forests

MDPI

Article

Regional Variability of the Romanian Main Tree Species Growth Using National Forest Inventory Increment Cores

Gheorghe Marin [1,2], Vlad C. Strimbu [3], Ioan V. Abrudan [1] and Bogdan M. Strimbu [4,*]

[1] Faculty of Silviculture and Forest Engineering, Transilvania University Brasov, 500036 Brasov, Romania; ghmarin@roifn.ro (G.M.); abrudan@unitbv.ro (I.V.A.)

[2] National Institute for Research and Development in Silviculture, 077190 Voluntari, Romania

[3] Faculty of Forestry, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; vlad.strimbu@alumni.ubc.ca

[4] College of Forestry, Oregon State University, Corvallis, OR 97331, USA

* Correspondence: bogdan.strimbu@oregonstate.edu

Received: 24 February 2020; Accepted: 2 April 2020; Published: 6 April 2020

Abstract: In many countries, National Forest Inventory (NFI) data is used to assess the variability of forest growth across the country. The identification of areas with similar growths provides the foundation for development of regional models. The objective of the present study is to identify areas with similar diameter and basal area growth using increment cores acquired by the NFI for the three main Romanian species: Norway spruce (*Picea abies* L. Karst), European beech (*Fagus sylvatica* L.), and Sessile oak (*Quercus petraea* (Matt.) Liebl.). We used 6536 increment cores with ages less than 100 years, a total of 427,635 rings. The country was divided in 21 non-overlapping ecoregions based on geomorphology, soil, geology and spatial contiguousness. Mixed models and multivariate analyses were used to assess the differences in annual dimeter at breast height and basal area growth among ecoregions. Irrespective of the species, the mixed models analysis revealed significant differences in growth between the ecoregions. However, some ecoregions were similar in terms of growth and could be aggregated. Multivariate analysis reinforced the difference between ecoregions and showed no temporal grouping for spruce and beech. Sessile oak growth was separated not only by ecoregions, but also by time, with some ecoregions being more prone to draught. Our study showed that countries of median size, such as Romania, could exhibit significant spatial differences in forest growth. Therefore, countrywide growth models incorporate too much variability to be considered operationally feasible. Furthermore, it is difficult to justify the current growth and yield models as a legal binding planning tool.

Keywords: spatial variability; annual rings; National Forest Inventory; ecoregions; mixed models; *Picea abies*; *Fagus sylvatica*; *Quercus petraea*

---

1. Introduction

The development of national forest growth and yield models served the society needs of the last century, but fails to address the current challenges posed by the rise in population, expected standard of life, and constant changes of the environment [1]. The perceived endless computational power available today recommends the distillation of the national models, such that they are tailored to specific questions or areas. Such detailed models address not only the society's expectations from the forest, but also serve as the basis of sustainable forest management. Arguably, the next refining modeling level is the identification of areas for which distinct models can be developed. The natural identification of such areas are the ecoregions. A plethora of definitions are available for an ecoregion, most of them being based on the work of Bailey [2], which relies on the idea of a "unified climate, geology, geomorphology, soil, potential natural vegetation, and predominant land use" [3]. Even though the idea of an ecoregion is clear, their delineation is rather controversial as they are biased toward a particular characteristic or approach (i.e., qualitative or quantitative), do not necessarily provide a holistic perspective on ecosystems, and do not necessarily operate at a specific level [4]. Therefore, in this study we refer to an ecoregion as an area "within which there is spatial coincidence in characteristics of geographical phenomena associated with differences in the quality, health, and integrity of ecosystems", according to Omernik [4]. Although more variables (especially climatic variables) could be included in ecoregion delineation, we focused on the analysis of non-climatic ones as they provide a cleared boundary definition. Irrespective of the details, an ecoregion is a pivotal landscape element, which is mandatory in regional and national management.

The presence of ecoregions in national planning is particularly important when significantly different climates and geomorphological areas span the country. The size of the country is not necessarily relevant, as even smaller countries can exhibit a large number of ecoregions, with an impact in forest management. Romania, for example, is almost evenly distributed among the main geomorphological areas (i.e., plains, hills, and mountains), and its vegetation is particularly diverse [5–7].

A significant source of forest data is the national forest inventories (NFIs). Most of the NFIs either experienced significant changes in the last 25 years in terms of design, the case of the USA or France [8,9], or were established for the first time, the case of the Eastern European countries [10]. The Romanian NFI is the only agency that supplies reliable national and regional level information for the United Nations Convention on Climate Change, Convention on Biological Diversity or the Forest Resource Assessment of the United Nations Food and Agriculture Organization [11]. The Romanian NFI is a continuous forest inventory, using a systematic sampling design [10]. The inventory covers the entire country during a 5-year cycle and is conducted in two phases: the first phase is photo-interpretation, which uses orthophoto maps on the scale 1:5000 taken by aerial flights, and the second phase is the terrestrial measurements. The measurements in areas of permanent sample plots are performed continuously every NFI cycle under multi-annual planning. The NFI divides the country into squares of 4 × 4 km. The 4 × 4 km squares are sub-divided into 16 squares each of 1 × 1 km. In the 1 × 1 km square located in the southwest corner of each 4 × 4 km square there is a permanent sample cluster (PSC) situated. The PSC is square-shaped with a side of 250 m. The sides of the squares are north-south or east-west oriented. There are four circular sample plots (SPs) situated in each corner of the PSC. The field data is collected in each circular SP. The density of the PSCs is determined according to the general landscape classification of mountains, hills, and plains. In the mountain and hilly regions, the NFI grid has cells of 4 × 4 km, whereas in the plain region the cells are 2 × 2 km (Figure 1). The differential design of Romanian NFI captures the relevant information while also considering the density of the forest within the general landscape. Altogether, the Romanian NFI has 31,201 PSC and 124,804 SP.

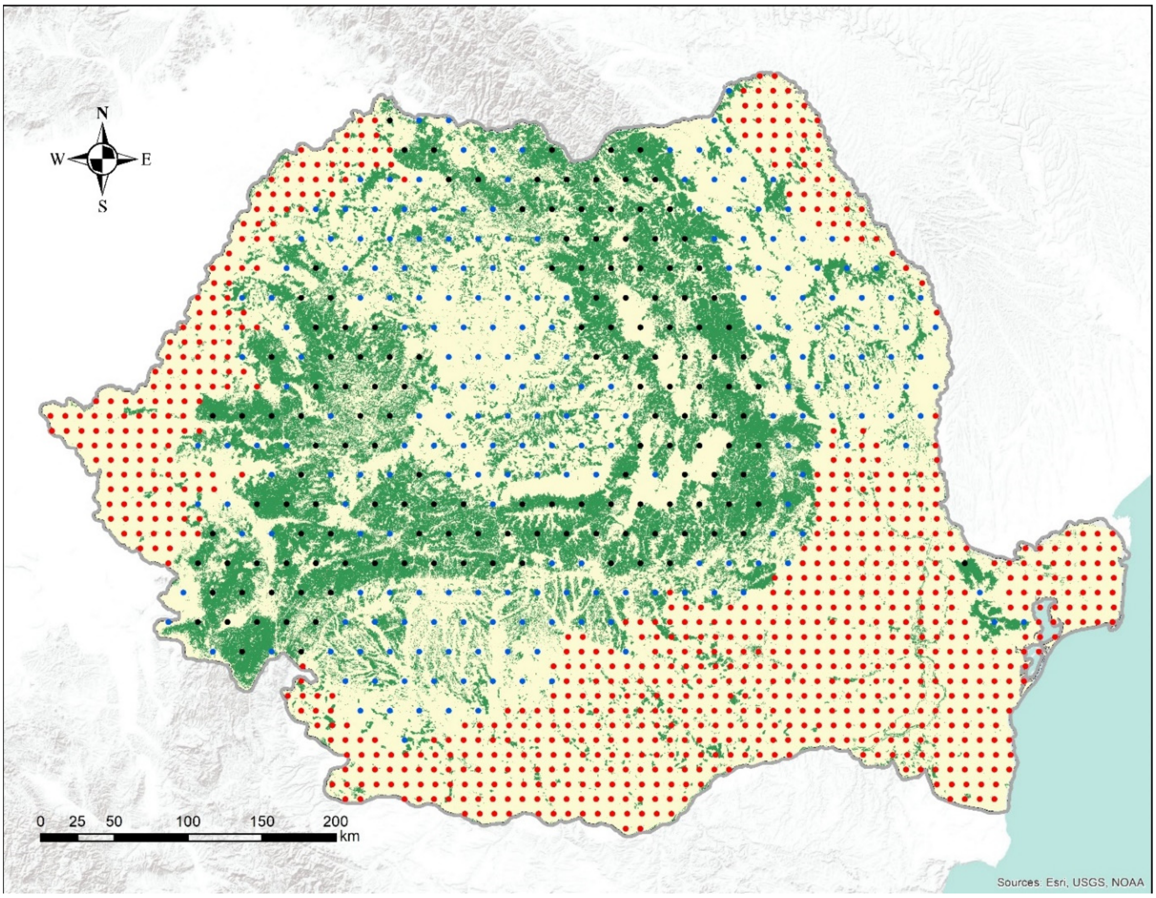

Figure 1. The PSC of the Romanian NFI overlaid on the general location of the forest, in green. The color of the PSC reflects the geomorphology: red for plains, blue for hills, and black for mountains. The spatial distribution of the PSCs does not reflect the actual density [12].

The Romanian NFI collected a large number of increment cores, which represent valuable information for the development, refinement and spatial delineation of regional growth models. Analyzing NFI growth data in combination with regional spatial units, such as the ecoregions, represents the next logical step in the development of improved growth and yield models. Therefore, the objective of this study is to identify the existence of spatial variation in tree growth for the three main forest species in Romania: Norway spruce (*Picea abies* (L.) H. Karst), European beech (*Fagus sylvatica* L.), and Sessile oak (*Quercus petraea* (Matt.) Liebl). Furthermore, if the presence of spatial variation is confirmed, different patterns of annual tree growth are to be examined based on the characteristics of the ecoregions. Even though other studies have used increment cores from inventory data to analyze forest growth [13–15], the use of NFI increment cores data on a large area for model development represents, to our knowledge, a novelty in the literature.

2. Methods

2.1. Romanian Ecoregions

One of the main drivers that could be responsible for tree growth variation across the country, if differences in growth exist, are likely the ecoregions. In this study, an ecoregion is defined as a contiguous area with similar geology, soils and geomorphology. The information describing the drivers of an ecoregion was supplied by the Romanian Academy. Based on the four drivers, we divided the country into 21 ecoregions (Figure 2). The ecoregions vary in size from 161,904 ha, the Maramures Plateau (323), to 2.8 million ha, the Transylvania Plateau (324) (Table 1). Out of the 21 countrywide ecoregions, only 15 were used in this study, as within the remaining six, the three species were not encountered.

Table 1. Romanian Ecoregions for which the growth of Norway spruce, European beech or Sessile oak was analyzed [16].

Ecoregion Name	Ecoregion Code	Soil	Geomorphology	Geology	Province	Area [ha]
Moldavian Plateau	121	Chernozems, Phaezems, Luvisols, Fluvisols, Gleysols	Plateau	Sands, Gravels, Marls, Loess, Sandstones	Moldavia	1,352,075
Moldavian Hills	122	Luvisols, Eutric Cambisols, Phaezems	Hills	Marls, Calcarous Marls, Sandstones, Conglomerates, Tuffs	Moldavia	806,488
Eastern Carpathians	131	Eutric Cambisols, Dystric Cambisols, Entic podzols, Haplic podzol, Rendzic leptosol	Mountains	Flysch deposits	Moldavia	1,546,525
Buzau-Vrancea piedmonts	221	Regosols, Luvisols, Eutric Cambisols	Hills	Sands, Clay-sands, Marls, Sandstones, Limestones	Moldavia	595,917
Getic plateau	222	Chernozems, Phaezems, Luvisols, Eutric Cambisols, Vertisols, Fluvisols, Gleysols	Plateau	Marls, Sandy-marls, Sandstones, Tuffs, Sands, Gravels, Loess,	Muntenia	1,934,478
Buzau-Vrancea mountains	231	Dystric Cambisols Eutric Cambisols	Mountains	Flysch deposits Conglomerates	Muntenia	550,591
East Southern Carpathians	232	Dystric Cambisols Entic podzols, Haplic podzol, Rendzic leptosol	Mountains	Schists, Phyllites, Gneiss, Conglomerates, Limestones,	Muntenia	1,028,094
West Southern Carpathians	233	Dystric Cambisols Eutric Cambisols, Entic podzols, Haplic podzol, Rendzic leptosol	Mountains	Limestones, Schists, Phyllites, Granites	Muntenia	449,804
Caras Hills	321	Luvisols, Vertisols	Hills	Argillaceous marls, Sands, Gravels	Banat	444,045
Cris Hills	322	Luvisols, Eutric Cambisols	Hills	Sands, Gravels, Loess deposits	Transylvania	679,685
Maramures plateau	323	Eutric Cambisols, Luvisols	Plateau	Marls, Tuffs, Sandstones	Transylvania	161,904
Transylvania Plateau	324	Luvisols, Phaezems, Chernozems	Plateau	Marls, Calcarous marls tuffs, Sandstones, Conglomerates	Transylvania	2,798,764
Banat Mountains	331	Eutric Cambisols, Luvisols, Dystric Cambisols, Entic podzols, Rendzic leptosol	Mountains	Schists, Granites, Gabbro, Limestones	Banat	708,961
Western Carpathians	332	Eutric Cambisols, Luvisols, Dystric Cambisols, Rendzic leptosol	Mountains	Schists, Gneiss, Granites, Limestones, Sandstones	Transylvania	1,054,126
Volcanic ridge	333	Andosols, Entic podzols	Mountains	Lahar deposits, Andesites	Transylvania	950,029

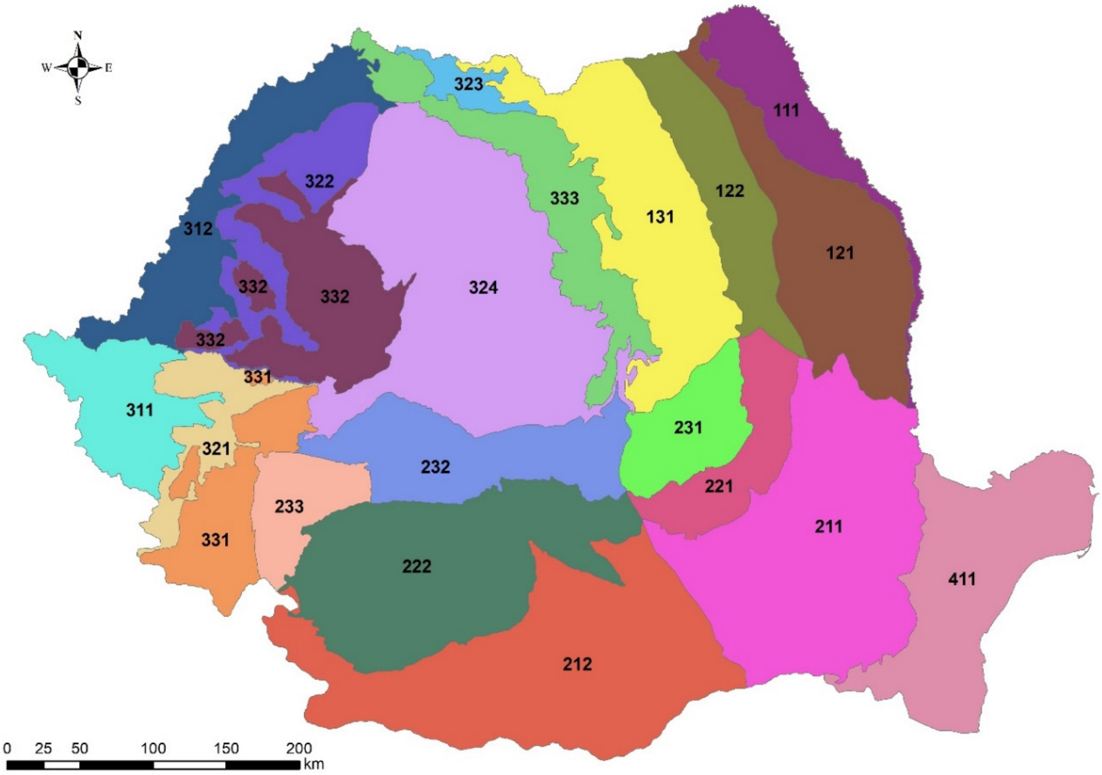

Figure 2. Romanian ecoregions delineated according to spatial contiguity, geology, soils, and geomorphology maps of the Romanian Academy [16].

2.2. Increment Cores

The species considered in this study, namely Norway spruce, European beech and Sessile oak, not only cover approximately 60% of the Romanian forests, but are also the main species in terms of economic, ecological, and social importance. To identify the presence of spatial variation in the growth of the tree species, we have used the increment cores of the Romanian NFI. The cores are extracted at each 5-year measurement at breast height (1.3 m) parallel with the contour line. The number of trees cored from each SP depends on the number of species: when only one species was present, then 3–4 cores were extracted, otherwise 2–3 cores/species were collected. For each cored tree, only one increment core was extracted and the cored trees are selected randomly, though are conditioned by specific constraints. The trees must belong to the dominant and co-dominant canopy class [17] and should not exhibit exterior damage. The cores are further mounted on a solid support, sanded, scanned and the width of each ring is measured using a graphical procedure. The main information extracted from the increment cores is the width of each ring and their succession. To ensure validity of the comparisons, we have included only the increment cores that were extracted from even-aged pure species stands. In addition, to ensure compatibility among various ecoregions, only stands with no thinning or no active management were considered. A more detailed description of the data can be found in Marin et al. [16].

The data used in this study consists of 6536 increment cores from 1655 PSC the last one being collected in 2011. The total number of rings is 427,635, out of which 136,904 rings are for Norway spruce, 241,240 rings for European beech, and 49,491 rings for Sessile oak. To focus the study on ages that are operational relevant, only rings with maximum age of 99 years were included. The number of rings (cores) for each ecoregion varies according to the species (Table 2), from 272 rings (4 cores) (i.e., European beech in the Maramures Plateau (323)) to 49,576 (986 cores) (i.e., Norway spruce in the Eastern Carpathians (131)). Each ring was described with five attributes: ecoregion, species, year, age, and width. The year is the calendar year of each ring within the increment cores, age represents the age of each ring, and ring width (RW) is the ring width in micrometers. Diameter at breast height (DBH) and basal area (BA) increments are derived from ring width, and are considered more appropriate to characterize tree growth than RW. To avoid values for DBH growth determined by special environmental conditions, we have used only cores from trees located inside the natural distribution range. Therefore, for Norway spruce, we have only included increment cores from the mountainous regions in the analysis, for European beech only those from the hill, plateau and mountainous regions, and for Sessile oak only those from the hill and plateau regions.

Table 2. Size and number of annual rings and increment cores across ecoregions and species.

	Number of Rings			**Number of Increment Cores**		
Ecoregion (code)	**Norway Spruce**	**European Beech**	**Sessile Oak**	**Norway Spruce**	**European Beech**	**Sessile Oak**
Moldavian Plateau (121)		2881	6575		41	93
Moldavian Hills (122)		8687	2385		112	29
Eastern Carpathians (131)	49,576	2286		986	332	
Buzau-Vrancea piedmonts (221)		11,572	4400		142	87
Getic plateau (222)		15,496	13,962		223	219
Buzau-Vrancea mountains (231)	15,749	24,447		336	292	
East Southern Carpathians (232)	27,969	30,700		506	387	
West Southern Carpathians (233)	4259	20,280		84	258	
Caras Hills (321)		1577	1419		20	17
Cris Hills (322)		2379	2969		31	44
Maramures plateau (323)		272	706		4	11
Transylvania Plateau (324)		13,763	17,075		187	253
Banat Mountains (331)	1654	36,007		47	427	
Western Carpathians (332)	9102	21,448		228	285	
Volcanic ridge (333)	28,595	23,445		568	287	
Total	136,904	241,240	49,491	2755	3028	753

2.3. *Analysis*

To assess the differences in annual growth among ecoregions, we have used mixed model and multivariate procedures. Each type of procedure addresses a different facet of the relationship between ecoregions and growth: the mixed model reflects the annual growth within a neighborhood of one year, whereas the multivariate considers the annual growth within the context of all years. In the absence of meteorological data, we implicitly considered the change in climate by constraining the analysis to the last 50 calendar years (i.e., since 1960). We have chosen as threshold the year 1960, as multiple studies pointed a shift in climate occurring at the end of the six decade of the twentieth century, not only in Europe [18–20] but also in the world [21–23]. Climate is an additional major driver of tree growth, besides site, but in this study we focus only on site, which forces the usage of a narrow time interval for assessment of spatial variability.

2.3.1. Mixed Models Analysis

To assess the impact of the ecoregion on the radial growth at breast height we have used a linear mixed modelling approach covariates age and DBH for DBH increment, or age and BA for BA increment (Equations (1) and (2)). The ecoregions were treated as fixed effects whereas the age was considered as random effect, as the age or each ring depends on the year.

$$DBH\ increment_{year} = Ecoregion + DBH_{year-1} + Age_{year} \tag{1}$$

$$BA\ increment_{year} = Ecoregion + BA_{year-1} + Age_{year} \tag{2}$$

We introduced age in the model to account for difference in radial growth with age [24–26]. We selected DBH and BA as covariate to account for the impact of the size of the tree on the growth.

Given the temporal dependency of the measurements and the nested structure of the data, we implemented a repeated measurements framework within the liner mixed model. Ecoregion and the covariate were considered as a fixed effect, whereas age was considered random. Among the possible covariance structures, we have considered the compound symmetry, variance components, and autoregressive of order 1 [27,28]. To identify the appropriate structure we have used the Akaike's Information Criterion (AIC) [29]. To formally determine the differences among ecoregions, if any, we have used the estimated marginal means, as recommended by Gotway and Stroup [30]. To detect the existence of residual autocorrelation, we used the Durbin–Watson test [31]. All analyses were performed in SAS 9.4 [32].

2.3.2. Multivariate Analysis

To simultaneously examine the spatial growth across all ecoregions we have used multivariate analysis having as variables width of the annual rings. Therefore, the multivariate analysis should have for each individual tree, and consequently each ecoregion, a series of at least 10 variables, depending on its age. However, trees grow differently through time, which means that rings with the same age must also be grouped by year. The requirement of having rings with the same age for each ecoregion and year since 1960 was not fulfilled. Therefore, instead of using individual trees, we have used groups of trees that have the same age and year. Even with this consolidation of data, old rings will be rare, meaning that only few trees would be considered in analysis. Consequently, the ring age should be reduced to a value that ensures at least one tree per calendar year.

Among the multivariate methods available for the analysis of the ring widths, we have used principal component analysis (PCA), hierarchical cluster analysis, and canonical discrimination analysis. The PCA represents an orthogonal transformation of the variable matrix that is used for variable reduction and data exploration [32]. We performed PCA to investigate if there is any evidence of grouping the growth by ecoregion or if this grouping is determined by a subset of ring widths. Hierarchical cluster analysis has a similar objective as PCA because it hierarchically clusters the observations in the dataset, but using an unsupervised method as the number of clusters is not established apriori. We have created clusters using the Ward method [33]. The cubic clustering criterion and the scree plot analysis of eigenvalues were employed in determining the number of clusters [34,35]. We complemented the hierarchical cluster analysis with canonical discrimination analysis, which grouped the ecoregions starting with an a priori number of groups [36]. We selected the number of groups of ecoregions as the number of clusters identified by the cluster analysis. The difference among the ecoregions was tested with Wilks' Lambda, Pillai's Trace, the Hotelling–Lawley Trace and Roy's Greatest Root [33]. We executed all the analyses in SAS 9.4 [32].

3. Results

3.1. Mixed Models Analysis

The tree growth charts revealed an obvious impact of the ecoregion on the diameter increment and basal area increment (Figure 3). Depending on the species and the variable measuring growth, there are ecoregions that clearly have different growth increments than the rest, such as the Eastern Carpathians (131) for Norway spruce, the Maramures plateau (323) for European beech, or the Caras hills (321) for Sessile oak for DBHi, or the Buzau-Vrancea mountains (231) for BAi. However, there seem to be regions which do not exhibit different increments, such as the Moldavian hills (122), the Buzau-Vrancea piedmonts (221), and the Transylvania Plateau (324) for the DBHi of Sessile oak. The inference on ecoregion impact on growth based on visual information was supported by the summary statistics for each species and attribute, as the increments varies by more than 100% for DBHi and BAi for European beech and Sessile oak (Table 3). The descriptive statistics paint a compelling argument, considering that the variance does not necessarily vary among ecoregions (Table 3). The summary statistics and the charts suggest different increments for some ecoregions, which support the formal analysis of the differences among ecoregions with mixed models.

Table 3. Estimates and standard errors (in parenthesis) for DBH increment (DBHi) and basal area increment (BAi) for Norway spruce, European beech and Sessile oak by ecoregion.

Ecoregion Name	**Norway Spruce**		**European Beech**		**Sessile Oak**	
	DBHi [mm]	**BAi [mm^2]**	**DBHi [mm]**	**BAi [mm^2]**	**DBHi [mm]**	**BAi [mm^2]**
Moldavian Plateau (121)			2.62 (1.655)	86.20 (136.97)	3.06 (1.282)	87.46 (82.572)
Moldavian Hills (122)			6.65 (1.419)	223.12 (168.848)	7.7 (1.696)	343.7 (158.178)
Eastern Carpathians (131)	4.81 (1.790)	242.41 (183.54)	3.26 (1.437)	95.93 (119.595)		
Buzau-Vrancea piedmonts (221)			3.79 (1.291)	116.32 (99.491)	3.45 (1.514)	109.59 (110.656)
Getic plateau (222)			3.49 (1.434)	104.26 (111.399)	2.78 (1.160)	86.88 (79.274)
Buzau-Vrancea mountains (231)	5.21 (1.796)	259.18 (174.2)	2.68 (1.266)	79.63 (93.75)		
East Southern Carpathians (232)	4.06 (1.552)	205.57 (148.561)	3.19 (1.293)	103.07 (99.455)		
West Southern Carpathians (233)	3.87 (1.663)	195.75 (162.814)	3.21 (1.214)	93.28 (89.638)		
Caras Hills (321)			1.23 (0.939)	35.37 (66.591)	1.08 (0.197)	51.65 (22.047)
Cris Hills (322)			2.63 (1.414)	123.64 (129.655)	4.15 (1.498)	144.01 (116.801)
Maramures plateau (323)			7.16 (1.336)	327.48 (143.497)	6.13 (1.738)	230.53 (232.496)
Transylvania Plateau (324)			3.32 (1.418)	98.47 (118.498)	3.4 (1.392)	120.2 (114.688)
Banat Mountains (331)	5.52 (1.848)	218.39 (172.912)	2.64 (1.331)	82.91 (97.022)		
Western Carpathians (332)	5.27 (1.699)	236.36 (167.421)	3.09 (1.158)	88.88 (82.883)		
Volcanic ridge (333)	4.35 (1.570)	220.25 (161.321)	3.27 (1.502)	108.19 (125.989)		

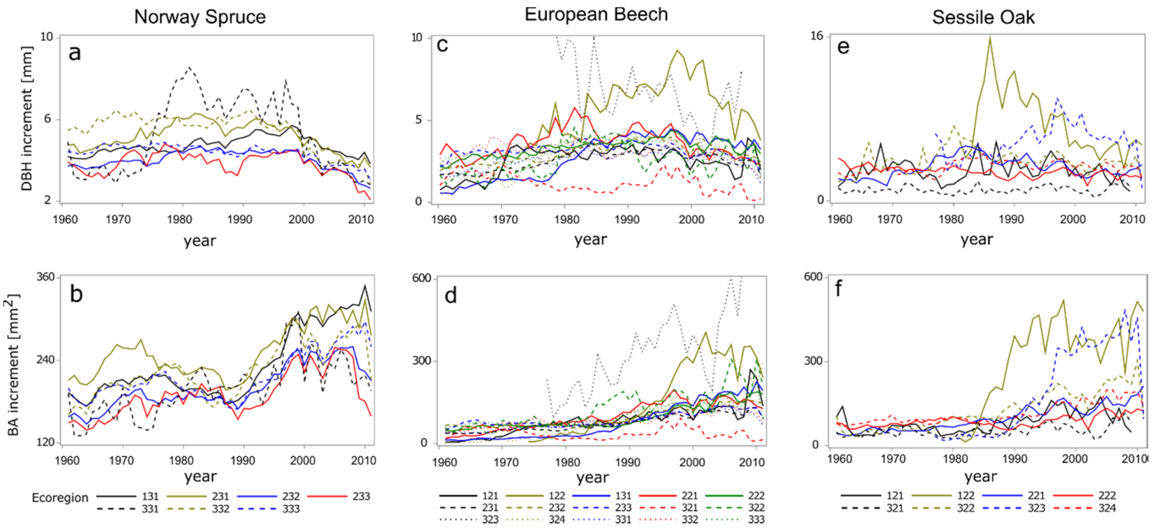

Figure 3. DBH increment and basal area increment mean by ecoregion for Norway spruce (**a**,**b**), European beech (**c**,**d**) and Sessile oak (**e**,**f**) over time.

While visual inspection and the summary statistics supported the hypothesis of the study that there are differences in increments among ecoregions, its formal assessment could reveal the existence of a multitude of different growth increments. Therefore, the inclusion of covariates in the analysis seemed justified, as the visual inspection of the relationships DBHi–DBH and BAi–BA revealed not only differences among some ecoregions, but also a trend, particularly for BAi (Figure 4).

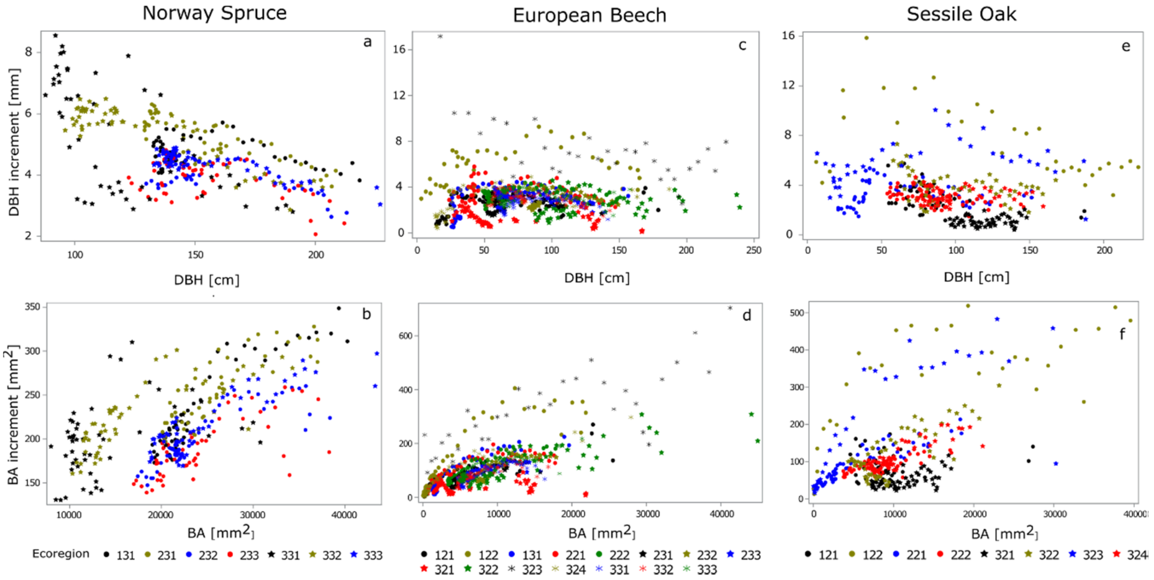

Figure 4. Mean DBH increment versus mean DBH and mean basal area increment versus mean basal area by ecoregion for Norway spruce (**a**,**b**), European beech (**c**,**d**) and Sessile oak (**e**,**f**).

Irrespective of the species, the AIC identified the first order autoregressive structure as the most suitable covariance structure. For Norway spruce, the ecoregions were found to have a significant effect on annual DBH growth and basal area growth. The highest estimate for average DBH increment was found in the Banat Mountains (331) ecoregion, and the lowest in the West Southern Carpathians (233) ecoregion. The estimated marginal means showed that most of the ecoregions are significantly different from one another in terms of growth (Table 4), except for eight pairs. In total, we found evidence that the DBH growth of Norway spruce significantly differs in six distinct ecoregions: the

Eastern Carpathians (131), Buzau-Vrancea mountains (231), East Southern Carpathians (232), West Southern Carpathians (233), Banat Mountains (331), and Volcanic Ridge (333). The seventh region analyzed, the Western Carpathians (332), was found to be similar with four other regions. There is no evidence that the results are artifacts [37], as the main assumption needed to be checked in repeated measurements analysis, namely that residuals are white noise, was fulfilled (i.e., the Durbin–Watson test indicated no autocorrelation).

Table 4. Impact on growth of Norway Spruce by ecoregions assessed with the estimated marginal means. Ecoregions not significantly different are identified for DBH increment and basal area increment with DBHi or BAi, respectively. The empty cells indicate significant difference.

Ecoregion	131	231	232	233	331	332	333
131							
231			DBHi				
232						BAi	
233					DBHi/BAi	DBHi	DBHi
331						DBHi	DBHi
332							DBHi
333							

The growth of European beech also varies significantly by ecoregion, the highest average DBH increment being found in the Maramures Plateau (323), and the lowest in the Caras Hills (321) (Table 3). However, not all regions were significantly different from one another, mirroring the Norway spruce. In the case of European beech, we noticed groups of ecoregions that have both similar DBH and BA increments (Table 5). We found nine groups of such ecoregions: Moldavian Plateau (121) with Eastern Carpathians (131); Eastern Carpathians (131) with Caras Hills (321) and Transylvanian Plateau (324); Getic Plateau (222) with East Southern Carpathians (232), Caras Hills (321) and Volcanic Ridge (333); West Southern Carpathians (233) with Western Carpathians (332); Caras Hills (321) with Transylvanian Plateau (324) and Volcanic Ridge (333). Another 11 ecoregion pairs were similar in terms of DBH increment and four in terms of BA increment (Table 5). Similarly to Norway spruce, there was no evidence that the results are based on methods violating analytical assumptions, as the Durbin–Watson test indicated no autocorrelation of the residuals.

Sessile oak mirrored the findings for Norway spruce and European beech, the ecoregions having a significant effect on tree growth (Table 6). The highest average growth was in the Moldavian Hills (122) ecoregion and the lowest in the Caras Hills (321) (Table 3). The regions exhibited mostly different growth from one another, with the exception of three pairs: the Buzau-Vrancea piedmonts (221) and Caras Hills (321); Caras Hills (321) and Cris Hills (322); Caras Hills (321) and Transylvania Plateau (324) (Table 6). There are also other four other similar pairs, but only from a DBH increment perspective. The Durbin–Watson test also found no autocorrelation of the residuals. It can be concluded that there are seven ecoregions spanning the Romanian areal of Sessile oak that significantly differ in tree growth: the Moldavian Plateau (121), Moldavian Hills (122), Buzau-Vrancea piedmonts (221), Getic Plateau (222), Cris Hills (322), Maramures plateau (323) and Transylvania Plateau (324). Caras Hills (321) was found similar in DBH or BA increment with four other ecoregions.

Table 5. Impact on growth of European beech by ecoregions assessed with the estimated marginal means. Ecoregions not significantly different are identified for DBH increment and basal area increment with DBHi or BAi, respectively. The empty cells indicate significant difference.

Ecoregion	**121**	**122**	**131**	**221**	**222**	**231**	**232**	**233**	**321**	**322**	**323**	**324**	**331**	**332**	**333**
121			DBHi/BAi							DBHi					
122							DBHi				DBHi				
131									DBHi/BAi	DBHi		DBHi/BAi			
221					BAi				DBHi/BAi			DBHi			DBHi
222							DBHi/BAi		DBHi/BAi			BAi			DBHi/BAi
231													BAi		
232									DBHi/BAi				BAi		DBHi
233														DBHi/BAi	
321												DBHi/BAi	DBHi		DBHi/BAi
322															
323															
324															
331															DBHi
332															
333															

Table 6. Impact on growth of Sessile oak by ecoregions assessed with the estimated marginal means. Ecoregions not significantly different are identified for DBH increment and basal area increment with DBHi or BAi, respectively. The empty cells indicate significant difference.

Ecoregion	121	122	221	222	321	322	323	324
121								
122								
221					DBHi/BAi	DBHi		DBHi
222					DBHi			
321						DBHi/BAi		DBHi/BAi
322								DBHi
323								
324								

3.2. Multivariate Analysis

As expected, a value less than 50 ensured at least one tree per calendar year and ecoregion. Depending on the species, the number of annual rings that was used in all multivariate analyses is either 20 for sessile oak or 30 for Norway Spruce and European beech. Irrespective of the attribute measuring the growth, DBHi or BAi, the three multivariate analyses supported the finding of mixed model investigation for all three species, as a significant separation among regions was revealed. The PCA, for which the first two principal components explained at most 80% of the growth variation, which occurred for BAi of sessile oak, (i.e., 79% for Norway Spruce and 73% for European beech), did not reveal an evident grouping according to the ecoregion (Figure 5). Therefore, globally, there are other aspects of tree growth which are more important in delineating growth than ecoregions.

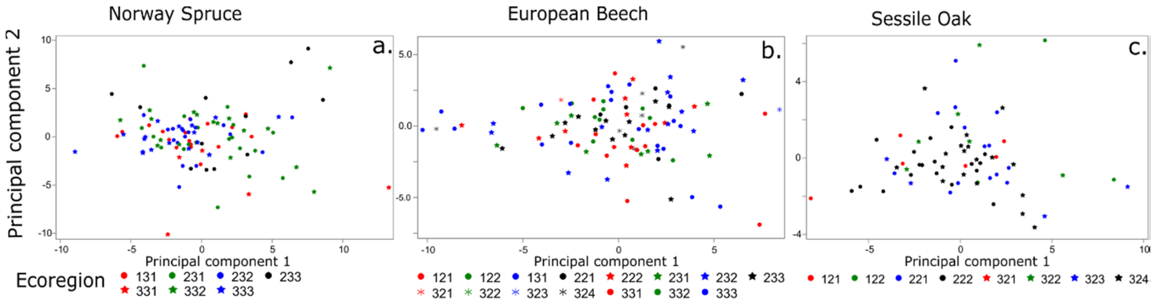

Figure 5. Grouping by ecoregions for Norway spruce (**a**), European beech (**b**), and Sessile oak (**c**) with principal components 1 and 2 as axes. Because similar results were obtained for DBHi and BAi, we have represented only the results for DBHi.

According to the cubic clustering criterion, the hierarchical cluster analysis found three groups of ecoregions for all three species (Figure 6), regardless the attribute measuring growth. Mirroring PCA findings, the groups were not as clearly delineated as mixed models analysis, but the results show distinct growing patterns among the three areas as pointed by the minimum difference among the groups (Table 7). The clear separation of the ecoregion is the results of the amount of information covered by the first two or three eigenvectors, which are responsible for the groups, that is at least 78%. Furthermore, the difference among the groups was more than 15% (the case of Norway spruce), but almost 50% for European beech and Sessile oak (i.e., >45%). The hierarchical clustering revealed that Norway spruce growing in the ecoregions Eastern Carpathians (131), Western Carpathians (332) and the volcanic ridge (333) are similar and distinct from the rest. The results were less conclusive for the European beech and sessile oak, as a clear pattern did not emerge from the tree hierarchy.

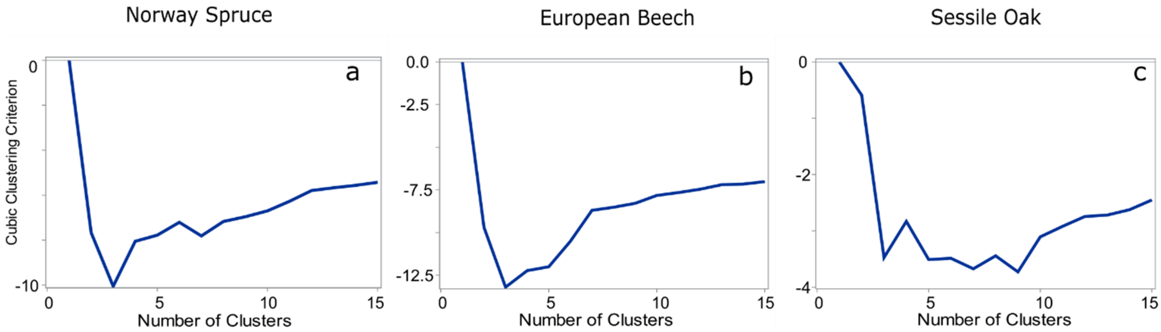

Figure 6. Identification of the number of groups of ecoregions using Ward's Minimum Variance and Cubic Clustering Criterion for Norway spruce (**a**), European beech (**b**) and Sessile oak (**c**). Because similar results were obtained for DBHi or BAi, we have represented only the results for DBHi.

Table 7. Grouping of ecoregions with similar growth according to the hierarchical cluster analysis.

Species	Groups of Ecoregions	Minimum Difference among Groups	% of Variation Explained	
			DBHi	**BAi**
Norway spruce	**3**	0.29	83.7	91.8
European beech	3	0.25	70.1	83.2
Sessile oak	3	0.25	71.5	87.5

Among all the multivariate methods, the canonical discrimination analysis was the only one that showed an obvious difference in growth between ecoregions (Figure 7), regardless of the attribute (i.e., DBHi or BAi). All four multivariate tests indicated that for all three species, the class means vectors are not equal. It was clear that Norway spruce from the Western Carpathians (131) grow differently than the West Southern Carpathians (233), and both from the rest of the ecoregions (Figure 7a). Whereas PCA and hierarchical cluster analysis failed to identify ecoregions with distinct growth from European beech, the canonical discriminant analysis succeeded, as the Moldavian plateau (121) and Moldavian hills (122) exhibit different growing patterns from the rest and between them (Figure 7b). We also found a clear delineation of ecoregions by growth for sessile oak, with the Buzau-Vrancea Piedmonts (221) showing different DBHi and BAi than the Transylvania plateau (324), which are both distinct from the other ecoregions. It should be noticed that fewer ecoregions can be considered by the canonical discriminant analysis (Figure 7c), as the ecoregions with less trees, consequently less factorial combinations, are not included (e.g., in the case of sessile oak, which has only four ecoregions, compared with eight in the mixed model analysis).

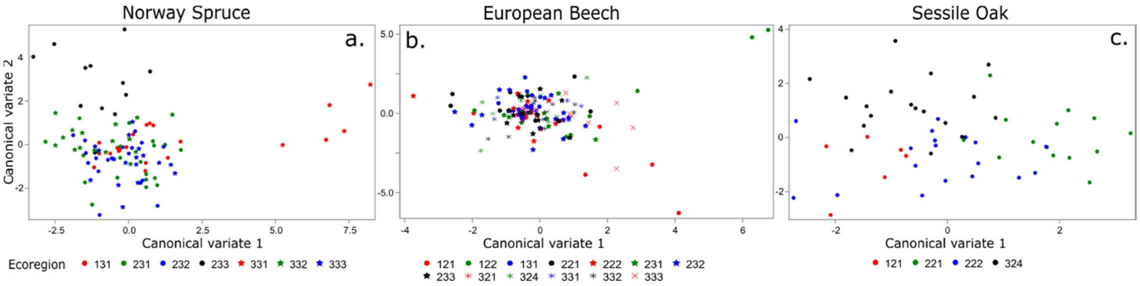

Figure 7. Grouping by ecoregions for Norway spruce (**a**), European beech (**b**), and Sessile oak (**c**) with canonical variables as axes. Because the same conclusion is reached for DBHi and BAi only the plots for DBHi are presented.

4. Discussion

Tree growth is influenced by a wide range of factors across a multitude of gradients [38]. Knowledge about this variation can lead to improved and localized forest growth models, with direct impact on forest management, forest operations and planning [39–41]. Our analysis was able to identify spatial/regional variations in the annual growth of the main tree species even for a country close to the median size (ranked 81 by IndexMundi), such as Romania.

The mixed models analysis showed that growth significantly differs by ecoregion. For all three species, several ecoregions grouped, indicating that regionalization of various forest related attributes or models is required. In the case of Norway spruce, there was similarity in DBH and BA increment between ecoregions Western Southern Carpathians (233) and Banat Mountains (331). One explanation for the analogous growth can be geomorphology, as all regions were mountainous, have similar soils and aspect (south facing) and are spatially adjacent. Spatial proximity can represent an important factor when comparing ecoregions because it can encompass numerous factors that influence growth. Among the most cited of those factors is climate, with effects at multiple levels in tree physiology [42–44], but others such as genetics, disturbances or localized stress events can also have an impact on tree development [45]. The DBH growth in the Banat Mountains (331) was also not different from Western Carpathians (332) and Volcanic ridge (333) ecoregions. This correspondence could be based on geomorphological factors, as soils, geology and location are different or it can also be attributed to other confounding factors. DBH growth also did not differ between Western Southern Carpathians (233) and Western Carpathians (332) and Volcanic ridge (333). As the ecoregions Banat Mountains (331) and Volcanic ridge (333) show similar DBH increment and mostly BA increment, these two ecoregions are good candidates for being joined from the perspective of Norway spruce growth. The highest average growth (Banat Mountains (331)) and the lowest (West Southern Carpathians (233)) occurred in a mountainous region with a similar soil composition, but a different altitude. Banat Mountains (331) are having a lower altitude with stepped leveling appearance and remnant limestone geology, whereas West Southern Carpathians (233) present higher altitudes, with leveled relief and limestone geology. The altitude can represent a proxy for other variables influencing growth, such as temperature, precipitation or for areas prone to stress and disturbances.

In the case of European beech, similar growth was found between pairs of plateau regions (ecoregions Buzau-Vrancea piedmonts (221), Getic plateau (222), Caras Hills (321), Transylvanian plateau (324)). As beech has its native range at these altitudes, it is expected that growth in these ecoregions is higher and also closer in terms of increments. However, the fact that these ecoregions are not completely equivalent, illustrates that the spatial variability of growth is present even within same geomorphology and that other factors can be involved in determining tree growth. These can be soil or geology, but also climatic variables or the presence of localized stress events. The average growth in the Maramures Plateau (323) is different from all the other ecoregions, with the highest basal area increment estimate. One possible explanation for this difference could be attributed to the combined effects of growing conditions and other factors such as regional climate or natural distribution of the genetic material. The growth similarity between Eastern Carpathians (131) and some plateau regions (Moldavian Plateau (121), Caras Hills (321), Transylvania Plateau (324)) indicates again that there are multiple factors influencing growth, and that geomorphology is not the only defining factor.

For Sessile oak, only a few ecoregions showed growth similarities. The Caras Hills (321) ecoregion exhibited similar growth with four other ecoregions where Sessile oak is present (Buzau-Vrancea piedmonts (221), Getic plateau (222), Cris Hills (322) and Transylvania Plateau (324)), all being located at the foothills of the mountains. This indicates that this foothill ecoregion represents a location of average growth when compared with other Sessile oak ecoregions, and could be combined with the others. Highest average growth occurred in a hilly ecoregion (Moldavian Hills (122)) and a much lower one in the neighboring one, the Moldavian Plateau (121). The unambiguous difference between these two regions underlines the spatial differentiation in tree growth for Sessile oak. As in Norway spruce, the altitude represents a potential differentiation factor, with the plateau ecoregion being around 200–500 m high and the hills around 500–900 m high.

Two models for tree growth were developed in this study, and ecoregions could be differentiated by both models. Some authors [46,47] suggest that both DBH and BA increment are appropriate in growth modelling, while Russell [48] suggests that DBH increment might decrease the model error more than BA. The results of this study showed that, for all three species and especially for European beech and Sessile oak, both the DBH increment and BA increment models converged towards same results in a high number of cases. This is a clear indication that ecoregions have an effect on tree growth, irrespective of the type of variable used to measure increment. There were instances where only DBH increment indicated a growth differentiation between ecoregions, as this variable might be more suitable for increment modelling [48].

The multivariate analysis examined simultaneously all the DBHi or BAi, looking at the growth pattern along the life of each individual tree. The PCA and cluster analysis suggested that DBHi cannot evidently group ecoregions and cannot be grouped by certain periods of time. This means that within the same species, variation of growth in time did not represent a grouping factor. The canonical discrimination analysis indicated that there is growth difference by ecoregion for both Norway spruce and European beech. However, for Sessile oak, the canonical variables have discriminatory power for classifying growth into ecoregions, irrespective of DBHi or BAi. As the canonical variables are a linear combination of yearly growth, DBHi in certain years could determine the inclusion in an ecoregion. Sessile oak has its native range in warm areas which are more prone to draught and having water as limiting factor. Although further analysis in combination with climate data is required, it is possible that certain ecoregions were more influenced by changes in climatic conditions, which were instrumental in this growth differentiation of ecoregions.

One main finding of the mixed models analysis was that geomorphology plays a major role in the spatial variation of growth. Ecoregions were found to have similar growth increments, even when soil, geology or location differ. The geomorphology was found to be relevant for all three species. One explanation for this finding is that geomorphology changes the specific soil characteristics [49] and indirectly influences growth. It is also possible that geomorphology has driven the historical human impact on forest cover and growth (i.e., higher impact in flatter areas and lower in mountains ones), and therefore influencing in this alternate manner the vegetation development [50]. Another explanation can be that climate conditions present in that geomorphology type have a strong impact on tree growth [44,51,52], which can be a stronger driver than soil [53]. Non-climatic variables such as geomorphology can represent a proxy for different climatic characteristics [54,55], as spatially adjacent ecoregions with different altitudes exhibited very different growth increments. However, even when considering only non-climate variables, spatial variability was evident.

5. Conclusions

The spatial variation of growth for tree species represents an essential aspect of forest management planning, modelling and reporting [56]. This study aimed at determining the existence of variation in DBH and BA growth over the area of a medium sized country located in a temperate region. A series of 21 ecoregions summarized the ecological conditions for the entire country.

Using mixed models and multivariate analysis on 6536 increment cores from the Romanian NFI, we were able to establish that tree growth is significantly different between various ecoregions for Norway spruce, European beech and Sessile oak. Numerous factors such as geology, soil and geomorphology are responsible for the difference in growth, with the latter being frequently present in the differentiation of ecoregions. An important finding of this study was that global, country wide, growth models incorporate far too much variability from an operational perspective. They can be used for country-wide resource estimations, but it is hard to justify their usage as a legal binding planning tool.

As the change in climate also influences the vegetation growth, and consequently, the type and amount of products and services supplied by each ecosystem, further dendrological studies that include climate and temporal analysis are needed for a better understanding of tree growth variability.

Author Contributions: G.M. organized data collection and framed the study, V.C.S. interpreted and wrote the manuscript, I.V.A. wrote portions of the manuscript, B.M.S. analyzed, interpreted, and wrote portions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: This research was partially funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture, grant number 2019-67019-29462, the McIntire Stennis project OREZ-FERM-875, and the Romanian National Authority for Scientific Research and Innovation, CCCDI—UEFISCDI, project number ERANET-FACCE ERAGAS—FORCLIMIT (82/2017), within PNCDI II.

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

References

1. Zianis, D.; Muukkonen, P.; Mäkipää, R.; Mencuccini, M. *Biomass and Stem Volume Equations for Tree Species in Europe*; Silva Fennica Monographs 4: Tampere, Finland, 2005.
2. Bailey, R.G. Delineation of ecosystem regions. *Environ. Manag.* **1983**, *7*, 365–373. [CrossRef]
3. Hughes, R.M.; Omernik, J.M. Ecological regions (ecoregions). In *Environmental Geology*; Springer: Dordrecht, The Netherlands, 1999; pp. 155–159. ISBN 978-1-4020-4494-6.
4. Omernik, J.M. Perspectives on the nature and definition of ecological regions. *Environ. Manag.* **2004**, *34*, S27–S38. [CrossRef] [PubMed]
5. Indreica, A.; Turtureanu, P.D.; Szabó, A.; Irimia, I. Romanian forest database: A phytosociological archive of woody vegetation. *Phytocoenologia* **2017**, *47*, 389–392. [CrossRef]
6. Šijačić-Nikolić, M.; Milovanović, J.; Nonic, M. (Eds.) *Forests of Southeast Europe under a Changing Climate: Conservation of Genetic Resources*; Advances in Global Change Research; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; ISBN 978-3-319-95266-6.
7. Stapf, O. Conspectul Florei României. *Nature* **1899**, *59*, 221. [CrossRef]
8. Bechtold, W.A.; Patterson, P.L. *The Enhanced Forest Inventory and Analysis Program -National Sampling Design and Estimation Procedures*; U.S. Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC, USA, 2005; p. 85.
9. Vidal, C.; Belouard, T.; Herve, J.C.; Rober, N.; Wolsak, J. *A New Flexible Forest Inventory in France*; USDA Forest Service: Portland, ME, USA, 2007; pp. 67–73.
10. Tomppo, E.; Gschwantner, T.; Lawrence, M.; McRoberts, R.E. (Eds.) *National Forest Inventories: Pathways for Common Reporting*; Springer: Dordrecht, The Netherlands, 2010; ISBN 978-90-481-3232-4.
11. IFN National Forest Inventory. Available online: https://roifn.ro/site/en/ (accessed on 6 August 2019).
12. Marin, G.; Bouriaud, O.; Dumitru, M.; Nitu, D. Romania. In *National Forest Inventories: Pathways for Common Reporting*; Springer: Heidelberg, Germany, 2010; pp. 473–480.
13. Charru, M.; Seynave, I.; Morneau, F.; Bontemps, J.-D. Recent changes in forest productivity: An analysis of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. *For. Ecol. Manag.* **2010**, *260*, 864–874. [CrossRef]
14. Evans, M.E.K.; Falk, D.A.; Arizpe, A.; Swetnam, T.L.; Babst, F.; Holsinger, K.E. Fusing tree-ring and forest inventory data to infer influences on tree growth. *Ecosphere* **2017**, *8*, e01889. [CrossRef]
15. Metsaranta, J.M. Dendrochronological procedures improve the precision and accuracy of tree and stand age estimates in the western Canadian boreal forest. *For. Ecol. Manag.* **2020**, *457*, 117657. [CrossRef]
16. Marin, G.; Abrudan, I.; Strimbu, B.M. Increment cores of the National Forest Inventory from Romania. *Math. Comput. For. Nat. Resour. Sci.* **2019**, *11*, 294.
17. Nyland, R.D. *Silvicuture: Concepts and Applications*; McGraw-Hill: New York, NY, USA, 1996.
18. Kuglitsch, F.G.; Toreti, A.; Xoplaki, E.; Della-Marta, P.M.; Zerefos, C.S.; Türkeş, M.; Luterbacher, J. Heat wave changes in the eastern Mediterranean since 1960. *Geophys. Res. Lett.* **2010**, 37. [CrossRef]
19. Zuidhoff, F.S.; Kolstrup, E. Changes in palsa distribution in relation to climate change in Laivadalen, northern Sweden, especially 1960–1997. *Permafr. Periglac. Process.* **2000**, *11*, 55–69. [CrossRef]
20. Gregory, P.J.; Marshall, B. Attribution of climate change: A methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. *Glob. Chang. Biol.* **2012**, *18*, 1372–1388. [CrossRef]

21. Wang, S.; Zhang, M.; Li, Z.; Wang, F.; Li, H.; Li, Y.; Huang, X. Glacier area variation and climate change in the Chinese Tianshan Mountains since 1960. *J. Geogr. Sci.* **2011**, *21*, 263–273. [CrossRef]
22. Yue, T.X.; Fan, Z.M.; Liu, J.Y. Changes of major terrestrial ecosystems in China since 1960. *Glob. Planet. Chang.* **2005**, *48*, 287–302. [CrossRef]
23. Posmentier, E.S.; Cane, M.A.; Zebiak, S.E. Tropical pacific climate trends since 1960. *J. Clim.* **1989**, *2*, 731–736. [CrossRef]
24. Husch, B.; Beers, T.W.; Kershaw, J.A. *Forest Mensuration*, 4th ed.; John Wiley and Sons: Hoboken, NJ, USA, 2002.
25. Pretzsch, H. *Forest Dynamics, Growth and Yield*; Springer: Berlin, Germany, 2009.
26. Weiskittel, A.R.; Hann, D.W.; Kershaw, J.A.; Vanclay, J.K. *Forest Growth and Yield Modeling*; Wiley-Blackwell: Chichester, UK, 2011; Volume 430.
27. Crowder, M.J.; Hand, D.J. *Analysis of Repeated Measures; Monographs on Statistics and Applied Probability*; Chapman and Hall: London, UK, 1990.
28. Fitzmaurice, G.M.; Laird, N.M.; Ware, J.H. *Applied Longitudinal Analysis*; Wiley: Hoboken, NJ, USA, 2004; ISBN 978-0-471-21487-8.
29. Pinheiro, J.; Bates, D. *Mixed Effects Models in S and S-PLUS*; Springer: New York, NY, USA, 2000.
30. Gotway, C.A.; Stroup, W.W. A generalized linear model approach to spatial data analysis and prediction. *J. Agric. Biol. Environ. Stat.* **1997**, *2*, 157–178. [CrossRef]
31. Neter, J.; Kutner, M.H.; Nachtsheim, C.J.; Wasserman, W. *Applied Linear Statistical Models*; WCB McGraw-Hill: Boston, MA, USA, 1996.
32. SAS Institute. *SAS®9.4*; SAS Institute Inc.: Cary, NC, USA, 2013.
33. Rencher, A.C. *Methods of Multivariate Analysis*; John Wiley and Sons: New York, NY, USA, 2002.
34. Hardle, W.; Simar, L. *Applied Multivariate Statistical Analysis*; Springer: New York, NY, USA, 2003.
35. Tabachnick, B.G.; Fidell, L.S. *Using Multivariate Statistics*; Allyn and Bacon: Needham Heights, MA, USA, 2001.
36. Strimbu, B.M.; Hickey, G.M.; Strimbu, V.G.; Innes, J.L. On the use of statistical tests with non-normally distributed data in landscape change detection. *For. Sci.* **2009**, *55*, 72–83.
37. Seppelt, R.; Richter, O. "It was an artefact not the result": A note on systems dynamic model development tools. *Environ. Model. Softw.* **2005**, *20*, 1543–1548. [CrossRef]
38. Oliver, C.D.; Larson, B.C. *Forest Stand Dynamics*, updated ed.; John Wiley & Sons, Inc.: New York, NY, USA, 1996; ISBN 978-0-471-13833-4.
39. Hasenauer, H. Concepts within tree growth modeling. In *Sustainable Forest Management: Growth Models for Europe*; Hasenauer, H., Ed.; Springer Berlin Heidelberg: Berlin/Heidelberg, Germany, 2006; pp. 3–17. ISBN 978-3-540-31304-5.
40. Strimbu, V.C.; Bokalo, M.; Comeau, P.G. Deterministic models of growth and mortality for jack pine in boreal forests of western Canada. *Forests* **2017**, *8*, 410. [CrossRef]
41. Taylor, A.R.; Chen, H.Y.H.; VanDamme, L. A review of forest succession models and their suitability for forest management planning. *For. Sci.* **2009**, *55*, 23–36.
42. Savva, Y.; Oleksyn, J.; Reich, P.B.; Tjoelker, M.G.; Vaganov, E.A.; Modrzynski, J. Interannual growth response of Norway spruce to climate along an altitudinal gradient in the Tatra Mountains, Poland. *Trees* **2006**, *20*, 735–746. [CrossRef]
43. Andreassen, K.; Solberg, S.; Tveito, O.E.; Lystad, S.L. Regional differences in climatic responses of Norway spruce (Picea abies L. Karst) growth in Norway. *For. Ecol. Manag.* **2006**, *222*, 211–221. [CrossRef]
44. Kramer, K.; Leinonen, I.; Loustau, D. The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: An overview. *Int. J. Biometeorol.* **2000**, *44*, 67–75. [CrossRef] [PubMed]
45. Zhang, Q.; Alfaro, R.I.; Hebda, R.J. Dendroecological studies of tree growth, climate and spruce beetle outbreaks in Central British Columbia, Canada. *For. Ecol. Manag.* **1999**, *121*, 215–225. [CrossRef]
46. Shifley, S.R. *A Generalized System of Models Forecasting Central States Tree Growth*; Research Paper NC-279; US Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1987; Volume 279.
47. West, P.W. Use of diameter increment and basal area increment in tree growth studies. *Can. J. For. Res.* **1980**, *10*, 71–77. [CrossRef]

48. Russell, M.B.; Weiskittel, A.R.; Kershaw, J.A., Jr. Comparing strategies for modeling individual-tree height and height-to-crown base increment in mixed-species Acadian forests of northeastern North America. *Eur. J. For. Res.* **2014**, *133*, 1121–1135. [CrossRef]
49. Griffiths, R.P.; Madritch, M.D.; Swanson, A.K. The effects of topography on forest soil characteristics in the Oregon Cascade Mountains (USA): Implications for the effects of climate change on soil properties. *For. Ecol. Manag.* **2009**, *257*, 1–7. [CrossRef]
50. Sandel, B.; Svenning, J.-C. Human impacts drive a global topographic signature in tree cover. *Nat. Commun.* **2013**, *4*, 2474. [CrossRef]
51. Laubhann, D.; Sterba, H.; Reinds, G.J.; De Vries, W. The impact of atmospheric deposition and climate on forest growth in European monitoring plots: An individual tree growth model. *For. Ecol. Manag.* **2009**, *258*, 1751–1761. [CrossRef]
52. Scharnweber, T.; Manthey, M.; Criegee, C.; Bauwe, A.; Schröder, C.; Wilmking, M. Drought matters–Declining precipitation influences growth of *Fagus sylvatica* L. and *Quercus robur* L. in north-eastern Germany. *For. Ecol. Manag.* **2011**, *262*, 947–961. [CrossRef]
53. Toledo, M.; Poorter, L.; Peña-Claros, M.; Alarcón, A.; Balcázar, J.; Leaño, C.; Licona, J.C.; Llanque, O.; Vroomans, V.; Zuidema, P.; et al. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. *J. Ecol.* **2011**, *99*, 254–264. [CrossRef]
54. Adams, H.R.; Barnard, H.R.; Loomis, A.K. Topography alters tree growth–climate relationships in a semi-arid forested catchment. *Ecosphere* **2014**, *5*, art148. [CrossRef]
55. Tardif, J.; Camarero, J.J.; Ribas, M.; Gutiérrez, E. Spatiotemporal variability in tree growth in the central pyrenees: climatic and site influences. *Ecol. Monogr.* **2003**, *73*, 241–257. [CrossRef]
56. Spiecker, H. Tree rings and forest management in Europe. *Dendrochronologia* **2002**, *20*, 191–202. [CrossRef]