Fluctuations in Gross Volume Increment Estimated by the Lithuanian National Forest Inventory Compared with Annual Variations in Single Tree Increment

GINTARAS KULBOKAS[1,2], **VAIVA KAZANAVIČIŪTĖ**[1,2], **ANDRIUS KULIEŠIS**[2], **ALGIRDAS AUGUSTAITIS**[1], **EDMUNDAS PETRAUSKAS**[1], **MARIUS MIKALAJŪNAS**[1], **ADOMAS VITAS**[1] **AND GINTAUTAS MOZGERIS**[1*]

[1]*Vytautas Magnus University, K. Donelaičio g. 58, LT-44248 Kaunas, Lithuania, gintautas.mozgeris@vdu.lt, phone +370 37 752291*

[2]*State Forest Service, Pramonės pr. 11A, LT-51327 Kaunas, Lithuania*

Kulbokas, G., Jurevičienė, V., Kuliešis, A., Augustaitis, A., Petrauskas, E., Mikalajūnas, M., Vitas, A. and Mozgeris, G. 2019. Fluctuations in Gross Volume Increment Estimated by the Lithuanian National Forest Inventory Compared with Annual Variations in Single Tree Increment. *Baltic Forestry* 25(2): 273–280.

Abstract

There are significant inter-annual fluctuations of growing stock volume changes of living trees estimated by the Lithuanian National Forest Inventory (NFI). In the current study, we compared two sources of information on forest productivity: conventional NFI data and dendrochronological data based on the tree cores collected simultaneously with the measurements of the fourth Lithuanian NFI cycle during 2013–2017 on the same permanent plots (total number of cores was 4,967). The main finding is that the dendrochronological basal area increment data confirmed the depression of gross stand volume increment around 2006–2007 (based on Lithuanian NFI measurements in 2008–2009), followed by a steep increase during 2008–2011 (NFI from 2010–2013). The findings explain the differences between projected growing stock volume change, which have been used for forest reference level estimation according to land use, land-use change and forestry sector regulation, and the one recently provided in National Greenhouse Gas Inventory Reports.

Keywords: Growing stock volume change, basal area increment, forest reference level, greenhouse gas reporting

Introduction

There are numerous objectives of conducting the National Forest Inventory (NFI) in Lithuania and other countries. The NFIs serve as the main provider of statistical data on forest resources, their state, change and use. The NFI data can be used for forestry strategic planning, quantification of forest ecosystem services, such as biodiversity and carbon sequestration. Therefore, comparable, transparent and comprehensive forest information is important for decision-making both at national and the European levels (Kuliešis and Kulbokas 2009, Tomter et al. 2012, Alberdi et al. 2016, Bosela et al. 2016). This requires scrupulous inventory procedures, and the outputs need to be carefully understood and explained.

According to the Law on Forests of the Republic of Lithuania (Seimas … 1994), the NFI, which is based on sampling method, is a type of state-level forest inventory and is aimed at data provision for national and international reporting. There are many common features of the Lithuanian NFI and continuous inventories in other European countries, such as Sweden, Norway, Finland, Denmark, Iceland, Estonia, Latvia, Poland, Romania, Hungary, Austria, the Czech Republic and France (Lawrence et al. 2010). Exhaustive statistics are available from the Lithuanian NFI, such as area, growing stock volume, volume change, dead wood accumulated in forest, volume of felled trees and felling rates, newly afforested areas, tree and forest damage, and forest regeneration (Kuliešis et al. 2010, 2016, 2017). Since its beginning in 1998, the Lithuanian NFI has been executed using 5-year inventory cycles, meaning that only 20% of all permanent plots are surveyed annually. The inventory plots are randomly distributed through the whole country and revisited every 5 years. The fifth NFI cycle started in 2018 on the plots, which were previously surveyed in 1998, 2003 and so on. As a rule, annual measurements are executed during April-November, aiming to not exceed a difference in inventory date by more than 20 days, compared to the inventory date of 5 years previously. This approach predetermines the 5-year periods for increment estimation. Depending on the date of survey, there may be two types of permanent plots: those with trees that stopped growing last year and those with trees that have grown during the year of measurements. To compile annual statistics, data from the current year plots are combined with the estimates from the four preceding years. Therefore, the annual Lithuanian NFI country-level statistics are based on measurements conducted during the last 5 years.

Among the numerous applications of NFI data, its use in greenhouse gas (GHG) inventories is essential. The increasing role of forests in climate change mitigation action (the European Parliament and Council 2018) also raises more concern about conformity of the NFI data used for calculation of carbon stock changes and GHG emissions/removals. The NFI data is a core data source for GHG emissions/removals estimation from the land use, land-use change and forestry (LULUCF) sector in Lithuania. It provides data on land uses and land-use changes, growing stock volume changes and volume of wood harvested. However, a careful look at the national GHG inventory (Konstantinavičiūtė et al. 2018) shows very high inter-annual fluctuations of growing stock volume changes of living trees estimated during the whole accounting period since 1990 (Figure 1). The attempts to explain the inter-annual fluctuations rely heavily on expert knowledge. For example, the lowest extremity, estimated during 1996–1997, could be a consequence of spruce dieback after droughts and pest invasions in large areas of Lithuanian spruce stands, which resulted in greatly increased harvest (see Discussion for references). Nevertheless, other fluctuations do not have strong explanations and require further research on causality. To reduce the impact of the single-year measurements, a data smoothing approach was applied to annual GHG inventories (Konstantinavičiūtė et al. 2018), e.g. the annual growing stock volume change is calculated for the whole 5-year period as an average value of five components, actually measured during five preceding years. Due to the lack of the most recent re-measurement data, extrapolation is applied to project future growing stock volume changes until actual data becomes available. Extrapolation is needed because each NFI re-measurement refers to the middle of the GHG reporting period.

Figure 1. Growing stock volume change used for GHG inventory in Lithuania (source: Konstantinavičiūtė et al. 2018)

The need to explain fluctuations is of utmost importance considering requirements of the LULUCF regulation (EU 2018/841), i.e. estimation of forest reference level, ensuring a robust and credible accounting system. The data used for forest reference level estimation (forest management practices observed during 2000–2009, according to the LULUCF regulation) falls into the period of strong depression of growing stock volume change (Figure 1) and thus may have a strong impact on the projected forest growing stock volume changes and forest management planning. To better understand the causes of these fluctuations, we compared two sources of information on forest productivity, collected by focussing on different inventory approaches. The primary aim of the study is to assess the relationship between the increment of individual trees and the mean growing stock volume change in stand groups and check the reliability of the NFI statistics by dendrochronological investigation of single trees, in explaining inter-annual variations reported in GHG inventories.

Material and Methods

Materials used for the current study originated from the Lithuanian NFI; however, we further distinguished two types of input information, depending on the objectives, principles and the period of data collection and processing. First, we used conventional NFI data collected during the period since its launch in 1998 until 2017. Only measurements conducted on permanent sample plots, established during the first NFI cycle, i.e. during 1998–2002, were utilised. This means, to ensure the consistency of data, that neither the information collected on temporary sample plots nor the permanent sample plots entering the category of forest land during the later NFI cycles were considered. Out of numerous NFI variables, the mean annual stand volume increment during the 5-year period (in m^3/ha) was extracted. Data processing followed conventional Lithuanian NFI routines (Kuliešis et al. 2009, 2010), i.e. the annual forest variable was estimated based on measurement on field sample plots during the preceding 5 years, e.g. data from 1998–2002 were used to get the annual variable referred to as 2002, data from 1999–2003 matched to 2003 and so on. Hereafter, this time point is referred to as the NFI year. To harmonise the achieved statistics with the methods of GHG assessment in the LULUCF sector, the NFI year was reduced by 2, i.e. resulting in an annual variable based on measurements in 1998–2002 being assigned to 2000 and so on. Hereafter, this is referred to as the GHG year. Basic characteristics of Lithuanian forests based on the NFI sample plots used in this study during the whole period covered are introduced in Table 1.

Table 1. Basic mean forest characteristics at the beginning and the end of analysed period

Main tree species	NFI (year)	GHG (year)	Area (th.ha)	Age (years)	H_{AB}* (m)	D_{AB}**, (cm)	Stocking level	Growing stock volume (m³/ha)	Mean annual (5 years) gross volume increment (m³/ha)	Mean annual volume change during 2002–2017 (m³/ha)
Pine	2002	2000	669.8	62	26.8	35.3	0.81	268.6±3.5	8.3	
	2017	2015	641.5	73	28.2	36.0	0.82	347.1±4.2	9.7	5.24
Spruce	2002	2000	348.3	50	28.3	37.1	0.66	218.2±5.5	7.6	
	2017	2015	359.7	51	29.3	37.7	0.70	255.9±6.1	11.1	2.51
Birch	2002	2000	366.3	47	24.7	27.4	0.83	210.1±4.2	7.9	
	2017	2015	374.1	48	26.3	28.1	0.78	218.5±5.0	8.7	0.56
Aspen	2002	2000	122.3	44	28.0	34.5	0.75	275.7±9.1	9.9	
	2017	2015	134.1	40	29.7	36.0	0.74	260.0±10.7	11.8	-1.05
Black alder	2002	2000	174.4	43	22.1	26.3	0.86	215.6±6.3	8.5	
	2017	2015	210.6	45	24.3	28.0	0.83	242.3±7.3	10.2	1.78
Grey alder	2002	2000	120.8	30	16.4	16.9	0.78	157.6±5.5	7.8	
	2017	2015	109.5	35	17.6	17.4	0.71	174.8±6.6	8.6	1.14
Total	2002	2000	1923.9	52	25.6	32.4	0.78	232.9±2.1	8.1	
	2017	2015	1929.9	56	27.0	33.2	0.77	271.5±2.4	9.8	2.57

* Site index, H_{AB}, is estimated according to current mean height and age of the main storey and expresses mean height at reference age

** Site index, D_{AB}, is estimated according to current mean diameter at breast height (DBH) and age of the main storey and expresses mean DBH at reference age

The second data set (hereafter referred to as dendrochronological data) used in our study was based on tree cores collected in parallel with the measurements of the fourth Lithuanian NFI cycle during 2013–2017 on the same permanent plots. Core samples were taken at breast height of the selected dominating trees in the same stand but growing outside the permanently monitored NFI plot. Only trees older than 40 years (30 years for grey alder) were included in the survey, resulting in a total number of 4967 cores, distributed by species as follows: 2393 cores of pine, 925 spruce, 817 birch, 210 aspen, 347 black alder and 276 grey alder. The annual tree-ring width was later measured from bark to pith with an accuracy of 0.01 mm using an electronic transducer and a binocular scope fixed over the moving stage of "Lintab 6" equipment and processed using TSAP-Win™ software (RinnTech 2019). The individual tree-ring width series were synchronised visually by comparing ring width graphs (Eckstein 1989) and calculating Pearson's correlation coefficients among them (Baillie and Pilcher 1973). Then, basal area increment (BAI) series were derived from the tree-ring width. Annual BAI (at year t) was calculated based on ring width (w), and radius length (R), employing the following equations:

$$BAI = \pi(R_t^2 - R_{t-1}^2) \tag{1}$$

$$R_{t-1} = R_t - w_t \tag{2}$$

The BAI was calculated in the area inward from the outside edge of annual tree-rings (hereafter referred to as non-smoothed data). To compare the BAI with the mean annual stand volume increment from NFI data, it was also averaged using the same principles, i.e. using the moving average of BAI during the preceding 5 years (hereafter referred to as smoothed data). Additional to analysing all cored-tree data, we created a reduced tree data set, hereafter referred to as reduced and smoothed data. It included the estimates of trees, which had BAIs during 2006–2007 less than during 2011–2012 (the years with the lowest and highest values of gross volume increment according to the NFI, respectively).

Because the primary objective of the current paper is to introduce the initial findings of our study, which are very important to enhance the Lithuanian NFI and GHG assessment in the LULUCF sector systems, we utilised a rather simplistic approach to compare annual variations in Lithuanian NFI estimates with the trends in dendrochronological data. First, we visually compared the annual trends of BAI based on tree-level measurement and the mean annual stand volume increment from NFI data, taking into consideration the cored-tree species and the dominating tree species on the NFI sample plot. Then, we rescaled all data sets using the standardisation. Linear regression models were created and evaluated using the NFI data as the dependent and tree-level BAI data as the independent data sets. A non-parametric Wilcoxon matched-pairs test was used to compare paired groups (i.e. the NFI and dendrochronological data). Fixed date (year) starting from 2000 until 2012 was used as a pairing variable. The Box–Ljung statistic for all variables was calculated to test the assumption against autocorrelation. Statistical processing was implemented using SPSS software package (IBM 2017).

Results

The fluctuations in the smoothed growing stock volume changes graph used for the GHG inventory in Lithuania (Figure 1) were also followed by the values of mean 5-year gross stand volume increment (based on the NFI data) and basal area increment of single tree (based on the dendrochronological “smoothed” data) by tree species (Figure 2). There was some clear decrease in increment values around 2006 and then a more steep increase, reaching maximum values by the end of the considered period.

Usually the NFI data were autocorrelated at all lag distances (Table 2); however, the level of autocorrelation in dendrochronological data depended on the data treatment approach and tree species. For example, BAI data for spruce usually were not autocorrelated regardless of treatment. Non-smoothed dendrochronological data were usually not autocorrelated, except for aspen.

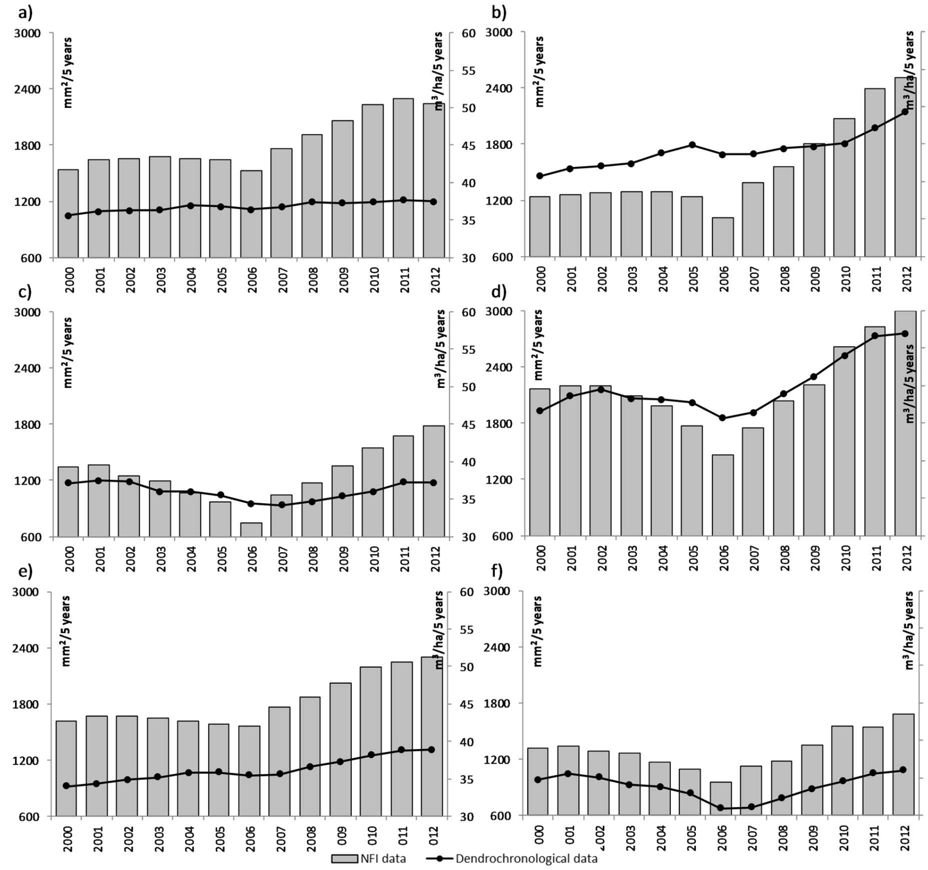

Figure 2. Mean 5-year basal area increment of single tree (based on the dendrochronological “smoothed” data) and mean 5-year gross stand volume increment (based on NFI data) by tree species: (a) pine, (b) spruce, (c) birch, (d) aspen, (e) black alder and (f) grey alder

Regardless of the treatment of dendrochronological data, BAI values during the 13-year period considered were strongly associated with the gross stand volume increment, based on NFI data (Table 3). The Wilcoxon test for all species supported the null hypothesis ($p = 0.650–0.972$), meaning that there was no significant difference in paired series gathered using different methodologies, i.e. collected within the frame of the NFI and achieved using tree-level dendrochronological investigation. Regression models created with NFI data as the dependent and tree-level BAI data as the independent data sets were usually characterised by significant coefficients of determination.

Discussion and Conclusions

The main conclusion of this study is that the dendrochronological BAI data confirmed the depression of gross stand volume increment around 2006–2007 (based on Lithuanian NFI measurements in 2008–2009), followed by steep increase during 2008–2011 (NFI for 2010–2013). The gross stand volume increment decreased during 2002–2006 (NFI for 2004–2008) in birch, aspen and grey alder stands, but the decrease was lower in black alder, pine and spruce forests. The decrease of increment in the spruce, aspen and birch stands in 1993–1997 was associated with the impacts of droughts in 1992 and 1994 and wind damage in 1995 (Ozolincius et al. 2005, Augustaitis et al. 2007, 2015, Juknys et al. 2014). These were followed by attacks of forest pests: *Dendrolimus pini* L. and *Lymantria monacha* L. in pine forest (Gedminas et

Table 2. Results of autocorrelation tests (value of Box-Ljung statistic) and associated significance (p-level). The $p > 0.05$ is identified in bold (suggesting no autocorrelation)

Lag	Type of dendrochronological BAI data											
	Pine		Spruce		Birch		Aspen		Black alder		Grey alder	
	Value	*p*	Value	*p*	Value	*p*	Value	*p*	Value	*p*	Value	*p*
	NFI data											
1	9.887	0.002	8.739	0.003	8.285	0.004	8.239	0.004	9.902	0.002	7.844	0.005
2	14.292	0.001	11.998	0.002	10.774	0.005	10.233	0.006	14.723	0.001	10.657	0.005
3	15.092	0.002	12.565	0.006	10.774	0.013	10.263	0.016	15.679	0.001	10.680	0.014
4	15.108	0.004	12.595	0.013	12.815	0.012	12.283	0.015	15.696	0.003	13.289	0.010
5	15.934	0.007	13.468	0.019	18.610	0.002	17.362	0.004	16.667	0.005	18.224	0.003
6	17.596	0.007	15.559	0.016	25.896	0.000	22.449	0.001	19.457	0.003	24.285	0.000
7	20.004	0.006	17.535	0.014	28.491	0.000	24.072	0.001	23.037	0.002	26.485	0.000
8	23.504	0.003	20.071	0.010	29.250	0.000	24.388	0.002	26.771	0.001	27.073	0.001
9	28.010	0.001	23.474	0.005	29.263	0.001	24.409	0.004	30.734	0.000	27.073	0.001
10	33.616	0.000	27.545	0.002	29.405	0.001	24.419	0.007	34.829	0.000	27.125	0.002
11	38.647	0.000	31.596	0.001	29.994	0.002	24.423	0.011	38.212	0.000	27.333	0.004
	Dendrochronological smoothed data											
1	6.595	0.010	5.237	0.022	8.740	0.003	8.129	0.004	9.176	0.002	8.775	0.003
2	9.074	0.011	6.512	0.039	10.370	0.006	10.113	0.006	12.810	0.002	10.146	0.006
3	10.522	0.015	6.940	**0.074**	10.475	0.015	10.141	0.017	13.624	0.003	10.492	0.015
4	10.601	0.031	6.945	**0.139**	13.521	0.009	10.984	0.027	13.636	0.009	15.293	0.004
5	10.714	**0.057**	7.055	**0.217**	21.231	0.001	13.008	0.023	13.744	0.017	25.292	0.000
6	10.783	**0.095**	7.058	**0.316**	29.040	0.000	14.200	0.027	13.927	0.030	32.863	0.000
7	11.581	**0.115**	7.066	**0.422**	32.632	0.000	14.730	0.040	14.721	0.040	34.516	0.000
8	16.437	0.037	8.266	**0.408**	33.631	0.000	15.491	**0.050**	18.245	0.019	34.543	0.000
9	23.186	0.006	12.888	**0.168**	33.722	0.000	16.501	**0.057**	25.782	0.002	35.060	0.000
10	31.186	0.001	20.163	0.028	36.195	0.000	17.971	**0.055**	36.576	0.000	37.329	0.000
11	41.064	0.000	32.650	0.001	39.393	0.000	21.377	0.030	47.866	0.000	39.732	0.000
	Dendrochronological reduced and smoothed data											
1	6.251	0.012	5.039	0.025	8.035	0.005	7.191	0.007	7.313	0.007	8.438	0.004
2	7.695	0.021	6.102	0.047	9.138	0.010	8.559	0.014	9.322	0.009	9.797	0.007
3	7.910	0.048	6.343	**0.096**	9.425	0.024	8.559	0.036	9.492	0.023	10.134	0.017
4	7.963	**0.093**	6.344	**0.175**	13.101	0.011	9.409	**0.052**	9.570	0.048	14.807	0.005
5	8.728	**0.120**	6.447	**0.265**	20.665	0.001	11.134	**0.049**	10.012	**0.075**	24.287	0.000
6	9.239	**0.161**	6.450	**0.375**	27.121	0.000	12.033	**0.061**	10.251	**0.114**	31.588	0.000
7	9.457	**0.222**	6.468	**0.486**	29.572	0.000	12.325	**0.090**	10.532	**0.160**	33.301	0.000
8	10.411	**0.237**	7.361	**0.498**	30.127	0.000	12.792	**0.119**	11.974	**0.152**	33.350	0.000
9	13.226	**0.153**	11.304	**0.255**	30.244	0.000	13.507	**0.141**	15.854	**0.070**	33.769	0.000
10	17.035	**0.074**	18.118	**0.053**	32.899	0.000	14.774	**0.141**	21.925	0.015	35.932	0.000
11	22.689	0.020	29.774	0.002	36.067	0.000	18.223	**0.077**	29.230	0.002	38.426	0.000
	Dendrochronological non-smoothed data											
1	0.198	**0.656**	1.259	**0.262**	1.353	**0.245**	6.204	0.013	4.499	0.034	2.736	**0.098**
2	5.173	**0.075**	1.323	**0.516**	1.727	**0.422**	9.211	0.010	6.128	0.047	2.766	**0.251**
3	5.634	**0.131**	2.087	**0.554**	2.307	**0.511**	10.311	0.016	6.989	**0.072**	2.768	**0.429**
4	5.984	**0.200**	2.101	**0.717**	4.216	**0.378**	11.331	0.023	8.037	**0.090**	4.812	**0.307**
5	6.871	**0.230**	2.235	**0.816**	6.414	**0.268**	13.708	0.018	9.468	**0.092**	9.222	**0.101**
6	6.960	**0.325**	2.967	**0.813**	8.904	**0.179**	17.105	0.009	10.600	**0.102**	12.373	**0.054**
7	7.597	**0.370**	2.973	**0.887**	9.178	**0.240**	21.676	0.003	13.750	**0.056**	13.065	**0.071**
8	7.631	**0.470**	2.978	**0.936**	9.178	**0.328**	23.636	0.003	15.325	**0.053**	13.491	**0.096**
9	7.741	**0.560**	6.473	**0.692**	10.124	**0.341**	24.742	0.003	16.387	**0.059**	13.505	**0.141**
10	7.809	**0.647**	7.679	**0.660**	10.521	**0.396**	25.035	0.005	17.174	**0.071**	13.521	**0.196**
11	7.850	**0.727**	9.129	**0.610**	10.545	**0.482**	25.106	0.009	17.309	**0.099**	14.481	**0.208**

Table 3. Results of linear regression (coefficients of determination, R^2) and the non-parametric Wilcoxon matched-pairs test (T, Z and p-level) used to compare the NFI-based mean 5-year gross stand volume increment and basal area increment of single trees, processed using three different approaches. The number of valid observations is 13. Bold values of R^2 are associated with $p < 0.05$

Tree species	Type of dendrochronological basal area increment data											
	Smoothed				Reduced and smoothed				Non-smoothed			
	R^2	T	Z	p	R^2	T	Z	p	R^2	T	Z	p
Pine	**0.734**	43	0.175	0.861	**0.802**	41	0.314	0.753	-0.036	45	0.035	0.972
Spruce	**0.690**	43	0.175	0.861	**0.728**	44	0.105	0.917	**0.656**	45	0.035	0.972
Birch	**0.423**	43	0.175	0.861	**0.509**	44	0.105	0.917	**0.344**	40	0.384	0.701
Aspen	**0.858**	40	0.384	0.701	**0.848**	45	0.035	0.972	**0.345**	44	0.105	0.917
Black alder	**0.841**	39	0.454	0.650	**0.840**	44	0.105	0.917	**0.525**	42	0.245	0.807
Grey alder	**0.639**	45	0.035	0.972	**0.639**	45	0.035	0.972	**0.295**	44	0.105	0.917

al. 2004, Ozolincius et al. 2005, Augustaitis 2007) and *Ips typograhus* in spruce forest (Ozolinčius 2012). The depression in increment was associated with the relatively cold and dry end of winter in 2005–2006, a cool and dry spring and drought during the vegetative growth period, i.e. April–July 2006. Significant increase in precipitation in 2010 followed by a very warm spring and the vegetative growth period resulted in significant increases in increment and productivity of prevailing tree species in Lithuania, especially aspen, spruce, pine and black alder. No stimulating effect of higher air temperature and precipitation amount was reported for birch and grey alder (Augustaitis et al. 2018). In principle, the trends reported here are consistent with previous findings that local conifers, as well as aspen and black alder, are the best adapted tree species to recent climate change in

Lithuania, whereas grey alder and silver and downy birches are the least adapted (Augustaitis et al. 2018). Thus, a warmer and more humid vegetation period resulted in reduction of birch and grey alder increment and stand productivity in general, reflected in the trends discussed above.

Even though NFI data may be considered as an objective and many-sided source of information on the forests, studies involving measurements of tree rings can provide a long set of additional data, especially needed to understand the impacts of environmental factors on tree growth, especially in the past (Spiecker 2002, Neuskomm et al. 2014). Long-term observations on permanent plots usually provide valuable information over time. Reconstruction of past annual stand productivity enables researchers to avoid the influences of single tree competition in their evaluations (Castagneri et al. 2012). Large amounts of data, obtained from forest inventory plots, are particularly important for forest management assessment; however, they are sometimes insufficient to explain inter-annual variation due to the periodic manner of surveys, typically with 5- or 10-year time gaps (Babst et al. 2014). Therefore, dendroclimatic studies (i.e. based on analysis of tree rings relating to climate data) are increasingly important worldwide and in the region and can be used to predict growth of forest stands relating to climate change (Elling et al. 2009, Sensula et al. 2015, Solomina et al. 2017, Matveev et al. 2018). For example, radial increment study of native species (*Pinus sylvestris* and *Quercus robur*) in Voronezh region, Russia, disclosed links to precipitation, as well as its distribution between seasons and months during the year (Matveev et al. 2018). Rohner et al. (2016) reported correlations between BAI and mean/extreme temperatures. Strong positive correlations between BAI and spring precipitation, and negative correlations between BAI and summer precipitation are reported, confirming the impact of precipitation on growth of forest trees, especially in the period of March–June (Ellenberg and Leuschner 2016, Rohner et al. 2016). Rohner et al. (2016) also claims that “the identified climate–growth relationships are not likely to generally depend on the years in which the inventories take place”.

The abovementioned causes of decreased stand volume increment and thus decreased growing stock volume change are very valuable for clarifying differences between projected growing stock volume change (i.e. used for forest reference level estimation according to the LULUCF regulation) and the one recently reported in the National GHG Inventory Reports. Concerning forest reference level estimation, there are two important messages from our results: data used in Lithuanian forest reference level estimation consider actual climatic conditions but no projection on climate change is included in modelling; and, most importantly, projected decreasing growing stock volume change is to a large extent determined by the lower stock change measured in the reference period (2005–2009). According to the LULUCF regulation (EU 2018/841), the forest reference level should be based on the continuation of sustainable forest management practices, as documented for 2000–2009 with regard to dynamic age-related forest characteristics in national forests, using the best available data not excluding the influence of climate change (Forsell et al. 2018). Indeed, NFI data of 2005–2009 based on re-measurement of permanent sample plots established during 2000–2004 (Figure 2, assessment data for 2007) are the best available data in Lithuania and these results fall into a gross stand volume increment depression (but not the lowest) compared with the following assessments in 2007–2012. The differences are 10–22% in NFI data and 13–39% in dendrochronological data. Such results suggest a preliminary explanation of differences between projected carbon stock changes in living biomass and those recently reported by the National GHG Inventories. The results of this study support the assumption of climatic conditions having a strong influence on inter-annual growing stock change fluctuations but harvest levels do not show such large fluctuations (Lietuvos 2017).

Here, we focussed on short-term changes in forest growth, analysing the changes using two different data acquisition methods and describing different objects of interest. To provide stronger explanations for observed fluctuations, a longer time span for comparison is needed. More dendrochronological data based on tree cores are expected to be provided by NFI measurements on temporary sampling plots during 2019–2023, representing the entire forest area of Lithuania. More in-depth analysis of such dendrochronological data together with NFI data can provide valuable clarifications of growing stock volume change patterns considering both the development of forest management practices and the climate change impact on tree growth.

Acknowledgements

The study was implemented within the frame of the National Research Programme “Sustainability of Agro-, Forest and Water Ecosystems” Project FOREstRESS (No. SIT-3/2015).

References

Alberdi, I., Gschwantner, T., Bosela, M., Redmond, J., Riedel, T., Snorrason, A., Gasparini, P., Braendli, U.; Fridman, J., Tomter, S., Kulbokas, G., Lanz, A. and Vidal, C. 2016. Harmonisation of Data and Information on the Potential Supply of Wood Resources. In: Vidal, C., Alberdi, I., Hernandez, L., Redmond, J. (Eds.): National Forest Inventories – Assessment of Wood Availability and Use. Chapter 3. Springer International Publishing, New York, p. 55–79.

Augustaitis, A. 2007. Pine sawfly (*Diprion pini* L.) – Related changes in Scots pine crown defoliation and possibilities of recovery. *Polish Journal of Environmental Studies* 16(3): 363–369.

Augustaitis, A., Augustaitienė, I., Baumgarten, M., Bičenkienė, S., Girgždienė, R., Kulbokas, G., Linkevičius, E., Marozas, V., Mikalajūnas, M., Mordas, G., Mozgeris, G., Petrauskas, E., Pivoras, A., Šidlauskas, G., Ulevičius, V., Vitas, A. and Matyssek, R. 2018. Tree-ring formation as an indicator of forest capacity to adapt to the main threats of environmental changes in Lithuania. *Science of the Total Environment* 615: 1247–1261.

Augustaitis, A., Augustaitienė, I., Činga, G., Mažeika, J., Deltuvas, R., Juknys, R. and Vitas, A. 2007. Did the Ambient Ozone Affect Stem Increment of Scots Pines (*Pinus sylvestris* L.) on Territories under Regional Pollution Load? Step III of Lithuanian Studies. *Scientific World Journal* 7(S1): 58–66.

Augustaitis, A., Augustaitienė, I., Mozgeris, G., Juknys, R., Vitas, A. and Jasinevičienė, D. 2015. Growth patterns of Scots pine (*Pinus sylvestris* L.) under the current regional pollution load in Lithuania. *iForest* 8: 509–516.

Babst, F., Bouriaud, O., Alexander, R., Trouet, V. and Frank, D. 2014. Toward consistent measurement of carbon accumulation: A multi-site assessment of biomass and basal area increment across Europe. *Dendrochronologia* 32: 153–161.

Bosela, M., Redmond, J., Kucera, M., Marin, G., Gschwantner, T., Petras, R., Korhonen, K., Kuliešis, A., Kulbokas, G., Fischer, C., and Lanz, A. 2016. Stem quality assessment in European National Forest Inventories: an opportunity for harmonised reporting? *Annals of Forest Science* 73(3): 635–648.

Castagneri, D., Nola, P., Cherubini, P. and Motta, R. 2012. Temporal variability of size-growth relationships in a Norway spruce forest: The influences of stand structure, logging, and climate. *Canadian Journal of Forest Research* 42: 550–560.

Ellenber, H. and Leuscher, C. 2010. Vegetation Mitteleuropas mit den Alpen: in ökologischer, dynamischer und historischer Sicht. 6. Auflage. Eugen Ulmer Verlag, UTB, Stuttgart, 1357 pp.

Elling, W., Dittmar, C., Pfaffelmoser, K. and Rötzer, T. 2009. Dendroecological assessment of the complex causes of decline and recovery of the growth of silver fir (*Abies alba* Mill.) in Southern Germany. *Forest Ecology and Management* 257: 1175–1187.

European Parliament and Council 2018. Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. *Official Journal of the European Union* 61: 1–25. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG&toc=OJ:L:2018:156:TOC

Forsell, N., Korosuo, A, Federici, S., Gusti, M., Rincón-Cristóbal, J.-J., Rüter, S., Sánchez-Jiménez, B., Dore, C., Brajterman, O. and Gardiner, J. 2018. Guidance on developing and reporting Forest Reference Levels in accordance with Regulation (EU) 2018/841. Version 25, June 2018. 110 pp. Available online at: http://pure.iiasa.ac.at/id/eprint/15375/1/Submitted_TG_20180622_clean.pdf

Gedminas, A., Vaivada, S. and Lynikiene, J. 2004. Influence of needle-eating insect pests on radial increment of pine trees. *Ekologija* 1: 16–20.

IBM 2017. IBM SPSS Statistics software package. Version 25. Armonk, New York, USA.

Juknys, R., Augustaitis, A., Vencloviene, J., Kliučius, A., Adomas, V., Bartkevičius, E. and Jurkonis, N. 2014. Dynamic response of tree growth to changing environmental pollution. *European Journal of Forest Research* 133(4): 713–724.

Konstantinavičiūtė, I., Byčenkienė, S., Kavšinė, A., Zaikova, I., Juška, R., Žiukelytė, I., Lenkaitis, R., Kazanavičiūtė, V., Mačiulskas, M., Juraitė, T., Čeičytė, L., Merkelienė, J., Tijūnaitė, R., Kairienė, E., Žiukelytė, I. and Šulinskas, K. 2018. Lithuania's National Inventory Report 2018: Greenhouse Gas Emissions 1990–2016. Ministry of Environment; Environmental Protection Agency; State Forest Service, Vilnius. 617 pp. (in English). Available online at: http://klimatas.gamta. lt/files/LT_NIR_20180415_final.pdf (cited 12th January 2019)

Kuliešis, A., Kasperavičius, A., Kulbokas, G., Brukas, V., Petrauskas, E. and Mozgeris, G. 2017. Lithuania. In: S. Barreiro, M.J. Schelhaas, R.E. McRoberts, G. Kändler (Eds.): Forest inventory-based projection system for wood and biomass availability. Springer International Publishing, New York, Managing Forest Ecosystems, 29: 223–239.

Kuliesis, A., Kasperavicius, A. and Kulbokas, G. 2010. National Forest Inventory Reports – Lithuania. In: Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E. (Eds.): National Forest Inventories – Pathways for Common Reporting. Springer-Verlag, Heidelberg-Dordrecht-London-New York, p. 351–374.

Kuliešis, A., Kasperavičius, A. and Kulbokas, G. 2016. Lithuania. In: Vidal, C., Alberdi, I., Hernandez, L., Redmond, J. (Eds.): National Forest Inventories – Assessment of Wood Availability and Use. Chapter 28. Springer International Publishing, New York, p. 521–547.

Kuliešis, A. and Kulbokas, G. 2009. Assessment of Growing Stock Components for Data Harmonization in International Reporting. Lithuanian Case Study. *Baltic Forestry* 15(1): 58–64.

Kuliešis, A., Kulbokas, G., Kasperavičius, A. and Kvalkauskienė, M. 2009. Lietuvos Nacionalinė Miškų Inventorizacija 2003–2007. [Lithuania's National Forest Inventory 2003–2007]. Miškų ištekliai ir jų kaita. [Forest resources and their dynamics]. Lututė, Kaunas, 284 pp. (in Lithuanian and in English).

Lawrence, M., McRoberts, R.E., Tomppo, E., Gschwantner, T. and Gabler, K. 2010. Comparisons of National Forest Inventories. In: Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E. (Editors), National Forest Inventories – Pathways for Common Reporting. Springer-Verlag, Heidelberg, Dordrecht, London, New York, p. 19–32.

Matveev, S., Milenin, A. and Timashchuk, D. 2018. The effects of limiting climate factors on the increment of native tree species (*Pinus sylvestris* L., *Querqus robur* L.) of the Voronezh region. *Journal of Forest Science* 64: 427–434.

Ozolinčius, R. 2012. Possible Effects of Climate Change on Forest Biodiversity, Tree Growth and Condition: Review of Research in Lithuania. *Baltic Forestry* 18: 156–167

Ozolinčius, R., Mikšys, V. and Stakėnas, V. 2005. Growth-independent mortality of Lithuanian forest tree species. *Scandinavian Journal of Forest Research* 20: 153–160.

Packalen, T., Sallnäs, O., Sirkiä, S., Korhonen, K., Salminen, O., Vidal, C., Robert, N., Colin, A., Belouard, T., Schadauer, K., Berger, A., Rego, F., Louro, G., Camia, A., Räty, M. and San-Miguel, J. 2014. The European Forestry Dynamics Model (EFDM): Concept, design and results of first case studies. JCR Science and Policy Reports. Publications Office of the European Union, Luxembourg. 17 pp. doi:10.2788/153990.

RinnTech 2019. TSAP-Win™ software platform for tree ring analyses. RINNTECH e.K., Heidelberg, FRG.

Rohner, B., Weber, P. and Thurig, E. 2016. Bridging tree rings and forest inventories: How climate effects on spruce and beech growth aggregate over time. *Forest Ecology and Management* 360: 159–169.

Seimas of the Republic of Lithuania 1994. Lietuvos Respublikos miškų įstatymas [Law on Forests of the Republic of Lithuania]. Available online at: https://www.e-tar.lt/portal/lt/legalAct/TAR.5D6D055CC00C/vyZMmKTQnZ [cited January 7, 2019] (in Lithuanian).

Sensula, B., Wilczyński, S. and Opała, M. 2015. Tree growth and climate relationship: Dynamics of Scots pine (*Pinus sylvestris* L.) growing in the near-source region of the combined heat and power plant during the development of the pro-ecological strategy in Poland. *Water, Air, and Soil Pollution* 226–220.

Solomina, O. N., Bushueva, I.S., Dolgova, E.A., Zolotokrylin, A. N., Kuznetsova, V. V., Kuznetsova, T. O., Kukhta, A. E., Lazukova, L. I., Lomakin, N. A., Matskovsky, V. V., Matveev, S. M., Mikhailov, A. Y., Mikhalenko, V. N., Pozhidaeva, D. S., Rumyantsev, D. E., Sakulina, G. A., Semenov, V. A., Khasanov, B. F., Cherenkova, E. A. and Chernokulsky, A. V. 2017. Zasukhi Vostochno-Evropeiskoi ravniny po gidrometeorologicheskim i dendrokhronologicheskim dannym. [Droughts of the East European Plain in Hydrometeorological and Dendrochronological Data]. 'Nestor-History' Publ. House, St. Petersburg (Russia). 360 pp. (in Russian with English abstract)

Spiecker, H. 2002. Tree rings and forest management in Europe. *Dendrochronologia* 20/1–2: 203–216.

State Forest Service 2016. Miškų ūkio statistika 2016 [Lithuanian Statistical Yearbook of Forestry]. Valstybinė miškų tarnyba, Kaunas. 184 pp. (in Lithuanian and in English) Available online at: http://www.amvmt.lt/Images/Veikla/STAT/MiskuStatistika/2016/Metrastis_2016_CD.pdf

State Forest Service 2017. Lietuvos miškų ūkio statistika, 2017 [Lithuanian Statistical Yearbook of Forestry, 2017]. Valstybinė miškų tarnyba, Kaunas. 184 pp. (in Lithuanian and in English) Available online at: http://www.amvmt.lt/Images/Veikla/STAT/MiskuStatistika/2017/Metrastis_2017_CD.pdf

Tomter, S.M., Gasparini, P., Gschwantner, T., Hennig, P., Kulbokas, G., Kuliesis, A., Polley, H., Robert, N., Rondeux, J., Tabacchi, G. and Tomppo, E. 2012. Establishing Bridging Functions for Harmonizing Growing Stock Estimates: Examples from European National Forest Inventories. *Forest Science* 58(3): 224–235.