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Exploring Texture Diversity of Beech-Spruce-Fir Stands through Development Phase Analysis in the Frakto Virgin Forest of Greece

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Abstract: The structural diversity of old-growth forests is a fundamental element as regards ecosystem stability and functionality. The current study aims at exploring the texture diversity in the unique virgin Frakto forest of Greece through the determination of the forest development phases and their related stages. Eight sample plots of 0.25 hectares each were randomly distributed to serve the field research needs. During the single phases, a significant number of variables at the stand level, such as the total dead and living timber volume and the density expressed as the number of stems per hectare and basal area, were calculated, and their values were merged into three main stages. The Frakto virgin forest was found to be dominated by the optimal stage (61.7%), followed by the decay stage (22.7%), and the initial stage (15.6%), in alignment with relevant distributions reported for other European virgin forests. Statistically significant differences in terms of stem density and woody volume between the stages demonstrated increased structural diversity and heterogeneity, a typical characteristic of primeval forests. The results offer an insight into forest growth dynamics under natural processes, thus providing a knowledge base for the promotion of sustainable forest management.

Keywords: ecosystem dynamics; development cycle; old growth forest; stand structure; stand diversity

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1. Introduction

Old-growth and primeval forests are passing through a natural development cycle with recurring stages of forest development [1], which are classified by the state of development of homogeneous and spatially contiguous tree collectives within certain limits [2]. The shifting mosaic of patches in different phases of forest development reflects apart from the life cycle, the disturbance regime, and the structural diversity of a forest [2] and is thus widely used as a framework for describing stand dynamics, structure, and biodiversity in European temperate forests [3].

The large-scale forest structural diversity is determined by the occurrence of the different forest development phases as well as the expansion and distribution of the individual phases [4]. The structural diversity of an old-growth forest is the result of long-lasting, complex evolutionary processes [5], and therefore, it constitutes a fundamental element with regard to the stability and functionality of the ecosystem. Furthermore, old-growth forest structural diversity can be used to estimate biodiversity [6–8], as the influence of the different development phases on fauna and flora species has been well documented [9–12]. An insight into forest growth dynamics provides a knowledge base on the impacts of natural processes on the forest and the ways these processes can be reproduced through management practices, which is fundamental for implementing sustainable forest management [6].

To assess the spatial heterogeneity and the development dynamics of European temperate forests, the "forest cycle" concept [13] with a cyclic succession of development phases [14,15] has been adopted. According to this concept, all succession stages can be found in individual areas at the same time, appearing as a heterogeneous mosaic of patches due to local and regional disturbances that set the succession process in these areas back asynchronously. In primeval European beech forests this process takes place on a fine scale as this type of forests are subject to single tree mortality or up to three crown scale mortality (40–140 m^2) [16–18]. The formation of such canopy openings is crucial for the establishment and subsequent development of natural regeneration [15], which leads to small clusters of evenly sized trees [19].

The "forest cycle" concept has undergone several adaptations over the years, which gradually led to a multitude of definitions for development phases. The approach best known as a Central European approach was based on the work of Leibundgut [20–22] and Körpel [23–25], who both classified the forest development cycle into development stages and further into development phases. Several other approaches were developed later [26–29], introducing more details for the identification of the development phases, which ranged from five to ten. The forest development cycle was defined through different quantitative attributes of the phases in sequence and different criteria and algorithms for assigning patches of different structure and size to forest development stages or phases. All currently existing classification methods have in common the assumption that the characteristics of certain stand structural attributes are made a priori [1]. Structural attributes are usually defined by basic structural characteristics such as tree density, basal area, growing stock, diameter structure, crown engagement ratio, that is, the share of the sum of crown projections from the area of the research plot, and amount of deadwood; these characteristics, however, provide only limited information on the spatial arrangement of the forest [15].

The determination of these patches and phases has often been performed using subjective field observations and simplistic or loosely defined mapping criteria, with the resulting maps being observer-dependent [3]. Furthermore, the transitions, both temporal and spatial, from one phase to the next are fluid, and maps showing the spatial distribution of development phases are usually very subjective and not reproducible [30].

Several approaches to increasing the objectivity of field mapping have evolved. Some of them make use of a regular grid that divides a study area into numerous square subplots, where a rule-based classification system is applied [28,31,32]. An advantage of these 'grid' approaches is the ability to preserve the spatial scale (grain size) of mapping [8]. However, these still suffer from the observer's subjectivity, which allows no objective and reproducible distinction of the development phases and multitemporal comparison of the field-mapping results [8,33].

Meyer [28] presented a protocol for the identification and quantification of development phases in nature reserves, which was based on structural characteristics of reserves that can be compared and allowed for long-term observations. Tabaku [29] developed a similar protocol for virgin forests based on that of Meyer [28] regarding forest development phases, which were tested on small-scale areas. Specifically, it is based on the wood volume change of a stand between two different recorded time points. In this way, it is possible to determine phases of development in natural forest cycles.

Hence, the aims of the current research were the following:

(a) To document the texture diversity of the unique old-growth virgin Frakto forest in northeastern Greece through identification, frequency spatial distribution, and arrangement of the forest development phases;
(b) To investigate the specific stand structural attributes that may differ significantly among the three major developmental stages.

2. Materials and Methods

The study site is located in the northern part of the Greek central Rhodope Mountains at the borderline with Bulgaria at altitudes ranging from 1500 m to 1953 m (Figure 1). Due to its remoteness, the area has undergone no human intervention for several hundred years. In 1980, an area of 589.25 ha of the Frakto forest was nominated by the Greek Ministry of Agriculture as a preserved monument of nature [34]. Forest roads were built in 1977, and only then were some of the highest parts of the forest possible to reach. Limited forestry operations, including logging activities, appear to have been carried out about the same time to harvest the immense wood stock of the peripheral zone of the later nominated Frakto Natural Monument area. These activities were by no means extended to the protected area, which remained completely untouched [35].

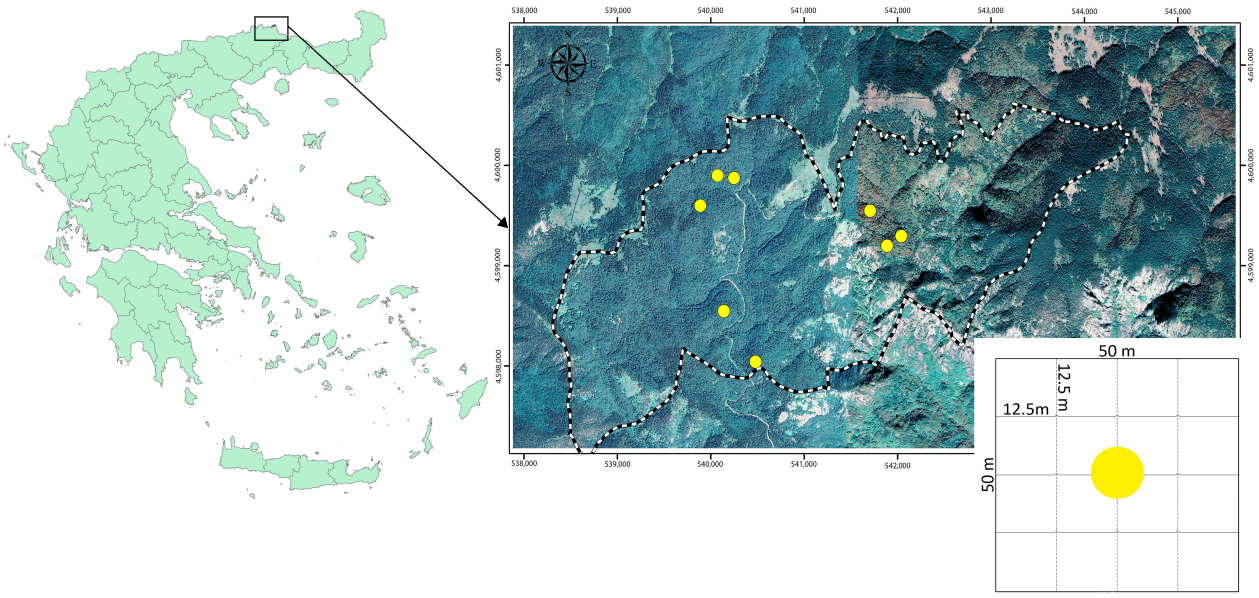

Figure 1. Location of the study site and plot distribution. Plots are marked with yellow dots.

The nominated protected area consisted of two core zones, measuring 502.00 ha and 87.25 ha, respectively. The protected status involved absolutely no form of exploitation other than scientific research [34,36]. The study site also forms part of the broader GR1140001 Natura Site "Dasos Fraktou" as well as part of the Rodopi Mountain Range National Park [37]. Furthermore, it has been identified among the potential areas covered by ancient forest in the framework of the program "Ancient high conservation value forest (A-HCVF)" in the Mediterranean countries [38], while its acknowledged ecological significance can serve as a model to explore the dynamic evolution of natural forest ecosystems. The area hosts high plant diversity [39–41] and valuable habitats for numerous species, including large carnivores [42].

The site is characterized by igneous rocks, mainly of volcanic and plutonic origin, while the soils are predominantly slightly acidic sandy loams. The average temperature is 11.4 °C, with an annual precipitation of around 694 mm. The forests are dominated by beech (*Fagus sylvatica* L.) with an admixture of fir (*Abies alba* Mill.) and spruce (*Picea abies* L.), and the forest association found is *Abieti-fagetum-picetosum*. As an indicator of texture diversity, forest development phases were extensively mapped at the study site based on the method developed by Drössler and Meyer [31] and on the basis of the work of Tabaku [29]. Accordingly, the forest cycle was divided into eight development phases: regeneration, initial, early optimum, middle optimum, late optimum, plenter, terminal, decay, and gaps.

To quantify development phases within the virgin forest, eight experimental plots of square shape with 50 m sides were established. The distribution of these plots within

the area covered by mixed beech-fir-spruce stands in the Preserved Monument of Nature Frakto virgin forest was random [43]. Randomness was achieved by using the "create random points" command of a Geographic Information Systems environment (ArcGIS 10.2) as suggested by Raptis et al. [44]. Each plot was divided into 16 equal subplots, square in shape with sides of 12.5 m (Figure 1). An area of 156.25 m^2 (12.5 × 12.5) was selected so as to represent the size of the crown projection area of a mature beech [31] and to capture development phases [29,31]. This plot size corresponds to the extent of gap-scale processes that drive the structural and successional patterns [15], because the size of gaps represents the area for a newly beginning forest cycle [31].

In each subplot the Breast Height Diameter (DBH) (cm) and height (m) of all living and standing dead trees above 7 cm, lying deadwood with ≥10 cm diameter, and ≥2 m length were measured using a caliper and LaserAce Hypsometer (Trimble), the crown projection area (CPA) with a spherical densiometer [45], and the natural regeneration coverage ratio was visually assessed.

Subsequently, the volume of living trees and standing dead trees as far as beech is concerned was calculated according to the two-parameter (DBH and height) equation derived by Raptis et al. [46], while that of fir and spruce was derived from local volume tables of the Forest Service of Drama. The volume of lying deadwood was calculated using Huber's formula, and the volume of stumps was calculated as the volume of a cylinder with a height equal to 0.3 m [47]. The proportion of deadwood in relation to the total volume of standing and lying wood was then calculated, as was the normalized interquartile range showing the dispersion of diameters of all the trees.

Affiliation of each subplot to a forest development phase was established by using the previously described dataset and a dichotomous key [31] (Figure 2). Specifically, the defining criteria in order to determine the development phase in each subplot were the maximum diameter (DBH_{max}) and maximum height (H_{max}) in each subplot, the coverage percentage of natural regeneration (CR), the CPA, the proportion of deadwood (DWP), the normalized interquartile range (NIQR), and the DBH size classes of the trees on the regeneration surfaces.

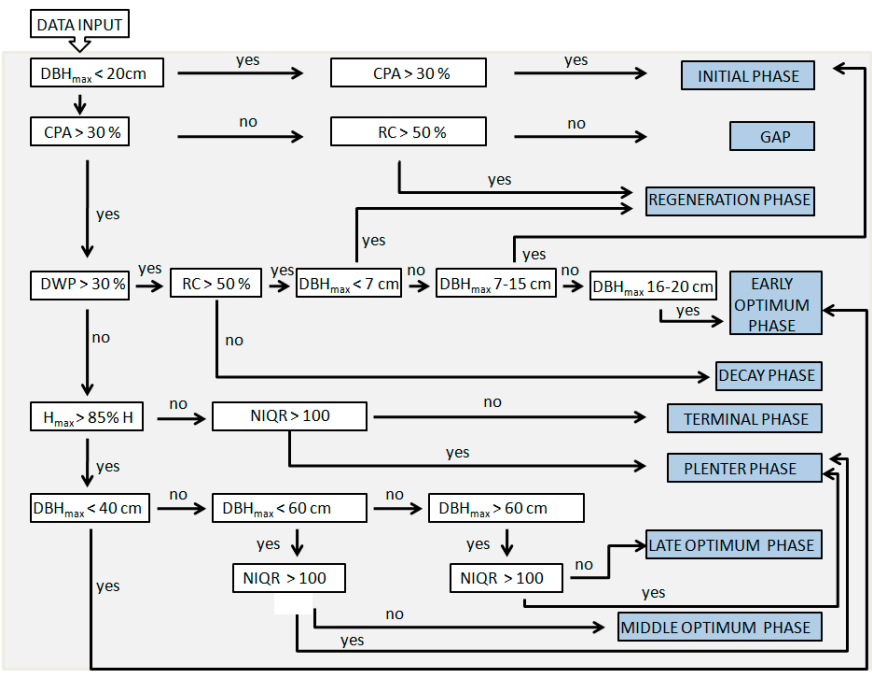

Figure 2. A dichotomous key for the affiliation of development phases in 12.5 × 12.5 m subplots (adapted from Tabaku [29] and Drössler and Meyer [31]).

Development phases were presented graphically by using colors and different graphic patterns for each phase. Their presence was defined through their participation as a percentage in the research plots. The average texture diversity of the virgin forest was estimated based on the frequency and spatial distribution of the phases.

Furthermore, based on the stand structure variables recorded and the identified development phases, the latter were aggregated into major development stages according to Mataji [48], which was based on Körpel's [25] model. Körpel [25] identified three development stages, which are characterized by a temporal sequence of natural processes that cause changes in forest structure such as regeneration and growth (initial stage), maturity and senescence (optimum stage), and breakdown (decay stage). In the initial stage, trees are growing, resulting in an increase in stand biomass while tree density and canopy cover are high. The initial stage is followed by the optimum stage when dominant trees have reached the overstory, resulting in a mature stand, while the decay stage takes over as old trees die, forming gaps and leading to a disintegration of the stand while regeneration establishes itself in the gaps. Taking into account the stand structure characteristics of each stage, the phases according to Tabaku [29] were affiliated with each stage. The initial stage can be compared with the regeneration and initial phase, the optimum stage with the optimum and plenter phase, and the decay stage with the terminal and decay phase, including gaps [31].

In order to confirm the significant differences in stand structure parameters between development stages, one-way analysis of variance (one-way ANOVA) was performed along with Tukey HSD post-hoc analysis for multiple comparisons after normality and homogeneity checking. A Kolmogorov–Smirnov (KS) test was used to determine data normality.

The statistical analysis was conducted using *R* (CRAN) ver. 4.1.3 [49].

3. Results and Discussion

The plenter phase is prevailing with 48.44%, while the terminal phase is following with 16.41%. The late optimum phase participates with 12.50%, the middle optimum phase with 10.16%, and the early optimum phase with 6.25%. The regeneration phase has a lower participation rate of 3.12%, followed by the gaps (1.56%), and the decomposition phase (1.56%) (Table 1).

The extent of the development phases can be compared with the results of Tabaku [29] for the virgin forests of Albania and those of Drössler and Meyer [31] for the virgin forests of Slovakia, where the same methodology was implemented. The percentage of gaps in the study of Tabaku [29] was 2%, as was the percentage in Drössler and Meyer's [31] study of the Havešová and Kyjov virgin forests in Slovakia. In the present study, the percentage of the gap phase amounts to 1.56%. The regeneration phase was estimated at 3.12%; the initial phase was absent, while the optimum phase was estimated at 28.91%. A comparison of the results with those for other virgin forests in Europe showed 6% and 4.6%, considering the initial phase, and 17.4% in the Havešová virgin forest and 12.2% in the Kyjov virgin forest for the optimum phase [31]. Comparatively, the results of the present study show a greater participation in the optimum phase (28.91%). The plenter phase and terminal phase occupy 64.85% of the surface, which is consistent with Drössler and Meyer's [31] results, where the two phases occupied about 60% of the surface. However, the plenter phase individually shows a much higher percentage in the virgin forest of Frakto (48.44%). Based on the affiliation criteria of the plenter phase, a great diameter difference appears in a small area, indicating the presence of both young and old trees. This can be attributed to a prolonged regeneration period or the spatial overlap of the decay and early optimum phases, as has also been indicated in the findings of Meyer et al. [50] and Drössler and Meyer [31]. The terminal phase, with a percentage of 16.41%, appeared reduced when compared with the other two studies. Additionally, the decay phase showed a smaller percentage (1.56%) in relation to the corresponding one in the virgin forests of Slovakia, which amounted to 14%. Greater representation of the terminal and decay phases by 40% was found by Leibundgut [51] in the Perucica virgin forest, as well as by Anic and

Mikac [52] in their study of the Corcova uvala virgin forest, where the terminal phase reached 60%. Visnjic et al. [53], on the contrary, found a small representation of the decay and terminal phases, which, in combination with the increased percentage of the initial phase, led them to the conclusion that in the virgin forest Ravna Vala, the transition to forest renewal had taken place. However, with the strong representation of the optimum and plenter phases, in the Frakto virgin forest, it can be assumed that higher percentages of the terminal and decay phases are expected in the future.

Table 1. Total and per plot spatial proportion (%) of forest development phases defined according to the protocol of Tabaku (1999).

Development Phases	Plot 1 (%)	Plot 2 (%)	Plot 3 (%)	Plot 4 (%)	Plot 5 (%)	Plot 6 (%)	Plot 7 (%)	Plot 8 (%)	Total Spatial Proportion (%)
Gap	0	6.25	6.25	0	0	0	0	0	1.56
Regeneration Phase	6.25	0	6.25	0	6.25	0	0	6.25	3.12
Initial Phase	0	0	0	0	0	0	0	0	0.00
Early Optimum Phase	6.25	12.5	0	0	0	0	18.75	12.5	6.25
Middle Optimum Phase	18.75	12.5	0	0	18.75	6.25	12.5	12.5	10.16
Late Optimum Phase	6.25	12.5	31.25	6.25	18.75	6.25	12.5	6.25	12.50
Plenter Phase	43.75	43.75	37.5	68.75	43.75	68.75	43.75	37.5	48.44
Terminal Phase	12.5	12.5	12.5	25	12.5	18.75	12.5	25	16.41
Decay Phase	6.25	0	6.25	0	0	0	0	0	1.56

The determination of development phases in relatively small areas (Figure 3) shows that the most frequent and older phases, i.e., the late optimum phase, planter, and terminal phases, appear in larger uniform areas than the youngest and rarest, such as the regeneration phase. The plenter phase formed a uniform area, which in six cases exceeded 700 m^2 at plot level; the terminal phase in one case exceeded 600 m^2, while in four other cases it exceeded 300 m^2 at plot level. The boundaries of the plot may lead to the interruption of bigger and more uniform areas during a development phase. Both the decay phase and the regeneration phase, as well as gaps, were found in small-single plot areas. The same conclusion was drawn by Tabaku [29] and Drössler and Meyer [31], and in particular, this is the case for the plenter and terminal phases. Similar conclusions were reached for the virgin forest Ravna vala in Bosnia Herzegovina, where the plenter phase formed a larger uniform area while the decay and regeneration phases appeared individually [53]. Mayer and Neumann [54] observed larger, uniform areas of the optimum phase and the terminal phase in the Corcova Uvala Forest in Croatia.

The species' contribution to the main structural attributes of the forest in total and per development phase are presented in Tables 2 and 3.

Table 2. Species contribution (%) to the main structural attributes of the Frakto forest.

Species	Density (%)	Basal Area	Volume of Living Trees	Deadwood Volume
Beech	84	67	63	26
Silver fir	10	13	16	69 [1]
Spruce	6	20	21	
Unidentified	-	-	-	5

[1] The value refers to silver fir and spruce deadwood.

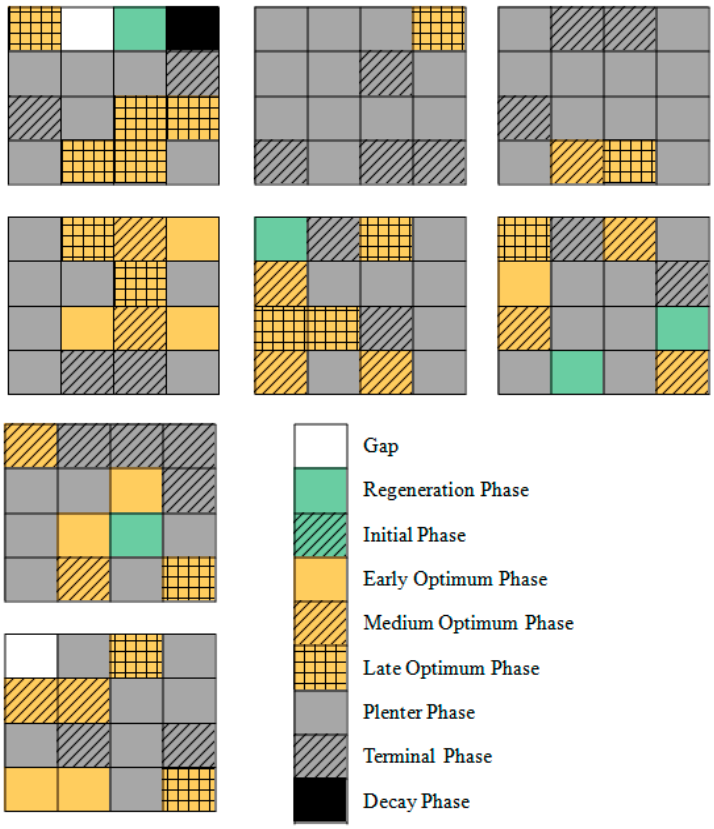

Figure 3. Development stages determined on 12.5 × 12.5 m squares in the Frakto virgin forest.

Table 3. Species contributions (%) per development phase to the main structural attributes of the Frakto forest [2].

Development Phase	Species	Density (N/ha)	Basal Area (m^2/ha)	Volume of Living Trees (m^3/ha)
Gap	Beech	100	100	100
	Silver fir	-	-	-
	Spruce	-	-	-
Regeneration Phase	Beech	74.1	78.1	77.8
	Silver fir	6.3	1	0.4
	Spruce	19.6	21	21.7
Initial Phase	Beech	-	-	-
	Silver fir	-	-	-
	Spruce	-	-	-
Early Optimum Phase	Beech	89.3	96	91.1
	Silver fir	9.4	2.3	0.8
	Spruce	1.3	1.7	2.2
Middle Optimum Phase	Beech	89.1	79.2	79.5
	Silver fir	6.4	8	9.8
	Spruce	4.5	10.6	10.6
Late Optimum Phase	Beech	84.4	75.6	73.3
	Silver fir	8.7	12.8	14.5
	Spruce	6.9	11.6	12.3
Plenter Phase	Beech	82.5	63.6	60.8
	Silver fir	11.3	14.3	16.5
	Spruce	6.2	22.1	22.7
Terminal Phase	Beech	81.9	56.6	54.5
	Silver fir	6.3	12.2	13.5
	Spruce	11.8	31.2	32
Decay Phase	Beech	46.6	64.9	68.6
	Silver fir	49.5	20.8	20.2
	Spruce	3.8	14.3	11.1

[2] All mean values were calculated based on the mean values at the subplot level.

Table 4 shows the main stand structure attributes in several development phases of the forest. The maximum density was observed in the early optimum phase, with a decreasing trend towards the older development phases. In the late optimum phase as well as the plenter phase, it was around 900 trees ha^{-1}, while in the decay phase it decreased to 672 ± 226. The number of trees showed a similar trend in the studies of Drössler [54] and Tabaku [29]. The mean DBH and basal areas showed a reverse trend, increasing toward the most advanced development phases.

Table 4. Stand characteristics at the different development stages of the Frakto virgin forest.

Development Phase	Number of Subplots	Density (N/ha)	DBH (cm)	Basal Area (m^2/ha)	Volume of Living Trees (m^3/ha)	Deadwood Volume (m^3/ha)
Gap	2	192 ± 91	12.30 ± 5.80	3.09 ± 0.36	18.46 ± 5.17	146.24 ± 38.92
Regeneration Phase	4	224 ± 45	23.97 ± 6.41	14.91 ± 12.31	140.46 ± 139.86	465.12 ± 215.87
Initial Phase	-	-	-	-	-	-
Early Optimum Phase	8	1152 ± 445	14.67 ± 3.21	25.37 ± 12.44	196.69 ± 120.47	150.18 ± 189.04
Middle Optimum Phase	13	1014 ± 414	19.87 ± 5.73	44.55 ± 15.65	401.01 ± 157.06	255.82 ± 196.87
Late Optimum Phase	16	908 ± 402	23.78 ± 8.62	53.64 ± 13.31	505.65 ± 138.29	112.54 ± 92.97
Plenter Phase	62	905 ± 290	22.85 ± 5.97	56.29 ± 18.55	537.32 ± 199.44	167.54 ± 134.25
Terminal Phase	21	776 ± 292	27.86 ± 10.18	60.89 ± 20.65	614.05 ± 267.47	160.19 ± 152.83
Decay Phase	2	672 ± 226	27.85 ± 1.65	76.91 ± 32.92	868.88 ± 485.89	433.84 ± 283.41

Regarding the volume of living trees, the minimum value of 18.46 ± 5.17 m^3/ha corresponds to gaps. In the early optimum phase, it reached 196.69 ± 120.47 m^3/ha; in the late optimum phase, the plenter phase, and the terminal phase, it ranged between 505.65 ± 138.29 and 614.05 ± 267.47 m^3/ha. Drössler [54] and Tabaku [29] observed that the maximum living wood volume occurred in the plenter phase or the late optimum phase. In the present study, the maximum value of 868.88 ± 485.89 m^3/ha responds to the decay phase derived only from two subplots. This probably occurred because of the presence of a limited number of old trees with bigger diameters, accompanied by a high percentage of deadwood, which constitutes the criterion for classifying the plot in the decay phase. This sole criterion for the classification of a subplot to the decay phase can be considered a disadvantage of the method, which has also been noted by Drössler [55].

The largest deadwood volumes were observed in the regeneration and decay phases compared to the other development phases, reaching 465.12 ± 215.87 and 433.84 ± 283.41 m^3/ha, respectively. These values are consistent with the results obtained by Drössler and Meyer [31], who reported around 400 m^3/ha for each of these phases. In natural forest ecosystems deadwood input originates apart from age-based tree mortality and canopy competition, from natural disturbances that ensure a constant supply of deadwood to the ecosystem [37]. However, deadwood variation between development phases has been widely reported [56–58] as in each development phase different deadwood elements are generated, considering that the proportion and size of dead matter vary according to age and tree maturation [59]. Advanced forest successional development phases are stated to have high amounts of deadwood [60] as deadwood input increases whenever trees exceed the maturity phase [58].

As shown in Figure 4, the investigated area was dominated by the optimal stage (61.7%), followed by the decay (22.7%), and the initial stage (15.6%). The high proportion of optimal and terminal stages is consistent with that of other virgin forests [55]. Statistically significant differences were demonstrated among these three major development stages in the forest of Frakto in terms of tree density, mean DBH, basal area, and volume of living trees, thereby proving the mapping base of the forest's structural heterogeneity (Figure 4). The variables did not present normality problems according to the Kolmogorov–Smirnov (KS) test ($p > 0.05$). Specifically, the stem number decreased from 1059 ± 430 trees/ha in the initial stage to 691 ± 329 trees/ha in the decay stage, which presents a significantly lower frequency compared to the youngest stages. On the contrary, large timber was observed in

the optimal and decay stages compared to that of the initial stage, which was reflected in the DBH, basal area, and volume of living trees. The optimal stage was characterized by an abundance of large trees that had reached maturity, while the decay stage was characterized by a lower number of old trees and increasing deadwood, thereby representing the gradual disintegration that takes place during this stage as old trees die, small gaps form, and understory reinitiation takes place. In the forest of Frakto, all development stages were identified. The stand's structural attributes reflect the changes the forest is subject to as it passes through the development stages by undergoing the processes of creation and disintegration. A crucial role for this ongoing process is the formation of small gaps in natural forests [16] as a result of many reasons such as the breaking of big branches, dying trees, and windthrow [16]. If disturbance happens at a small scale, the decay stage shifts to the initial stage, where the density is high and the gaps are filled with the canopy of other trees. The number of trees decreases as a result of the density dependent mortality, while an increase in volume and basal area can be noticed as the stand develops towards the optimum stage.

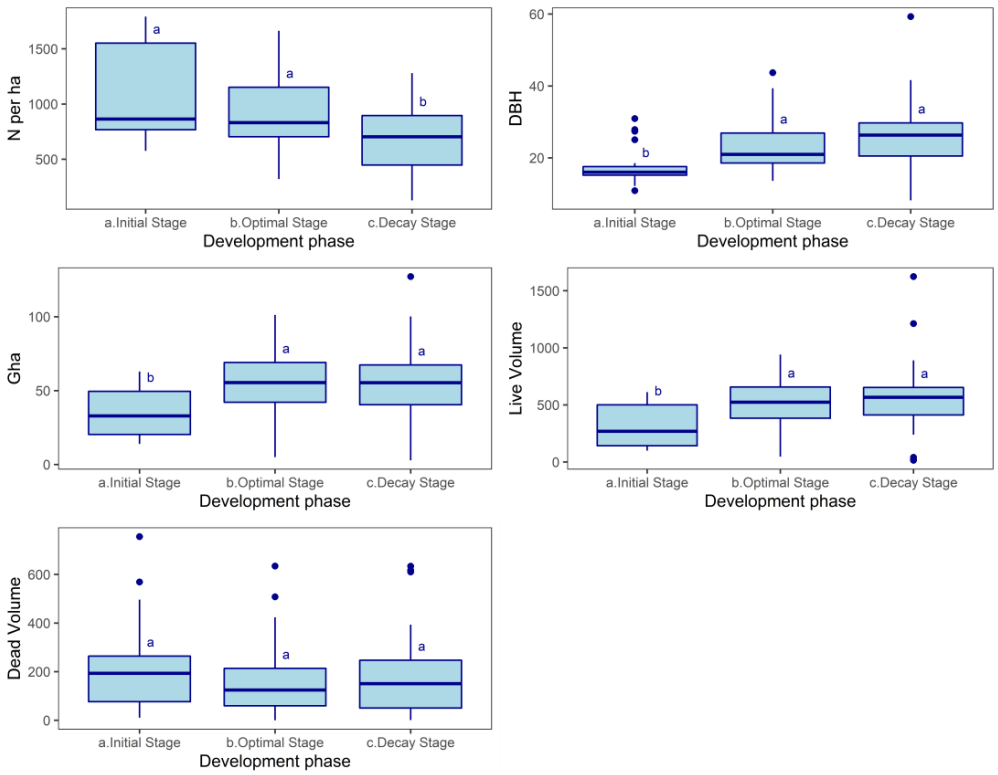

Figure 4. Heterogeneity in density, DBH, basal area, and living volume in the respective development stages of the Frakto virgin forest.

4. Conclusions

Based on the determination of the development phases, it is concluded that the Frakto virgin forest is characterized by high heterogeneity, characteristic of the primeval forests. The frequency and spatial distribution of the phases showed a pattern typical for primeval beech forests, with high proportions of plenter and terminal phases. Development phases, with mainly older, more or less vital individuals predominate. The predominance of these older phases with a multitude of structural features is characterized by strong variation regarding tree dimensions. The high percentage of the plenter phase indicates that small and old trees with large breast height diameters are located close to each other. This strong differentiation can be explained by the spatial and temporal overlap of different tree generations, as the older development phases overlap with the regeneration processes. Since the regeneration of the forest is associated with the creation of gaps, which occur

in small areas and in a small percentage, the development of the forest goes through a small-scale shifting of the development phases.

The close spatial connection and the frequent alternation of the older and younger, poorly structured development phases explain why larger areas with a heterogenous structure instead of a homogenous structure prevail. Finally, the observed alternation of this mosaic of "stable" and "unstable" phases explains the stability of the Frakto virgin forest, just as it has been documented for other virgin forests too.

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