sampling designs of European NFIs. Note, however, that particular regions within countries may deviate from the general scheme. Large-area NFI campaigns are either continuously or periodically conducted. In continuous NFIs, the sampling frame is systematically divided into disjoint panels (e.g. Roesch, 2007), where an

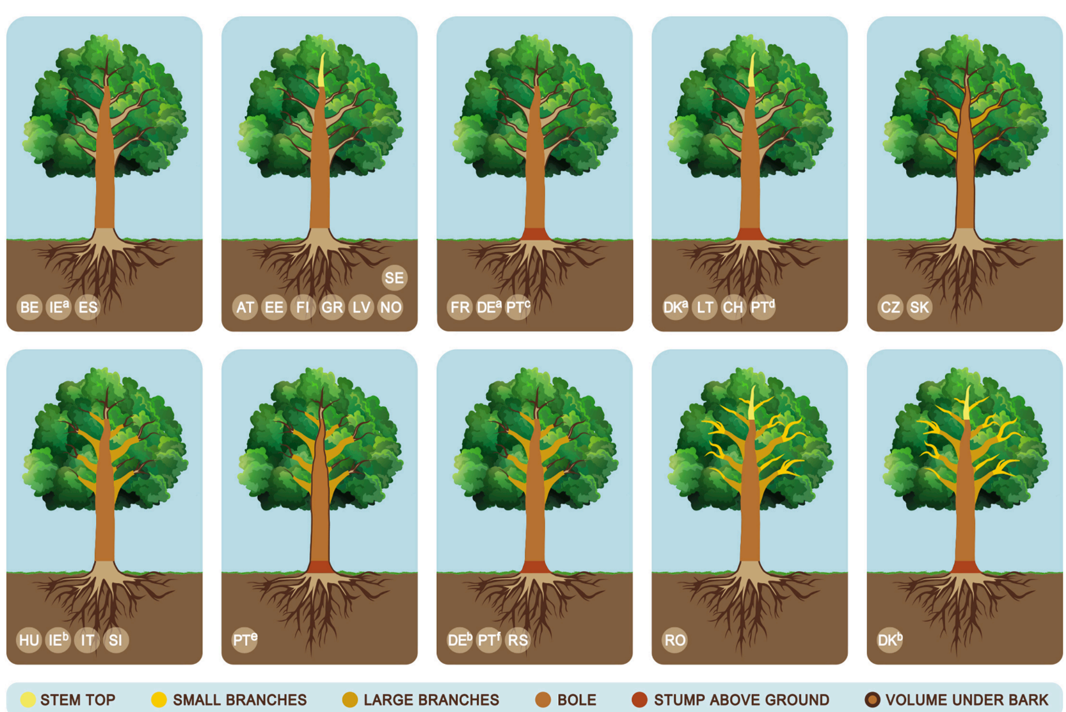

Fig. 5. Tree parts taken into account in the growing stock definitions of European NFIs, illustrated by the respective colors. Remarks: [a]Conifers; [b]Broadleaves; [c]Other oaks and other broadleaves; [d]*Acacia* sp., *Castanea sativa*, *Eucalyptus globulus*, *Pinus pinaster*, *Pinus pinea*, other conifers; [e]*Quercus suber*; [f]*Quercus rotundifolia*.

individual panel is a set of samples that are measured on one and the same occasion (e.g. year). Individual panels cover either the whole country by interpenetrating panels (e.g. Kuliešis et al., 2010a; Lanz et al., 2019b; Breidenbach et al., 2020a) or certain counties by regional panels (e.g. Alberdi Asensio et al., 2010). Periodic NFIs often complete the field inventory within one or a few years and cover the whole country by a single panel (ICNF, 2016; DAFM, 2018; Kleinn et al., 2020). Once all sample plots are measured, the procedure reinitiates in the subsequent year in continuous inventories or after a break of up to ten years in periodic inventories. The sampling density is either uniform over the whole country, or varies according to regional stratification of the forest area. A remote-sensing-based assessment previous to the field inventory pre-classifies sample plots into forest, potential forest, and non-forest, while other inventories conduct the forest-non-forest decision terrestrially during the field assessment. Two- or more-phase sampling utilises a higher sampling density in the first phase remote sensing interpretation previous to the terrestrial inventory (Mandallaz, 2008; Lanz et al., 2019b; Gasparini and Di Cosmo, 2016; Grafström et al., 2017). Sample plots are either single sampling locations or clusters. Permanent sample plots are invisibly marked for refinding and polar coordinates of sample trees are recorded, while temporary plots are used and visited only once. NFI sampling designs involve cost-benefit considerations and optimisation that aim on a reasonable relation between resources spent in terms of e.g. travel costs, personnel costs and workflow organisation on the one hand and the amount and quality of measurements and yielded information on the other hand (e.g. Patterson and Reams, 2005).

4.2. Systematic sampling approaches

NFI sampling schemes accommodate country-specific conditions (McRoberts et al., 2012a) and most commonly rely on systematic sampling. Terrestrial sampling is based on regular grids (Lawrence et al. 2010) and grid sizes range between 1.0 km × 0.5 km and 5.0 km × 5.0 km. In the less productive regions of Northern European countries, grid sizes up to 20.0 km × 20.0 km are used (Table 2). Different sampling densities within a country relate to spatial differences in forest conditions, i.e. percentage of forest land, forest productivity, and road networks (e.g. Axelsson et al., 2010; Robert et al., 2010; Tomter et al., 2010; Marin et al., 2016; Bouriaud et al., 2020). The grid intersection points are either the center points of single plots, or the corner or center points of cluster plots. In restricted random sampling, the location of usually single plots is randomly selected in an area of determined size and shape established at the grid intersection points (e.g. O'Donovan and Redmond, 2010), or, in tessellated sampling designs within the grid-cells (e.g. Gasparini et al., 2013; Hervé, 2016; Kučera, 2016). NFIs that use cluster plots rely often on square-shaped clusters with side-lengths ranging between 150 and 1800 m. Alternative cluster shapes are L- and open rectangular shapes (Korhonen, 2016). Some NFIs offset the cluster position from the grid intersection point and the plot location from the cluster corners (e.g. Jansons and Licite, 2010; Kuliešis et al., 2010a). Permanent plots and temporary plots are usually arranged in separate grids. Semi-temporary plots denote plots that are re-measured only once (Hervé, 2016), or at large time intervals (Rondeux et al., 2010).

4.3. Sample plot features

Sample plots are the basic unit for comprehensive terrestrial measurements and the ground reference for remotely sensed data (Section 4.9). The plot configuration describes the size, shape, and components of plots serving as sampling units for various tree–, stand- and site-specific variables (Vidal et al., 2016a). Also line-intersect samples for e.g. lying dead wood are occassionally attached to the plots (e.g. Kučera, 2016; Breidenbach et al., 2020a). Maps and registers often provide information on administrative regions, ownership categories, ecoregions, land use, forest management or forest types and are attributed either to the plot centre or to sub-divisions of the sample plot area. For GS monitoring, European NFIs use either plots consisting of one circle to include and measure all trees above a certain dbh-threshold (Tomé et al., 2016; Tomter, 2016), or concentric circular plots with fixed radii that consist of two (e.g. Kušar et al., 2010; Bosela and Seben, 2016; Gasparini and Di Cosmo, 2016; Lanz et al., 2016; Marin et al., 2016), three (e.g. Kuliešis et al., 2003; Alderweireld et al., 2016; Hervé, 2016; Kolozs and Solti, 2016; Nord-Larsen and Johannsen, 2016; Pantic et al., 2016; DAFM, 2018), or four circles (e.g. Alberdi et al., 2016a) arranged at a common center point. The concentric circles refer to different dbh-thresholds, the inner circle having the lowest and the outer the highest dbh-threshold (Fig. 7). Angle-count sampling according to Bitterlich (1948) is still applied by two NFIs (Gschwantner et al., 2016; Riedel et al., 2016, Kleinn et al., 2020), with a maximum circle size limit recently introduced by the Austrian NFI (Berger et al., 2020). Many European NFIs have lately introduced additional small and mostly circular off-centre plots for trees below the dbh-threshold to improve the data basis about regeneration trees and to support international harmonisation.

The number, size and dbh-thresholds of concentric circles and similarly the basal area factor of angle-count sampling is chosen depending on the dbh-distribution in a country, the number of sample trees to be measured, the workflow of assessments at the plot locations, and the envisaged coefficient of variation between sample plots (Loetsch et al., 1973). Compared to other plot layouts, circular plots are efficient under European forest conditions, they are relatively easy to establish, can be efficiently marked with a single mark at the plot centre, and enable the best visibility over the plot from the central point. The periphery zone of the plot is the smallest possible relative to the plot area and minimizes the number of borderline trees that require exact distance measurement.

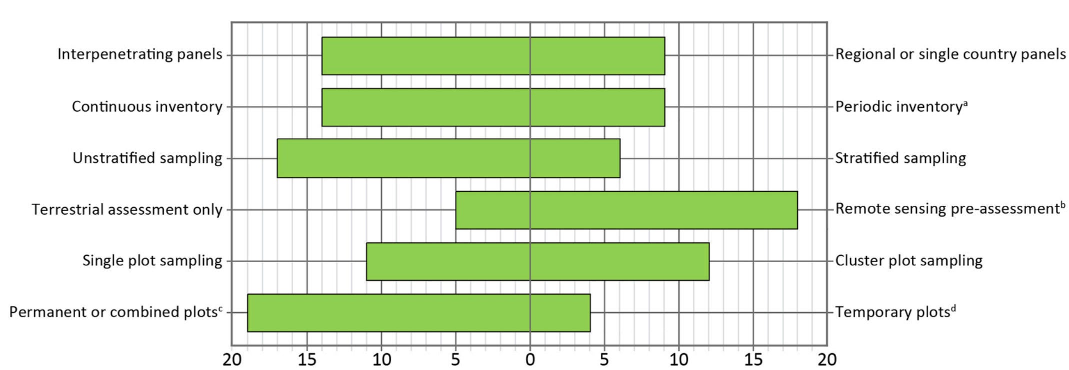

Fig. 6. Sampling schemes by number of European NFIs. Remarks: [a] One NFI changes since 2020 towards continuous inventory (SI); [b] Three NFIs use two- or more-phase sampling (CH, IT, SE); [c] Six NFIs use combined permanent and temporary plots (BE, DK, EE, FI, RO, SE); [d] One NFI re-measures plots once, denoted as semi-temporary plots (FR).

Table 2
Features of terrestrial NFI sampling used for growing stock monitoring. Remarks: [a] GR: random plot selection; [b] NO: temporary plots for periodically conducted county-level inventories; [c] SI: since 2020 change towards continuous inventory with 2.0 km × 2.0 km grid and interpenetrating panels.

NFI – Country	Grid size (km × km)	Plot arrangement					
		Clustering	Cluster features			Plot features	
			Shape	Side-length (m)	Plot number	Type	Configuration
Austria	3.9 × 3.9	Cluster	Quadratic	200	4	Permanent	Angle count sampling, Circular plot
Belgium	1.0 × 0.5	Single plots	–	–	1	Permanent and semi-temporary	Concentric circular plots
Czech Republic	2.0 × 2.0	Single plots	–	–	1	Permanent	Concentric circular plots
Denmark	2.0 × 2.0	Cluster	Quadratic	200	4	Permanent and temporary	Concentric circular plots
Estonia	5.0 × 5.0	Cluster	Quadratic	800	8	Permanent and temporary	Concentric circular plots
Finland	3.0 × 3.0 to 20.0 × 20.0	Cluster	L- and [-shape	1200 – 1800	5 to 14	Permanent and temporary	Concentric circular plots
France	1.0 × 1.0	Single plots	–	–	1	Semi-temporary	Concentric circular plots
Germany	2.0 × 2.0 to 4.0 × 4.0	Cluster	Quadratic	150	4	Permanent	Angle count sampling
Greece [a]	–	Cluster	Hexagonal	20 – 40	10	Temporary	Angle count sampling
Hungary	4.0 × 4.0	Cluster	Quadratic	200	4	Permanent	Concentric circular plots
Ireland	2.0 × 2.0	Single plots	–	–	1	Permanent	Concentric circular plots
Italy	1.0 × 1.0	Single plots	–	–	1	Temporary	Concentric circular plots
Latvia	4.0 × 4.0	Cluster	Quadratic	250	4	Permanent	Concentric circular plots, Rectangular plot
Lithuania	4.0 × 4.0	Cluster	Quadratic	250 – 500	4 to 8	Permanent and temporary	Concentric circular plots, Rectangular plot
Norway [b]	3.0 × 3.0 to 9.0 × 9.0	Single plots	–	–	1	Permanent	Single circular plot
Portugal	2.0 × 2.0	Single plots	–	–	1	Temporary	Single circular plot
Romania	2.0 × 2.0 and 4.0 × 4.0	Cluster	Quadratic	250	4	Permanent and temporary	Concentric circular plots
Serbia	4.0 × 4.0	Cluster	Quadratic	200	4	Permanent	Concentric circular plots
Slovakia	4.0 × 4.0	Single plots	–	–	1	Permanent	Concentric circular plots
Slovenia [c]	4.0 × 4.0 (2.0 × 2.0)	Single plots	–	–	1	Permanent	Concentric circular plots
Spain	1.0 × 1.0	Single plots	–	–	1	Permanent	Concentric circular plots
Sweden	3.0 × 3.0 to 20.0 × 20.0	Cluster	Quadratic	300 – 1800	4 to 12	Permanent and temporary	Concentric circular plots
Switzerland	1.4 × 1.4	Single plots	–	–	1	Permanent	Concentric circular plots

4.4. *Sample tree measurements*

The measurement and assessment of sample tree variables such as tree species, dbh, tree height, and upper diameter (Tomppo et al., 2010a; Vidal et al., 2016a) provide the input data for single-tree volume models (Section 4.6). Tree-shape categories may be also required (e.g. Alberdi et al., 2016a). The dbh is the most cost-efficiently and precisely measurable tree variable (Spurr, 1952), while other measurements are more time-consuming, associated with larger uncertainties (Berger et al., 2014), and therefore measured only on a subset of sample trees (Section 4.5). Some NFIs measure the circumference at breast height instead of dbh (e.g. Alderweireld et al., 2016; Hervé, 2016). Classical callipers and measuring tapes are in frequent use (Table 3). Large diameter trees above the calliper scale length require diameter measurement with a tape (e.g. Düggelin et al., 2020). Electronic diameter measurement devices feature automatic reading, data storage and wireless data transmission to the field computer. The efficiency of height measurements has increased through the use of ultrasonic distance measurement, especially in dense stands. Crown length is obtained as difference between the tree height and height to the crown base. Upper diameters are measured either at a fixed height of e.g. seven meters with a pole calliper (Lanz et al., 2016), at relative heights of e.g. 30 % tree height with indirect methods (Gschwantner et al., 2016; Riedel et al., 2016), or at the height corresponding to e.g. 10 % of bole diameter decrease (Morneau, 2015). New instruments like Terrestrial LiDAR sensors may become used in future large-area field inventories (Bauwens et al., 2016; Ghimire et al., 2017).

4.5. *Methods of sub-sampling*

Many NFIs take a smaller sub-sample for time-consuming height and upper diameter measurements within the larger sample of dbh-measured trees, also denoted as two-stage sampling (Mandallaz, 2008; Mandallaz and Massey, 2012). Four methodical groups regarding sub-sampling can be identified among European NFIs. A basic distinction can be drawn between NFIs that take the measurements on all sample trees (Method 1), from NFIs that use a sub-sample (Methods 2 – 4) (Fig. 8). Method 2 refers to NFIs that use two sets of volume models, one set of more precise volume models for the smaller sub-sample and using e.g. dbh, height and upper diameter as predictors, and a second set of tariff functions (e.g. Herold et al., 2019; Breidenbach et al., 2020a) or non-parametric functions (e.g. Korhonen and Kangas, 1997) that are parameterised with the sub-sample volumes and applied to calculate the volumes of the trees in the larger sample. Method 3 uses the sub-sample tree measurements to parameterise data-models such as height curves (e.g. Sloboda et al., 1993; Ozolins, 2002; Kuliešis et al., 2014) or upper diameter models (e.g. Korhonen, 1992; Sloboda et al., 1993; Gabler and Schadauer, 2008), which are used to predict the missing heights or upper diameters of not measured sample trees. The predicted data enter the volume models as input variables. Method 4 uses the sub-sample tree measurements to derive stand-specific variables like dominant height or mean height required as explanatory variables in volume models (e.g. Tomé et al., 2007b; Dagnelie et al., 2013). Stand variables can also be used as explanatory variables in height curves (Bastrup-Birk et al., 2010; Kuliešis et al., 2014; Gasparini and Di Cosmo, 2016) or tariff functions (Herold et al., 2019) and constitute hybrids of Methods 2 and 4 or 3 and 4.

The sub-sample trees are either a systematic or randomised choice per sample plot. Conditional inclusion probabilities aim at optimising the sub-sample by e.g. including sub-sample trees proportional to model residuals and to a targeted number of re-measured sub-sample trees (Lanz et al., 2019b). Due to harvests, the number of sub-sample trees cannot be exactly predicted prior to field measurements, however, a sufficient number of measurements is required for the species, dbh-classes and stand layers represented in the sample. The size of sub-samples is usually between 10 and 35 % of dbh-measured sample

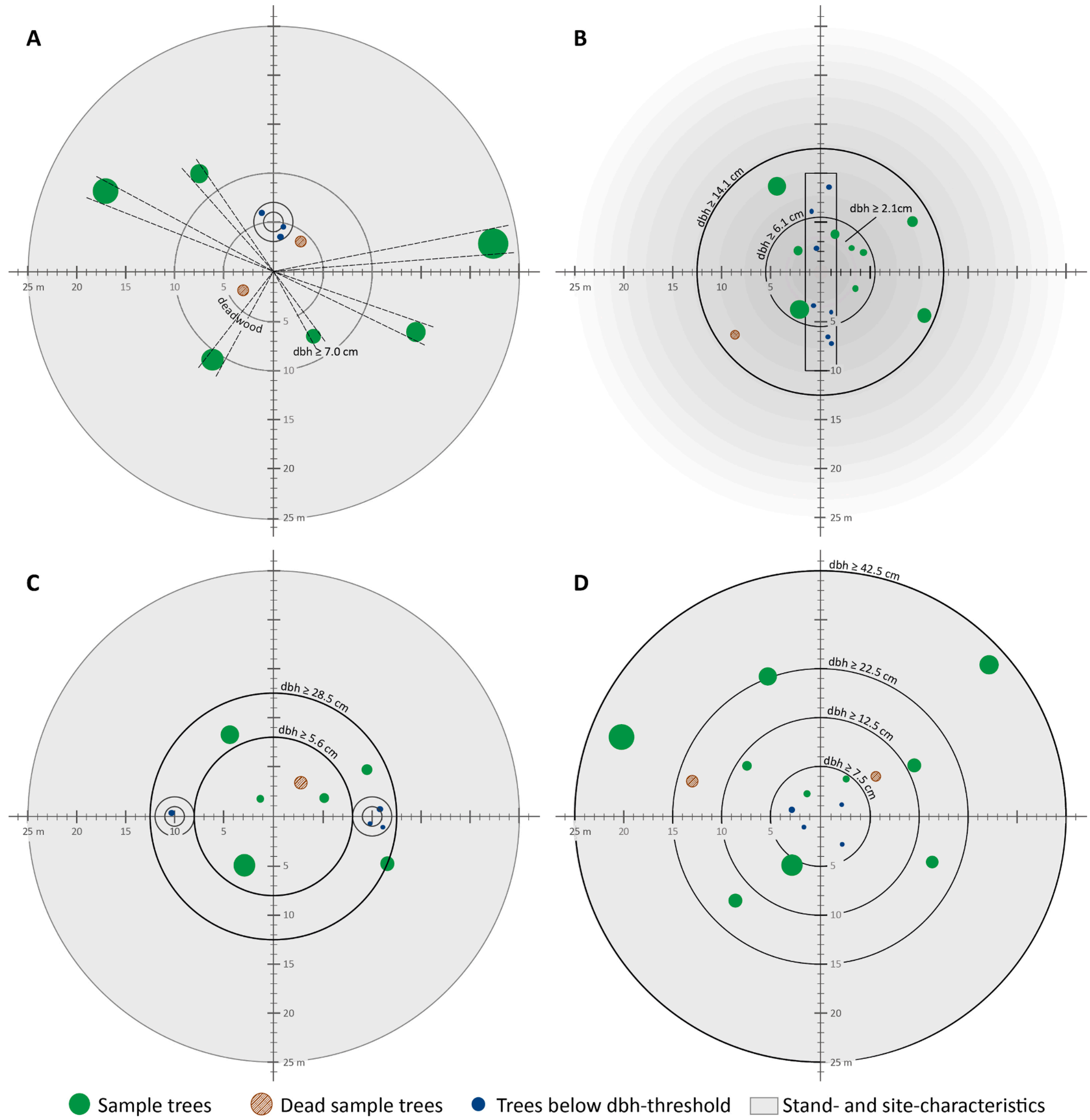

Fig. 7. Examples of plot configurations used for growing stock monitoring, harmonised presentation: A) Germany - Angle-count sampling and concentric regeneration plots; B) Latvia and Lithuania – two concentric circles, with one quarter of the inner circle serving as third tree sampling unit, and rectangular regeneration plot; C) Romania – two concentric circles and two regeneration plots; D) Spain – four concentric circles and inner circle serving as regeneration plot.

trees. Common inclusion procedures are every 6th or 7th sample tree, every 10 m^2 or 15 m^2 of represented basal area per hectare, angle-count sampling with large basal area factors of e.g. 12 m^2/ha or basal area factors depending on the stem number, or a randomised choice of e.g. 6 trees per plot. Stand variables like dominant height or mean height are obtained from the two to five largest trees, or from the central dbh-class. Some NFIs measure also trees outside the plot in the surrounding stand to derive stand variables.

Table 3
Sample tree measurements and instruments used for growing stock monitoring by number of NFIs. Remarks: [a] Ten NFIs use the measuring tape only for large-diameter trees; [b] References: Bitterlich (1992), Laser Technology (2006), Haglöf Sweden (2014-2017), IFER (2020).

Variable	Classical calliper	Electronic calliper	Measuring tape [a]	Pole calliper	Relascope® [b]	Criterion® [b]	Vertex® [b]	Field-map® system [b]
Dbh	14	4	13					
Girth			2					
Upper diameter				1	2	1		2
Tree height					1		18	4
Height to crown base							2	

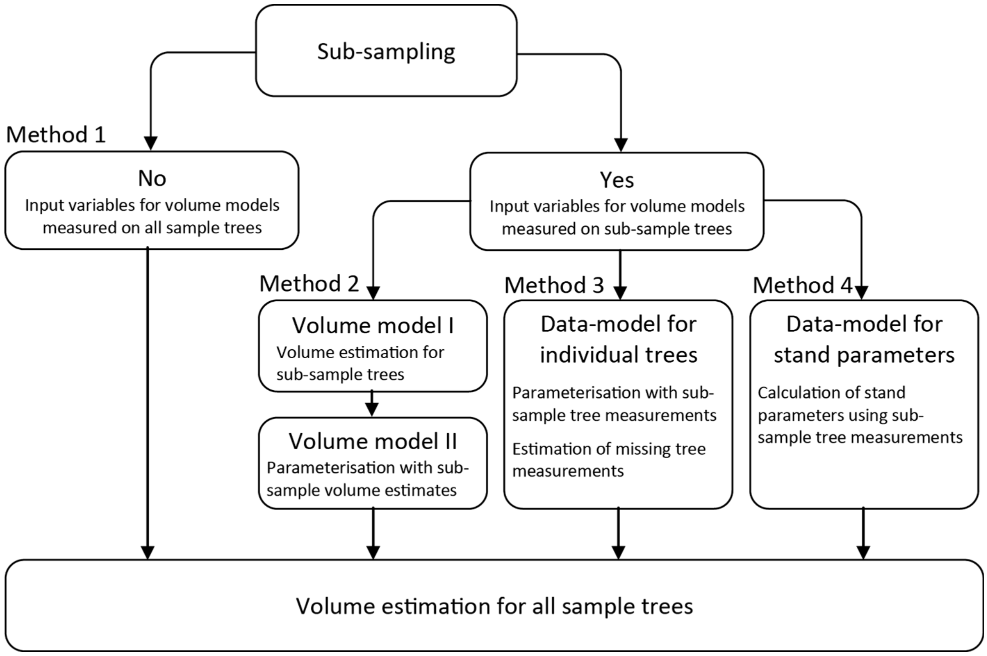

Fig. 8. The use of sub-sampling by European NFIs. Tree height: Method 1 - AT, BE (broadleaved stands), GR, RO, RS, ES; Method 2 - FI, NO, SE, CH, FR; Method 3 - CZ, DK, EE, DE, HU, IE, IT, LT, LV, PT, SK, SI (since 2020); Upper diameter: Method 2 – CH; Method 3 - AT, DE; Dominant height: Method 4 - BE (conifer stands), IT, PT; Mean height: Method 4 - DK, SI.

4.6. *Volume models*

4.6.1. *Development of volume models*

Country- and tree species-specific single-tree volume models are implemented by European NFIs to estimate the sample tree volumes based on the previously described measurements. Volume models are developed and parameterised using large data sets of thousands to ten-thousands of measured trees, representing the forest conditions or relevant regions within a country, and obtained in customised and laborious measurement campaigns. The measurements have been gathered at harvesting sites or research plot networks following detailed measurement instructions (e.g. Grundner and Schwappach, 1922; Pettersson, 1955; Vestjordet, 1967; Braun, 1969; Näslund, 1971; Madsen, 1987; Petráš and Pajtík, 1991; Kaufmann, 2001), or on standing trees on NFI plots (e.g. Laasasenaho, 1976, 1982; Morneau 2015). The recorded data include section-wise stem diameter measurements, tree species, dbh, height, upper diameters, crown length, stand and site variables, and essentially have to cover the existing range of dendrometric attributes (Köhl et al., 2006). The volume of stem sections is obtained by the formulae of Huber (1828), Smalian (1837), or the frustum of a cone and summed up for the whole tree. Volume tables were constructed from the measurements until the first half of the 20th century, and later in some cases served as data basis for the parametrisation of volume functions and adaptation to country-level conditions (e.g. Čokl, 1957; Kuliešis and Kenstavičius, 1976; Sopp and Kolozs, 2000). As the tree shape may change over time, recurrent tree measurements can be used to evaluate the validity of volume models (e.g. Kušar et al., 2013; Herold et al., 2019) or to parameterise up-dated models (e.g. ICONA, 1990; Morneau, 2015; Kangas et al., 2020). Other NFIs update the height-curves and upper-diameter models for each inventory (e.g. Gabler and Schadauer, 2008), or take into account the current local diameter-height relationship (e.g. Tomter et al., 2010; DAFM, 2018).

4.6.2. *Volume model types*

Single-tree volume models can be grouped by the modelling concept, the function type and the required input variables. Taper curves, form factor functions, and volume functions are applied by European NFIs (Table 4). Frequently, more than one set of volume models is implemented, to obtain different target volumes of over-bark or under-bark stem volume (e.g. Braastad, 1966; Brantseg, 1967; Vestjordet, 1967; Petráš and Pajtík, 1991; Bauger, 1995; Paulo and Tomé, 2006; Tsitsoni, 2016), to include or exclude the branch volume of broadleaves (e.g. Petráš and Pajtík, 1991), to allow different top-diameter limits (Madsen, 1987), or to estimate the assortments of standing stems (Laasasenaho, 1976, 1982; Rohner et al., 2019). The function types of volume models include power and exponential functions as well as linear combinations of usually transformed variables. To capture the variation in stem forms across the country, the volume models require either upper diameters as

Table 4
Modelling concepts of single-tree volume models used by European NFIs for growing stock estimation.

Modelling concept	Description	Country - NFI
Taper curve	Taper curves describe the stem shape along the stem axis from the base point up to the stem tip and predict the stem diameter at a specified height, or the height for a specified diameter. The integral of stem taper curves produces the stem volume and defined stem segments.	DE, DK, FI, IE
Form factor function	Form factor functions describe the relationship between the tree volume and the reference cylinder volume having a cross-sectional area equal to the basal area at a defined height (e.g. breast height) and a height equal to the stem length.	AT, LT, CZ, EE, FR
Volume function	Volume functions directly describe the tree volume depending on a set of explanatory variables.	BE, CH, DK, ES, FI, GR, HU, IT, LV, NO, PT, RO, RS, SE, SI, SK

input variables (e.g. Braun, 1969; Laasasenaho 1976, 1982; Kublin, 2003), or stand and site variables (e.g. Čokl, 1957; Dagnelie et al., 2013; Herold et al., 2019), or regional volume models for different tree shapes are parametrised (e.g. ICONA, 1990). A compilation of form factor and volume functions applied by European NFIs is given in Appendix B. For taper curve models please refer to Laasasenaho (1982), Madsen (1985), Riemer et al. (1995) and Kublin (2003, 2013). The predicted tree volumes differ among NFIs in terms of included tree parts as specified by the national GS definitions (Section 3.2).

4.7. Expansion to larger areas

4.7.1. Growing stock estimators

The sample of trees measured at the sample plots are required to estimate the parameters of the population and the uncertainty of the estimates. In terms of GS, the population parameters are typically the mean volume per unit of area and the totals for countries or other defined geographic areas. An estimator denotes the calculation rule by which an estimate i.e. the value of a population parameter is obtained from the sample. Design-based estimators are usually applied for large-area GS monitoring by European NFIs (Kangas and Maltamo, 2006; Tomppo et al., 2010a) as they are unbiased for reasonably large samples. Design-based estimators and their properties derive from the inclusion probabilities of sample trees (Mandallaz, 2008). The corresponding GS of an individual NFI sample plot per hectare is equivalent to the sum of sample tree volumes multiplied by their respective representation factor that is the inverse of their inclusion probability:

$$V_{ha,j} = \sum_{i=1}^{m_j} V_{i,j} \bullet \mathrm{f_i} \tag{1}$$

where $V_{i,j}$ is the volume of the i^{th} tree on the j^{th} sample plot, m_j is the total number of sample trees on the sample plot j, f_i is the representation factor, and $V_{ha,j}$ is the GS per hectare of plot j. In the basic form under simple random sampling, the GS estimators of the arithmetic mean volume per hectare and the corresponding standard error SE for a given stratum are:

$$\widehat{\overline{V}} = \frac{\sum_{j=1}^{n} V_{ha,j}}{n} \tag{2}$$

and

$$SE(\widehat{\overline{V}}) = \sqrt{\frac{\sum_{j=1}^{n} \left(V_{ha,j} - \widehat{\overline{V}}\right)^2}{n-1}} \bullet \frac{1}{\sqrt{\mathrm{n}}} \tag{3}$$

where $\widehat{\overline{V}}$ is the mean volume per hectare, $SE(\widehat{\overline{V}})$ is the standard error of the mean, and n is the number of plots in the stratum. Total GS ($\widehat{V}_{total}$) in the stratum and its standard error are obtained by multiplication of the mean volume per hectare with the stratum area A:

$$\widehat{V}_{total} = \widehat{\overline{V}} \bullet \mathrm{A} \tag{4}$$

and

$$SE(\widehat{V}_{total}) = SE(\widehat{\overline{V}}) \bullet \mathrm{A} \tag{5}$$

In most cases, forest area (A_{forest}) will also be a quantity estimated from NFI data and the mean GS per unit of forest area is the ratio of the estimated total volume in forest and the estimated forest area (Mandallaz, 2008). Variants of these basic estimators are implemented by European NFIs and concern mainly the use of strata weights and specifics in the standard error calculation such as using cluster-level estimates, or groups of clusters. Most NFIs deliberately use the above variance estimators although they are known to be conservative for systematic sampling, i.e. they overestimate the variance (Magnussen et al., 2020). The Finnish NFI by default takes the spatial correlation of sample plots into consideration (Matérn, 1960), which results in nearly unbiased model-based variance estimators. Post-stratification is applied to maintain the additivity of regional estimates with country-level estimates (e.g. Lanz et al., 2019b) or to construct less variable groups of plots for age classes, growth stages or species composition (Moravcik et al., 2010). Weights are also applied for the combination of permanent and temporary plot estimates (Axelsson et al., 2010) or for the combination of the individual years into an multiannual NFI cycle estimate (Adermann, 2010). Further details on forest inventory estimators are available from the textbooks of Schreuder et al. (1993), Gregoire and Valentine (2007), and Mandallaz (2008).

4.7.2. Uncertainty components

Sampling error is estimated as the variation between the sampling units (Formula 3) and originates from measuring only a sample of plots. Cunia (1965) identified volume model error and measurement errors as additional uncertainty sources, and similarly Gertner and Köhl (1992) devided non-sampling errors into function error, measurement error and classification error. The function error is due to the use of volume models to predict the individual-tree volume (Section 4.6) and can be attributed to model misspecification, uncertainty in the values of independent variables, uncertainty in model parameter estimates, and residual variability around model predictions (McRoberts and Westfall, 2014). The models required to predict unmeasured input variables of volume models (Section 4.5) are also a source of uncertainty (Westfall et al., 2016). The measurement error can be distinguished into instrumental error and operator error (Schreuder et al., 1993). The uncertainty components influence the accuracy and precision of GS results, the first describes the systematic deviation ("bias") from the true value, while the second refers to the reproducibility under unchanged conditions (Cochran, 1977). Köhl (2001) found that sampling error makes by far the highest contribution to the overall uncertainty and that bias may occur as a result of model errors or measurement errors. Therefore, NFIs have implemented comprehensive Quality Assurance and Quality Control (QA/QC) measures that include detailed field instructions, training of personnel, control surveys, testing of measurement instruments, evaluation and updating of models, and investigation of the influence of measurement errors and model uncertainties on large-area volume estimates (e.g. Gasparini et al., 2009; Berger et al., 2012, 2014; Breidenbach et al., 2014; McRoberts and Westfall, 2014; Traub et al., 2019).

4.8. Wood quality and assortments

The mere information about GS does not sufficiently address the information needs on available wood resources and potential end-use. All European NFIs assess quality-related tree variables such as tree species, diameter, curvature, branchiness, and damages (Bosela et al., 2016). A direct classification of sample trees in stem quality classes is conducted by about two thirds of European NFIs, but only one quarter uses the stem quality variables to estimate assortments (Bosela et al., 2016). The assortment of standing stems usually relies on taper curve models (e.g. Laasasenaho, 1982; Kaufmann, 2001; Kublin, 2003) for the distinction of stem segments according to length and diameter classes of timber trade guidelines, and on the field assessments of stem quality traits (Eckmüllner et al., 2007; Rohner et al., 2019). Despite doubts in the reliability of visual appraisals of external quality features (Bosela et al., 2016), several studies demonstrated the potential for stem grading of standing trees (Eckmüllner et al., 2007; Rais et al., 2014; Power and Havreljuk, 2016; Malinen et al., 2018). The assortment models by Petráš and Nociar (1990, 1991a, 1991b), Mecko et al. (1993), and Petráš and Mecko (1995) are based on a large sample material collected across Slovakia and were applied in a case study using an independent data set from Czech Republic (Vidal et al., 2016c). Nevertheless, a transnational application of stem quality models on larger areas is at present complicated by the existing differences in national timber trade regulations and different wood quality-related assessments of NFIs (Bosela et al., 2016; Power and Havreljuk, 2016).

4.9. Air- and spaceborne data sources

Most innovations in NFIs involve remote sensing technologies to provide faster and less expensive observations, to increase the precision through stratification, and to expand the range of applications by producing small-area estimates and forest thematic maps (Bjerreskov et al., 2021; Kangas et al., 2018; McRoberts and Tomppo, 2007). The classification in forest and non-forest plots prior to terrestrial assessments is frequently applied by NFIs, saves travel costs, and aerial photographs support the navigation and access to the sample plots during field work (Table 5). Double sampling for stratification is used to increase the accuracy of forest area and volume estimates or to optimise sampling intensity (Barrett et al., 2016; Grafström et al., 2017; Räty et al., 2018; Haakana et al., 2019; Bouriaud et al., 2020). Forest area mapping and small-area GS estimates are less frequent but increasingly reach the operational large-area implementation (Astrup et al., 2019; Ginzler et al., 2019). Most European NFIs use aerial photography, usually from digital multi-spectral sensors. The reasons for their intensive use in Europe include the long tradition of use, the high spatial resolution of often below 0.25 m, the higher costs of satellite imagery with comparable resolution, the established cooperations between land surveying and forest research institutes, and the higher probability of cloud-free data (Koch, 2013).

Matching of 3-dimensional aerial images is increasingly used in NFI map production (e.g. Breidenbach and Astrup, 2012; Astrup et al., 2019). Satellite data are still less common, however, the opening of the Landsat archive and free availability of historical time-series promoted their use. Landsat and SPOT data were the more frequently used spaceborne data sources (Barrett et al., 2016). More recently and attracting increasing attention, the Sentinel satellites of the Copernicus-Programme of the European Space Agency (ESA) provide data with high spatial and temporal resolution (Breidenbach et al., 2020b; Puliti et al., 2020; Löw and Koukal, 2020; Bjerreskov et al., 2021). Airborne laser scanning (ALS) was first used for stand level inventories (e.g. Næsset, 1997; 2002; Breidenbach et al., 2008), but was later integrated into NFIs for small-area GS estimation and forest map production (e.g. Hollaus et al. 2009, Nord-Larsen and Schumacher, 2012; Steinmann et al., 2013; Nilsson et al., 2017). Fig. 9 shows examples of forest resource maps. The combination of airborne, spaceborne and other auxiliary data sources to improve estimates is a natural development in forest inventories (Irulappa-Pillai-Vijayakumar et al., 2019; Breidenbach et al., 2021).

Table 5
Use of remote sensing data related to growing stock monitoring by number of NFIs. Remark: [a] primarily forest/non-forest classification, eight NFIs distinguish further non-forest land use classes.

Purpose	Aerial photographs	Satellite images	Airborne laser scanning
Land use and land cover classification[a]	16	3	0
Field work support	13	1	0
Forest map	7	4	4
Forest stratification	4	1	1
Small area estimation	2	2	4

5. Harmonisation

5.1. European harmonisation process

The European NFIs were primarily established to serve the information needs at country level and accommodate the respective topographies, climates, forest types, commercial interests, and change rates in forests (McRoberts et al., 2012a), entailing a lack of international comparability. For improving the comparability of large-area forest resources information in Europe a harmonisation process commenced in the 1990s. The EFICS (1997) study collated the differences between European NFIs and identified a considerable need for harmonisation (Päivinen and Köhl, 2005). In 2003, the European NFIs formed the European National Forest Inventory Network (ENFIN, 2021) to promote the cooperation between NFIs as comprehensive monitoring systems and to support forest-related decision-making processes with harmonised information. Under COST Action E43, the harmonisation principles and the general harmonisation approach were developed (Tomppo et al., 2010a), consisting of common reference definitions and bridging functions as basic components (Tomppo et al., 2010b), and applied to convert estimates based on country-level definitions into estimates according to the common reference definitions (McRoberts et al., 2010; Tomppo and Schadauer, 2012). The harmonisation process was continuously carried forward in the subsequent COST Action FP1001 (Vidal et al., 2016a), three Framework Contracts with the Joint Research Centre (JRC) and the Horizon 2020 project DIABOLO (2015) (Vidal et al., 2016b), with recent harmonisation of stem volume and GS.

5.2. Harmonisation of growing stock

Since the beginning of NFI harmonisation in Europe, GS has been recognised as a crucial component of comparable international forest resource information (e.g. Köhl et al., 2000; Päivinen and Köhl, 2005; Vidal et al., 2008). The limited comparability of GS estimates can be attributed to five basic variables in GS definitions that determine the quantity of GS: the manner of growth (tree or shrub), living status (dead or alive), standing status (standing, leaning, or lying), tree size (dbh threshold), and the tree parts taken into account (bole, bark, stump, stem top, branches, roots) (Vidal et al., 2008). The five variables and related thresholds were defined for the harmonisation and reference definitions for stem volume and GS were established and agreed by the NFIs during COST Action E43 (Vidal et al., 2008; Gschwantner et al., 2009; Lanz et al., 2010). Accordingly, the harmonised reference definition of GS is the *volume of living and standing stems over a specified land area* that *includes the stem volumes from stump height to the stem top and the bark* but *excludes the branches*, and refers to *all trees with a dbh > 0 cm (height > 1.3 m)*. The reference definition was applied in the case studies by Tomter et al. (2012) and Ståhl et al. (2012) and focused on the main differences, i.e. dbh-thresholds and included tree parts. Kuliešis et al. (2011) investigated the comparability of GS estimates for Scots pine of the Baltic NFIs. The harmonisation of individual sample tree volume estimates by Gschwantner et al. (2019) generated comparable GS for 21 European NFIs and introduced additional reference volumes to meet different information needs about whole stems, the merchantable stem part, and merchantable branches of broadleaves. The un-harmonised national GS estimates showed differences compared to the reference definition of COST Action E43 in the range of −10 to +30 % (Fig. 10), indicating the relevance of international harmonisation.

5.3. Further harmonisation progress

Several recent harmonisation advances are thematically closely connected to comparable GS estimation in Europe. Alberdi et al. (2016b) elaborated a common reference definition for forest available for wood supply, Fischer et al. (2016) studied the effects of environmental, economical and social restrictions on the forest area and GS available for wood supply, and Alberdi et al. (2020) quantified the harmonised area available for wood supply and related above-ground biomass for 13 European countries. Bosela et al. (2016) explored the stem quality assessments by European NFIs and proposed methods towards harmonisation. Korhonen et al. (2014) and Henning et al. (2016) developed a large-area implementation of comparable above-ground biomass estimation by 27 NFIs. Vauhkonen et al. (2019) presented harmonised future projections of GS, above-ground carbon, and fellings based on the European Forest Dynamics Model EFDM (Packalen et al., 2014). The common European NFI estimator (Lanz, 2012) allows for processing NFI plot-level data from different sampling designs of diverse cluster sizes

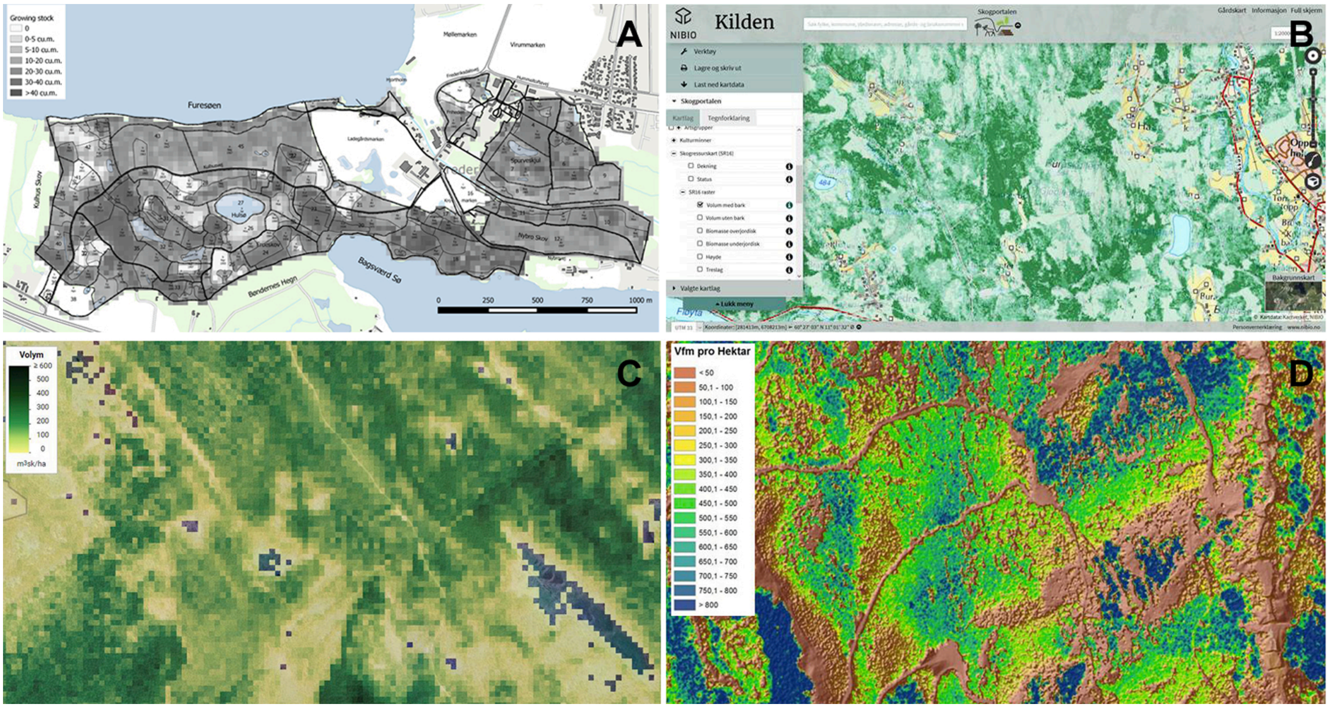

Fig. 9. Examples of growing stock maps based on remote sensing and NFI ground plot data: A) Danish forest resources map, ALS, 25 m × 25 m raster grid (Source: Nord-Larsen and Schumacher, 2012/UCPH); B) Norwegian forest resources map, photogrammetric point clouds, 16 m × 16 m raster grid (Source: Astrup et al., 2019/NIBIO); C) Forest attribute map of Sweden, ALS, 12.5 m × 12.5 m raster grid (Source: Nilsson et al., 2017/SLU); D) Growing stock mapping of the Austrian NFI, ALS and image matching, 1 m × 1 m raster grid (Source: BFW).

and sampling densities to produce population totals, means, and sampling errors using a comparable estimation procedure across countries. The estimator and software implementation is continuously developed further under the new Forest Inventory Estimation and Analysis (nFIESTA) system. It includes components of model-based estimation and integrates field data and auxiliary map data from various time points to produce up-to-date forest resource statistics (Adolt et al., 2019; Lanz et al., 2019a).

6. Outlook and conclusion

6.1. Changing environmental conditions

European forests are entering a phase of transition under changing climate conditions, most apparently revealed by increasing occurrence of natural disturbances like insect infestations, windthrow and wildfires (e.g. Seidl et al., 2017; Dupuy et al., 2020; Hlásny et al., 2021), shifts in tree species composition (e.g. Rigling et al., 2013; Zimmermann et al., 2013; Dyderski et al., 2018), and changes in growth patterns (e.g. Bosela et al., 2021; Charru et al., 2017; Spieker et al., 2012). Consequences can be expected on the level of GS, forest productivity, available wood resources and qualities, carbon sequestration, forest biodiversity, protective forest functions, and other forest ecosystem services (e.g. Rego et al., 2013; Mina et al., 2017; Morin et al., 2018; Scheidl et al., 2020). Empirical data needs on large spatial and long temporal scales have been repeatedly pointed out as an important pre-requisite to monitor, analyse and predict the forest transition under changing climate conditions, and to derive adaptive forest management options for establishing resilient forests forming a stable GS (e.g. Ruiz-Benito et al., 2020; Santopuoli et al., 2020; Schuldt et al., 2020).

6.2. Forest-based bioeconomy

The forest sector plays an important role in the development of the EU bioeconomy towards reduced dependence on non-renewable resources, sustainable management of natural resources, climate change mitigation and adaptation (European Parliament and Council of the European Union, 2009; EC, 2018b). Future prospects include further diversification and innovations in wood-based products (Näyhä et al., 2014; Hurmekoski et al., 2018), an increased use of construction wood, biochemicals and biofuels (Jonsson et al., 2021), and a gain in economic importance of emerging products like dissolving pulp and wood-based textiles (Kallio, 2021; Schier et al., 2021). Recent decades have indeed shown a steady increase of wood harvests in Europe (Köhl et al., 2015; Forest Europe, 2020), while at the same time forests are recognised for biodiversity conservation, carbon sequestration, and other ecosystem services that may conflict with increasing harvest levels (Eyvindson et al., 2018). An adequate balance of forest management goals between wood production and non-wood forest ecosystem services (Verkerk et al., 2020) and a realistic understanding of forest capacities in terms of wood supply under changing climate conditions (e.g. Braun et al., 2016) emphasises the central role of timely and harmonised GS information at European level (e.g. Vidal et al., 2016a; Vauhkonen et al., 2019; Alberdi et al., 2020).

6.3. Emerging data requirements

As a primary source of representative large-area forest information, NFIs integrate the scientific bases of forest mensuration, biometrics and statistics, and rely on terrestrial as well as air- and spaceborne data (Tomppo et al., 2010a; Vidal et al., 2016a). NFIs have therefore become an important data source for environmental research, reporting processes, policy decisions, and forest management planning (e.g. Fridman et al., 2014; Brändli and Hägeli, 2019; Breidenbach et al., 2020a), and routinely include many measurements that attract contemporary interest. For informing the future knowledge-based bioeconomy in Europe, emerging data needs can be differentiated into three basic components:

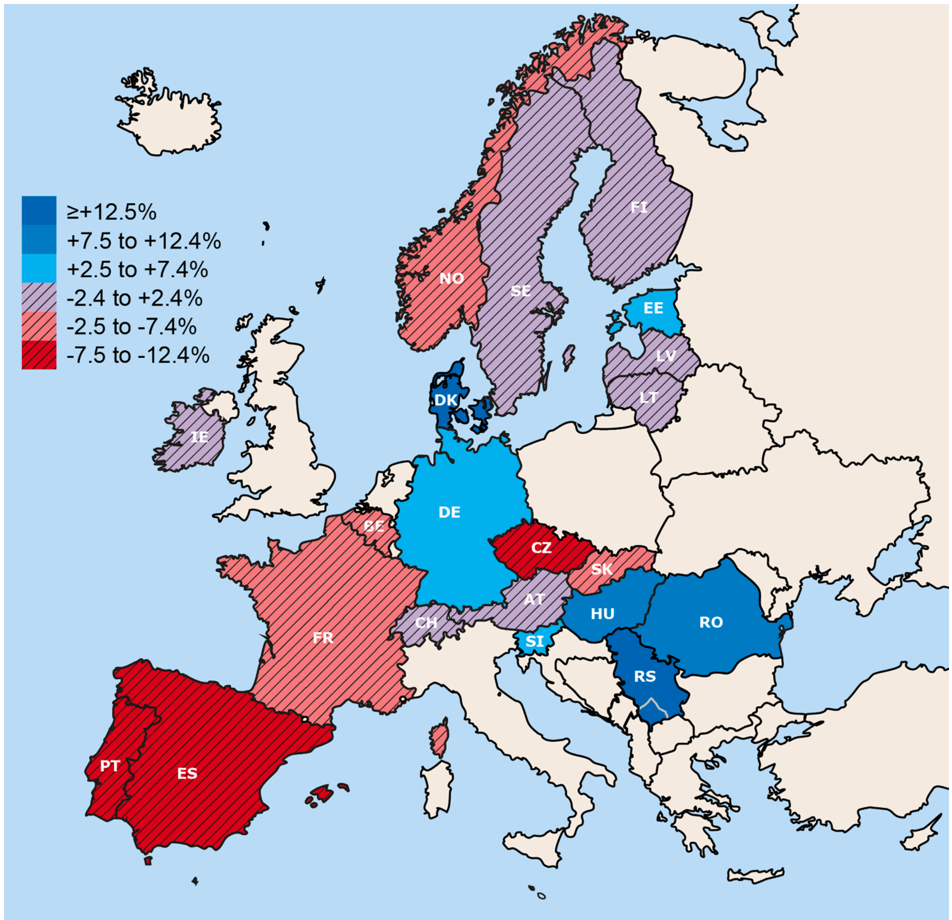

Fig. 10. Difference between un-harmonised and harmonised growing stock estimates for 21 countries in percent (%). Positive deviation: un-harmonised $>$ harmonised, negative deviation: un-harmonised $<$ harmonised. Harmonised according to the reference definition of Cost Action E43 (Vidal et al., 2008; Lanz et al., 2010).

- maintenance, extension and harmonisation of existing NFI data series to enable the analysis of forest ecosystem changes on large spatial and long temporal scales,
- implementation of higher spatial and temporal resolution through remote sensing methods to cope with accelerated climate-driven changes, and
- integration of additionally required variables to close data gaps.

In terms of GS, the monitoring and investigation of changes due to mortality, natural disturbances, harvest, and on the other hand growth and regeneration for forming a future climate-adapted tree generation are gaining increased importance. Sampling designs allowing for annually updated estimates are becoming more common in European NFIs, e.g. the NFIs of Austria, France, Slovenia, and Switzerland changed to continuous inventories in recent years. Data from air- or satellite-based sensors open new perspectives of high-frequency outputs with high spatial resolution (Kangas et al., 2018; McRoberts and Tomppo, 2007). Methodological aspects to be addressed relate to the combination of remote sensing and terrestrial plots as reference and validation data, in particular the effects of field plot size and configuration on model-based and model-assisted GS estimates (Maltamo et al., 2007; Scrinzi et al., 2015; Tomppo et al., 2016; Berger et al., 2020), the up-dating of plot-level volume estimates to match with the remote sensing date (McRoberts et al., 2016; Fortin, 2020), the precision and harmonisation of local plot-level tree volume estimates (Adamec et al., 2019; Bouriaud et al., 2019; Gschwantner et al., 2019; Herold et al., 2019), and the influence of positional errors (Saarela et al., 2016). The development of small area GS estimators facilitates a change in forest management inventories from subjective visual stand estimates to statistical principles through spatially explicit maps generated from earth observation spatial data and NFI plots as training data (Kangas et al., 2018; Maltamo et al., 2020; Rahlf et al., 2021). Risk assessment and vulnerability mapping (e.g. Forzieri et al., 2021) of GS supports adaptive forest management and requires translation into forest management objectives at the level of local management units as well as consideration of related uncertainties.

NFI field plot measurements will remain instrumental since many forest characteristics require ground measurements to be assessed with sufficient accuracy, including regeneration, increment, and wood quality. A substantial amount of field plots is necessary to build the models relating remote-sensing information to plot-level data. Terrestrial laser-scanning technologies provide future potential in tree volume and biomass estimation and for assessing timber quality in European forests (e.g. Kankare et al., 2014; Bauwens et al., 2016; Bosela et al., 2016; Ghimire et al., 2017). Wood density is a highly variable attribute, both between and within species, and may gain relevance in terms of wood quality for the future wood-based product sector (Kerfriden et al., 2021). The composition of GS in terms of assortment structure closely relates to the opportunities of substituting materials like steel and concrete by wood-based products and replacing fossil fuels by bioenergy (e.g. Profft et al., 2009; Braun et al., 2016; Köhl et al., 2020) and requires enhanced and internationally harmonised wood quality assessments according to a flexible classification system that takes into account possible changes in the wood market, new technologies and future wood products (Köhl et al., 2006).

6.4. Conclusion from history

Looking back on European history (Appendix A) reveals analogies to present developments, including multiple conflicting forest uses, periods of adverse climate conditions, and strong reliance of human life and economy on wood as versatile energy, construction and manufacturing material. The sustainable utilisation of wood resources was achieved comparably late, although forest regulations reach back to the Middle Ages (Rubner, 1967; Hasel and Schwartz, 2002) and the importance of maintaining natural resources was recognised in ancient times (Scanavis and Sakellari, 2010; Papanastasis et al., 2010; Tsoumis, 2017). Several reasons explain the delayed response and include the enormous need for wood, the comparatively late onset of forest sciences, and the even later emergence of large-area sample-based GS monitoring techniques. As opposed to earlier times, nowadays, large-area forest monitoring by NFIs provides the opportunity of informing evidence-oriented decisions under changing climate conditions based on reliable and robust estimates, clear and unambiguous definitions, sound statistical methods, and knowledge about related uncertainties, thus enabling sustainable wood supply for the future European bioeconomy.

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Declaration of Competing Interest

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Appendices A and B. Supplementary material

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References

Adamec, Z., Adolt, R., Drápela, K., Závodský, J., 2019. Evaluation of different calibration approaches for merchantable volume predictions of Norway Spruce using nonlinear mixed effects model. Forests 10, 1104. https://doi.org/10.3390/f10121104.

Adermann, V., 2010. National Forest Inventory Reports: Estonia. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 171–184.

Adolt, R., Fejfar, J., Lanz, A., 2019. nFIESTA (new Forest Inventory ESTimation and Analysis): Estimation methods. Technical report, Diabolo project granted by European Union's Horizon 2020 programme, 27 p. https://cordis.europa.eu/project/id/633464/results/ (accessed 21 September 2021).

Alberdi Asensio, I., Condés Ruiz, S., Millán, J.M., Martinez, S., de Toda, S., Sánches Peña, G., Pérez Martin, F., Villanueva Aranguren, J.A., Vallejo Bombin, R., 2010. National Forest Inventory Reports: Spain. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for common reporting. Springer, Netherlands, pp. 527–540.

Alberdi, I., Hernández, L., Condés, S., Vallejo, R., Canellas, I., 2016a. National Forest Inventories Reports: Spain, in: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer, Cham, pp. 749-767.

Alberdi, I., Michalak, R., Fischer, C., Gasparini, P., Brändli, U.-B., Tomter, S.M., Kuliešis, 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., 2016b. 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.

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.

Alderweireld, M., Rondeux, J., Latte, N., Hébert, J., Lecomte, H., 2016. National Forest Inventories Reports: Belgium (Wallonia). In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 159–179.

Alfonso XI, Rey de Castilla, 1877. Libro de la Montería del Rey D. Alfonso XI. Con un discurso y notas del Excmo. Señor José Gutierrez de la Vega. Tomo I y II. Imprenta y fundicion de M. Tello, Impresor de Cámara de S. M., Madrid.

Anonymous, 1914. Värmlands läns skogar. Betänkande avgivet av Kommissionen för försökstaxering av virkeskapital, tillväxt m.m. av skogarna i Värmlands län. Jämte Plan till en taxering av Sveriges samtliga skogar. Stockholm.

Astrup, R., Rahlf, J., Bjørkelo, K., Debella-Gilo, M., Gjertsen, A.-K., Breidenbach, J., 2019. Forest information at multiple scales: Development, evaluation and application of the Norwegian forest resources map SR16. Scand. J. For. Res. 34 (6), 484–496.
Axelsson, A.-L., Stahl, G., Söderberg, U., Pettersson, H., Fridmann, J., Lundström, A., 2010. National Forest Inventory Reports: Sweden, in: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer Netherlands, pp. 541-553.
Barreiro, S., Schelhaas, M.-J., Kändler, G., Antón-Fernández, C., Colin, A., Bontemps, J.-D., Alberdi, I., Condés, S., Dumitru, M., Ferezliev, A., Fischer, C., Gasparini, P., Gschwantner, T., Kindermann, G., Kjartansson, B., Kovácsevics, P., Kucera, M., Lundström, A., Marin, G., Mozgeris, G., Nord-Larsen, T., Packalen, T., Redmond, J., Sacchelli, S., Sims, A., Snorrason, A., Stoyanov, N., Thürig, E., Wikberg, P.-E., 2016. Overview of methods and tools for evaluating future woody biomass availability in European countries. Ann. For. Sci. 73 (4), 823–837. https://doi.org/10.1007/s13595-016-0564-3.
Barrett, F., McRoberts, R.E., Tomppo, E., Cienciala, E., Waser, L.T., 2016. A questionnaire-based review of the operational use of remotely sensed data by National Forest Inventories. Remote Sens. Environ. 174, 279–289. https://doi.org/10.1016/j.rse.2015.08.029.
Barták, J., 1929. Z minulosti štátneho lesného hospodárstva v okolí Banskej Bystrice a Starých Hôr. Slovenská Grafia, Banská Bystrica, p. 207.
Basto, E.A.L., 1936. Inquérito Económico-Agrícola, Vol IV. Universidade Técnica de Lisboa.
Bastrup-Birk, A., Nord-Larsen, T., Johannsen, V.K., Skovsgaard, J.P., Butterschøn, R., Vesterdal, L., 2010. National Forest Inventory Reports: Denmark. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 157–169.
Bauger, E., 1995. Funksjoner og tabeller for kubering av stående trær: Furu, gran og sitkagran på Vestlandet. Rapport fra Skogforsk 16/95, 26 p.
Bauwens, S., Bartholomeus, H., Calders, K., Lejeune, P., 2016. Forest inventory with terrestrial LiDAR: A comparison of static and hand-held mobile laser scanning. Forests 7, 127. https://doi.org/10.3390/f7060127.
Berg, E. von, 1859. Die Wälder in Finnland. Helsinki, 63 p.
Berger, A., Gschwantner, T., Gabler, K., Schadauer, K., 2012. Analysis of tree measurement errors in the Austrian National Forest Inventory. Austrian J. For. Sci. 129, 149–177.
Berger, A., Gschwantner, T., McRoberts, R.E., Schadauer, K., 2014. Effects of measurement errors on individual tree stem volume estimates for the Austrian National Forest Inventory. For. Sci. 60 (1), 14–24. https://doi.org/10.5849/forsci.12-164.
Berger, A., Gschwantner, T., Schadauer, K., 2020. The effects of truncating the Angle Count Sampling method on the Austrian National Forest Inventory. Ann. For. Sci. 77, 16. https://doi.org/10.1007/s13595-019-0907-y.
Bitterlich, W., 1948. Die Winkelzählprobe. Allgemeine Forst- und Holzwirtschaftliche Zeitung 59, 4–5.
Bitterlich, W., 1992. Spiegel-Relaskop – Handbuch Teil 1 und 2. Relaskop-Technik Vertriebsges.m.b.H, Salzburg, Austria, p. 35.
Bjerreskov, K.S., Nord-Larsen, T., Fensholt, R., 2021. Classification of nemoral forests with fusion of multi-temporal Sentinel-1 and 2 data. Remote Sens. 13, 950. https://doi.org/10.3390/rs13050950.
BMLF and FBVA, 1960. Österreichische Waldstandsaufnahme 1952/56 – Gesamtergebnis. Bundesministerium für Land- und Forstwirtschaft und Forstliche Bundesversuchsanstalt Wien, 323 p.
Bosela, M., Redmond, J., Kučera, M., Marin, G., Adolt, R., Gschwantner, T., Petráš, R., Korhonen, K., Kuliešis, A., Kulbokas, G., Fischer, C., Lanz, A., 2016. Stem quality assessment in European National Forest Inventories: An opportunity for harmonised reporting? Ann. For. Sci. 73 (3), 635–648. https://doi.org/10.1007/s13595-015-0503-8.
Bosela, M., Seben, V., 2016. National Forest Inventories Reports: Slovakia, in: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer, Cham, pp. 731-747.
Bosela, M., Tumajer, J., Cienciala, E., Dobor, L., Kulla, L., Marčiš, P., Popa, I., Sedmák, R., Sedmáková, D., Sitko, R., Šebeň, V., Štěpánek, P., Büntgen, U., 2021. Climate warming induced synchronous growth decline in Norway spruce populations across biogeographical gradients since 2000. Sci. Total Environ. 752, 141794. https://doi.org/10.1016/j.scitotenv.2020.141794.
Bouriaud, O., Stefan, G., Saint-André, L., 2019. Comparing local calibration using random effects estimation and Bayesian calibrations: a case study with a mixed effect stem profile model. Ann. For. Sci. 76, 65. https://doi.org/10.1007/s13595-019-0848-5.
Bouriaud, O., Marin, G., Hervé, J.-C., Riedel, T., Lanz, A., 2020. Estimation methods in the Romanian National Forest Inventory. Nova, Environmental Science, Engineering and Technology.
Braastad, H., 1966. Volumtabeller for bjørk. Meddr norske SkogforsVes 21, 23-78.
Bradshaw, R.H.W., 2004. Past anthropogenic influence on European forests and some possible genetic consequences. For. Ecol. Manag. 197 (1-3), 203–212. https://doi.org/10.1016/j.foreco.2004.05.025.
Brändli, U.-B., Hägeli, 2019. Swiss NFI at a glance, in: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and models of the fourth Assessment. Springer International Publishing, Cham, pp. 3–35.
Brantseg, A., 1967. Furu sønnafjells. Kubering av stående skog. Funksjoner og tabeller. Meddr norske SkogforsVes 22, 689–739.
Braun, R., 1969. Österreichische Forstinventur – Methodik der Auswertung und Standardfehlerberechnung. Mitteilungen der Forstlichen Bundesversuchsanstalt Wien 84, 60 p.
Braun, R., 1974. Die methodische Entwicklung der österreichischen Forstinventur. In: FBVA, 100 Jahre Forstliche Bundesversuchsanstalt. Carl Ueberreuter, Wien, pp. 173–222.
Braun, M., Fritz, D., Weiss, P., Braschel, N., Büchsenmeister, R., Freudenschuß, A., Gschwantner, T., Jandl, R., Ledermann, T., Neumann, M., Pölz, W., Schadauer, K., Schmid, C., Schwarzbauer, P., Stern, T., 2016. A holistic assessment of greenhouse gas dynamics from forests to the effects of wood products use in Austria. Carbon Manag. 7 (5–6), 271–283. https://doi.org/10.1080/17583004.2016.1230990.
Breidenbach, J., Kublin, E., McGaughey, R., Andersen, H.-E., Reutebuch, S., 2008. Mixed-effects models for estimating stand volume by means of small footprint airborne laser scanner data. Photogramm. J. Finl. 21, 4–15.
Breidenbach, J., Astrup, R., 2012. Small area estimation of forest attributes in the Norwegian National Forest Inventory. Eur. J. For. Res. 131 (4), 1255–1267.
Breidenbach, J., Antón-Fernández, C., Petersson, H., McRoberts, R.E., Astrup, R., 2014. Quantifying the model-related variability of biomass stock and change estimates in the Norwegian National Forest Inventory. For. Sci. 60 (1), 25–33. https://doi.org/10.5849/forsci.12-137.
Breidenbach, J., Granhus, A., Hylen, G., Eriksen, R., Astrup, R., 2020a. A century of National Forest Inventory in Norway – Informing past, present, and future decisions. For. Ecosyst. 7, 46. https://doi.org/10.1186/s40663-020-00261-0.
Breidenbach, J., Waser, L.T., Debella-Gilo, M., Schumacher, J., Rahlf, J., Hauglin, M., Puliti, S., Astrup, R., 2020b. National mapping and estimation of forest area by dominant tree species using Sentinel-2 data. Can. J. For. Res. 51 (3), 365–379. https://doi.org/10.1139/cjfr-2020-0170.
Breidenbach, J., Ivanovs, J., Kangas, A., Nord-Larsen, T., Nilsson, M., Astrup, R., 2021. Improving living biomass C-stock loss estimates by combining optical satellite, airborne laser scanning, and NFI data. Can. J. For. Res. 51 (10), 1472–1485. https://doi.org/10.1139/cjfr-2020-0518.
Brenac, L., 1984. Connaissances et statistiques des forêts françaises avant l'inventaire forestier national. Revue forestière française XXXVI 77–90. https://doi.org/10.4267/2042/21712.
Brukas, A., Jakubonis, S., Kuliešis, A., Rutkauskas, A., 2002. Forest management planning and its development in Lithuania (in Lithuanian). Naujasis lankas, Kaunas, p. 188.
Campbell, B., 2000. The writings of the Roman land surveyors - Introduction, text, translation and commentary. Journal of Roman studies, Monograph 9, 570 p. https://doi.org/10.2307/3184871.
Charru, M., Seynave, I., Hervé, J.-C., Bertrand, R., Bontemps, J.-D., 2017. Recent growth changes in Western European forests are driven by climate warming and structured across tree species climatic habitats. Ann. For. Sci. 74, 33. https://doi.org/10.1007/s13595-017-0626-1.
Cochran, W., 1977. Sampling Techniques. Wiley, New York, p. 448.
Čokl, M., 1957. Prirejene Alganove in Schafferjeve tarife ter njihova raba pri inventraizaciji sestojev. Zbornik gozdarstva in lesarstva 2, 165–195.
Colón, H., 1988. Descripción y cosmografía de España. Manuscrito de la Biblioteca Colombina, Padilla Libros, Sevilla.
Cotta, J.H., 1804. Systematische Anleitung zur Taxation der Waldungen. Berlin, J.D, Sander, p. 261.
Cunia, T., 1965. Some theory on reliability of volume estimates in a forest inventory sample. For. Sci. 11, 115–128.
DAFM, 2018. Ireland's National Forest Inventory – Field procedures and methodology. Department of Agriculture, Food and the Marine. https://www.gov.ie/en/publication/823b8-irelands-national-forest-inventory/ (accessed 21 September 2021).
Dagnelie, P., Palm, R., Rondeux, J., 2013. Cubage des arbres et des peuplements forestiers - Tables et équations. Les Presses agronomiques de Gembloux, 176 p.
Daubrée, L., 1912. Statistique et atlas des forêts de France, 2 vol. Imprimerie Nationale, Paris, p. 724.
De Coene, K., Ongena, T., Stragier, F., Vervust, S., Bracke, W., De Maeyer, P., 2012. Ferraris, the legend. Cartogr. J. 49 (1), 30–42. https://doi.org/10.1179/1743277411Y.0000000013.
Delijska, B., Manoilov, P., 2004. Elsevier's dictionary of forestry. Elsevier, Amsterdam, p. 1060.
Deltuvas, R., 2019. Forest and game management in Lithuania Minor (in Lithuanian). Klaipėda, 344 p.
Det Statistiske Centralbyraa, 1910. Norges officielle Statistik V 109. Jordbrukstællingen i Kongeriket Norge 30 September 1907 - Arealet og dets anvendelse. Kristiana, 157 p.
DIABOLO, 2015. Distributed, Integrated And Harmonised Forest Information For Bioeconomy Outlooks. http://diabolo-project.eu/ (accessed 21 September 2021).
Di Cosmo, L., Gasparini, P., Tabacchi, G., 2016. A National-scale, stand-level model to predict total above-ground tree biomass from growing stock volume. For. Ecol. Manag. 361, 269–276. https://doi.org/10.1016/J.foreco.2015.11.008.
Drexhage, M., Colin, F., 2001. Estimating root system biomass from breast-height diameters. Forestry 74, 491–497. https://doi.org/10.1093/forestry/74.5.491.
Düggelin, C., Abegg, M., Bischof, S., Brändli, U.-B., Cioldi, F., Fischer, C., Meile, R., 2020. Schweizerisches Landesforstinventar. Anleitung für die Feldaufnahmen der fünften Erhebung 2018–2026. WSL Berichte. Eidg. Forschungsanstalt für Wald. Schnee und Landschaft, Birmensdorf.
Dupuy, J.-L., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., Fernandes, P., 2020. Climate change impact on future wildfire danger and activity in southern Europe: a review. Ann. For. Sci. 77, 35. https://doi.org/10.1007/s13595-020-00933-5.
Dyderski, M.K., Paź, S., Frelich, L.E., Jagodziński, A.M., 2018. How much does climate change threaten European forest tree species distributions? Glob. Change Biol. 24 (3), 1150–1163. https://doi.org/10.1111/gcb.2018.24.issue-310.1111/gcb.13925.
EC, 2003. Natura 2000 and forests 'Challenges and Opportunities' - Interpretation Guide. Office for Official Publications of the European Communities, Luxembourg, 101 p.

EC, 2013. A new EU Forest Strategy: for forests and the forest-based sector. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 17 p.
EC, 2018a. Progress in the implementation of the EU Forest Strategy 'A new EU Forest Strategy: for forests and the forest sector'. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 11 p.
EC, 2018b. A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment - Updated Bioeconomy Strategy Publications Office of the European Union, Luxembourg, 103 p.
Eckmüllner, O., Schedl, P., Sterba, H., 2007. Neue Schaftkurven für die Hauptbaumarten Österreichs und deren Ausformung in marktkonforme Sortimente. Austrian J. For. Sci. 124, 215–236.
EFICS, 1997. Study on European forestry information and communication system – Reports on forest inventory and survey systems, Volumes 1 and 2. European Communities, Luxembourg.
ENFIN, 2021. European National Forest Inventory Network. http://www.enfin.info/ (accessed 21 September 2021).
Etverk, I., 1998. Eesti riigimetsad ja nende majandamine 1918-1998 [Estonian state forests and management in 1918-1998]. Tallinn, 233 p.
European Parliament and Council of the European Union, 2009. Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Official Journal of the European Union.
European Parliament and Council of the European Union, 2018. EU-Regulation 2018/841 of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU.
Evelyn, J., 1760. Sylva, or, a discourse of forest-trees and the propagation of timber. Jo. Martin and Ja. Allestry, Printers to the Royal Society 247 p.
Eyvindson, K., Repo, A., Mönkkönen, M., 2018. Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. For. Pol. Econ. 92, 119–127. https://doi.org/10.1016/j.forpol.2018.04.009.
FAO, 1948. Forest Resources of the World. Unasylva 2(4), Washington, DC.
FAO, 1998. The Global forest resources assessment 2000 - Terms and definitions. FRA Working Paper 1, 19 p.
FAO, 2001. The global forest resources assessment 2000 – Main report. FAO Forestry Paper 140, Rome, 479 p.
FAO, 2004. Global forest resources assessment update 2005 – Terms and definitions. Forest Resources Assessment Programme, Working paper 83/E, 34 p.
FAO, 2010. Global forest resources assessment 2010 – Terms and definitions. Forest Resources Assessment Programme, Working paper 144/E, 27 p.
FAO, 2012. Global forest resources assessment 2015 – Terms and definitions. Forest Resources Assessment Working Paper 180, 31 p.
FAO, 2015. Global forest resources assessment 2015 – Desk reference. Food and Agriculture Organisation of the United Nations, Rome, 245 p.
FAO, 2018. Global forest resources assessment 2020 – Terms and definitions. Forest resources assessment working paper 188, FAO Rome, 26 p.
FAO, 2020. Global Forest Resources Assessment 2020 - Main report. Food and Agriculture Organisation of the United Nations, Rome, 164 p. http://dx.doi.org/10.4060/ca9825en.
Fischer, C., Gasparini, P., Nylander, M., Redmond, J., Hernandez, L., Brändli, U.-B., Pastos, A., Rizzo, M., Alberdi, I., 2016. Joining criteria for harmonizing European Forest Available for Wood Supply estimates - Case studies from National Forest Inventories. Forests 7, 104. https://doi.org/10.3390/f7050104.
Fischer, C., Traub, B. (Eds.), 2019. Swiss National Forest Inventory – Methods of the fourth assessment. Springer International, Managing Forest Ecosystems 35, 431 p. http://dx.doi.org/10.1007/978-3-030-19293-8.
Fisher, R.A., 1950. Statistical methods for research workers. Edinburgh and London.
Forest Europe, 2015. State of Europe's Forest 2015. Ministerial Conference on the Protection of Forests in Europe. Forest Europe Liaison Unit, Madrid, p. 312–p.
Forest Europe, 2020. State of Europe's Forest 2020. Ministerial Conference on the Protection of Forests in Europe. Forest Europe Liaison Unit Bratislave, p. 392–p.
Fortin, M., 2020. Updating plots to improve the precision of small-area estimates: the example of the Lorraine region, France. Can. J. For. Res. 50 (7), 648–658. https://doi.org/10.1139/cjfr-2019-0405.
Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., Beck, P. S.A., Camps-Valls, G., Chirici, G., Mauri, A., Cescatti, A., 2021. Emergent vulnerability to climate-driven disturbances in European forests. Nature Communications 12, 1081. https://doi.org/10.1038/s41467-021-21399-7.
Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Ringvall, A.H., Ståhl, G., 2014. Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. Silva Fenn. 48, 1095. https://doi.org/10.14214/sf.1095.
Fridman, J., Westerlund, B., 2016. National Forest Inventories Reports: Sweden, in: Vidal C. et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer, Cham, pp. 769–782.
Fryjordet, T., 1962. Skogadministrasjonen i Norge gjennom tidene, Bind II, Tiden etter 1857. Landbruksdepartementet Skogdirektoratet og Direktoratet for Statens skoger, Oslo, p. 710.
Fryjordet, T., 1992. Skogadministrasjonen i Norge gjennom tidene, Bind I, Skogforhold, skogbruk og skogadministrasjon fram til 1850. Landbruksdepartementet og Direktoratet for Statens skoger.
Fuhrmann, S., 2007. Digitale historische Geobasisdaten im Bundesamt für Eich- und Vermessungswesen (BEV) - Die Urmappe des Franziszeischen Kataster. Österreichische Zeitschrift für Vermessung und Geoinformation 25, 24–35.
Gabler, K., Schadauer, K., 2007. Some approaches and designs of sample-based National Forest Inventories. Austrian J. For. Sci. 124, 105–133.
Gabler, K., Schadauer, K., 2008. Methods of the Austrian Forest Inventory 2000/02 – Origins, approaches, design, sampling, data models, evaluation and calculation of the standard error. BFW-Berichte 142, 121.
von Gadow, K., 2005. Forsteinrichtung – Analyse und Entwurf der Waldentwicklung. Universitätsverlag Göttingen 342 p.
Gasparini, P., Bertani, R., De Natale, F., Di Cosmo, L., Pompei, E., 2009. Quality control procedures in the Italian national forest inventory. J. Environ. Monit. 11, 761–768. https://doi.org/10.1039/b818164k.
Gasparini, P., Di Cosmo, L., Cenni, E., Pompei, E., Ferretti, M., 2013. Towards the harmonization between National Forest Inventory and Forest Condition Monitoring. Consistency of plot allocation and effect of tree selection methods on sample statistics in Italy. Environ. Monit. Assess. 185 (7), 6155–6171. https://doi.org/10.1007/s10661-012-3014-1.
Gasparini, P., Di Cosmo, L., 2016. National Forest Inventories Reports: Italy. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 485–506.
Geburek, T., Milasowszky, N., Frank, G., Konrad, H., Schadauer, K., 2010. The Austrian Forest Biodiversity Index: All in one. Ecol. Indic. 10 (3), 753–761. https://doi.org/10.1016/j.ecolind.2009.10.003.
Gertner, G.Z., Köhl, M., 1992. An assessment of some nonsampling errors in a national survey using an error budget. For. Sci. 38, 525–538.
Ghimire, S., Xystrakis, F., Koutsias, N., 2017. Using terrestrial laser scanning to measure forest inventory parameters in a Mediterranean coniferous stand of western Greece. PFG – Journal of Photogrammetry. Remote Sensing and Geoinformation Science 85 (4), 213–225.
Ginzler, C., Price, B., Bösch, R., Fischer, C., Hobi, M.L., Psomas, A., Rehush, N., Wang, Z., Waser, L.T., 2019. Area-Wide Products. In: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and Models of the Fourth Assessment. Springer International Publishing, Cham, pp. 125–142. https://doi.org/10.1007/978-3-030-19293-8.
Gomes, B.B., 1865. Relatório florestal sobre as Matas da Machada e Valle de Zebro. Imprensa Nacional, Lisboa, p. 52.
Grafström, A., Zhao, X., Nylander, M., Petersson, H., 2017. A new sampling strategy for forest inventories applied to the temporary clusters of the Swedish national forest inventory. Can. J. For. Res. 47 (9), 1161–1167. https://doi.org/10.1139/cjfr-2017-0095.
Graves, H.S., 1906. Forest Mensuration. John Wiley and Sons, New York, p. 458.
Gregoire, T.G., Valentine, H.T., 2007. Sampling strategies for natural resources and the environment. Chapman and Hall 494 p.
Grundner, F., Schwappach, A., 1922. Massentafeln zur Bestimmung des Holzgehaltes stehender Waldbäume und Waldbestände, Sechste Auflage. Paul Parey, Berlin, 154 p.
Gschwantner, T., Schadauer, K., Vidal, C., Lanz, A., Tomppo, E., Di Cosmo, L., Robert, N., Englert Duursma, D., Lawrence, M., 2009. Common tree definitions for National Forest Inventories in Europe. Silva Fenn. 43, 303–321. https://doi.org/10.14214/sf.463.
Gschwantner, T., Berger, A., Büchsenmeister, R., Hauk, E., 2016. National Forest Inventories Reports: Austria. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 135–157.
Gschwantner, T., Alberdi, I., Balázs, A., Bauwens, S., Bender, S., Borota, D., Bosela, M., Bouriaud, O., Cañellas, I., Donis, J., Freudenschuß, A., Hervé, J.-C., Hladnik, D., Jansons, J., Kolozs, L., Korhonen, K.T., Kucera, M., Kulbokas, G., Kuliešis, A., Lanz, A., Lejeune, P., Lind, T., Marin, G., Morneau, F., Nagy, D., Nord-Larsen, T., Nunes, L., Pantić, D., Paulo, J.A., Pikula, T., Redmond, J., Rego, F.C., Riedel, T., Saint-André, L., Šebeň, V., Sims, A., Skudnik, M., Solti, G., Tomter, S.M., Twomey, M., Westerlund, B., Zell, J., 2019. Harmonisation of stem volume estimates in European National Forest Inventories. Ann. For. Sci. 76 (1) https://doi.org/10.1007/s13595-019-0800-8.
Haakana, H., Heikinen, J., Katila, M., Kangas, A., 2019. Efficiency of post-stratification for a large-scale forest inventory – case Finnish NFI. Ann. For. Sci. 76, 9. https://doi.org/10.1007/s13595-018-0795-6.
Haglöf Sweden AB, 2014-2017. Users Guide Vertex IV and Transponder T3 V1.0 German, 2014-03-18/Rev.2017-04-11. 26 p.
Harley, J.B., Woodward, D. (Eds.), 1987. The history of cartography. University of Chicago Press, Chicago.
Hartig, G.L., 1795. Anweisung zur Taxation der Forste, oder zur Bestimmung des Holzertrags der Wälder. Heyer, Giessen, 200 p.
Hasel, K., Schwartz, E., 2002. Forstgeschichte – Ein Grundriss für Studium und Praxis. Kessel, Remagen, p. 394.
Heinonen, T., Pukkala, T., Mehtätalo, L., Asikainen, A., Kangas, J., Peltola, H., 2017. Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry. For. Policy Econ. 80, 80–98. https://doi.org/10.1016/j.forpol.2017.03.011.
Helms, J.A., 1998. The dictionary of forestry. CAB International. the Society of American Foresters, Wallingford, p. 210.
Henning, L., Korhonen, K.T., Lanz, A., Riedel, T., 2016. Final Report, Specific Contract nr. 17 "Use of National Forest Inventories data to estimate biomass in the European Forests" in the context pf the "Framework contract for the provision for forest data and services in support to the European Forest Data Centre". Joint Research Centre of the European Commission, Ispra, Italy.
Hennius, A., 2018. Viking age tar production and outland exploitation. Antiqu. 92 (365), 1349–1361. https://doi.org/10.15184/aqy.2018.22.

Herold, A., Zell, J., Rohner, B., Didion, M., Thürig, E., Rösler, E., 2019. State and change of forest resources. In: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and models of the fourth Assessment. Springer International Publishing, Cham, pp. 205–230.

Hervé, J.-C., 2016. National Forest Inventories Reports: France. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 385–404.

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., Turčáni, M., 2021. Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. For. Ecol. Manag. 490, 119075. https://doi.org/10.1016/j.foreco.2021.119075.

Hollaus, M., Wagner, W., Schadauer, K., Maier, B., Gabler, K., 2009. Growing stock estimation for alpine forests in Austria: A robust lidar-based approach. Can. J. For. Res. 39 (7), 1387–1400. https://doi.org/10.1139/X09-042.

Huber, F.X., 1828. Hilfstabellen für Bedienstete des Forst- und Baufaches zunächst zur leichten und schnellen Bestimmung des Massengehaltes roher Holzstämme und der Theile derselben, und auch zu anderem Gebrauche für jedes landesübliche Maaß anwendbar. Fleischmann, München, 130 p.

Hundeshagen, J.C., 1826. Die Forstabschätzung auf neuen, wissenschaftlichen Grundlagen, nebst einer Charakteristik und Vergleichung aller bisher bestandenen Forsttaxations-Methoden. Laupp, Tübingen, 428 p.

Hurmekoski, E., Jonsson, R., Korhonen, J., Jänis, J., Mäkinen, M., Leskinen, P., Hetemäki, L., 2018. Diversification of the forest industries: role of new wood-based products. Can. J. For. Res. 48 (12), 1417–1432. https://doi.org/10.1139/cjfr-2018-0116.

ICNF, 2016. 6° Inventário Florestal Nacional - Relatório Final. Instituto da Conservação da Natureza e das Florestas. 284 p.

ICONA, 1990. Segundo Inventario Forestal Nacional - Explicaciones y Métodos. Ministerio de Agricultura, Pesca y Alimentación. Servicio de Inventario Forestal, 174 p.

IFER, 2020. Field-Map - Technology designed for field data collection and processing. https://www.fieldmap.cz/ (accessed 21 September 2021).

Ilvessalo, Y., 1923. Tutkimuksia yksityismetsien tilasta Hämeen läänin keskiosissa. Acta Forestalia Fennica 26 (2), 7090. https://doi.org/10.14214/aff.7090.

Ilvessalo, Y., 1924. Finnlands Wälder. Waldvorräte und Zustand der Wälder. Metsätieteellisen koelaitoksen julkaisuja 9.

Ilvessalo, Y., 1927. The forests of Suomi Finland. Results of the general survey of the forests of the country carried out during the years 1921-1924. Communicationes ex Instituto Quaestionum Forestalium Finlandie 11.

IPCC, 2003. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.), Good practice guidance for land use, land-use change and forestry. Institute for Global Environmental Strategies (IGES), Hayama, Japan.

IPCC, 2006. Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Published: IGES, Japan.

Irulappa-Pillai-Vijayakumar, D.B., Renaud, J.-P., Morneau, F., McRoberts, R.E., Vega, C., 2019. Increasing precision for French forest inventory estimates using the k-NN technique with optical and photogrammetric data and model-assisted estimators. Remote Sens. 11, 991. https://doi.org/10.3390/rs11080991.

IUFRO, 1959. The Standardization of symbols in forest mensuration. University of Maine 32, p.

IUFRO, 2021. SilvaTerm Database. https://www.iufro.org/science/special/silvavoc/silvaterm/(accessed 21 September 2021).

Jansons, J., Licite, I., 2010. National Forest Inventory Reports: Latvia. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for common reporting. Springer, Netherlands, pp. 341–349.

Johann, E., 1983. Waldbereitungen. In: Braun, R. (Ed.), Österreichs Wald in Vergangenheit und Gegenwart. Österreichischer Agrarverlag, Wien, pp. 135–143.

Jonsson, R., Rinaldi, F., Pilli, R., Fiorese, G., Hurmekoski, E., Cazzaniga, N., Robert, N., Camia, A., 2021. Boosting the EU forest-based bioeconomy: Market, climate, and employment impacts. Techn. Forecast. Soc. Change 163, 120478. https://doi.org/10.1016/j.techfore.2020.120478.

Kallio, A. Maarit I., 2021. Wood-based textile fibre market as part of the global forest-based bioeconomy. For. Pol. Econ. 123, 102364. https://doi.org/10.1016/j.forpol.2020.102364.

Kangas, A., Maltamo, M., 2006. Forest Inventory – Methodology and Applications. Springer, Dordrecht, p. 362.

Kangas, A., Astrup, R., Breidenbach, J., Fridman, J., Gobakken, T., Korhonen, K.T., Maltamo, M., Nilsson, M., Nord-Larsen, T., Næsset, E., Olsson, H., 2018. Remote sensing and forest inventories in Nordic countries – roadmap for the future. Scand. J. For. Res. 33 (4), 397–412. https://doi.org/10.1080/02827581.2017.1416666.

Kangas, A., Henttonen, H.M., Pitkänen, T.P., Sarkkola, S., Heikkinen, J., 2020. Re-calibrating stem volume models – is there a change in the tree trunk form from the 1970s to the 2010s in Finland? Silv. Fenn. 54, 10269. https://doi.org/10.14214/sf.10269.

Kankare, V., Joensuu, M., Vauhkonen, J., Holopainen, M., Tanhuanpää, T., Vastaranta, M., Hyyppä, J., Hyyppä, H., Alho, P., Rikala, J., Sipi, M., 2014. Estimation of the timber quality of scots pine with terrestrial laser scanning. Forests 5, 1879–1895. https://doi.org/10.3390/f5081879.

Kaufmann, E., 2001. Estimation of standing timber, growth and cut. In: Brassel, P., Lischke, H. (Eds.), Swiss National Forest Inventory: Methods and models of the second assessment. Swiss Federal Research Institute WSL, Birmensdorf, pp. 162–196.

Kerfriden, B., Bontemps, J.-D., Leban, J.-M., 2021. Variations in temperate forest stem biomass ratio along three environmental gradients are dominated by interspecific differences in wood density. Plant Ecol. 222 (3), 289–303. https://doi.org/10.1007/s11258-020-01106-0.

Kleinn, C., Kändler, G., Polley, H., Riedel, T., Schmitz, F., 2020. The National Forest Inventory in Germany: Responding to forest-related information needs. Allgemeine Forst- und Jagd Zeitung 191, 97–118.

Koch, B., 2013. Remote sensing supporting national forest inventories NFA. Knowledge reference for national forest assessments. FAO and SLU, 15 p.

Köhl, M., Traub, B., Päivinen, R., 2000. Harmonisation and Standardisation in Multi-National Environmental Statistics – Mission Impossible? Environ. Monit. Assess. 63, 361–380. https://doi.org/10.1023/A:1006257630216.

Köhl, M., 2001. Error sources and their influence on the NFI Inventory results. In: Brassel, P., Lischke, H. (Eds.), Swiss National Forest Inventory: Methods and models of the second assessment. Swiss Federal Research Institute WSL, Birmensdorf, pp. 297–305.

Köhl, M., Magnussen, S.S., Marchetti, M., 2006. Sampling methods, remote sensing and GIS multiresource forest inventory. Springer, Berlin, p. 373.

Köhl, M., Lasco, R., Cifuentes, M., Jonsson, Ö., Korhonen, K.T., Mundhenk, P., de Jesus Navar, J., Stinson, G., 2015. Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. For. Ecol. Manag. 352, 21–34. https://doi.org/10.1016/j.foreco.2015.05.036.

Köhl, M., Ehrhart, H.-P., Knauf, M., Neupane, P.R., 2020. A viable indicator approach for assessing sustainable forest management in terms of carbon emissions and removals. Ecol. Indic. 111, 106057. https://doi.org/10.1016/j.ecolind.2019.106057.

Koller, E. 1970. Forstgeschichte des Salzkammergutes. Österreichischer Agrarverlag. 584 p.

Kolozs, L., Solti, G., 2016. National Forest Inventories Reports: Hungary. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 439–450.

König, G., 1813. Anleitung zur Holztaxazion. Beckeŕsche Buchhandlung, Gotha, 260 p.

Koivuniemi, J., Korhonen, K.T., 2006. Inventory by compartments. In: Kangas, A., Maltamo, M. (Eds.), Managing Forest EcosystemsForest Inventory. Kluwer Academic Publishers, Dordrecht, pp. 271–278.

Korhonen, K.T., 1992. Calibration of upper diameter models in large scale forest inventory. Silva Fenn. 26, 231–239. https://doi.org/10.14214/sf.a15652.

Korhonen, K.T., Kangas, A., 1997. Application of nearest-neighbour regression for generalizing tree information. Scand. J. For. Res. 12, 97–101. https://doi.org/10.1080/02827589709355389.

Korhonen, K.T., Riedel, T., Lanz, A., 2014. Final Report, Specific contract nr. 13 “Use of National Forest Inventories data to estimate biomass in the European Forests” in the context of the “Framework contract for the provision of forest data and services in support to the European Forest Data Centre”, 2 December 2014. Joint Research Centre of the European Commission, Ispra, Italy.

Korhonen, K.T., 2016. National Forest Inventories Reports: Finland. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 369–384.

Kublin, E., 2003. Einheitliche Beschreibung der Schaftform - Methoden und Programme – BDATPro. Forstwissenschaftliches Centralblatt 122, 183–200. https://doi.org/10.1046/j.1439-0337.2003.00183.x.

Kublin, E., Breidenbach, J., Kändler, G., 2013. A flexible stem taper and volume prediction method based on mixed-effects B-spline regression. Eur. J. For. Res. 132, 983–997. https://doi.org/10.1007/s.10342-013-0715-0.

Kučera, M., 2016. National Forest Inventories Reports: Czech Republic. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 307–325.

Kuliešis, A., Kenstavičius, J., 1976. Modelling of stem form factors (In Russian). Lesovedenije 3, 85–91.

Kuliešis, A., Kasperavičius, A., Kulbokas, G., Kvalkauskienė, M., 2003. Lithuanian National Forest Inventory 1998 – 2002. Sampling design, methods, results. Naujasis lankas, Kaunas, 255 p.

Kuliešis, A., Kulbokas, G., Kasperavičius, A., 2010a. National Forest Inventory Reports: Lithuania. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for Common Reporting. Springer, Netherlands, pp. 351–374.

Kuliešis, A., Kulbokas, G., Kasperavičius, A., Kuliešis, A.A., 2010b. Forest inventory system and its development regarding to intensive forestry demands (in Lithuanian). Miškininkystė 2, 61–77.

Kuliešis, A., Kulbokas, G., Jansons, J., 2011. Comparability of Scots pine growing stock volume, estimated by NFI of Baltic countries. In: 5th International Scientific Conference, 24-25 November, Proceedings, Vol. 5, b. 2. Aleksandras Stulginskis University, Akademija, pp. 54–59.

Kuliešis, A., Kulbokas, G., Kuliešis, A.A., 2014. Validation of generalized height–diameter model based on Lithuanian NFI data. Balt. For. 20, 287–300.

Kuliešis, A., Tomter, S.M., Vidal, C., Lanz, A., 2016. Estimates of stem wood increments in forest resources: comparison of different approaches in forest inventory: consequences for international reporting: case study of European forests. Ann. For. Sci. 73 (4), 857–869. https://doi.org/10.1007/s13595-016-0559-0.

Kušar, G., Kovac, M., Simoncic, M., 2010. National Forest Inventory Reports: Slovenia. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for Common Reporting. Springer, Netherlands, pp. 505–526.

Kušar, G., Hladnik, D., Hočevar, M., 2013. The reliability of volume functions based on spruce tree species in Slovenia. Acta Silvae et Ligni 102, 43–54.

Laasasenaho, J., 1976. Männyn, kuusen ja koivun kuutioimisyhtälöt. Lisensiaattityö. Helsingin yliopisto, Metsänarvioimistieteen laitos, p. 89.

Laasasenaho, J., 1982. Taper curve and volume functions for pine, spruce and birch. Commun. Inst. For. Fenn. 108, 1–74.

Landsskogtakseringen, 1920. Taksering av Norges skoger utført av Landsskogtakseringen - 1. Østfold fylke. Hamar.

Landsskogtakseringen, 1933. Taksering av Norges skoger utført av Landsskogtakseringen, Oslo.
Lanz, A., Alberdi, I., Barbati, A., Barsoum, N., Brändli, U.-B., Chirici, G., Cienciala, E., Condes, S., Di Cosmo, L., Freudenschuss, A., Gabler, K., Gschwantner, T., Hylen, G., Ilvesniemi, H., Kušar, G., Kändler, G., Lawrence, M., McRoberts, R.E., Nabuurs, G.-J., Petersson, H., Priwitzer, T., Robert, N., Rondeux, J., Schadauer, K., Ståhl, G., Tomter, S., Tomppo, E., Tosi, V., Vidal, C., Weiss, P., Winter, S., 2010. A sample of COST Action E43 reference definitions. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for common reporting. Springer, Netherlands, pp. 595–607.
Lanz, A., 2012. Estimators for the E-Forest Platform. Ver. 1.11, 6 November 2012. Annex to the Final report, Specific Contract n. 8 "Statistical calculations at European level using design based estimators" in the context of the "Framework contract for the provision of forest data and services in support to the European Forest Data Centre". Joint Research Centre of the European Commission, Ispra, Italy.
Lanz, A., Abegg, M., Braendli, U.-B., Camin, P., Cioldi, F., Ginzler, C., Fischer, C., 2016. National Forest Inventories Country Reports: Switzerland. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 783–805.
Lanz, A., Adolt, R., Fejfar, J., Kohn, I., Morneau, F., Pesty, B., Riedel, T., 2019a. nFIESTA (new Forest Inventory ESTimation and Analysis): Demonstration study based on NFI plot data and large-area, high-resolution auxiliary data. Technical report, Diabolo project granted by European Union's Horizon 2020 programme, 35 p. https://cordis.europa.eu/project/id/633464/results/ (accessed 21 September 2021).
Lanz, A., Fischer, C., Abegg, M., 2019b. Sampling design and estimation prodecures, in: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and models of the fourth assessment. Springer International, Managing Forest Ecosystems 35, pp. 39–92.
Laser Technology Inc., 2006. Criterion RD 1000 User's manual 34, p.
Lawrence, M., McRoberts, R.E., Tomppo, E., Gschwantner, T., Gabler, K., 2010. Comparisons of National Forest Inventories. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for common reporting. Springer Netherlands, Dordrecht, pp. 19–32.
Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For. Ecol. Manag. 188 (1-3), 211–224. https://doi.org/10.1016/j.foreco.2003.07.008.
Lemoine-Isabeau, C., 1984. Les militaires et la cartographie des Pays-Bas méridionaux et de la Principauté de Liège à la fin du XVIIe et au XVIIIe siècle, Vol. 19. Musée royal de l'Armée, 296 p.
Lietuvos miškų statistika 1937 (1939). Miškų departamento leidinys. Kaunas, 298 p.
Loetsch, F., Haller, K.E., 1964. Forest Inventory, Vol. I. BLV Verlagsgesellschaft, 436 p.
Loetsch, F., Zöhrer, F., Haller, K.E., 1973. Forest Inventory, Vol II. BLV Verlagsgesellschaft, 469 p.
Longuetaud, F., Santenoise, P., Mothe, F., Kiessé, T.S., Rivoire, M., Saint-André, L., Ognouabi, N., Deleuze, C., 2013. Modeling volume expansion factors for temperate tree species in France. For. Ecol. Manag. 292, 111–121. https://doi.org/10.1016/j.foreco.2012.12.023.
Löw, M., Koukal, T., 2020. Phenology Modelling and Forest Disturbance Mapping with Sentinel-2 Time Series in Austria. Remote Sens. 12, 4191. https://doi.org/10.3390/rs12244191.
Lundmark, T., Bergh, J., Hofer, P., Lundström, A., Nordin, A., Poudel, B.C., Sathre, R., Taverna, R., Werner, F., 2014. Potential roles of Swedish forestry in the context of climate change mitigation. Forests 5, 557–578. https://doi.org/10.3390/f5040557.
Madsen, S.F., 1985. Compatible tree taper and volume functions for five different Conifers. Det Forstlige Forsøgsvæsen 40, 95–140.
Madsen, S.F., 1987. Volume equations for some important Danish forest tree species. Det Forstlige Forsøgsvæsen 41, 47–242.
Magnussen, S., McRoberts, R.E., Breidenbach, J., Nord-Larsen, T., Ståhl, G., Fehrmann, L., Schnell, S., 2020. Comparison of estimators of variance for forest inventories with systematic sampling-results from artificial populations. For. Ecosyst. 7, 1–19. https://doi.org/10.1186/s40663-020-00223-6.
Malinen, J., Kilpeläinen, H., Verkasalo, E., 2018. Validating the predicted saw log and pulpwood proportions and gross value of Scots pine and Norway spruce harvest at stand level by most similar neighbour analyses and a stem quality database. Silva Fenn. 52, id 9972. https://doi.org/10.14214/sf.9972.
Maltamo, M., Korhonen, K., Packalen, P., Mehtatalo, L., Suvanto, A., 2007. Testing the usability of truncated angle count sample plots as ground truth in airborne laser scanning-based forest inventories. Forestry 80 (1), 73–81. https://doi.org/10.1093/forestry/cpl045.
Maltamo, M., Packalen, P., Kangas, A., 2020. From comprehensive field inventories to remotely sensed wall-to-wall stand attribute data — a brief history of management inventories in the Nordic countries. Can. J. For. Res. 51 (2), 257–266. https://doi.org/10.1139/cjfr-2020-0322.
Mandallaz, D., 2008. Sampling techniques for forest inventories. Chapman and Hall 272 p.
Mandallaz, D., Massey, A., 2012. Comparison of estimators in one-phase two-stage Poisson sampling in forest inventories. Can. J. For. Res. 42 (10), 1865–1871. https://doi.org/10.1139/x2012-110.
Marin, G., Bouriaud, O., Dumitru, M., Nitu, M.D., 2016. National Forest Inventories Reports: Romania. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 683–698.
Marklund, L.G., 1988. Biomass functions for pine, spruce and birch in Sweden. Swedish University of Agricultural Sciences, Department of Forest Survey. Report 45, 71 p.
Matérn, B., 1960. Spatial variation. Meddelanden från Statens Skogsforskningsnstitut 49, 144 p.
McRoberts, R.E., Tomppo, E.O., 2007. Remote sensing support for National Forest Inventories. Remote Sens. Environ. 110 (4), 412–419. https://doi.org/10.1016/j.rse.2006.09.034.
McRoberts, R.E., Tomppo, E., Schadauer, K., Vidal, C., Ståhl, G., Chirici, G., Lanz, A., Cienciala, E., Winter, S., Smith, W.B., 2009. Harmonizing National Forest Inventories. J. For. 107, 179–187. https://academic.oup.com/jof/article/107/4/179/4599328.
McRoberts, R.E., Ståhl, G., Vidal, C., Lawrence, M., Tomppo, E., Schadauer, K., Chirici, G., Bastrup-Birk, A., 2010. National Forest Inventories: Prospects for harmonised international reporting. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for common reporting. Springer Netherlands, Dordrecht, pp. 33–43.
McRoberts, R.E., Tomppo, E.O., Schadauer, K., Ståhl, G., 2012a. Harmonizing National Forest Inventories. For. Sci. 58 (3), 189–190. https://doi.org/10.5849/forsci.12-042.
McRoberts, R.E., Winter, S., Chirici, G., LaPoint, E., 2012b. Assessing forest naturalness. For. Sci. 58, 294–309. https://doi.org/10.5849/forsci.10-075.
McRoberts, R.E., Næsset, E., Gobakken, T., 2013. Inference for lidar-assisted estimation of forest growing stock volume. Remote Sens. Environ. 128, 268–275. https://doi.org/10.1016/j.rse.2012.10.007.
McRoberts, R.E., Westfall, J.A., 2014. Effects of uncertainty in model predictions of individual tree volume on large area volume estimates. For. Sci. 60 (1), 34–42. https://doi.org/10.5849/forsci.12-141.
McRoberts, R.E., Næsset, E., Gobakken, T., 2016. The effects of temporal differences between map and ground data on map-assisted estimates of forest area and biomass. Ann. For. Sci. 73 (4), 839–847. https://doi.org/10.1007/s13595-015-0485-6.
Mecko, J., Petráš, R., Nociar, V., 1993. Konštrukcia nových stromových sortimentačných tabuliek pre smrekovec, hrab a brezu. Lesnícky časopis 39, 2096–2221.
Medarević, M., 2006. Planiranje gazdovanja šumama. Univerzitet u Beogradu, Šumarski fakultet, Beograd, p. 401.
Michelsen, K.-E., 1995. History of forest research in Finland. Part I - The unknown forest, The Finnish Forest Research Institute (Metla), Helsinki, p. 142.
Milizia Nazionale Forestale, 1936. Carta Forestale del Regno d'Italia in scala 1:100.000. http://193.205.194.133/ (accessed 21 September 2021).
Mina, M., Bugmann, H., Cordonnier, T., Irauschek, F., Klopcic, M., Pardos, M., Cailleret, M., Brando, P., 2017. Future ecosystem services from European mountain forests under climate change. J. Appl. Ecol. 54 (2), 389–401. https://doi.org/10.1111/1365-2664.12772.
Moravcik, M., Caboun, V., Priwitzer, T., 2010. National Forest Inventory Reports: Slovak Republic. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 489–503.
Morin, X., Fahse, L., Jactel, H., Scherer-Lorenzen, M., García-Valdés, R., Bugmann, H., 2018. Long-term response of forest productivity to climate change is mostly driven by change in tree species composition. Sci. Rep. 8, 5627. https://doi.org/10.1038/s41598-018-23763-y.
Morneau, F., 2015. Ajustement de nouveaux tarifs de cubage à 3 entrées pour l'Inventaire forestier national français. IGN, France, p. 19.
Näslund, M., 1971. New material for forest yield research. Royal College of Forestry, Stockholm. Studia Forestalia Suecica 89, 124 p.
Næsset, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data. Remote Sens. Environ. 61 (2), 246–253. https://doi.org/10.1016/S0034-4257(97)00041-2.
Næsset, E., 2002. Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data. Remote Sens. Environ. 80 (1), 88–99. https://doi.org/10.1016/S0034-4257(01)00290-5.
Näyhä A., Hetemäki L., Stern, T., 2014. New products outlook, in: Hetemäki, L. (Ed.), Future of the European forest-based sector: Structural changes towards bioeconomy. EFI, pp. 43 – 54.
Nilsson, M., Nordkvist, K., Jonzén, J., Lindgren, N., Axensten, P., Wallerman, J., Egberth, M., Larsson, S., Nilsson, L., Eriksson, J., Olsson, H., 2017. A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the national forest inventory. Remote Sens. Environ. 194, 447–454. https://doi.org/10.1016/j.rse.2016.10.022.
Nord-Larsen, T., Schumacher, J., 2012. Estimation of forest resources from a country wide laser scanning survey and national forest inventory data. Remote Sens. Environ. 119, 148–157. https://doi.org/10.1016/j.rse.2011.12.022.
Nord-Larsen, T., Johannsen, V.K., 2016. National Forest Inventories Reports: Denmark. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 327–345.
Nord-Larsen, T., Meilby, H., Skovsgaard, J.P., 2017. Simultaneous estimation of biomass models for 13 tree species: effects of compatible additivity requirements. Can. J. For. Res. 47, 765–776. https://doi.org/10.1139/cjfr-2016-0430.
O'Donovan, C., Redmond, J., 2010. National Forest Inventory Reports: Ireland. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 291–310.
Ozolins, R., 2002. Forest stand assortment structure analysis using mathematical modelling. Metsanduslikud uurimused XXXVII 33–42.
Packalen, T., Sallnäs, O., Sirkiä, S., Korhonen, K., Salminen, O., Vidal, C., Robert, N., Colin, A., Belouard, T., Schadauer, K., Berger, A., Rego, A., Louro, G., Camia, A., Räty, M., San-Miguel, J., 2014. The European Forestry Dynamics Model: concept, design and results of first case studies. JRC Science and Policy Reports Volume 93450, EUR 27004. Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/153990.
Päivinen, R., Lund, G.H., Poso, S., Zawila-Niedzwiecki, T. (eds.). 1994. IUFRO International Guidelines for Forest Monitoring. IUFRO World Series Vol. 5. IUFRO Secretariat, Vienna. 102 p.

Päivinen, R., Köhl, M., 2005. European Forest Information and Communication System (EFICS). European Forest Institute, Technical Report 17, 199 p.
Pantić, D., Medarević, M., Borota, D., 2016. National Forest Inventories Reports: Serbia. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 709–730.
Papanastasis, V.P., Arianoutsou, M., Papanastasis, K., 2010. Environmental conservation in classical Greece. J. Biol. Res. 14, 123–135.
Patterson, P.L., Reams, G.A. 2005. Combining panels for forest inventory and analysis estimation, in: Bechtold W.A., Patterson P.L. (Eds.), The enhanced forest inventory and analysis program – national sampling design and estimation procedures. USDA Forest Service, General Technical Report SRS-80, 69 – 74.
Paulo, J.A., Tomé, M., 2006. Equações para estimação do volume e biomassa de duas espécies de carvalhos: *Quercus suber* e *Quercus ilex*. Relatório científico do GIMREF. RC1/2006. Centro de Estudos Florestais, Instituto Superior de Agronomia, Lisboa.
Pereira, F.M.E., 1918. Livro da montaria, feito por D. João I, Rei de Portugal, conforme o manuscrito N° 4352 da Biblioteca Nacional de Lisboa. Academia das Sciências de Lisboa, Coimbra.
Perko, F., Kozorog, E., Boncina, A., 2014. Začetki načrtnega gospodarjenja z gozdovi na Slovenskem: Flameckovi in Lesseckovi načrti za Trnovski gozd ter bovške in tolminske gozdove, 1769–1771. ZGDS, Ljubljana, p. 416.
Perlin, J., 1989. A forest journey: The role of wood in the development of civilization. Harvard University Press, p. 445 p..
Petráš, R., Nociar, V., 1990. Nové sortimentačné tabuľky hlavných listnatých drevín. Lesnícky časopis 36, 535–552.
Petráš, R., Nociar, V., 1991a. Nové sortimentačné tabuľky hlavných ihličnatých drevín. Lesnícky časopis 37, 377–392.
Petráš, R., Nociar, V., 1991b. Sortimentačné tabuľky hlavných drevín. Veda, Bratislava, p. 304.
Petráš, R., Pajtík, J., 1991. Sústava česko-slovenských objemových tabuliek drevín. Lesnícky časopis 37, 49–56.
Petráš, R., Mecko, J., 1995. Models of volume, quality and value production of tree species in the Slovak Republic. Lesníctví-Forestry 41, 194–196.
Pettersson, H., 1955. Barrskogens volymproduktion. Meddelanden från Statens skogsforskningsinstitut 45, 391 p.
Power, H., Havreljuk, F., 2016. Predicting hardwood quality and its evolution over time in Quebec's forests. Forestry 91, 259–270. https://doi.org/10.1093/forestry/cpw059.
Prešern, J., Mihelič, J., Kobal, M., 2019. Growing stock of nectar- and honeydew-producing tree species determines the beekeepers' profit. For. Ecol. Manag. 448, 490–498. https://doi.org/10.1016/j.foreco.2019.06.031.
Prodan, M., 1965. Holzmesslehre. JD Sauerländer's Verlag, Frankfurt am Main, p. 644.
Profft, I., Mund, M., Weber, G.-E., Weller, E., Schulze, E.-D., 2009. Forest management and carbon sequestration in wood products. Eur. J. For. Res. 128 (4), 399–413. https://doi.org/10.1007/s10342-009-0283-5.
Puliti, S., Hauglin, M., Breidenbach, J., Montesano, P., Neigh, C.S.R., Rahlf, J., Solberg, S., Klingenberg, T.F., Astrup, R., 2020. Modelling above-ground biomass stock over Norway using national forest inventory data with ArcticDEM and Sentinel-2 data. Remote Sens. Environ. 236, 111501. https://doi.org/10.1016/j.rse.2019.111501.
Radkau, J., 2018. Holz – Wie ein Naturstoff Geschichte schreibt. Oekom, München, p. 349.
Rahlf, J., Hauglin, M., Astrup, R., Breidenbach, J., 2021. Timber volume estimation based on airborne laser scanning - Comparing the use of National Forest Inventory and forest management inventory data. Ann. For. Sci. 78 (2) https://doi.org/10.1007/s13595-021-01061-4.
Rais, A., Pretzsch, H., van de Kuilen, J.-W. G., 2014. Roundwood pregrading with longitudinal acoustic waves for production of structural boards. Eur. J. Wood Prod. 72 (1), 87–98. https://doi.org/10.1007/s00107-013-0757-5.
Räty, M., Heikkinen, J., Kangas, A., 2018. Assessment of sampling strategies utilizing auxiliary information in large-scale forest inventory. Can. J. For. Res. 48 (7), 749–757. https://doi.org/10.1139/cjfr-2017-0414.
Rego, F.C., 2001. Florestas Públicas. Direcção Geral das Florestas e Comissão Nacional Especializada de Fogos Florestais, Lisboa.
Rego, F., Louro, G., Constantino, L., 2013. The impact of changing wildfire regimes on wood availability from Portuguese forests. For. Policy Econ. 29, 56–61. https://doi.org/10.1016/j.forpol.2012.11.010.
Repola, J., 2009. Biomass equations for Scots pine and Norway spruce in Finland. Silva Fenn. 43, 625–647.
Ribeiro, C., Delgado, J.F.N.E., 1868. Relatório ácerca da Arborização Geral do Paiz, apresentado a sua Excellencia o Ministro das Obras Publicas, Commercio e Industria em resposta aos Quesitos do Artigo 18 do Decreto de 21 de Setembro de 1867. Ministério das Obras Publicas, Commercio e Industria. Typographia da Academia Real das Sciencias, Lisboa.
Riedel, T., Polley, H., Klatt, S., 2016. National Forest Inventories Reports: Germany. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 405–421.
Riemer, T., von Gadow, K., Slodoba, B., 1995. Ein Modell zur Beschreibung von Baumschäften. Allgemeine Forst- und Jagdzeitung 166, 144–147.
Rigling, A., Bigler, C., Eilmann, B., Feldmeyer-Christe, E., Gimmi, U., Ginzler, C., Graf, U., Mayer, P., Vacchiano, G., Weber, P., Wohlgemuth, T., Zweifel, R., Dobbertin, M., 2013. Driving factors of a vegetation shift from Scots pine to pubescent oak in dry Alpine forests. Glob. Change Biol. 19, 229-240. http://dx.doi.org/10.1111/gcb.12038.
Robert, N., Vidal, C., Colin, A., Hervé, J.-C., Hamza, N., Cluzeau, C., 2010. National Forest Inventory Reports: France. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 207–221.
Roesch, F.A., 2007. Compatible estimators of the components of change for a rotating panel forest inventory design. For. Sci. 53, 50–61.
Rohner, B., Fischer, C., Herold, A., Rösler, E., 2019. Assortments. In: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and Models of the Fourth Assessment. Springer International Publishing, Cham, pp. 231–241.
Rondeux, J., Sanchez, C., Latte, N., 2010. National Forest Inventory Reports: Belgium (Walloon Region). In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 73–87.
Rubner, H., 1967. Forstgeschichte im Zeitalter der industriellen Revolution. Duncker & Humblot, Berlin, p. 235.
Ruiz-Benito, P., Vacchiano, G., Lines, E.R., Reyer, C.P.O., Ratcliffe, S., Morin, X., Hartig, F., Mäkelä, A., Yousefpour, R., Chaves, J.E., Palacios-Orueta, A., Benito-Garzón, M., Morales-Molino, C., Camarero, J.J., Jump, A.S., Kattge, J., Lehtonen, A., Ibrom, A., Owen, H.J.F., Zavala, M.A., 2020. Available and missing data to model impact of climate change on European forests. Ecol. Model. 416, 108870. https://doi.org/10.1016/j.ecolmodel.2019.108870.
Ruiz-Peinado, R., Del Rio, M., Montero, G., 2011. New models for estimating the carbon sink capacity of Spanish softwood species. For. Syst. 20, 176–188. https://doi.org/10.5424/fs/2011201-11643.
Ruiz-Peinado, R., Montero, G., Del Rio, M., 2012. Biomass models to estimate carbon stocks for hardwood tree species. For. Syst. 21, 42–52. https://doi.org/10.5424/fs/2112211-02193.
Saarela, S., Grafström, A., Ståhl, G., Kangas, A., Holopainen, M., Tuominen, S., Nordkvist, K., Hyyppä, J., 2015. Model-assisted estimation of growing stock volume using different combinations of LiDAR and Landsat data as auxiliary information. Remote Sens. Environ. 158, 431–440. https://doi.org/10.1016/j.rse.2014.11.020.
Saarela, S., Schnell, S., Tuominen, S., Balazs, A., Hyyppä, J., Grafström, A., Ståhl, G., 2016. Effects of positional errors in model-assisted and model-based estimation of growing stock volume. Remote Sens. Environ. 172, 101–108. https://doi.org/10.1016/j.rse.2015.11.002.
Santopuoli, G., Temperli, C., Alberdi, I., Barbeito, I., Bosela, M., Bottero, A., Klopcic, M., Lesinski, J., Panzacchi, P., Tognetti, R., 2020. Pan-European sustainable forest management indicators for assessing climate-smart forestry in Europe. Can. J. For. Res. 51 https://doi.org/10.1139/cjfr-2020-0166.
Scheidl, C., Heiser, M., Kamper, S., Thaler, T., Klebinder, K., Nagl, F., Lechner, V., Markart, G., Rammer, W., Seidl, R., 2020. The influence of climate change and canopy disturbances on landslide susceptibility in headwater catchments. Sci. Total Environ. 742, 140588. https://doi.org/10.1016/j.scitotenv.2020.140588.
Scanavis, C., Sakellari, M., 2010. Fabulous Dryades were living in trees, in: D.U. Publishing (Ed.), Natural Environment in Ancient Greece, Orestiada, pp. 1-10.
Schenck, C.A., 1905. Forest mensuration. The University Press, p. 71.
Schier, F., Morland, C., Dieter, M., Weimar, H., 2021. Estimating supply and demand elasticities of dissolving pulp, lignocellulose-based chemical derivatives and textile fibres in an emerging forest-based bioeconomy. For. Pol. Econ. 126, 102422. https://doi.org/10.1016/j.forpol.2021.102422.
Schmid, S., Thürig, E., Kaufmann, E., Lischke, H., Bugmann, H., 2006. Effect of forest management on future carbon pools and fluxes: A model comparison. For. Ecol. Manag. 237 (1–3), 65–82. https://doi.org/10.1016/j.foreco.2006.09.028.
Schmitz, F., Polley, H., Hennig, P., Dunger, K., Schwitzgebel, F., 2006. The second National Forest Inventory - Inventory and evaluation Methods. Federal Ministry of Food, Agriculture and Consumer Production, Bonn, p. 95.
Schreuder, H.T., Gregoire, T.G., Wood, G.B., 1993. Sampling methods for multisource forest inventory. Wiley, New York, p. 446.
Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T.E.E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Körner, C., Larysch, E., Lübbe, T., Nelson, D.B., Rammig, A., Rigling, A., Rose, L., Ruehr, N.K., Schumann, K., Weiser, F., Werner, C., Wohlgemuth, T., Zang, C.S., Kahmen, A., 2020. A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic Appl. Ecol. 45, 86–103. https://doi.org/10.1016/j.baae.2020.04.003.
Schwappach, A., 1886. Handbuch der Forst- und Jagdgeschichte Deutschlands in 2 Bänden. Julius Springer, Berlin.
Scrinzi, G., Clementel, F., Floris, A., 2015. Angle count sampling reliability as ground truth for area-based LiDAR applications in forest inventories. Can. J. For. Res. 45 (4), 506–514. https://doi.org/10.1139/cjfr-2014-0408.
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. Change 7 (6), 395–402. https://doi.org/10.1038/nclimate3303.
Sievänen, R., Salminen, O., Lehtonen, A., Ojanen, P., Liski, J., Ruosteenoja, K., Tuomi, M., 2014. Carbon stock changes of forest land in Finland under different levels of wood use and climate change. Ann. For. Sci. 71 (2), 255–265. https://doi.org/10.1007/s13595-013-0295-7.
Simington, R.C., 1953. The Civil Survey A.D. 1654–1656: County of Wexford, Volume IX, 321 p..
Sloboda, B., Gaffrey, D., Matsumura, N., 1993. Regionale und lokale Systeme von Höhenkurven für gleichaltrige Waldbestände. Allgemeine Forst- und Jagdzeitschrift 164, 225–228.
Smalian, H.L., 1837. Beitrag zur Holzmeßkunst. Löffler, Stralsund, p. 87.
Society of American Foresters, 1916. Forest Terminology. Part I: Terms used in general forestry and its branches with the exception of forest protection and utilization. Society of American Foresters, 34 p.
Sopp, L., Kolozs, L., 2000. Fatömegszámítási táblázatok. Állami Erdészeti Szolgálat, Budapest.

Spieker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P. (Eds.), 2012. Growth trends in European forests: studies from 12 countries. Springer, Berlin, Heidelberg, 372 p.
Spurr, S.H., 1952. Forest Inventory. The Ronald Press Company, New York. 476 p.
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 harmonising forest statistics. For. Sci. 58, 214–223. https://doi.org/10.5849/forsci.10-067.
Steinmann, K., Mandallaz, D., Ginzler, C., Lanz, A., 2013. Small area estimations of proportion of forest and timber volume combining Lidar data and stereo aerial images with terrestrial data. Scand. J. For. Res. 28 (4), 373–385. https://doi.org/10.1080/02827581.2012.754936.
Stinghe, V.N., Sburlan, D.A., 1941. Agenda forestiera. Imprimeria Nationala, Bucuresti, pp. 2–9.
Stockmann, V., 2016. Dejiny lesníctva na Slovensku. Lesy Slovenskej republiky. Banská Bystrica. Patina 14, 1022 p.
Susmel, L., 1994. I rovereti di pianura della Serenissima. CLEUP Padova 160 p.
Szarka, P., Bavlšík, J., 2011. 250-ročná tradícia vypracovania lesných hospodárskych plánov na Slovensku. Lesnícke listy pre prax. Príloha časopisu Les 5–6, 8 p.
Tomé, M., Faias, S.P., Correia, A., 2007a. Equações de biomassa e de volume desenvolvidas no âmbito do tratamento dos dados do Inventário Florestal Nacional 2005-2006. Publicações GIMREF. RT 4/2007. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.
Tomé, M., Meyer, A., Ramos, T., Barreiro, S., Faias, S.P., Cortiçada, A., 2007b. Relações hipsométricas e equações de diâmetro de copa desenvolvidas no âmbito do tratamento dos dados do Inventário Florestal Nacional 2005-2006. Publicações GIMREF. RT 3/2007. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.
Tomé, M., Barreiro, S., Uva, J.S., 2016. National Forest Inventories Reports: Portugal. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 637–654.
Tomppo, E., Haakana, M., Katila, M., Peräsaari, J., 2008. Multi-Source National Forest Inventory – Methods and applications. Springer, Netherlands, Managing Forest. Ecosystems 18, 373 p. https://doi.org/10.1007/978-1-4020-8713-4.
Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E. (Eds.), 2010a. National Forest Inventories - Pathways for common reporting. Springer Netherlands, 612 p. http://dx.doi.org/10.1007/978-1-4020-8713-4.
Tomppo, E., Gabler, K., Schadauer, K., Gschwantner, T., Lanz, A., Ståhl, G., McRoberts, R.E., Chirici, G., Cienciala, E., Winter, S., 2010b. Summary of accomplishments. In: Tomppo, E., et al. (Eds.), National Forest Inventories – Pathways for Common Reporting. Springer, Netherlands, pp. 45–54.
Tomppo, E.O., Schadauer, K., 2012. Harmonisation of National Forest Inventories in Europe - Advances under COST Action E43. For. Sci. 58, 191–200. https://doi.org/10.5849/forsci.10-091.
Tomppo, E., Kuusinen, N., Mäkisara, K., Katila, M., McRoberts, R.E., 2016. Effects of field plot configurations on the uncertainties of ALS-assisted forest resource estimates. Scand. J. For. Res. 32 (6), 488–500. https://doi.org/10.1080/02827581.2016.1259425.
Tomter, S.M., Hylen, G., Nilsen, J.-E., 2010. Forest Inventory Country Reports: Norway. In: Tomppo, E., et al. (Eds.), National Forest Inventories - Pathways for common reporting. Springer, Netherlands, pp. 411–424.
Tomter, S.M., Gasparini, P., Gschwantner, T., Hennig, P., Kulbokas, G., Kuliešis, A., Polley, H., Robert, N., Rondeux, J., Tabacchi, G., Tomppo, E., 2012. Establishing bridging functions for harmonising growing stock estimates - Examples from European National Forest Inventories. For. Sci. 58, 224–235. https://doi.org/10.5849/forsci.10-068.
Tomter, S.M., 2016. National Forest Inventories Reports: Norway. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 601–619.
Tomter, S.M., Kuliešis, A., Gschwantner, T., 2016. Annual volume increment of the European forests - Description and evaluation of the national methods used. Ann. For. Sci. 73 (4), 849–856.
Traub, B., Cioldi, F., Düggelin, C., Keller, M., Ginzler, C., 2019. Quality in aerial-image interpretation and field survey, in: Fischer, C., Traub, B. (Eds.), Swiss National Forest Inventory – Methods and models of the fourth assessment. Springer International, Managing Forest Ecosystems 35, pp. 339-365.
Trubrig, J., 1896. Eine "Holzbeschau" in den landesfürstlichen Wäldern des Oberrinntales im Jahre 1459. Österreichische Vierteljahresschrift für Forstwesen 14, 346–359.
Tsitsoni, T., 2016. National Forest Inventories Reports: Greece. In: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer International Publishing, Cham, pp. 423–437.
Tsoumis, G.T., 2017. Forest and Environment in Ancient Greece (in Greek). University Studio Press, Thessaloniki, p. 120.
UNECE/FAO, 2000. Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand. Geneva timber and forest study papers No 17. United Nations, New York and Geneva, 445 p.
UNECE/FAO, 2011. The European Forest Sector Outlook Study II. UNECE/FAO Forestry and Timber Section, Geneva, 111 p.
United Nations, 1992. United Nations Framework Convention on. Climate Change. 33.
United Nations, 1998. Kyoto Protocol to the United Nations Framework Convention on. Climate Change. 20.
Uotila, A., Kouki, J., Kontkanen, H., Pulkkinen, P., 2002. Assessing the naturalness of boreal forests in eastern Fennoscandia. For. Ecol. Manag. 161 (1–3), 257–277. https://doi.org/10.1016/S0378-1127(01)00496-0.
Valbuena-Carabaña, M., de Heredia, U.L., Fuentes-Utrilla, P., González-Doncel, I., Gil, L., 2010. Historical and recent changes in the Spanish forests: a socio-economic process. Rev. Palaeobot. Palynol. 162 (3), 492–506. https://doi.org/10.1016/j.revpalbo.2009.11.003.
Van de Walle, I., Van Camp, N., Perrin, D., Lemeur, R., Verheyen, K., Van Wesemael, B., Laitat, E., 2005. Growing stock-based assessment of the carbon stock in the Belgian forest biomass. Ann. For. Sci. 62 (8), 853–864. https://doi.org/10.1051/forest:2005076.
Vasilevskis, A., 2007. Mežierīcība Latvijas teritorijā līdz 1919, in: Zviedre, A. (Ed.), Mežierīcība Latvijā. V. elements, Rīga, pp. 13-40.
Vauhkonen, J., Berger, A., Gschwantner, T., Schadauer, K., Lejeune, P., Perin, J., Pitchugin, M., Adolt, R., Zeman, M., Johannsen, V.K., Kepfer-Rojas, S., Sims, A., Bastick, C., Morneau, F., Colin, A., Bender, S., Kovácsevics, P., Solti, G., Kolozs, L., Nagy, D., Nagy, K., Twomey, M., Redmond, J., Gasparini, P., Notarangelo, M., Rizzo, M., Makovskis, K., Lazdins, A., Lupikis, A., Kulbokas, G., Antón-Fernández, C., Castro Rego, F., Nunes, L., Marin, G., Calota, C., Pantić, D., Borota, D., Roessiger, J., Bosela, M., Šebeň, V., Skudnik, M., Adame, P., Alberdi, I., Cañellas, I., Lind, T., Trubins, R., Thürig, E., Stadelmann, G., Ditchburn, B., Ross, D., Gilbert, J., Halsall, L., Lier, M., Packalen, T., 2019. Harmonised projections of future forest resources in Europe. Ann. For. Sci. 76, 79. https://doi.org/10.1007/s13595-019-0863-6.
Verkerk, P.J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G.J., Potočnik, J., Palahí, M., 2020. Climate-Smart Forestry: the missing link. For. Pol. Econ. 115, 102164. https://doi.org/10.1016/j.forpol.2020.102164.
Vestjordet, E., 1967. Funksjoner og tabeller for kubering av stående gran. Meddelelser fra Det norske Skogforsøksvesen 22, 539–574.
Vevstad, A., 1994. Usikkerhet gir frykt, in: Strand, L. (Ed.), Kilde til kunnskap. Landsskogtakseringen 75 år, Rapport nr. 9/94. NIJOS, Ås.
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.
Vidal, C., Alberdi, I., Hernández, L., Redmond, J., 2016a. National Forest Inventories - Assessment of wood availability and use. Springer, Cham, p. 845 p..
Vidal, C., Alberdi, I., Redmond, J., Vestman, M., Lanz, A., Schadauer, K., 2016b. The role of European National Forest Inventories for international forestry reporting. Ann. For. Sci. 73 (4), 793–806. https://doi.org/10.1007/s13595-016-0545-6.
Vidal, C., Gschwantner, T., Korhonen, K.T., Alberdi, I., Gasparini, P., Redmond, J., Ginzler, C., Fischer, C., Hervé, J.-C., Waser, L.T., Kuliešis, A., Kasperavičius, A., Bosela, M., Adolt, R., Petráš, R., Kučera, M., Fridman, J., Schadauer, K., 2016c. Progress towards harmonised assessment of availability and use of wood resources in Europe, in: Vidal, C., et al. (Eds.), National Forest Inventories – Assessment of wood availability and use. Springer, Cham, pp. 81-104.
Viola, F., 2011. Foreste della Serenissima: frammenti di storia forestale. Dipartimento Territorio e Sistemi Agro Forestali, Università di Padova, Lettura del 9 novembre 2011. Sezione Nord Est, Padova, pp. 660-684.
Volovič, G.B., 1559. Revizija pušč i perechodov zverinnych … v byvšem Velikom knjažestve Litovskom, sostavlennaja starostoju Mstibogovskim Grigorijem Bogdanovičem Volovičem v 1559 godu. Vilnius 1867, 381 p.
Weiss, P. (Ed.), 2006. Austrian biomass functions. Austian J. For. Sci. 123, 101 p.
Wessely, J., 1853. Die oesterreichischen Alpenländer und ihre Forste. Erster und zweiter Theil. Wilhelm Braumüller Verlag, Wien.
Westfall, J.A., McRoberts, R.E., Radtke, P.J., Weiskittel, A.R., 2016. Effects of uncertainty in upper-stem diameter information on tree volume estimates. Eur. J. For. Res. 135 (5), 937–947. https://doi.org/10.1007/s10342-016-0985-4.
Youngs, R.L., 2009. History, nature and products of wood, in: Owens, J.N., Lund, G.H. (Eds.), Forests and forest plants, Volume 2. Encyclopedia of Life Support Systems, pp. 131–157.
Zimmermann, N.E., Jandl, R., Hanewinkel, M., Kunstler, G., Kölling, C., Gasparini, P., Breznikar, A., Meier, E.S., Normand, S., Ulmer, U., Gschwantner, T., Veit, H., Naumann, M., Falk, W., Mellert, K., Rizzo, M., Skudnik, M., Psomas, A., 2013. Potential future ranges of tree species in the Alps, in: Cerbu, G.A., et al. (eds.), Management Strategies to Adapt Alpine Space Forests to Climate Change Risks, InTechOpen, pp. 37-48. http://dx.doi.org/10.5772/56279.
Zöhrer, F., 1980. Forst Inventur. Paul Parey, Hamburg und Berlin, p. 207.
Zon, R., 1910. The forest resources of the world. United States Department of Agriculture, Forest Service Bulletin No. 83. Government printing Office, Washington DC, 91 p.
Zon, R., Sparhawk, W.N., 1923. Forest Resources of the World. Volumes I and II. McGraw-Hill Book Company Inc., New York, p. 997.