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Improved large-area forest increment information in Europe through harmonisation of National Forest Inventories

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ABSTRACT

Consistent knowledge about the increment in European forests gained amplified importance in European policies and decision processes related to forest-based bioeconomy, carbon sequestration, sustainable forest management and environmental changes. Until now, large-area increment information from European countries was lacking international comparability. In this study we present a harmonisation framework in accordance with the principles and the approach established for the harmonisation of National Forest Inventories (NFIs) in Europe. 11 European NFIs, representing a broad range of increment measurement and estimation methods, developed unified reference definitions and methods that were subsequently implemented to provide harmonised increment estimates by NUTS regions (Nomenclature of territorial units for statistics of the European Union), main forest types and tree species groups, and to rate the impact of harmonisation measures. The main emphasis was on gross annual increment (GAI), however, also annual natural losses (ANL) and net annual increment (NAI) were estimated. The data from the latest available NFI cycles were processed. The participating countries represent a forest area of about 130 million ha, and 82% of the European Unions' (EU) forest area, respectively. The increments were estimated in terms of volume (m^3 $year^{-1}$, m^3 ha^{-1} $year^{-1}$) and above-ground biomass (t $year^{-1}$, t ha^{-1} $year^{-1}$). The harmonised GAI volume estimates deviate in a range of +12.3% to −26.5% from the estimates according to the national definitions and estimation methods. Within the study area, the harmonised estimates show a considerable range over the NUTS regions for GAI, from 0.6 to 12.3 m^3 ha^{-1} $year^{-1}$, and 0.8–6.4 t ha^{-1} $year^{-1}$, of volume and above-ground biomass, respectively. The largest increment estimates are found in Central Europe and gradually decrease towards the North, South, West and East. In most countries coniferous forests show larger increment estimates per hectare than broadleaved forests while mixed forests are at an intermediate level. However, in some instances, the differences were small or mixed forests revealed the largest increment

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estimates. The most important tree species groups in the study area are *Pinus* spp. and *Picea* spp., contributing 29% and 26% of the estimated total GAI volume, respectively. The shares of the prevalent broadleaved species are smaller with contributions of 9%, 7% and 6% by *Quercus* spp., *Fagus sylvatica* and *Betula* spp. The results underline the importance of harmonisation in international forest statistics. Looking ahead, harmonised large-area increment estimation is pivotal for accurate monitoring and evidence-based policy decisions in the changing context of future forest ecosystems dynamics, management strategies and wood availability.

1. Introduction

Increment is the increase of living trees in volume or biomass during a given period over a specified forest area and serves as versatile indicator in forest monitoring for assessing productivity, carbon sequestration, sustainable resource utilisation, and impact of environmental conditions on forests (e.g., Spiecker et al., 1996; Fridman et al., 2014; Breidenbach et al., 2020). Forest productivity essentially determines the sustainable harvest potential and consequently defines the possible contribution of forests to the green transition in Europe, which foresees an increased reliance on renewable resources (e.g., European Commission, 2020). Over the recent decades an increase of wood harvests has been already observed in Europe (Köhl et al., 2015) and led to augmented utilisation rates of net annual increment (NAI) as reported by Forest Europe (2020). Concurrently, European forests become increasingly exposed to changing climate conditions, as evidenced by natural disturbance occurrence (e.g., Seidl et al., 2017; Hlásny et al., 2021), changes in tree species composition and distribution (e.g., Dyderski et al., 2018; Scherrer et al., 2022), altered growth patterns (e.g., Charru et al., 2017; Bosela et al., 2021; Ols et al., 2022), and accelerated forest dynamics (e.g., Pretzsch et al., 2014; Thom et al., 2022). Hence, forest productivity, economic consequences of climate change and the future availability of wood on a sustainable basis have become a central question (e.g., Hanewinkel et al., 2013).

Sample-based National Forest Inventories (NFIs) are regularly conducted by the great majority of European countries to monitor the state and change of forest ecosystems (Tomppo et al., 2010; Vidal et al., 2016; Gschwantner et al., 2022). Within European NFIs, the estimation of changes in wood resources due to growth on the one side, and drain caused by felling and natural losses on the other side, has methodically developed already over the last century (e.g., Ilvessalo, 1927; Fridman et al., 2014; Gschwantner et al., 2016; Redmond et al., 2016; Breidenbach et al., 2020), and supported the data needs of international reporting processes like Forest Europe (2015a, 2020), the United Nations Framework Convention on Climate Change (United Nations, 1992) and its Kyoto Protocol (United Nations, 1998). Recently, consistent knowledge about increments at international scale gained amplified importance due to increasing evidence-based information requirements of European policies related to the EU Bioeconomy Strategy (European Commission, 2018), the new Forest Strategy for 2030 (European Commission, 2021), the proposal on a monitoring framework for resilient European forests (European Commission, 2023a), the European Green Deal (European Commission, 2019), the Paris Agreement (UNFCCC, 2016) and the LULUCF Regulation (European Parliament and Council, 2018).

European NFIs differ in their sampling designs and methods that usually originate from different NFI histories, country-specific conditions and information needs, and often accommodate the unique topographies, climates, forest types and commercial interests in countries (McRoberts et al., 2010). The information on national forest resources provided for international reporting are therefore often lacking comparability across country borders (Vidal et al., 2016). To improve the international consistency and comparability of forest information for European reporting and policy needs (Vidal et al., 2016), a harmonisation process of European NFIs was initiated in the late 1990s (Tomppo et al., 2010) and is a main objective of the European National Forest Inventory Network founded in 2003 (ENFIN, 2024). Common sets of terms and definitions for harmonised reporting were first used in the Global Forest Resources Assessment FRA 2000 (FAO, 2001) and the Temperate and Boreal Forests Resource Assessment TBFRA (UNECE/FAO, 2000) and were also published for the subsequent assessments (e.g. FAO, 2023). The general principles and harmonisation approach have been established in a participatory process and rely on reference definitions and so-called bridging functions that convert estimates based on national definitions into estimates according to a common reference definition (Vidal et al., 2008; McRoberts et al., 2009, 2010; Tomppo et al., 2010; Ståhl et al., 2012; Tomppo and Schadauer, 2012). The status of the European NFI harmonisation process was recently summarized by Gschwantner et al. (2022).

A previously conducted review of the increment estimation methods of European NFIs concluded several differences among countries, for example regarding sample grid characteristics, the use of permanent and temporary plots, periodicity of assessments, sample tree selection methods, sampling thresholds, field measurements, components of forest growth, and tree parts included in the estimates of volume increment (Gschwantner et al., 2016). Kuliešis et al. (2016) consider the use of permanent versus temporary sample plots as an essential difference, because it also determines the measurement techniques and estimation procedures. Since unambiguous definitions of gains and losses are a basic requirement of any change estimation, Alberdi et al. (2016) classified and defined the components of change as groundwork for NFI harmonisation of change estimates. However, a large-area implementation of harmonised increment estimation has not been realised until now.

Change estimation by NFIs and thus increment estimation considers a certain observation period, which is determined by an initial date t1 and a final date t2. Between t1 and t2 the number of living stems on a specified forest area changes because of gains due to the recruitment of young trees and losses due to felling or natural mortality (Alberdi et al. 2016). During the same time, wood is accumulated due to the growth of living trees. Based on the changes in the number and type of sample trees, disjoint components of growth have been defined (i.e. survivor, ingrown, cut and mortality trees) for the development of increment estimators of sample-based inventories (e.g., Grosenbaugh, 1958; Martin, 1982; Van Deusen et al., 1986; Roesch et al., 1989; Eriksson, 1995). Already Beers (1962) showed that, based on these components, different periodic increment quantities like gross and net increment can be defined. According to international reporting definitions, net increment is defined differently, either as the volume of gross increment minus the volume of natural losses *due to causes other than cutting by man* (UNECE/FAO, 2000; Forest Europe 2015b) or minus the volume of mortality due to *competition* (IPCC, 2006).

Our study involved 11 European NFIs from Austria (AT), Czech Republic (CZ), Finland (FI), France (FR), Germany (DE), Italy (IT), Poland (PL), Romania (RO), Spain (ES), Sweden (SE), and Switzerland (CH) which together represent a forest area of 131.5 million ha, and the European Union (EU) countries cover 82% of the EU forest area (Forest Europe, 2020). We present for the first time internationally comparable increment estimates for the 10 European NFIs, as the Swiss NFI contributed exclusively to the methodical part. The work has the overall aim to support evidence-based decision-making in European policy processes with harmonised and thus improved forest data (European Commission, 2023a) and mainly focuses on the estimation of gross annual increment (GAI), but we also consider annual natural losses

(ANL) and net annual increment (NAI). The specific objectives of the present work were to 1) compile and analyse up-to-date background information about NFI increment estimation methods, 2) establish a harmonised set of commonly applicable reference definitions on forest increment, 3) implement a harmonised estimation method for volume and above-ground biomass (AGB) increment, 4) estimate comparable increments for NUTS regions (Nomenclature of territorial units for statistics: geographic classification system of the European Union (Eurostat, 2021)), three main forest types and tree species groups, and to 5) compare national and harmonised increment estimates to evaluate the effect of harmonisation.

2. Material and methods

2.1. National Forest Inventory data

2.1.1. General description

The involvement of NFIs aimed for a broad coverage of different increment measurement and estimation approaches and different vegetation zones, forest conditions and management across Europe as described in the country reports collated by Tomppo et al. (2010) and Vidal et al. (2016). Similar to other harmonisation studies, an initial comprehensive analysis of estimation methods was conducted and provided up-to-date background knowledge for establishing the harmonisation framework of reference definitions and estimation methods for GAI and NAI. The methods of the 11 NFIs are described in more detail in Annex Table A1 for the latest available NFI cycles used in this study and conducted in the countries during the two last decades. The methods are briefly summarised herein:

- The time-span between consecutive NFI cycles ranges between 5 and 11 years.
- The prevalent sample tree selection method is concentric circular plots and is used by eight NFIs, three NFIs apply angle count sampling (Bitterlich, 1948) and one NFI uses single circular plots.
- Mainly permanent plots are used for increment estimation, two NFIs use a combination of both permanent and temporary plots, and one NFI relies solely on temporary plots (Gasparini et al., 2017).
- The dbh-thresholds range between 0.0 cm (1.3 m minimum height) and 12.0 cm.

The situation of one-time measured temporary plots similarly refers also to the initial inventory of future periodically revisited permanent plots. However, the main issue in sample-based increment estimation is the differentiation of sample trees into growth components as well as the time reference and related inclusion zones, deserving more detailed consideration in the following.

2.1.2. Growth components

Considering the possible changes in living stems between two points in time for an usual sample plot example reveals four main categories of sample trees: trees that remain in the sample (survivor), trees that newly enter the sample (ingrown tree), trees that die naturally or fall over e.g. through storms (mortality), and trees that leave the sample due to harvest (cut) (Fig. 1).

In angle count or horizontal point sampling, the category of ingrown sample trees is differentiated into the components of ingrowth, ongrowth and non-growth trees, depending on whether a tree changes from below to above the minimum dbh and from outside to inside the sample between two measurements (e.g., Martin, 1982; Van Deusen et al. 1986; Roesch et al. 1989; Eriksson, 1995; Gregoire, 1995; Roesch, 2007). The original definitions of growth components for permanent horizontal sample plots by Martin (1982) provided a guideline in this harmonisation study. Similar growth components apply to concentric circular plots (Hébert et al., 2005), as they can be regarded as a simplified form of horizontal point sampling with a finite number of plot circles. However, in many cases the dbh-thresholds assigned to the individual concentric circles and the length of the time interval between NFI cycles lead to no or only small numbers of ongrowth trees. Eriksson (1995) defined change components that include the growth components by Martin (1982) and four additional cases of trees that both enter and leave the sample between t1 and t2 due to cutting or natural fall over,

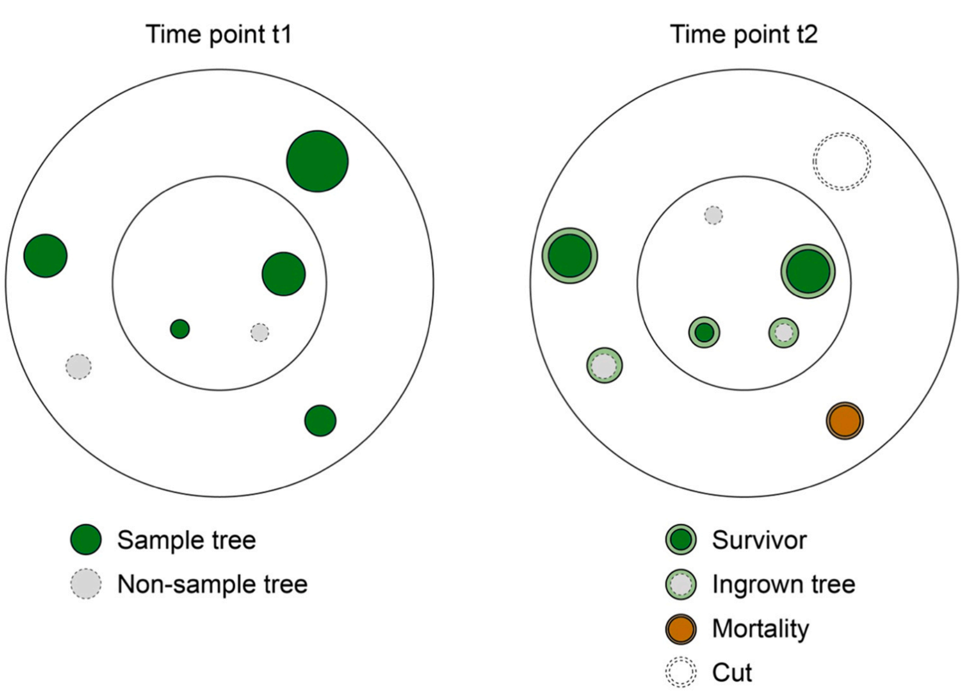

Fig. 1. Changes in living sample trees between two points in time exemplified for a sample plot featuring two concentric circles (black lines) for large trees (outer circle) and small trees (inner circle). Sample trees are displayed as coloured circles with circle size indicating the diameter at breast height (dbh).

and in practical terms can be denoted as ingrown-cut and ingrown-mortality trees. Except for the Czech NFI following the change components of Eriksson (1995), these intermediate changes are not detected by periodic multiannual assessments at t1 and t2 and usually are not included in the estimation. The growth components included in the increment estimates of European NFIs are given in Table 1, the corresponding sampling methods are collated in Annex Table A1, and the growth components according to Martin (1982) are described in Annex Table A2. While all growth components apply to angle count sampling, on concentric circular plots and single circular plots the new sample trees that pass the dbh-threshold between t1 and t2 are commonly considered as ingrown trees without further differentiation. The consideration of growth components in increment estimation by NFIs depends on the applied time reference (Section 2.1.3).

2.1.3. *Time reference*

Considering the defined growth components and their presence in the sample plot at t1 and t2 of the observation period, three basic approaches of increment estimation can be applied that refer either to the "initial-value", the "final-value" or to the "difference" (e.g., Bitterlich and Zöhrer, 1980; Schreuder et al. 1993; Hradetzky, 1995; Schieler, 1997; Lanz et al., 2019). The "initial-value" method uses the sample plots and sample trees of t1 to estimate the increment over the observation period, and refers to the forest area, stand and sample tree attributes at t1, in particular the sample tree inclusion zone at t1 to estimate the increment per hectare. The "final-value" method relates to the situation at the end of the observation period and uses the sample tree inclusion zone at t2 to estimate the increment per hectare. The "difference" method considers the different situations at the sample plots at t1 and t2 and therefore the changing sample tree inclusion zone at t1 and t2. The basic increment estimation approach of the participating NFIs is given in Table 2, however, it should be noted that certain minor deviations from the overall approach may occur due to practical aspects of measurement.

Table 2
The time reference used for increment estimation by the NFIs. Footnotes describe minor deviations from the overall approach.

Country	Time reference		
	Initial value (t1)	Final value (t2)	Difference (t1, t2)
Austria[a]	x		
Czech Republic[b]			x
Finland	x		
France[c]		x	
Germany[c]		x	
Italy		x	
Poland	x		
Romania		x	
Spain[b]		x	
Sweden	x		
Switzerland[b]		x	

[a] Final value for ingrowth trees.
[b] Value at the midpoint of the period between of two inventories for cut and mortality trees.
[c] Initial value for cut and mortality trees.

- The use of temporary plots thus suggesting the "final-value" method because the t1 values are unknown.
- The different length of observation periods thus suggesting the inclusion of all growth components of trees registered either at t1 or at t2.
- The national dbh-thresholds rendering a minimum dbh of 7.5 cm a commonly realisable option.

2.2. *Harmonisation of gross annual increment*

2.2.1. *Reference definition*

Considering the differences between NFIs, the available data and models as well as the bioeconomic focus of the research question, the subsequent reference definition for GAI was agreed and applied by the participating NFIs. The reference definition is determined by three main aspects:

The harmonisation regarding tree parts relies on the previous works about harmonised AGB estimation by Korhonen et al. (2014) and Henning et al. (2016), and harmonised tree volume estimation (Gschwantner et al., 2019, 2022). The reference definition focusses on the tree parts having greater economic relevance, i.e. stems and branches having a minimum diameter of 7 cm. Therefore, the harmonised gross annual increment is denoted as GAI_7 and defined as:

Gross annual increment (GAI_7) is the average annual increment of living trees over the specified forest area during the period between two NFI cycles. It is expressed in terms of volume ($m^3\ ha^{-1}\ year^{-1}$, $m^3\ year^{-1}$) or AGB increment ($t\ ha^{-1}\ year^{-1}$, $t\ year^{-1}$) and includes the growth components of survivor, ingrown, cut and mortality trees with a diameter at breast height $\geq$ 7.5 cm.

The reference definition is complemented by additional

Table 1
Growth components included in increment estimates of European NFIs.

Country	Survivor	Ingrown trees			Mortality	Cut
		Ingrowth	Ongrowth	Non-growth		
Austria	x	x				
Czech Republic	x	x	x	x	x	x
Finland[a]	x	x			x	x
France	x	x			x	x
Germany[b]	x	x	x	x	x	x
Italy[c]	x	x	x	x		
Poland[d]	x	x			x	x
Romania	x				x	x
Spain[e]	x	x	x	x	x	x
Sweden	x	x			x	x
Switzerland	x	x		x	x	x

[a] Concentric circular plots: All ingrown trees included, but no differentiation of ingrowth, ongrowth and non-growth (note: dbh-threshold = 0.0 cm or minimum height = 1.3 m).
[b] No differentiation between mortality and cut trees.
[c] Temporary sample plots: No differentiation of growth components; living trees present at t2 are included and thus belong to survivor and ingrown trees.
[d] Single circular plot: No differentiation of ingrowth, ongrowth and non-growth trees.
[e] No differentiation in the field until 2013 between mortality and cut trees.

specifications:

- *Volume increment includes the over-bark increment of the stem from stump height to the top diameter of 7 cm and for broadleaves large branches with minimum diameter of 7 cm.*
- *AGB increment includes the stem biomass from ground to the stem top, and large and small branches, and perennial foliage (needles).*
- *The inclusion of growth components takes into account the forest area at time point t2, for living trees at t2 (survivor and ingrown trees) the inclusion probability at t2 and their increment between t1 and t2, for harvested and mortality trees between t1 and t2 the inclusion probability at t1 (last measurement as living tree) and their increment between t1 and the time of harvesting or mortality.*

Regarding the time dimension (t1, t2) it has to be noted that 1) continuously conducted inventories may not differentiate NFI cycles and provide each year updated estimates of mean annual increments from periodic multiannual inventory plot assessments for the most recent period, and that 2) temporary plot inventories estimate increment from increment cores for a defined period of e.g. the latest 5 complete years preceding the recent measurements at t2 where the time point t1 does not necessarily coincide with the previous NFI cycle.

2.2.2. *Estimation of sample plot-level GAI_7*

The harmonised reference definition was applied by the NFIs at individual sample tree and plot level by relying on the respective sampling methods, i.e. concentric circular, single circular and angle count plots (Annex Table A1). For permanent plots, the volume and AGB of survivor trees can be estimated from the tree measurements at t1 and t2, and thus the periodic increment can be calculated as difference between the volumes and AGB at t1 and t2, divided by the number of years or vegetation seasons during that period. Fig. 2 shows the calculation of volume increment, AGB increment is calculated in the same way replacing volume by AGB. For ingrown trees, the volume and AGB are available only at time point t2 and thus require an estimate of the increment, e.g. through increment cores or models to obtain the sample tree volume and AGB at t1 (e.g., Sloboda, 1971; MAPA, 1990; Ledermann, 2006; Ledermann et al., 2017). Conversely, cut trees have the latest measurement at time point t1 and models are needed to estimate the volume and AGB at the time point of cutting (tc). Usually, tc is approximated by the half of the time span between t1 and t2, i.e. at t1.5, because the time of cutting is difficult to assess from stumps (Zöhrer, 1980) but usually practised in temporary plot designs. Mortality trees are present at t1 and t2, but change their status from living to dead during this period. Between t1 and t2 mortality trees still accumulate wood. Since dead trees decay, shrink and swell depending on the water content and temperature, the difference between t1 and t2 is not a reliable estimate of increment, and becomes less reliable as the length of the time period between t1 and t2 increases. Similar to cut trees, the increment is approximated as difference between the time of mortality (tm) and t1, however, mortality trees may show a growth decline before dying, in particular for certain mortality causes, and the increment may be set to zero in these cases. For temporary plots, tree measurements are available only at t2 and a differentiation into survivor and ingrown trees can usually not be made.

The individual sample tree increment estimates of the growth components were converted into increment estimates per ha. The inclusion probability of t2 is used to obtain per-ha values for living trees in the sample at t2 (survivor and ingrown trees). For cut and mortality trees the inclusion probability of t1 is used for permanent plots constituting the last measurement as living tree. On temporary plots, the estimation for cut and mortality trees depends on the available data and models (e.g. measurement of stumps and dead trees, assessment of the time point of harvesting and mortality), but follows the outlined approach. The individual sample tree increment estimates per ha were aggregated to plot level increment estimates, grouped by tree species and attributed to main forest types and NUTS regions. Forest type was defined according to Forest Europe (2020) as predominant (in terms of tree crown cover) coniferous, predominant broadleaved and mixed forest (predominant coniferous: >75% conifers, predominant broadleaved: >75% broadleaves, mixed: neither predominant coniferous nor predominant broadleaved). Unstocked plots were not attributed to a forest type but classified as temporarily unstocked.

2.2.3. *E-forest estimator*

To estimate harmonized GAI_7 volume and AGB, the common European NFI estimation system (Lanz, 2012) was employed. The E-forest estimator can process NFI plot data across countries and considers different sampling designs to produce comparable estimates. The E-forest estimator is further described by Alberdi et al. (2020). The data from the latest two NFI cycles available at the time of the study (years 2020–2022) were processed and comprise the two recent decades (Annex Table A1). The estimates were aggregated according to NUTS regions, forest types (i.e. predominant coniferous, predominant broadleaved and mixed forests), and tree species groups and were estimated as means per hectare per year (m^3 ha^{-1} $year^{-1}$ and t ha^{-1} $year^{-1}$) and totals per year (m^3 $year^{-1}$ and t $year^{-1}$). All NFIs considered productive and temporary unstocked forests, and excluded permanently unstocked forests, but differences had to be accepted regarding unproductive forests: five countries (CZ, FI, IT, PL, SE) included unproductive and protective forests, while five countries (AT, ES, DE, FR, RO) excluded unproductive, inaccessible and protective forests without yield. However, the forest definition was not the focus of this study, though the forest definition of FAO (UNECE/FAO, 2000; FAO, 2004, 2012) was

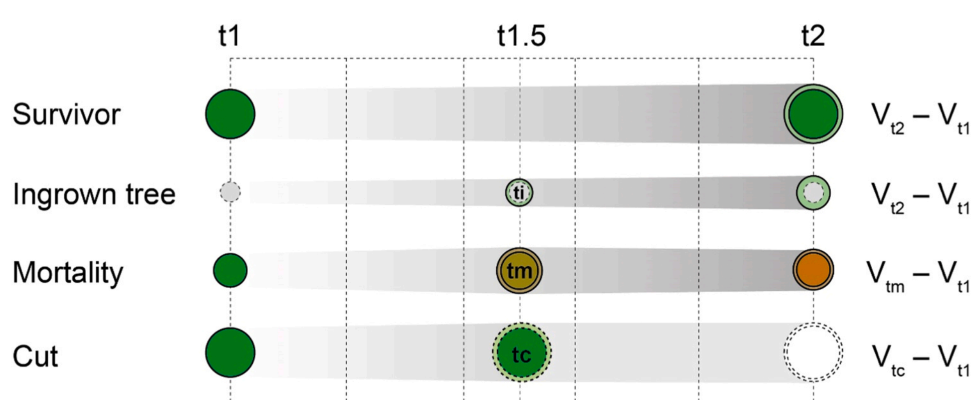

Fig. 2. Scheme of volume increment calculation for the individual growth components. Tree volumes at different points in time: time point t1 (V_{t1}), time point t2 (V_{t2}), and approximated at half of the time span at t1.5 the time point of mortality tm (V_{tm}), the time point of cut tc (V_{tc}) and the time point of ingrowth ti (V_{ti}). Shading indicates the development of growth components over time with increasing darkness towards the recent time point.

applied whenever possible and otherwise the national forest definition.

2.3. Harmonisation of net annual increment

While the estimation of GAI is widely established in European NFIs, the concept of net annual increment, computed as NAI = GAI – ANL, is less frequently applied for national level forest statistics. Nevertheless, ANL is frequently defined and used for the estimation and international reporting of NAI, to assess the net biomass accumulation and carbon sequestration in the forest when compared to fellings (e.g. Forest Europe, 2020). However, the understanding and computation of ANL affects the estimation of the NAI. Natural losses are defined e.g. by Forest Europe (2015b) as *losses to the growing stock* due to *mortality from causes other than cutting by man*, leading to the question whether salvage loggings (i.e. trees that died from natural causes but were subsequently harvested) should be considered as natural losses or not. IPCC (2006) considers only the mortality of *trees dying naturally from competition in the stem-exclusion stage of a* stand or forest and does not include losses due to disturbances. The mortality and harvest assessments by the NFIs are summarised in Annex Table A3. Furthermore, the assessment of natural losses in multiannual periodic inventories involves relatively large uncertainty since harvests contain both regular harvests and salvage loggings which are difficult to distinguish in the field with assessment intervals of usually 5 – 10 years. In some countries removal statistics are compiled from other sources than the NFI, and may include cut and natural losses or only cut. Thus, for assessing the sustainability of forest management, these statistics have to be compared either to the GAI or to NAI. Here, to promote the harmonisation of increment estimation and in particular the linkage to harvest statistics, common reference definitions for ANL and NAI were established that describe the part of volume or AGB lost before utilisation, thus following the economic concept of production losses (Verkerk et al., 2011; Mantau et al., 2016). Comparable to the harmonised GAI_7, the reference definition of harmonised net annual increment includes stems and branches with a minimum diameter of 7 cm and is denoted as NAI_7:

Net annual increment (NAI_7) is the gross annual increment (GAI_7) as defined above (Section 2.2.1) minus the average annual natural losses (ANL_7). NAI_7 is expressed corresponding to GAI_7 in terms of volume (m^3 ha^{-1} $year^{-1}$, m^3 $year^{-1}$) and AGB (t ha^{-1} $year^{-1}$, t $year^{-1}$), and refers to the same specified forest area, to the same period between two NFI cycles, uses the same dbh-threshold and includes the same tree parts.

Annual natural losses (ANL_7) are the average annual volume of trees that died during the period between two NFI cycles due to natural causes, and remained unharvested in the forest. Cut trees that are left in the forest are included. ANL_7 is expressed corresponding to GAI_7 in terms of volume (m^3 ha^{-1} $year^{-1}$, m^3 $year^{-1}$) and AGB (t ha^{-1} $year^{-1}$, t $year^{-1}$), and refers to the same specified forest area, to the same period between two NFI cycles, uses the same dbh-threshold and includes the same tree parts.

The reference definitions for the harmonised GAI_7, ANL_7 and NAI_7 are summarised in Annex Table A4.

3. Results

3.1. Harmonised and national gross annual increment

The harmonised GAI_7 estimation revealed differences compared to the national estimates in the range of +12.3% to −26.5%. Over all countries in the study area the total of harmonised GAI_7 estimates amount to 690 million m^3. The sum of country-level GAI national estimates was 710 million m^3 and 2.9% larger than the harmonised GAI_7 estimate. Fig. 3 shows the estimates in terms of volume according to the national definition and estimation procedures and the harmonised estimates using the reference definition, harmonised estimation method and the E-forest estimator. The deviations between harmonised and national estimates are in many cases due to various causes that add up to the overall deviation (Annex Table A5) and represent country-specific forest conditions.

3.2. Harmonised gross annual increment by NUTS regions

The overall distribution of the harmonised GAI_7 estimates per ha over the participating countries shows that the largest increment estimates are found in Central Europe and gradually decrease towards the North, South, West and East (Fig. 4). The increment estimates vary between the NUTS regions and show in some cases local large or small increments, thus indicating particular growth conditions. The smallest GAI_7 estimate is around 0.6 m^3 ha^{-1} $year^{-1}$ and the largest is around 12.3 m^3 ha^{-1} $year^{-1}$ for volume increment, and 0.8 t ha^{-1} $year^{-1}$ and 6.4 t ha^{-1} $year^{-1}$ for AGB increment, indicating a broad range of productivity in European forests. The differences between countries regarding the inclusion of unproductive forests have been previously mentioned (Section 2.2.3).

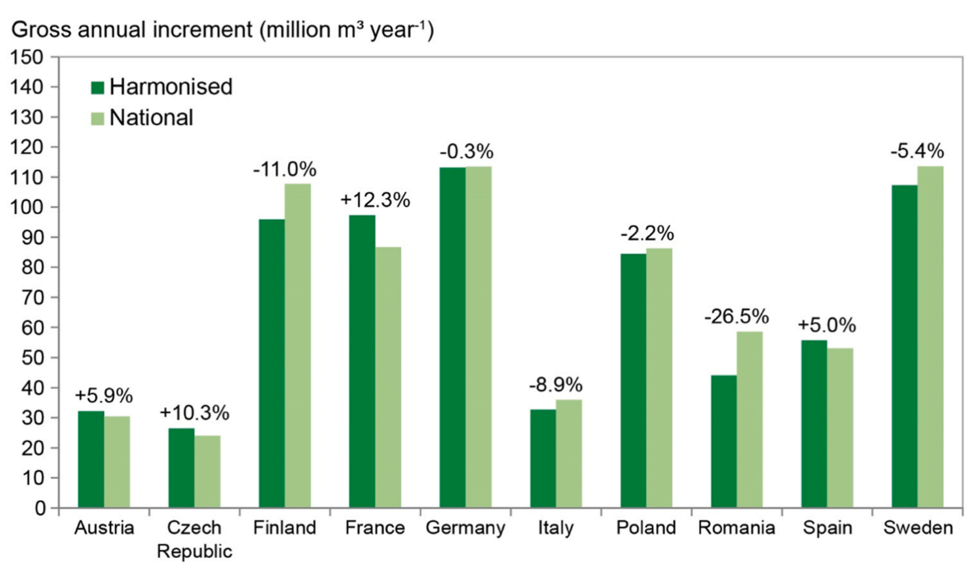

Fig. 3. Comparison of harmonised GAI_7 estimates and national GAI estimates. Percentage (%) = (Harmonised / National – 1) × 100.

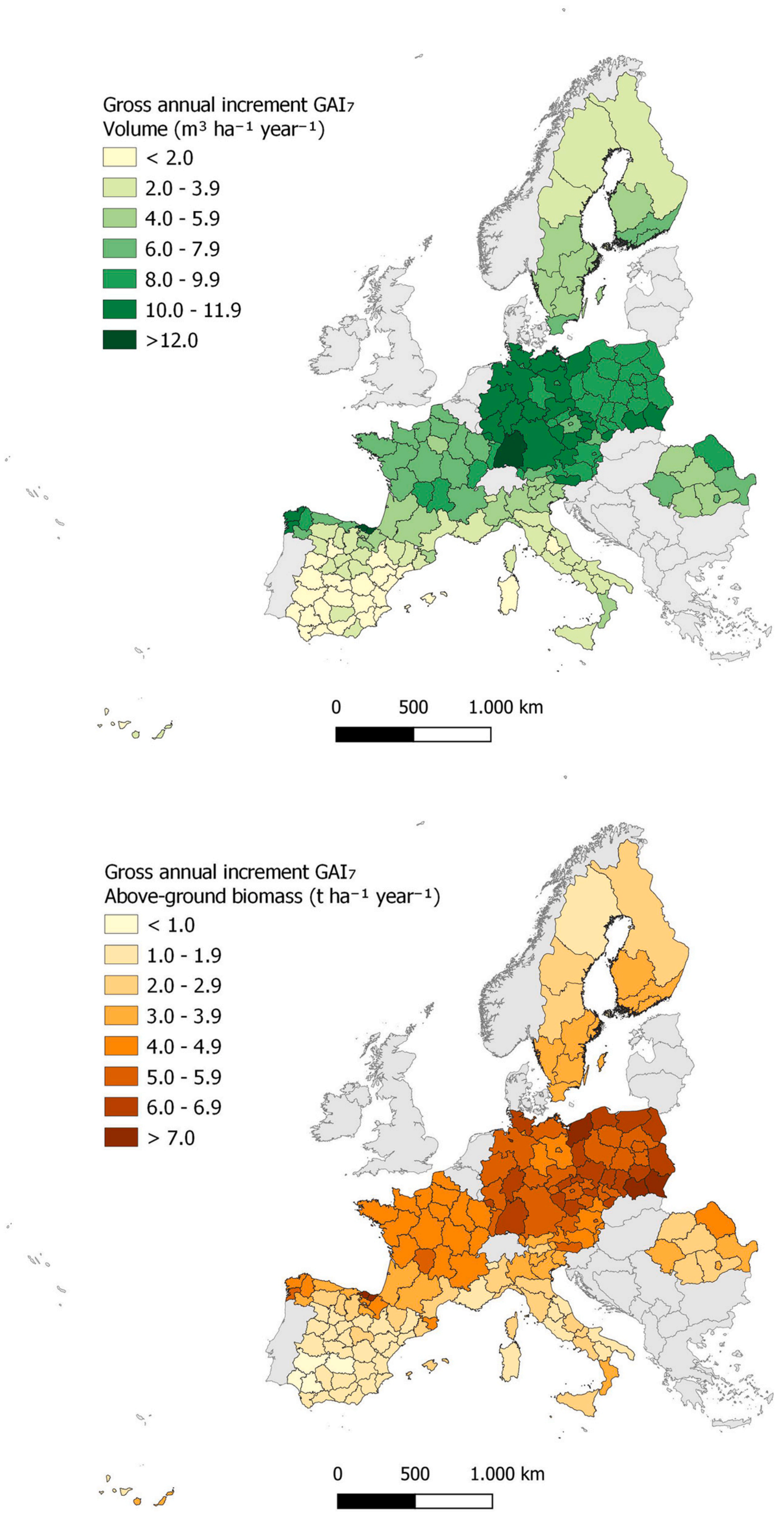

Fig. 4. Harmonised estimates of GAI_7 volume (above) and AGB (below) per ha forest in the NUTS regions of the participating countries. NUTS according to Eurostat (2021).

3.3. *Harmonised gross annual increment by forest types*

The distinction of main forest types revealed that about 55% of the estimated total GAI_7 volume in the study area (690 million m^3) was produced in conifer dominated forests, 26% in broadleaved dominated forests and 18% in mixed forests. In most countries the estimates of mean annual volume increment per hectare are largest in coniferous forests and smallest in broadleaved forests, and intermediate in mixed forests (Table 3). The relative difference between coniferous and broadleaved forests is more pronounced in CZ, FR, DE, IT, ES, and less

Table 3
Harmonised GAI_7 estimates by forest types of predominant coniferous, predominant broadleaved and mixed forests; Estimates (Est.) and Standard errors of the estimates (S.e.).

Country		Gross annual increment GAI_7											
		Volume (m^3 ha^{-1} $year^{-1}$)						AGB (t ha^{-1} $year^{-1}$)					
		Coniferous		Broadleaved		Mixed		Coniferous		Broadleaved		Mixed	
		Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.
AT	Austria	10.22	0.13	7.99	0.18	8.91	0.17	4.88	0.06	4.91	0.10	4.89	0.09
CZ	Czech Republic	11.49	0.18	6.88	0.28	9.20	0.32	6.39	0.09	5.17	0.22	5.95	0.20
FI	Finland	4.53	0.08	3.39	0.15	4.69	0.13	2.43	0.04	2.50	0.10	2.97	0.07
FR	France	8.64	0.09	5.72	0.04	6.79	0.08	4.72	0.05	4.03	0.02	4.20	0.05
DE	Germany	13.22	0.07	9.05	0.06	10.12	0.07	5.98	0.03	5.45	0.03	5.39	0.04
IT	Italy	5.65	0.10	3.27	0.03	4.45	0.10	3.05	0.05	2.49	0.02	2.88	0.06
PL	Poland	9.96	0.05	8.67	0.09	9.54	0.08	6.60	0.03	6.77	0.07	6.98	0.06
RO	Romania	5.13	0.10	5.30	0.11	9.97	0.14	2.66	0.05	2.64	0.05	5.08	0.07
ES	Spain	3.78	0.03	2.29	0.03	4.05	0.08	2.24	0.02	2.05	0.03	2.81	0.06
SE	Sweden	4.09	0.06	4.23	0.17	4.11	0.10	2.84	0.07	3.35	0.22	3.58	0.12

distinct for AT, FI and PL. In SE and RO, the difference between coniferous and broadleaved forests is small. While in SE the mixed forests show intermediate but similar increment estimates like coniferous and broadleaved forests, it is distinctly larger in the mixed forests of RO. The increment estimates for mixed forests in FI are larger than the two other forest types. Although the estimates of the countries show similarity, they also indicate the influence of the particular growth conditions in countries. The comparison of volume and AGB increment estimates indicates markedly smaller differences between coniferous, broadleaved and mixed forests in terms of AGB, due to the smaller wood basic densities of coniferous compared to broadleaved species.

3.4. Gross annual increment by tree species

In the study area, the coniferous and the broadleaved tree species contribute 420 million m^3 and 270 million m^3, equal to 62% and 38% of the estimated total harmonised GAI_7 volume of 690 million m^3, respectively. The most important genera are *Pinus* and *Picea*, accounting for 29% and 26% of the harmonised GAI_7 volume. The shares of the prevalent broadleaved species are substantially smaller with contributions of 9%, 7% and 6% by *Quercus* spp., *Fagus sylvatica* and *Betula* spp. *Abies* spp. contribute 3% of the harmonised total GAI_7, and each of the remaining species groups has shares below 2% (Fig. 5). Considering the GAI_7 estimation in terms of AGB, the contribution of conifers is smaller compared to volume and accounts for 57% while the share of broadleaves reaches 43%.

3.5. Harmonised net annual increment

According to the reference definition, ANL_7 is based on measurements of trees that die due to natural reasons and remain unharvested in the forest. Among the participating countries, the estimates of ANL_7 range between 0.3 and 1.6 m^3 ha^{-1} $year^{-1}$ and 0.2 and 1.1 t ha^{-1} $year^{-1}$, respectively. The estimated ANL_7 volume constitutes between 10% and 20% of the GAI_7 volume estimate, slightly less in DE and FI, and slightly more in RO (Table 4). The estimate of natural losses depends on the one hand on the occurrence of natural disturbances and mortality, and on the other hand on forest sanitary regulations and respective salvage logging practices. The NAI_7 volume estimates range in the participating countries between 1.4 and 10.3 m^3 ha^{-1} $year^{-1}$ and NAI_7 AGB estimates between 2.0 and 5.9 t ha^{-1} $year^{-1}$. NAI_7 estimates show a similar distribution over Europe as GAI_7 estimates (Section 3.2).

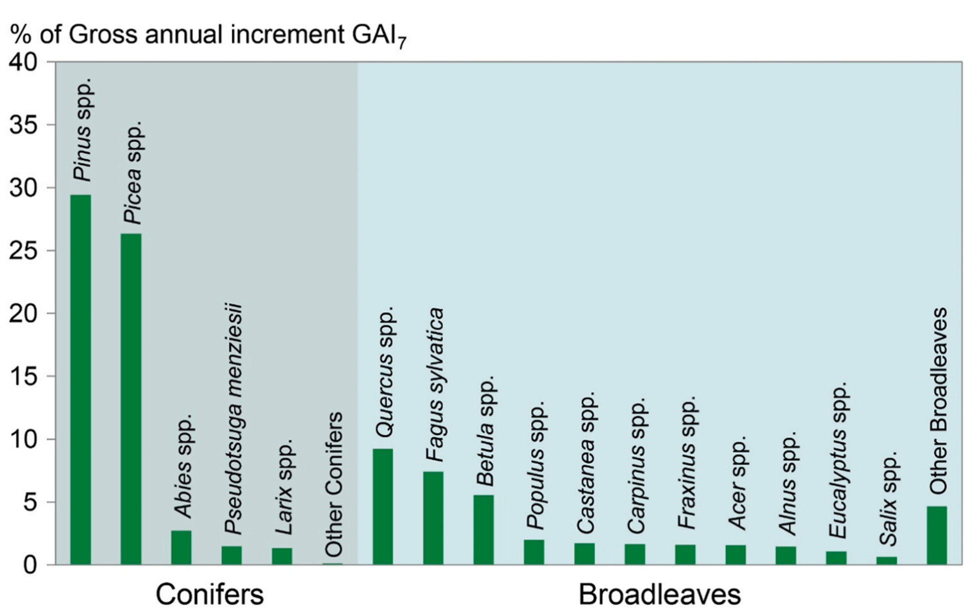

Fig. 5. Contribution of species groups to the estimated total harmonised GAI_7 volume.

Table 4
Harmonised NAI_7 estimates as result of GAI_7 – ANL_7; Estimates (Est.) and Standard errors of the estimates (S.e.).

Country		Gross annual increment GAI_7		Annual natural losses ANL_7		Net annual increment NAI_7		Gross annual increment GAI_7		Annual natural losses ANL_7		Net annual increment NAI_7	
		Volume (m^3 ha^{-1} $year^{-1}$)						AGB (t ha^{-1} $year^{-1}$)					
		Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.	Est.	S.e.
AT	Austria	9.51	0.10	1.06	0.05	8.45	0.11	4.85	0.05	0.60	0.03	4.25	0.05
CZ	Czech Republic	9.53	0.13	1.62	0.08	7.91	0.16	5.77	0.08	1.06	0.05	4.71	0.10
FI	Finland	4.44	0.07	0.26	0.02	4.19	0.07	2.51	0.04	0.30	0.01	2.21	0.04
FR	France	6.14	0.03	0.76	0.02	5.38	0.04	3.98	0.02	0.78	0.02	3.19	0.02
DE	Germany	11.23	0.04	0.96	0.02	10.27	0.05	5.68	0.02	0.51	0.01	5.17	0.02
IT	Italy	3.73	0.03	0.54	0.02	3.19	0.04	2.60	0.02	0.27	0.01	2.33	0.02
PL	Poland	9.21	0.04	0.95	0.03	8.26	0.05	6.45	0.03	0.59	0.02	5.86	0.04
RO	Romania	6.22	0.07	1.30	0.03	4.91	0.08	3.16	0.04	0.54	0.01	2.62	0.04
ES	Spain	2.97	0.02	0.35	0.01	2.62	0.02	2.18	0.02	0.21	0.00	1.96	0.02
SE	Sweden	4.01	0.05	0.59	0.06	3.42	0.08	2.57	0.07	0.37	0.03	2.21	0.08

4. Discussion

4.1. Increment patterns in Europe

The distribution of the harmonised GAI_7 estimates over the NUTS regions of the participating countries shows largest increments in Central Europe and gradual decreases towards the North, South, West and East. Within the overall distribution, some NUTS regions show larger or smaller increment estimates that indicate particular growth conditions depending on e.g. soil, climate, tree species and age-class composition. The pattern of increment estimates represents the situation based on the most recent NFI data at the time of the study conducted in the years 2020–2022. In the last years signs of changing increment patterns were increasingly observed in Europe. After a long period of predominantly increasing growth trends (e.g., Neumann and Schadauer, 1995; Elfving and Tegnhammar, 1996; Spiecker et al., 1996; Henttonen et al., 2017), reports on recent declines are becoming more frequent (e.g., Neagu, 2010; Charru et al., 2010, 2017; Ols et al., 2020, 2022; Schuldt et al., 2020; Bosela et al., 2021; Martinez del Castillo et al., 2022; Henttonen et al., 2024), and concern various tree species, forest management practices, environmental conditions, local as well as studies on larger scales. Along altitudinal or latitudinal gradients the growth responses frequently show declines at low altitudes and southern species distribution margins, while increases are observed at high altitudes and northern latitudes (e.g., Kauppi et al., 2014; Ponocná et al., 2016; Dulamsuren et al., 2017; Vospernik and Nothdurft, 2018; Rozenberg et al., 2020). Other studies detected either minor growth responses to changing climate (e.g., Hartl-Meier et al., 2014; Latreille et al., 2017), spatially heterogeneous or diverging tree growth reactions (e.g., Galván et al., 2014; Chagnon et al., 2023; Pretzsch et al., 2023), or synchronisation of growth over distant regions (Shestakova et al., 2016). In summary, the growth patterns in Europe are apparently changing and further growth decline and a diversification of growth reactions can be expected, thus suggesting the need for intensified monitoring to ensure future wood supply in an increasingly uncertain context of forest production.

4.2. Contribution of tree species

A considerable share of about 62% of the estimated harmonised GAI_7 volume in the study area was contributed by coniferous tree species and the remaining 38% by broadleaves. Particularly in Central European and Northern countries a large part of the estimated GAI_7 is contributed by conifers. The figures compare well to the species shares in Europe's growing stock (Forest Europe, 2020). Similarly, the differentiated main forest types of coniferous, mixed and broadleaved forests contribute 55%, 26% and 18% of the estimated GAI_7, respectively, and indicate the current relevance of coniferous forests and in particular of spruce and pine for the productivity of European forests. The area of these species has been artificially extended during the last centuries because of an increasing demand for coniferous wood and yield considerations (Johann, 2007). According to our results, in most countries coniferous stands had the largest average volume increment estimates per hectare, while in some other countries mixed forests showed larger increments. Broadleaved forests usually showed smaller volume increment estimates than coniferous and mixed forest stands. General explanations and conclusions from this comparison cannot be simply drawn since e.g. vegetation zones, site conditions, and forest management have to be included for evaluating the differences. Nevertheless, the ongoing changes in the tree species distribution and composition (e.g., Dyderski et al., 2018; Buras et al., 2020) and disturbance regimes (e.g., Seidl et al., 2017, Kärvemo et al., 2023, Vacek et al., 2023) suggest further changes in productivity levels and increment patterns which may negatively affect harvest and carbon sequestration potentials of European forests. A comprehensive understanding of these climate change impacts on forests requires adequate and statistically representative empirical ground-based data on large spatial and long temporal scales that, among other aspects, essentially involves international harmonisation (e.g., Ruiz-Benito et al., 2020; Schuldt et al., 2022).

4.3. Harmonisation of increment

The harmonisation of increment estimation was accomplished in terms of volume and AGB increment, includes GAI, ANL and NAI, and builds upon the previous works on harmonised individual-tree stem volume (Gschwantner et al., 2019) and harmonised above-ground biomass estimation (Korhonen et al., 2014; Henning et al., 2016). The differences between national and harmonised GAI volume estimates of +12.3% to −26.5% underscore the relevance of harmonisation as shown in earlier NFI harmonisation works (e.g., Tomter et al., 2012; Gschwantner et al., 2019; Alberdi et al., 2020). According to Ståhl et al. (2012), harmonisation can be achieved at different levels, where the level of sampling units can be expected to result in the best accuracy. In the present study the harmonisation measures were applied at the level of individual sample trees and plots, and harmonised estimates for NUTS regions, main forest types and tree species could be obtained in a straightforward manner using the common E-forest estimator (Lanz, 2012) which provided totals and means per hectare for GAI_7, ANL_7 and NAI_7 and sampling errors. The implemented harmonisation framework accounts for the variation between countries regarding growth components, tree parts and dbh-thresholds, which were previously concluded to be of primary relevance in the harmonisation of increment estimation (Gschwantner et al., 2016). The harmonisation did not include the forest definition, however, whenever possible and in many cases the forest definition of FAO (UNECE/FAO, 2000; FAO, 2004, 2012) was applied (CZ, ES, FI, FR, IT, RO) and the national definition otherwise (AT, DE, PL, SE). The difference between the national and the FRA forest definition was estimated to be <1% (AT, DE), but can also be larger as for example ~10% in PL. Further improvement of harmonised increment estimation, as e.g. the expansion to a larger area, the harmonisation of the underlying forest definition, and the comparable assessment of natural losses and harvests, facilitate comprehensive monitoring at European scale and evidence-based decisions in EU policies. The need for a *strategic forest planning in all EU member states … based on reliable monitoring and data* has been put forward in the new Forest Strategy for 2030 (European Commission, 2021) and mentions *a list of parameters relevant for harmonised EU monitoring that would be defined …* (European Commission, 2021). The recent proposal on a monitoring framework for resilient European forests (European Commission, 2023a) states that *the EU lacks a common system for the consistent collection and provision of accurate and comparable forest data* and mentions among others the aim to *support evidence-based decision-making by land managers and public authorities, promote research and innovation*. The related Annex (European Commission, 2023b) lists and describes NAI corresponding to the reference definition of this study and mentions a data collection frequency of 5 years, thus requiring additional harmonisation measures to obtain increment estimates at the required temporal resolution. Regarding harvests and natural losses, remote sensing approaches should be considered to support an improved and timely estimation, and usually will rely on satellite data (Kangas et al., 2018). Until now remote sensing methods have a minor role in increment estimation but may receive increasing attention. Nevertheless, field plot measurements are required as ground reference, for achieving sufficient accuracy and understanding the drivers of many NFI parameters including increment, regeneration, dead wood and harvest types. Many NFIs assess types of harvest and losses during field measurements (Vidal et al., 2016) but the differentiated types differ between countries. The harmonisation of ANL and NAI require a common understanding of these variables to support the future European forest monitoring (European Commission, 2023a).

5. Conclusions

Internationally comparable increment estimation including GAI, ANL and NAI was implemented for the first time on a large area covering 82% of the EU forest area. The results revealed once more the importance of harmonisation for international forest statistics. The presented approach was developed by covering a broad range of increment measurement and estimation methods of NFIs and therefore facilitates the future expansion to additional countries. The presented harmonisation supports the recent development of a European forest monitoring framework that aims at evidence-based decision-making in EU policy processes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

National Forest Inventory (NFI) data are not publicly available and require reasonable request and permission from the NFIs.

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Annex

Table A1
Overview about sampling methods and data collection in the NFI cycles used in the present study.

Country	NFI cycles		Plot type	Sample tree selection	Minimum dbh-thresholds (cm)			
	t1	t2			Plot 1	Plot 2	Plot 3	Plot 4
Austria	2000–2002	2007–2009	Permanent	Circular plot and angle count sample plot	5.0	10.5	-	-
Czech Republic	2011–2015	2016–2020	Permanent	Two concentric circular plots	7.0	27.0	-	-
Finland	2009–2013	2014–2018	Permanent	Two concentric circular plots and angle count sample plots	0.0	4.5	9.5	-
France	2009–2013	2014–2018	Permanent and Temporary	Three concentric circular plots	7.5	22.4	37.4	-
Germany	2002	2012	Permanent	Angle count sample plot	7.0	-	-	-
Italy[a]	not relevant	2005	Temporary	Two concentric circular plots	4.5	9.5	-	-
Poland	2010–2014	2015–2019	Permanent	Single circular plot	7.0	-	-	-
Romania	2008–2012	2013–2018	Permanent	Two concentric circular plots	5.6	28.6	-	-
Spain[b]	1995–2007	2004–2020	Permanent	Four concentric circles	7.5	12.5	22.5	42.5
Sweden	2012–2016	2017–2021	Permanent and Temporary	Three concentric circular plots	0.0	4.0	10.0	-
Switzerland	2004–2006	2009–2017	Permanent	Two concentric circular plots	12.0	36.0	-	-

[a] For temporary plots the increment is estimated from increment cores for a defined period of e.g. the latest 5 complete years preceding the recent measurements. Therefore, the time point of the previous NFI cycle is not relevant.

[b] The sampling unit is provincial (NUTS3), so the last two available inventories for each province have been taken in order to have the most current data available, regardless of the cycle of the NFI to which they belong.

Table A2
Definitions of growth components according to Martin (1982).

Growth component	Definition
Survivor	Trees which are above the minimum dbh and in the sample at both measurements t1 and t2
Ingrowth	Trees which are below the minimum dbh and in the sample at the first measurement t1 but exceed the minimum dbh at the second measurement t2
Ongrowth	Trees which are below the minimum dbh and out of the sample at the first measurement t1 but are above the minimum dbh and in the sample at the second measurement t2
Non-Growth	Trees which are above the minimum dbh and out of the sample at the first measurement t1 but are in the sample at the second measurement t2
Cut	Trees which are above the minimum dbh and in the sample at the first measurement t1 but are cut prior to the second measurement t2
Mortality	Trees which are above the minimum dbh and in the sample at the first measurement t1 but die prior to the second measurement t2

Table A3
Assessment of mortality and harvests in the participating NFIs. Remarks: [a] assessed without time reference, [b] since 2020.

Country	Mortality assessment		Harvest assessment	
	Standing dead trees	Natural fall over	Number of harvest types	Salvage logging
Austria	yes	yes	9	yes
Czech Republic	yes	yes	-	no
Finland	yes	yes	12	yes
France	yes	yes	4	no
Germany	yes	yes	2	no
Italy	yes[a]	yes[a]	-	no
Poland	yes	yes	6	yes[b]
Romania	yes	yes	4	no
Spain	yes	no	-	no
Sweden	yes	yes	4	yes
Switzerland	yes	yes	14	yes

Table A4
Summary of the reference definition established for the harmonisation of GAI and NAI in European NFIs.

Harmonisation issue		Reference definition
dbh-threshold		• 7.5 cm
Tree parts	Volume conifers	• Stem above stump height to top diameter of 7 cm
	Volume broadleaves	• Stem above stump height to top diameter of 7 cm • Branches with minimum diameter 7 cm
	AGB conifers	• Stump above ground • Stem above stump height including stem top • Branches (large and small) • Needles (except Larix sp.)
	AGB broadleaves	• Stump above ground • Stem above stump height including stem top • Branches (large and small)
Growth components	Components included	• Survivor increment • Ingrowth increment • Ongrowth increment • Non-growth increment • Cut increment • Mortality increment

(continued on next page)

Table A4 (*continued*)

Harmonisation issue		Reference definition
	Representation per hectare	• “Final-value method” • dbh at t2: survivor, ingrowth, ongrowth, non-growth • dbh at t1: cut, mortality
Natural losses		• Trees that died between t1 and t2 due to natural causes, and remained unharvested in the forest. Cut trees left in the forest are included.

Table A5
Deviations between harmonised and national GAI volume definitions, classified whether they lead to positive or negative differences from the harmonised definition.

Country	Deviation
Austria	Positive: dbh-threshold = 5.0 cm; stem top. Negative: broadleaved branches; cut and mortality.
Czech Republic	Positive: dbh-threshold = 7.0 cm; ingrowth cut and mortality. Negative: increment under bark; difference method.
Finland	Positive: dbh-threshold = 0.0 cm; stem top. Negative: none
France	Positive: none Negative: broadleaved branches.
Germany	Positive: dbh-threshold = 7.0 cm; stump above-ground. Negative: none
Italy	Positive: dbh-threshold = 4.5 cm; coniferous branches. Negative: cut and mortality.
Poland	Positive: dbh-threshold = 7.0 cm; coniferous branches; Negative: cut and mortality.
Romania	Positive: stem top; coniferous branches; ingrowth. Negative: none
Spain	Positive: none Negative: broadleaved branches.
Sweden	Positive: dbh-threshold = 0.0 cm; stem top. Negative: broadleaved branches.

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