

Article

Using Continuous Forest Inventory Data for Control of Wood Production and Use in Large Areas: A Case Study in Lithuania

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Abstract: Background and Objectives: Significant progress in developing European national forest inventory (NFI) systems could ensure accurate evaluations of gross annual increment (GAI) and its components by employing direct measurements. However, the use of NFI data is insufficient for increasing the efficiency of forest management and the use of wood, as well as for meeting sustainable forestry needs. Specification of forest characteristics, such as GAI and its components, identification of the main factors that impact forest growth, accumulation of wood, and natural losses are among the key elements promoting the productivity of forest stands and possibilities of rational use of wood in large forest areas. The aims of this research were (a) to validate the quality of forest statistics provided by a standwise forest inventory (SFI) and (b) to reveal the potential benefits of rational wood use at the country level through the analysis of forest management results, which are based on GAI, including its components derived from the NFI. Materials and Methods: SFI and NFI data from 1998–2017 were collected from 5600 permanent sample plots and used to evaluate the main forest characteristics. Potential wood use was estimated based on the assumption that 50–70% of the total GAI is accumulated for final forest use. Results: Mean growing stock volume (GSV) is underestimated by 7–14% on average in the course of SFI. Therefore, continuous monitoring of the yield changes in forest stands, detection of factors negatively affecting yield and its accumulation, and regulation of these processes by silviculture measures could increase potential forest use in Lithuania. Conclusions: Implementation of sample-based NFI resulted in an improvement of forest characteristics and led to an increase in GSV and GAI. Continuously gathered data on GAI and its components are a prerequisite for efficient forest management and control of the use of wood.

Keywords: forest areas; growing stock volume; gross annual increment; natural losses; standwise forest inventory

1. Introduction

Discussion of the principles of forest management, based on the control of gross annual increment (GAI) and its components (growing stock volume change, volume of felled and dead trees), began in Europe in the 19th and 20th centuries [1–3]. This method was not initially accepted in practice because of the requirement of regularly and continuously recording all removed, dead, and remaining trees. This was considered a serious obstacle to the wider application of this method [4]. The demand for wood, expansion and intensification of the multifunctional use of forest products and services [5–7] and competition between different forest use options has increased significantly in recent decades. Therefore, ideas for improving the use of forest resources and their control mechanisms have emerged anew. During the last 30–40 years, modern national forest inventories (NFI) were launched in many European countries [8]. NFI based on sampling methods and permanent sample plots became a reliable tool, allowing us to estimate, control, and regulate the total GAI and the ratio between its components, as well as to ensure rational wood use in large areas [4].

Volumes of potential wood use, which is based on the information gathered during standwise forest inventories (SFIs), are often subjective [9,10]. In most cases, stand volumes are underestimated [11–13]. Information based on SFI data mostly gives subjective forest development and wood use predictions [14,15]. Lithuania's NFI and SFI from 1998 to 2017 were both regularly implemented in parallel on all state and private forests [16–18]. These data are valuable in order to discover discrepancies between data received through SFI and NFI [13,19].

An effective prerequisite for the establishment of forest management by using a control method on large forest areas of many European countries was created at the end of the 20th and beginning of the 21st century, after the development and improvement of European forest inventories using the sampling method [4,20]. With an increasing demand for rational use of forest resources, making decisions based on objective information became particularly important [7,21,22]. Currently, 29 European countries are carrying out NFI and regularly remeasuring permanent sample plots. Another four countries use temporary sample plots in their NFI. Modern NFIs ensure an objective assessment of both the growing stock volume (GSV) and GAI [8,20,23]. Nevertheless, only 11 countries out of the 33 that used NFI presented data on GAI and its components for SOEF 2011, and nine other countries presented estimations of GAI based on tree borings [4]. The objective assessment of GAI and its components requires at least 10–15 years of direct measurements. The GSV and GAI data can then be used for decision-making in forest management and wood-use control in large areas.

European forests differ in terms of productivity, stand rotation length, determiners of silviculture tradition, forestry intensity, ratios between components of GAI, and, in particular, natural losses [24]. The control and regulation of natural losses can be interpreted by examining two opposite scenarios. The first corresponds to forest management, in accordance with the model of plantation scale—When the number of planted trees and removed trees are similar to each other, and the entire grown population is consumed completely. The second corresponds to strict reserves, which are primarily in forests where all wood grown is left to nature. An intermediate situation will lead to sustainable forest management of various intensities. An optimized, removable volume of potentially self-thinned trees (before they die) in naturally developing and intensively managed stands allows for the effective reduction of natural losses. The ratio between felling and the net increment is acceptable for forestry of lower intensity. In using this ratio, the amount of natural mortality is left uncovered, which comprises 10–30% of GAI. Natural losses (mortality of trees), distinguishing GAI from the net annual increment (NAI), are among the main parameters that characterize the possibility of increasing the efficiency of silviculture in order to maintain biodiversity. Existing forest statistics for large regions and countries show that natural mortality is within the range of 3–35% [25,26]. In countries with resistant stands, for stands exhibiting a short rotation period (50–60 years) or stands subjected to very intensive tending and thinning regimes, natural losses do not exceed 3–7% [27]. However, in extensive forestry, with long-term rotation and low resistance of forests, especially to negative climatic factors, the rate of mortality can reach 30–35% or more from the GAI [25]. Intensive and timely thinning is a key factor in increasing the productivity

and stability of stands. This results in their resistance, and the accumulation of 50–80% of GAI at maturity age [28–32].

The aims of this research were to validate the quality of forest statistics provided by the SFI and reveal the potential benefits of the rational use of wood at the country level. This information was gathered through the analysis of forest management results, which are based on GAI and its components derived from NFI. To achieve this goal, the following tasks were executed:

- validate the accuracy of information received through SFI;
- evaluate the ratio between the main parts of GAI, as well as its accumulation and use in the country's forests in order to minimize natural losses; and
- identify the correspondence between potential forest productivity and wood-use intensity.

2. Materials and Methods

The forest inventory system, implemented in Lithuania since 2010, consist of continuous NFI, running since 1998; SFI, based mainly on visual methods, running regularly since 1922; and inventory of mature stands by the sampling method (MSI) established in 2009. All inventories use unified standards and models. NFI data are used for strategic planning of forest management as well as wood use, and estimation of the validity of other methods. SFI presents data on the stand level every 10 years. Forest stand data, registered in Forest Cadastre, are updated every year, using a yield model adapted to Lithuanian conditions. The yield model parameters are regularly validated using NFI data. Data about mature stands at the country level are controlled by NFI, and at the state forest enterprise local units level by MSI.

The accuracy of the data received by SFI was validated in this article by comparing these unknown accuracy data with continuous NFI, statistically sound and known accuracy data, obtained from continuously remeasured permanent sample plots. GAI and its components are very important for increasing forest management efficiency and its regulation. They are derived by direct measurements of permanent plots.

The data on permanent 500-m² sample plots, which were established during the first Lithuanian NFI (1998–2002) and remeasured three times (2003–2007, 2008–2012, and 2013–2017), were used in this research (Table 1). Standard deviations of the main parameters—Forest areas, GSV, and GAI—Were estimated using statistical standards [33] adapted to the design of the Lithuanian NFI [34]. In forests of strict and natural reserves, protection of ecosystems (classified as groups I and II) is mainly for the enhancement and maintenance of biodiversity, as well as for ecosystem services. Wood use in forests of group I is completely prohibited; in forests of group II (named ecosystem protection forests), very limited management activities are conducted, but wood use is not among the main goals of forest management. Forests designated for economic purposes (classified as groups III and IV) are used for wood supply (FAWS).

Table 1. The number of permanent plots * established in Lithuanian forests by national forest inventory of 1998–2017 and used in the current study.

Years of Establishment and Remeasurement	Forest Ownership			Forest Groups		
	State	Private	Reserved for Restitution	I–II	III–IV	Total
1998–2002	2549	1585	1052	672	4514	5186
2003–2007	2581	1991	713	713	4572	5285
2008–2012	2646	2261	551	731	4727	5458
2013–2017	2727	2422	451	727	4873	5600

* The forest area measured in plots was recalculated into equivalent 500-m² plots.

For solving different tasks, different data were used. For estimation of area, growing stock volume change data of all NFI periods were used. For estimation of GAI and its components, measurements from 1998–2007 and 2008–2017 were used. Stands of oak and ash, occupying only 1–3% of forest land area, were included to solve not all tasks. For an illustration of the dynamic of total yield and its components, the management of pine stands growing on average productivity sites was used.

Information based on SFI data was used for wood-use estimation and the forecasting of forest resources in Lithuania for many years since 1922. SFI was carried out on a regular basis from 1998 to 2017 (e.g., every 10 years). The required accuracy for GSV estimation was $\pm 15\%$. Data on forest stands are stored in the Forest Cadastre database, and updated every year using the yield model [29]. The main method of inventory—Visual, with some measurements of subjectively selected sample trees—Is the source of systematic deviations. Annually updated forest statistics received in the course of SFI were validated by comparing them with known accuracy forest statistics, assessed by NFI for the same date.

Estimation of GAI components is a prerequisite for efficient forest management and rational wood use. During the NFI remeasurement, all trees were divided into surviving, ingrown, dead, felled living, and, separately, felled dead trees [34,35]. For each plot, the gross volume increment (Z_M) and its components over three five-year periods were estimated:

$$Z_M = \Delta + M_{KF} + M_{KI} + M_O \quad (1)$$

where Δ is the volume change over five years in m^3 :

$$\Delta = M_2 - M_1 \quad (2)$$

M_1 is the stem wood volume of living trees at the beginning of the measurement period, M_2 is the stem wood volume of living trees at the end of the first measurement period, M_{KF} is the volume of stems felled during the final felling, M_{KI} is the volume of stems felled during the intermediate felling, and M_O is the volume of dead trees over a five-year period.

Potential wood use consists of intermediate felling designated for the improvement of forest stand development, as well as self-thinning regulation and final felling designated for timber harvesting at the final stage of forest management. The potential yield of stands and the purposefulness of their use were determined by the GAI analysis, its components, and the accumulated volume at the maturity age, which were all estimated using the NFI.

The area of final use was estimated using the OPTINA model [36], first for 2013–2022 and then for 2023–2032. The OPTINA model was designed to create an even distribution of areas by age classes. The time (in years) during which the currently mature stands could be felled was then estimated. Based on the state of the stands and wood quality, it was estimated that currently mature stands of grey alder and aspen (which are made up of low-quality wood) would be felled in no longer than 12 years, conifers and other softwood broadleaves in 14–16 years, and hardwood broadleaves in 20–30 years [11,12]. The area of final use for the next four decades was estimated by dividing the area of mature stands of each decade by 10–16 years. The area of mature stands for each future decade was obtained by shifting the area of age classes and assuming the finally felled area of the last decade.

To ensure and prolong sustainability, the final annual wood use was determined by:

$$M_{KF} = Q_{KF} \cdot V_{KF} \quad (3)$$

where M_{KF} is the stem wood volume of living trees accumulated in mature stands for final use, in m^3/year ; Q_{KF} is the area, which can be used annually by the final use, in ha:

$$Q_{KF} = \frac{Q_F}{A_K} \quad (4)$$

where Q_F is the area of forest land designated for wood production, in ha; A_K is the lower limit of the final felling age plus time required for stand regeneration after felling, in years; and V_{KF} is the volume of stem wood of living trees at the age of final felling, in m^3/ha , expressed as the sum of GAI minus the sum of the intermediate felling and annually dead tree stem volumes during the rotation period:

$$V_{KF} = \sum [Z_{MA} - (M_{KIA} + M_{OA})], \quad (5)$$

where Z_{MA} is GAI at age A, in m^3/ha ; is the volume of stem wood of living trees cut down during intermediate felling, mainly by thinning and sanitary felling, at age A, in m^3/ha ; and M_{OA} is the volume of stem wood of trees that have died at age A, in m^3/ha . The GAI accumulated in mature stands was estimated according to the 2007–2017 NFI data.

The use of GSV by tending–thinning was based on the theoretical assumption that 50–70% of the total GAI is accumulated for final use, whereas the remaining share is comprised of intermediate felling or natural losses [4,28]. To minimize natural losses, it is necessary to focus on the removal of 25–35% of the gross volume increment by tending or other intermediate felling before the trees are dead [4].

To reduce natural losses by 10%, the following targeted increment use value was accepted: 30% in young stands, and 25–28% in subsequent thinning. Intermediate felling areas were estimated based on the area of stands of a respective age. To estimate the replication periodicity of tending and thinning, a correlation was established between the area of tending and final cuttings. Young stands (up to the age of 20 years) in forests with an age structure close to the norm and even final felling for some decades, like in Lithuania, should be planned to have a 1.5–2.0-fold larger area, while the area for thinning should be 2–3-fold higher than the area annually felled by final felling. Therefore, all young stands up to 20 years old must be tended up to twice, and older stands must be thinned 2–3 times. At the end of thinning, sanitary cuttings may be applied if necessary.

GAI was analyzed by tree species, forest ownership, functional forest group, and age. To eliminate the influence of uneven distribution of areas by age on mean GAI, a standard increment was applied and calculated as the mean arithmetic value of increment for each age class during the whole rotation period.

GAI, accumulated in mature stands over the entire rotation period and determined on the basis of the balanced NFI data over the last 15 years, was used for testing the results received by the yield model [29]. A forest management program based on the forest yield model was developed, explaining how to achieve required intermediate and final forest management results. Then both the possible final and intermediate use were predicted. The following forest management program was tested on the sites of average productivity (2012 NFI data) under the following conditions: the thinning must be started no later than at 20 years of age and repeated every 20–30 years, performed in coniferous stands three times on average, and in softwood deciduous stands twice on average. Modeled data were compared with the estimations generated by NFI data.

3. Results

3.1. Validation of SFI-Assessed Forest Statistics

3.1.1. Forest Area

Forest area according to the 2017 NFI covers 2,239,900 ha of Lithuania, of which 2,124,100 ha is forest stand area. There is 547,049,000 m^3 of growing stock volume (stem wood of living trees over bark) in this area. Forest stands of the six main tree species occupy 94.4% of all forest stand area (Table 2). Stands of oak, ash, and other species make up the other 5.6% of forest stand area. Forest area and its distribution by age classes are the main indicators of current and future wood use. Results of both the NFI and SFI inventories show an increase in forest stand area from 2002 to 2017 of 126,000 ha (Table 2). Nevertheless, the last result, estimated for the year 2017 by SFI at 1,974,000 ha and by NFI at 2,006,000 ha, differs by 32,000 ha. SFI data for 2002–2017 show a decrease in the area of spruce stands, whereas the NFI data show an increase in the area of spruce stands. These differences can be explained

by a 10-year period of successive SFI and an approximate one-year period of continuous NFI. SFI, for example, had finished the registration of the results of spruce stand losses due to wind damage from 1992 to 1996, and due to insects and drought only in 2006; NFI, however, detected these areas from the beginning of NFI in 1998–2002, and the reestablishment of declined spruce stand areas was later recorded.

Table 2. Forest stand area (Q_F) changes in 2002–2017 according to national forest inventory (NFI) and standwise forest inventory (SFI) data, deviation of SFI data from NFI data.

Forest Type	Forest Area and Their Changes, 1000 ha								Deviation SFI 01.01.2018 from NFI 2017
	NFI Data				SFI Data			Changes 2018–2003	
	2002	$P, \% *$	2017	$P, \% *$	Changes 2017–2002	01.01.2003	01.01.2018		
Pine	684	2.3	680	2.3	−4	712	712	0	32
Spruce	356	3.3	377	3.2	21	445	430	−15	53
Birch	394	3.1	432	2.9	38	392	454	62	22
Aspen	126	5.6	146	5.2	20	57	96	39	−50
Black Alder	182	4.6	235	4.1	53	120	160	40	−75
Grey Alder	138	5.3	136	5.4	−2	122	122	0	−14
Total	1880	1.2	2006	1.1	126	1848	1974	126	−32

* $P, \%$ —Accuracy of estimation.

SFI data show 22,000–53,000 ha larger areas for each of the main tree species stands (pine, spruce, and birch; Table 2) and 14,000–75,000 ha less area for stands of other broadleaved species. NFI determines the dominant tree species (forest type) by the prevailing GSV in the first story, estimated by the measurement of sampling trees. Species composition during SFI is assessed by the visual method in 10% of classes, in special cases giving priority to coniferous and hard broadleaves as more desirable species. The results (Table 2) of the forest stand area analysis show that the species composition estimated by SFI has shifted to more valuable coniferous and hardwood broadleaved species.

Changes in the distribution of forest stand areas by age classes (10 years) were analyzed on the basis of NFI data for state forests (Figure 1). Distribution of forest stand areas by age classes is unique to each forest type. The majority of tree species attain their maximum forest area in the five- to six-year age classes, grey alder in the three- to four-year age classes, and spruce and birch in the one- to three-year age classes. The increase in forest stand area over a span of 10 years is typical of pine stands from the fourth age class, spruce stands from the second age class, and birch and other broadleaved species from the first age class. The decreases in area of pine stands in the first to third age classes and spruce stands in the first to second age classes are typical (Figure 1). This shows that, in most cases, young stands of pine and spruce species are not sufficiently tended, and that soft broadleaved species replace coniferous species at the beginning of stand formation.

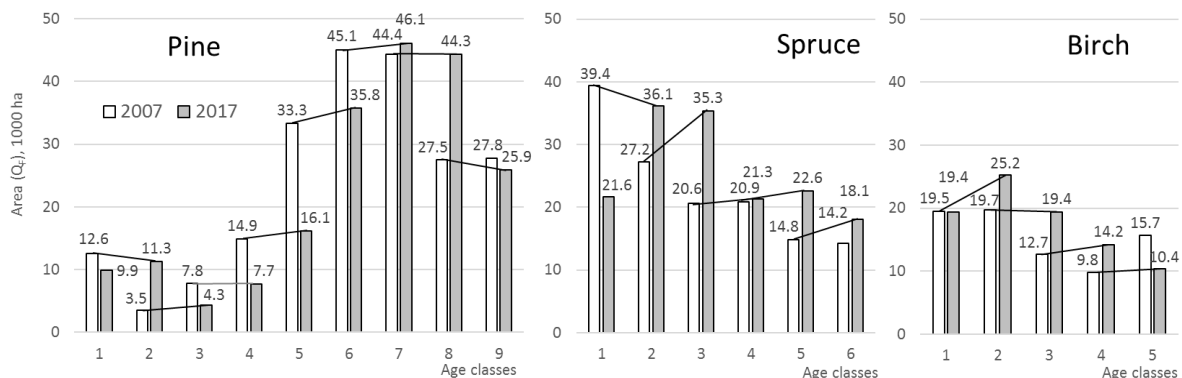


Figure 1. Changes of forest stand area distribution by age classes during 2007–2017 in state forest available for wood supply (FAWS).

3.1.2. Growing Stock Volume

Growing stock volume is the most important part of the total yield accumulated in the stand. Total GSV has been analyzed by forest type (i.e., by dominant tree species (Table 3). SFI underestimates mean GSV by 7–14% compared with the NFI of all stands (Table 3). In broadleaved stands, the obtained differences are higher in most cases. One of the reasons of higher differences is more complicated inventory of broadleaved stands to compare with inventory of coniferous stands. The deviation of SFI data from NFI data decreased by 7 percentage points (pp) over 15 years, as a result of more careful training of SFI surveyors to get them to respect NFI results. Differences in grey alder GSV assessed by SFI and NFI changed from −18.3 and −25.8% in 2002 to +9.9 and −0.9% in 2017, respectively, due to the harmonization and correction of 20% of grey alder form factor functions [37].

Table 3. Comparison of mean growing stock volume (GSV) of all and mature stands in FAWS, assessed by SFI and NFI, depending on forest type and inventory year.

Inventory (NFI), Assessment (SFI) Year	Inventory Object	Inventory Type, Characteristics	Species									
			Pine	Spruce	Birch	Aspen	Black Alder	Grey Alder	Oak	Ash	Others	All
GSV, m ³ /ha, Accuracy of Estimation (±P, %), Difference of SFI from NFI, %												
2002	All stands	NFI GSV	264	214	200	270	213	153	233	199	152	227
		±P, %	1.3	2.5	2.1	3.4	2.9	3.3	6.0	5.5	9.6	0.9
		SFI-NFI, %	−12.9	−10.7	−16.0	−20.0	−9.4	−18.3	−18.4	−17.1		−13.7
	Mature stands	NFI GSV	361	332	278	355	318	198	316	291	190	301
		±P, %	4.9	3.0	2.9	2.6	5.1	3.4	15.2	13.6		1.5
		SFI-NFI, %	−18.3	−8.4	−17.6	−24.2	−8.8	−25.8	−22.8	−20.6		−16.6
2017	All stands	NFI GSV	333	249	203	250	234	172	220	201	184	257
		±P, %	1.3	2.4	2.3	4.1	2.9	3.3	6.7	12.5	7.7	1.0
		SFI-NFI, %	−9.6	−8.4	−6.9	−13.2	−3.0	+9.9	−15.9	−15.4		−6.6
	Mature stands	NFI GSV	416	386	313	383	342	212	336	224	268	336
		±P, %	3.5	3.0	2.6	3.5	4.0	3.5	12.9	26.5		1.5
		SFI-NFI, %	−15.1	−11.7	−15.7	−18.5	−3.5	−0.9	−26.2	−13.0		−12.8

GSV at maturity is underestimated during SFI to a higher degree compared with all stands (Table 3). Differences between the mean GSV of all mature stands of FAWS, estimated by SFI and NFI, are, on average, −15%. These differences from 2002 to 2017 decreased from −16.6% to −12.8% (i.e., to a lesser extent compared with changes in the underestimation of GSV of all stands in all forests). Underestimation of the GSV of mature pine, spruce, birch, aspen, and black alder stands by SFI are statistically reliable because the deviations exceed the accuracy of estimation 2–6 fold (Table 3). Mostly stable deviations of GSV are observed in pine and birch stands, which make up 15–18%, while the largest deviation, in aspen stands, is 18–24% of GSV. Deviations of GSV of mature grey alder stands over 15 years decreased from approximately −26% to −1% due to the harmonization and correction of grey alder form factor functions [37].

3.2. GAI, Its Components, and Development

Growth Intensity and GAI Structure

The intensity of growth in Lithuanian forests, expressed as a percentage of GAI from the volume of stem wood of living trees, equals 3.5% on average. This growth varies from 3.0–3.1% in pine, oak, and ash stands with a rotation period of 110+ years, to 3.6% in birch, 3.9–4.0% in spruce, aspen, and black alder, and 5.0% in grey alder stands, growing 40–80 years. The intensity of growth of all tree species decreased from 9.7% to 2.1%, with the increase in stand age from 20 years and under, to 100 years and over. A 0.3–0.4 pp increase in growth intensity from 2003 to 2017 was observed.

Total yield and five yield components were estimated for 1998 to 2017 according to data of remeasurements in NFI permanent plots from 2007 to 2017 (Figure 2). Mean GAI over the span of 10 years increased, on average, by 1.74 m³/ha, for most tree species in the range 1.1–1.6 m³/ha and for stands of fast-growing species—Spruce and aspen—in the range 2.5–3.4 m³/ha (Figure 2a). The increase in GAI during the period of analysis was a result of stands' age structure changes, especially in spruce

stands and stands with spruce admixture, completely reestablished after heavy damage by wind, insects, and drought from 1992 to 1996, together with the positive influence of climate change.

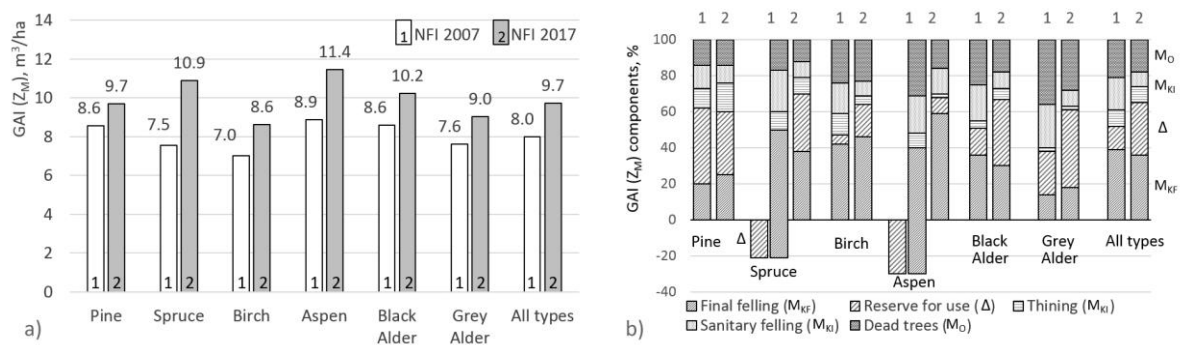


Figure 2. Gross annual increment (a) and its components (b) in FAWS according to national forest inventory (NFI) 2007 (1) and NFI 2017 (2) data.

The share of final felling volume in GAI changed from 14–20% in grey alder and pine stands to 70–71% in spruce and aspen stands from 1998 to 2007 (Figure 2b). The low final use of pine stands is due to a lack of mature stands, but is now gradually increasing. Due to its low quality, there is no demand for grey alder wood in the market, and it is characterized by the largest reserve for future use. The consequences of the 1992 to 1996 dieback of spruce stands and spruce trees in other stands (particularly aspen) initiated the negative GAI change in 1998 to 2007. However, the impact of adverse events on stand growth has decreased and final use, according to data from 2008–2017, did not exceed the GAI in each forest type (Figure 2b).

The share of dead tree stem volume over five years for all forest types gradually decreased from 21% in 1998–2007 to 17% in 2008–2017 (Figure 2b). The share of dead tree stem volume in stands of broadleaved tree species in most cases exceeded 20% due to the very low thinning intensity. The volume of thinning is stable, comprising, on average, 9% of GAI. The share of thinning in GAI of broadleaved tree species in the last decade has not exceeded 2–6%; however, in pine stands, it is 16%, and in spruce stands, it is 9%. For this reason, sanitary felling in all forest types is more intensive compared with thinning, and in stands of broadleaved tree species, the difference is 2-fold or more. This acts as a reserve to increase thinning volume and then increase the sustainability of stands, as well as to increase the share of living trees instead of low-quality wood from stems of dead trees.

Reserve for future wood use (i.e., the GAI minus dead trees and minus felled trees by intermediate felling) during the last decade has increased to 29%. Reserve for future wood use is especially high in stands of black alder (37%), grey alder (43%), and pine (35%) forest (Figure 2b).

3.3. Results of Natural Self-Thinning in Lithuanian Forest Stands in 2003–2017

The dynamics of the mean annual volume of dead trees from 1998 to 2017, according to the NFI data, shows the continuing increase in volume of dead trees along with increasing age of stands (Figure 3).

This means that the self-thinning process of stands is not yet finished. According to the data of three NFI five-year cycles, the largest annual volume of dead trees (2.7 – $3.8 m^3/ha$) was found in mature grey alder, aspen, and black alder stands (Figure 4a). The lowest volume of dead trees is typically characteristic of the most intensively thinned pine and partial spruce stands. When pine stands reach 41–60 years old, a decrease in dead tree stem volume is observed (i.e., the end of self-thinning), which is theoretically expected in the middle-aged, near-mature stand stage. This peculiarity is found in pine stands during all three NFI cycles (Figure 3). The highest annual mortality of trees and ever-increasing volume of dead trees is characteristic of mature and overmature, especially softwood deciduous, stands. In these stands, 3 – $4 m^3/ha$ of trees die annually (Figure 4a).

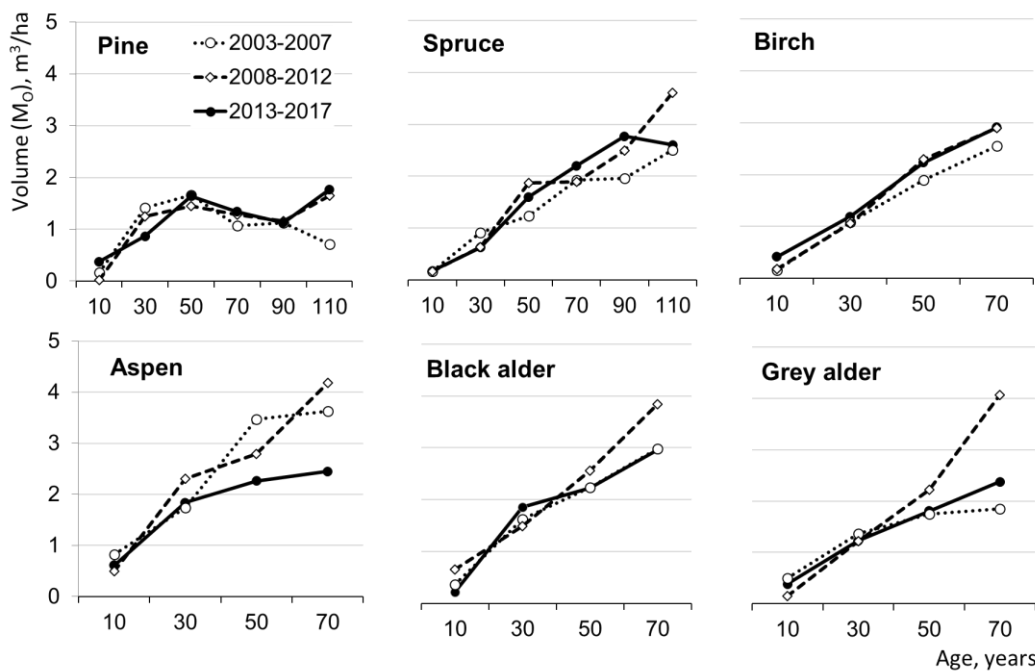


Figure 3. Comparison of annually dead tree stem volume in Lithuanian forests according to NFI data from 2003–2017.

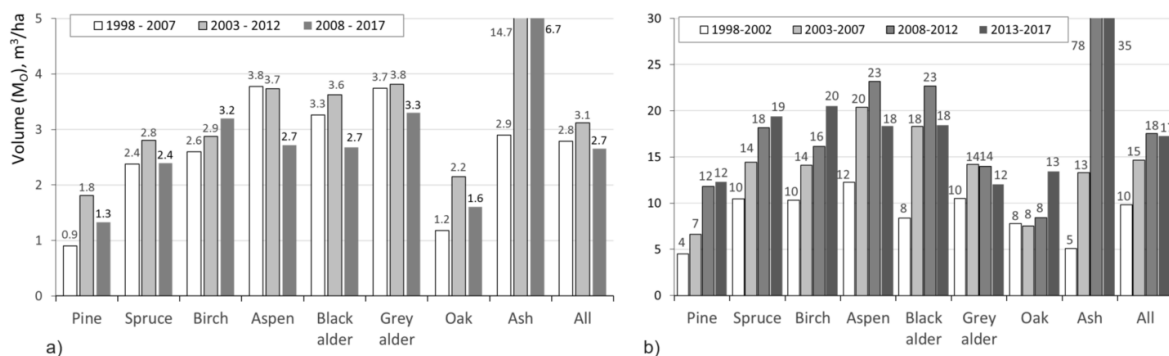


Figure 4. Comparison of annually dead (a) and accumulated dead (b) tree stem volume in mature stands of Lithuanian FAWS, 1998–2017.

As a result of intensive mortality in mature and overmature stands, the “reserve” of dead trees in these stands grows rapidly (Figure 4b). In 20 years (1998–2017), the volume of merchantable dead trees in mature stands has almost doubled (from 9.8 to 17.6 m³/ha). This was caused by the increase in the mean age of mature and overmature stands. In the last five years (2013–2017), stabilization of accumulated merchantable dead wood in stands at the mean level for all tree species of 17 m³/ha, and varying from 12 m³/ha (pine, grey alder) up to 18–20 m³/ha for stands of other species, was observed. The stabilization of dead tree stem wood volume in mature stands of FAWS was achieved by a balance between the volume of annually dead trees and the volume of decomposition of dead wood, as well as the absence of heavy storms or other heavy damage to the forests (Figure 4).

3.4. Wood-Use Planning on the Basis of the GAI Parameters Analysis

3.4.1. Area of Final Wood Use

Ideally, an even supply of wood should be ensured for both final and intermediate forest use. In organizing sustainable and sufficiently intensive forest management, intermediate forest use is

often achieved. Besides the final felling in FAWS, regeneration felling is also carried out in stands of ecosystem protected forests—Functional forest group II, at the age of natural maturity, which is considerably later than in FAWS (Table 4).

Table 4. The annual actual, even, and prospective final felling areas (Q_{KF}), in 1000 ha.

Forest Ownership	Actual, Equivalent		Even, According to Forest Groups (NFI 2012) and Unregenerated Area by 2014.01.01			Prospective in Forests of III–IV Groups	
	2009–2013	2014–2018	II	III–IV	Total	2013–2022	2023–2032
State	10.9 *	11.2 *	1.2	10.7	11.9	11.5	10.0
Private	9.9 **	10.4 ***	0.8	13.9	14.7	9.8	12.0
Reserved	n.d.	n.d.				2.2	2.5
Total	20.8	21.6	2.0	24.6	26.6	23.5	24.5

* actual = approved by the Minister of Environment; ** by forest management plans 2004–2013; *** 2007–2016.

Area of even final use is determined for each forest type, estimated by dominant tree species, dividing the FAWS area by the duration of rotation periods (Table 4, [38]). To ensure continuous and consistent wood use, it is very important, at least on the country level, and preferably on the level of forests of different ownership forms as well, to keep final felling areas as close as possible to the even-use areas.

The area of even use was calculated by taking into account areas of removable stands of FAWS (based on NFI 2012 data) and unregenerated territories (based on 1 January 2014 forest assessment data). The area of even use is comprised of 10,700 ha of state forests, and 13,900 ha of private forests, as well as forests reserved for restitution of ownership rights (Table 4). The area total final use in state FAWS from 2009 to 2018 was, and remains, 2–5% higher than the area of even use. The more intensive wood use is explained by the need to regenerate the accumulated areas of overmature, soft, deciduous stands as soon as possible.

An increase in the predicted final use area for future decades as a result of approaching near-mature forest stands with area per class to more than the area for even use has become typical for pine stands (Figure 5).

This situation was predetermined by the considerable area of pine forests planted on abandoned agricultural land in the postwar years. In birch stands of state forests, the opposite situation is characteristic (gradual, with age decreasing true felling area). Such a decrease in final felling area in birch stands is the result of the approaching near-mature birch stands with less area per age class than is needed for even future use. Decreases in the real felling area of birch stands in private forests will occur two decades later, and will partially compensate for the decrease of birch stand felling in state forests (Figure 5). Decreases in near-mature birch stand area in state forests are the result of the intolerance of birch as a valuable tree species for forest development in state forests 40–50 years ago (Figure 1). The largest difference between real and even-use areas of final felling is observed in spruce stands. This difference is the result of at least a twofold increase in spruce stand area in the first two age classes after the restoration of damaged 40-year-old and older spruce stands on large areas 20–25 years ago (Figure 5). Total annual forest felling area is expected to increase in state and private forests up to 24,000–25,000 ha in 2024–2033, and to decrease by 19,000–20,000 ha in 2044–2053, as a result of age class distribution changes (Figure 5). This will result in a maximum of 20% difference from the area of even use, at 24,600 ha (Table 4).

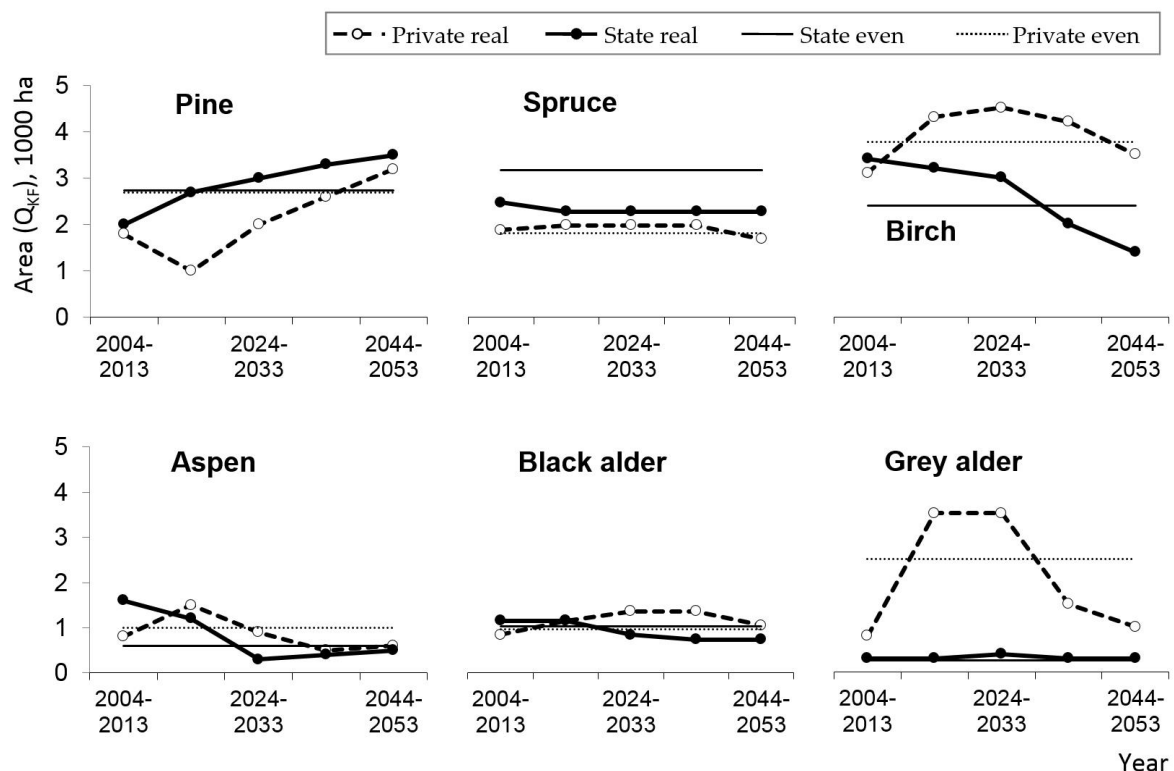


Figure 5. The current (2004–2013) and prospective tendencies of area changes of final felling in state and private FAWS.

3.4.2. Estimation of Intermediate and Final Use Wood Volume

The results of the analysis of GAI components for the first 10 years (1998–2007) show that the share of increment accumulated for final use together with the positive volume change as the reserve for future wood use in all forests contains 51% of GAI, whereas during the second 10-year period (2008–2017), it increased to 65%. At the same time, a significant decrease of intermediate (by 10 pp) and final felling (3 pp; Figure 2) is observed. By removing 25–30% of GAI from the stand during stand-intensive growth, and minimizing the preconditions for the appearance of natural losses, as well as evenly using mature stands, it is possible to obtain 5.5 million m³ of stem wood, or 4.5 million m³ of commercial wood, in state FAWS, annually (Table 5). In this way, 31% of the wood is removed by intermediate felling, and 69% is removed by final felling (Table 5). Almost 3 million m³ of stem wood would be obtained from coniferous stands, 2.4 million m³ from softwood broadleaved, and an insignificant part of the wood from hardwood broadleaved stands. This would correspond to a rational use of GAI of 6.69 million m³ determined for 2008–2012 in state FAWS, reaching a consumption level (5.52 million m³, Table 5) of 83% from the GAI.

The proposed use of forest yield in state FAWS, according to the GAI and its components (NFI 2012 data) and the share of increment accumulated in mature stands, was validated by comparing them with the outputs of the forest yield model (Table 6, Figure 6). Sanitary felling can be carried out no later than 10 years before final felling. The simulation of the development of the stands of the five main tree species by the yield model showed that, by applying 2–3 rounds of intensive thinning and any necessary sanitary cuttings, thus reducing natural losses by 10%, it is possible to not only reach the current level of productivity in mature stands, but also to increase it (Table 6, Figure 6). The differences in the values of accumulated shares of GAI in mature stands of the main tree species of Lithuania obtained during the simulation and evaluated by the NFI 2012 data do not exceed 5% (Table 6).

Table 5. Estimation of possible to use wood annually by various felling, depending on gross increment and accumulated stems volume in mature stands of state FAWS (Forest available for wood supply). NFI 2012.

Prevailing Tree Species	Intermediate Felling (M_{KI})									Final Felling (M_{KF})			Total Annually Felled Volume of Stem ($M_{KI} + M_{KF}$), $M m^3$	
	Tending			Thinning			Sanitary			Total Annually Felled Stem, $M m^3$	Area, 1000 ha	Volume * of Mature Stands m^3/ha		Volume of Stem in Annually Felled Stands $M m^3$
	Area of Stands at Tending Age, 1000 ha	Increment m^3/ha	Stem Wood for Tending, $M m^3$	Area of Stands at Thinning Age, 1000 ha	Increment, m^3/ha	Stem Wood for Thinning $M m^3$	Area of Stands at Sanitary Cutting Age, 1000 ha	Increment, m^3/ha	Stem Wood for Sanitary Cutting, $M m^3$					
Con **	83.5	2.7	0.07	275.1	9.8	0.75	106.2	8.8	0.24	1.06	5.0	380.5	1.90	2.96
Soft **	80.8	3.8	0.09	71.3	9.6	0.19	122.1	9.2	0.28	0.56	5.8	322.5	1.87	2.43
Other **	8.9	3.2	0.01	25.8	6.3	0.05	7.4	7.9	0.01	0.07	0.2	301.5	0.06	0.13
Total	173.2	3.4	0.17	372.2	9.6	0.99	235.7	9.0	0.53	1.69	11.0	341.5	3.83	5.52

* Volume decreased by the volume of biodiversity trees: $10.5 m^3/ha$; ** Con = coniferous (pine, spruce), Soft = softbroadleaved (birch, aspen, alders), other = others (oak, ash, and others).

Table 6. Forest stand development program and results of its application for state FAWS in sites of average productivity according to the forest yield model. NFI 2012.

Forest Type	Area, M ha	SI H_{AB} , m	Parameters of Thinning					Productivity and Its Components, m^3/ha												
			INITIAL		Number of Thinning	Duration between Thinning, Years	Rotation, Years	Yield Model Results						NFI 2007–2017						
			Age	Stocking Level				Accumulated (M_{KF})	Thinning (M_{KI})		Mortality (M_O)		Total ($\sum Z_{MA}$)	Annual	Accumulated Volume of Mature Stands	Even Gross Increment				
					Total	Annual	Total		From Them Sanitary	Annual	Total	Annual				2007	2017			
Pine	0.28	27	20	1.0	3 + 1 *	30	110	$\frac{417}{57}$	3.8	$\frac{242}{33}$	$\frac{32}{4}$	2.2	$\frac{77}{10}$	0.7	$\frac{736}{100}$	6.7	397	7.4	8.6	
Spruce	0.19	28	20	0.9	3 + 1 *	20	80	$\frac{398}{58}$	5.0	$\frac{222}{32}$	$\frac{32}{5}$	2.8	$\frac{64}{10}$	0.8	$\frac{683}{100}$	8.5	385	7.7	10.8	
Birch	0.16	26	20	1.0	2 + 1 *	30	70	$\frac{317}{65}$	4.5	$\frac{117}{25}$	$\frac{17}{4}$	1.7	$\frac{36}{8}$	0.7	$\frac{470}{100}$	6.7	318	6.3	9.0	
Aspen	0.06	29	20	1.0	2	20	50	$\frac{384}{70}$	7.7	$\frac{134}{25}$	-	2.7	$\frac{24}{4}$	0.5	$\frac{542}{100}$	10.8	384	9.5	13.0	
Black alder	0.08	23	20	1.0	2 + 1 *	30	70	$\frac{344}{63}$	4.9	$\frac{165}{30}$	$\frac{31}{5}$	2.4	$\frac{41}{7}$	0.6	$\frac{550}{100}$	7.9	332	7.5	9.9	
Total	0.77							$\frac{381}{60}$	4.7	$\frac{195}{31}$	$\frac{29}{5}$	2.3	$\frac{57}{9}$		$\frac{633}{100}$		370			
Balance of felling, %								66		34	5		66		34	5				

* sanitary cuttings; SI—Site index, expressed by mean height (m) at reference age.

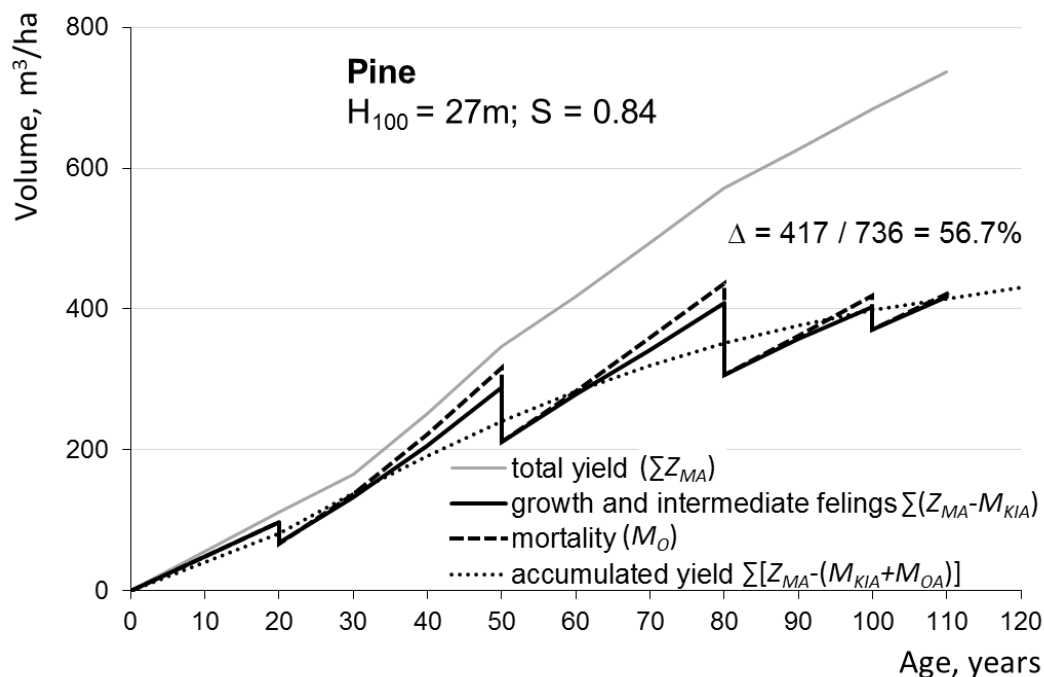


Figure 6. Dynamics of gross volume increment and its accumulated share in pine stands growing in sites of average productivity according to yield model [29] and NFI 2012 data.

During the simulation, the aim was to reduce potential self-thinning by maximizing intermediate use. For pine stands growing on sites with $SI = 27$ m and an initial stocking level at age 20 equal to 1.0, thinning was applied at 20, 50, and 80 years at an intensity of 30%, 27%, and 25% from accumulated growing stock volume. At the age of 100 years, light (8%) sanitary cuttings were applied (Figure 6). As a result of these simulations, during the rotation period, 242 m³/ha volume at stand age of intermediate felling was received, and for final use at stand age of 110 years, 417 m³/ha wood volume was accumulated.

Natural losses were decreased by up to 10%. The ratio between the volumes of final felling, thinning, and sanitary felling obtained by simulation for stands of main species (Table 6) as 66:29:5, compared to the existing ratio of 72:15:13. The existing ratio shows a strong focus on more intensive final and sanitary felling. The results of the analysis of GAI structure, its dynamics, correlations with felling intensity for two decades (Figure 2), and testing of these results against the yield model and NFI 2012 data, suggest keeping the size of final felling together with reserve for future use at 57–70% and intermediate felling at 25–33%, and decreasing natural losses to 7–10% from GAI (Tables 5 and 6).

The forest area designated for final felling and GSV accumulated per unit area is the main factor defining possible wood use in final felling. Forestry practice and wood use often reveal a demand for data on the GSV of mature stands for five- to 10-year periods, as well as for all rotation periods.

3.5. Prediction of GSV of Mature Stands

GSV change for a 10-year period was predicted by analyzing the GSV and GAI of mature and near-mature (one age class prior to maturity) stands and parameters (areas, mean GSV, GAI, and the level of GAI accumulation in stand) designated for felling. The GSV of mature stands predicted for 2017 (from 2007) was controlled by NFI 2017 data (Figure 7).

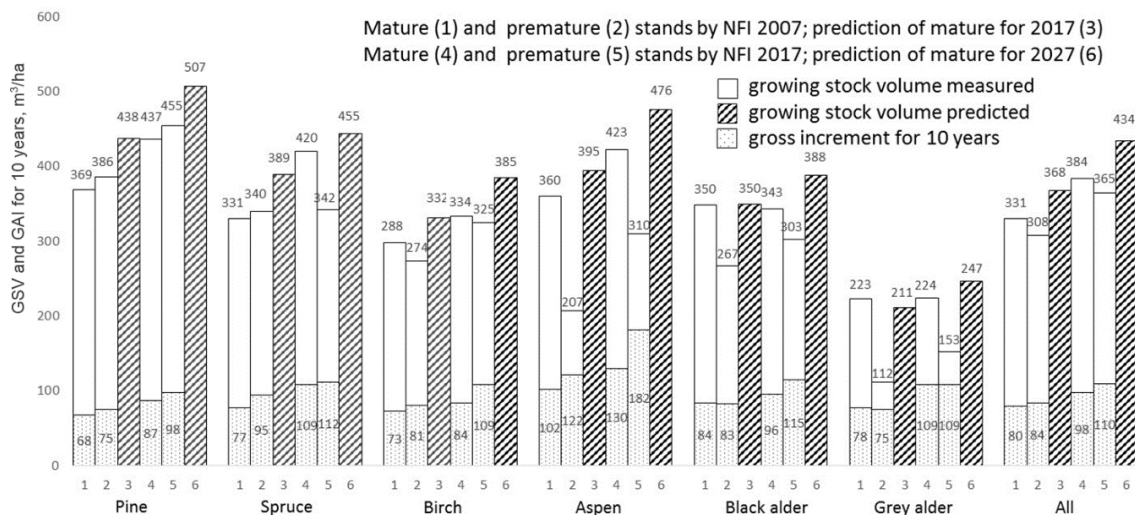


Figure 7. Prediction of growing stock volume of mature stands in FAWS of state forests for the years 2017 and 2027 using data from the NFI 2007 and NFI 2017, respectively.

Considering that thinning in near-mature and mature stands is not allowed, and that the mean age of mature stands exceeds that of near-mature stands by 15–25 years, the level of GAI accumulation in near-mature stands was determined to be 70%, and for mature stands it was 50% of the total GAI. The predicted GSV of pine, birch, and black alder mature stands for the year 2017 did not exceed 2%, and predictions for other species did not exceed 6–7% (Figure 7), compared with data in the NFI 2017. The GSV of mature stands was predicted in the same way for 2027. Overall, the GAI of NFI 2017 exceeds the GAI of NFI 2007 by 13–28% in mature stands, and 15–33% in near-mature stands. The highest differences between the GAI of 2017 and 2007 were observed for pine, aspen, and grey alder stands. Assuming that GAI for stands of the same age in 2018–2027 will remain the same as in 2008–2017, the GSV of mature stands of state forests will continuously increase and should be 434 m³/ha by the end of the period, exceeding the GSV of mature stands in 2017 by 50 m³/ha, compared with the GSV of mature stands increasing by 53 m³/ha from 2008 to 2017.

Total yield for the rotation period was estimated by multiplying the mean GAI by the length of the rotation period (Table 7). The GAI, estimated by three different inventory periods, varies by 8–12% from the mean value. The ratio of accumulated GAI in the stand with total GAI according to the data of three different inventory periods varies in the range of 52–65% (Table 7). High variation is also characteristic of ratios of GAI accumulated in stands, estimated by different inventories for the appropriate forest type. The damage to large forest areas caused by wind, insects, and diseases can destroy normal development, and the balance of GAI for stands of appropriate forest types for sometimes more than five or 10 years. One way to decrease the aforementioned variation and predict nontypical deviations is to increase the time of measurements. This will be carried out more often in the future, depending on the results of successive inventories. For this reason, GSV at maturity age for all rotation periods is predicted at present using the ratio estimated by the yield model [29]. The yield model gives practically the same range (50–68%) for the ratio of accumulated GAI in the stand with total GAI, but the values of ratio for appropriate forest types are very stable. When using the same approach, estimated mean GSV values of mature stands for all rotation periods deviate from those inventoried by NFI 2017 by 2–5% in all FAWS, taking higher deviations into account (+23% and +13%) in pine and black alder stands (Table 7).

Table 7. Estimation of mostly likelihood growing stock volume of mature stands for rotation period in all FAWS correspondingly to the state of forest, estimated by NFI 2007 and NFI 2017.

Characteristics	Forest Type					
	Pine	Spruce	Birch	Aspen	Black Alder	Grey Alder
Mean, even GAI (Z_M), m ³ /ha/year	8.7 ± 0.7	9.5 ± 1.0	7.7 ± 0.9	10.6 ± 1.3	9.2 ± 1.0	7.9 ± 0.7
Rotation period (felling age (A_K) + 9), years	110	80	70	50	70	40
Total yield during rotation period, m ³ /ha [$Z_M \times (A_K + 9)$]	946 ± 77	760 ± 80	539 ± 63	540 ± 65	644 ± 70	316 ± 28
Ratio of mean accumulated volume (change + final felling) and total yield ($(\Delta + M_{KF}) \times 100 / (Z_M \times (A_K + 9))$), % according to NFI data	64.5 ± 3.0	52.5 ± 22.0	56.4 ± 6.5	53.8 ± 12.5	63.0 ± 6.0	56.2 ± 8.5
according to yield model	54	50	60	68	60	64
Growing stock volume at maturity age (V_{KF}) according to total yield and its accumulation level, m ³ /ha	511	380	323	367	386	202
and its deviation from NFI 2017, %	22.8	−1.6	3.2	4.2	12.9	−4.7

3.6. The Key Factors Predetermining Wood-Use Volume

The main factors determining overall wood use, without being divided into final and intermediate wood use, were revealed in this research as follows: the total forest area; the share designated for the production of wood as FAWS; forest productivity, expressed as the average GAI during the rotation period; natural losses (i.e., stems of dead trees due to causes other than cutting); and output of commercial wood from stem volume, including wood harvesting losses and forest trees left in the forest for the maintenance and enhancement of biodiversity. The generalized potential total wood use volume was estimated by considering the mean GAI in the range of 8.0–9.0 m³/ha per year, the share of FAWS within the range of 70–90% from the total forest area, natural losses in the range of 0.6–1.4 m³/ha per year, and the commercial wood output (75–85%) from the GSV (Table 8).

Table 8. The general potential wood use depending on forest stand productivity, forest area available for wood supply, natural losses, and output of commercial wood from stem volume.

Mean Gross Annual Increment (Z_M), m ³ /ha/year	Forest Area Available for Wood Supply, %	Natural Losses, m ³ /ha/year								
		1.4			1.0			0.6		
		Output of Commercial Wood from Stem Volume, %								
		75	80	85	75	80	85	75	80	85
Potential Mean Annual Commercial Wood Volume, m ³ /ha/year										
8.0	70	3.5	3.7	3.9	3.7	3.9	4.2	3.9	4.1	4.4
	80	4.0	4.2	4.5	4.2	4.5	4.8	4.4	4.7	5.0
	90	4.5	4.8	5.0	4.7	5.0	5.4	5.0	5.3	4.7
8.5	70	3.7	4.0	4.2	3.9	4.2	4.5	4.1	4.4	4.7
	80	4.3	4.5	4.8	4.5	4.8	5.1	4.7	5.1	5.4
	90	4.8	5.1	5.4	5.1	5.4	5.7	5.3	5.7	6.0
9.0	70	4.0	4.3	4.5	4.2	4.5	4.8	4.4	4.7	5.0
	80	4.6	4.9	5.2	4.8	5.1	5.4	5.0	5.4	5.7
	90	5.1	5.5	5.8	5.4	5.8	6.1	5.7	6.0	6.4

The data provided in Table 8 show that, in changing forest management and wood-use conditions (i.e., increasing the stand's productivity, reducing the natural losses of forest growth, and seeking to obtain the standard yield of commercial wood), the amount of commercial wood can be increased significantly. Currently, the actual level of wood use comprises 4.5 m³/ha of commercial wood output per year. This is in response to 87% of FAWS, to the mean GAI 8.5 m³/ha per year, 75% output of commercial wood from stem volume, and 1.4 m³/ha natural losses (Table 8). Annual removal of 5.0 m³/ha, or about 10 million m³ of merchantable wood in the current forest area, can be achieved in the future, having increased the intensity of thinning, thus reducing natural losses to 1.0 m³/ha, as well as having an increased output level of commercial wood during harvesting, which would be close to the standard 80–85%.

4. Discussion

In this research, deviations of forest characteristics, estimated by SFI, were revealed. The general potential wood use depending on forest stand productivity, ratios between its components (especially the ratio of natural losses), forest area available for wood supply, as well as other parameters, were proposed. By simulating forest growth and use, a way to reduce forest growth losses by up to 10% from the GAI was suggested. Observations on permanent research objects [32], forest stand yield development results [11,28,30,31,39], information from NFIs of different European countries [24], the results of this study, and theoretical calculations show that natural losses in managed forests can be reduced by up to 10%. In seeking to achieve this target, it is necessary to intensify thinning by 25–35% from the GAI, as well as to decrease areas of overmatured stands. This is also evident from the forest assessment results estimating natural losses in European forests [25], and from the analysis of European forest development [14].

The removable amount of wood from the accumulated GAI in forest stands was specified on the basis of the regularities in the GAI distribution into separate components and their dynamics. Regulation of the ratio between separate GAI components, especially in young stands, creates the prerequisites for reducing natural losses and leads to the possibility of increasing wood use by 4.5–5.0 m³ of commercial wood from 1 ha of forest area, which is more than is currently used (3.5–3.8 m³/ha). In the recent past, potential wood use, based only on standwise forest inventory data for 2005 to 2010, and expressed by volume of commercial wood, was predicted at 2.4–3.1 m³/ha for state forests, 2.2 m³/ha for private forests, and 2.5–2.7 m³/ha for the entire country [9,10]. Predictions of the future wood supply from European forests under new management trends for Lithuania are questionable due to the accepted 2005–2060 mean GAI (4.6–5.4 m³/ha) and GSV values (182–213 m³/ha; [15]). Having the specified volumes of mature stands according to the first results of the NFI and focusing on the minimum natural losses of forest growth, the output from state forests in the 21st century was predicted to rise to 5.1 m³/ha of commercial wood, and 4.7 m³/ha in private and other forests [38,40].

In European forestry practice, the first attempt [25] to assess and provide information on natural losses for large areas was made in 2000, but it was a single act that was not applied on a larger or more regular scale. The ratio of the stem wood volume of felled living trees and net increment used in forest resource assessments in Europe [41] is aimed more at indicating the harvesting intensity than at assessing the efficiency of forest management, because the assessment and control of natural losses in this case are ignored. The share of GAI accumulated in mature stands (i.e., the volume of mature stands) would also be relevant for the evaluation of the efficiency of forest management in adequate forest site conditions.

The ratio of wood assortments produced in the forest with total stem wood volume accumulated in stands in the age of the final felling indicates the rationality of forest harvesting and the efficiency of forest use as a whole. In this way, the efficiency of forest management and wood use could be evaluated according to the following parameters:

- (i) by the share of felled living versus dead tree stem volume in GAI,
- (ii) by the share of natural losses in GAI,
- (iii) by the share of intermediate use (tending + thinning versus sanitary felling) in total use of living trees, and
- (iv) by GSV at maturity age and output of commercial wood during harvesting.

In seeking to use wood as rationally as possible, it is very important to use the objective data on the GAI and its components. The NFIs in this way comprise a reliable and efficient tool providing information on forest management and forest harvesting efficiency, as well as on the rational regulation of forest growth and wood-use control at the national level.

5. Conclusions

- (1) SFI, due to a 10-year remeasurement period, cannot respond to forest area changes as adequately and objectively as it does to NFI. Species composition by SFI is subjectively shifted to more valuable coniferous and hardwood broadleaved species.
- (2) SFI underestimates mean GSV by 7–14% on average, and by 13–17% in mature stands, compared with NFI estimations. Deviations decreased by 4–7 pp on average over 15 years as a result of more careful training and improvement of SFI by surveyors taking the results of the NFI data analysis into account.
- (3) Permanent NFI plots create the possibility of monitoring the growth of trees from their germination until their death. These features distinguish the NFI as the comprehensive tool for data received from various other inventories.
- (4) The productivity of Lithuanian forests from 1998 to 2017 increased from 8.0 to 9.7 m³/ha; 54–67% of GAI was removed by final and intermediate felling, 12–29% of GAI contains reserve for future use, and 17–21% of GAI is comprised of natural losses. GSV of mature stands from 2008 to 2017 increased by 53 m³/ha; the GSV of mature stands is predicted to increase by 50 m³/ha over the next decade.
- (5) The most important reasons for the significant increase in natural losses are as follows: (a) low-intensity tending and thinning in the past and present (9% of GAI in all forests, and 11% in state forests), predetermining insufficient resistance of mature stands with the annual loss of trees reaching 3–5 m³/ha, and (b) growing of stands, especially softwood broadleaves, 20–40 years longer than the optimum cutting age.
- (6) To increase the efficiency of forest management, reduce natural losses, and augment the usable part of the yield, it is necessary to intensify intermediate felling by removing 25–35% of the GAI until the final felling age, and to reduce areas of overmature stands that are not resistant to adverse natural factors.
- (7) Continuous monitoring of forest stand yield using NFI data, the timely disclosure of factors negatively affecting both yield and its accumulation, and regulation of these processes by forest management measures revealed potential ways to increase forest use in Lithuanian FAWS, as compared to predictions and calculations based on the recent past.

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