SYLWAN 168 (7): 459-477, July 2024
https://doi.org/10.26202/sylwan.2024022
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

A forest age-structure model as a foundation for the concept of the 'Desired Forest'

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ABSTRACT

The work detailed here relates to a concept for a new forest model of the 'Desired Forest'; as well as its use in the development of model age structures for Forest Management Unit (FMUs) in relation to the six main forest-forming tree species of Poland, *i.e.* pine, spruce, birch, oak, beech and alder; with account taken of management method ('clear-cutting' v 'shelterwood'), as well as cutting ages and adopted regeneration periods. Model age structures offer a basis upon which to determine desired sizes of initial cuts whose consistent application will lead to achievement of the desired (model) age structure of FMUs in the long run. The model of the 'Desired Forest' is based on a holistic approach by which to investigate the impacts on a forest of all environmental factors that can have determinations made for them. Data on the probability of survival of stands within different age classes were utilized to develop model structures representing stand age-class distributions, and to determine the area of initial cuts necessary for the 'desired' model structure to be maintained. A holistic approach was adopted, which encompassed both survival related to natural disturbance factors and human-induced survival, considering forest harvesting or decisions not to harvest. Furthermore, the probability of a stand transitioning from group A after regeneration to the corresponding group B age class was used to characterize the age classes in the shelterwood FMUs. Transitions and survival rates offered a basis for the development of model age structures for different shelterwood practices (uniform, group, and stepwise), as well as two scenarios regarding the length of regeneration periods: 10 years or more than 10 years. Stands in the regeneration class were described in two ways: by the age (age class) of the mature tree layer and the age of the regeneration layer.

In the clear-cutting FMUs, the share of the area of stands of younger age classes was the largest, albeit decreasing gradually; while age classes older than the cutting age were represented to the most limited extent. Irrespective of the dominant species in the FMU, there was a group of stands that exceeded the assumed cutting age.

In the shelterwood FMUs, the structure by area for age classes depended on the adopted cutting age and on the assumed regeneration period. The longer the regeneration period, the smaller the fraction of stands accounted for by trees in the youngest age classes.

KEY WORDS

optimisation, planning, pine, sustainability, yield

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Received: 14 May 2024; Revised: 8 June 2024; Accepted: 12 June 2024; Available online: 11 August 2024

Introduction

The underlying principle of a forest-management operation is the determining of the general direction of forest and timber-resource development, as well as the adoption of management options that provide (under existing environmental conditions) the achievement of objectives arising from the dominant function of the forest. This direction should reflect a 'desired' age structure of the forest management unit (FMU), made up of stands distinguished in terms of their similar production possibilities (*e.g.* on account of site type).

For forest management to be effective, it is crucial that there be comprehensive management information regarding the condition and structure of timber resources, along with forecasts in respect of their long-term changes (Stępień, 1998). A fundamental decision made by foresters to ensure sustainability and proper forest development entails the accurate determining of the level of harvesting of timber (Banaś, 1996). This determination is vital in the context, not only of short-term forest management plans covering 10 years, but also of long-term forecasts spanning several decades (Poznański, 2013).

The formulation of long-term objectives in forestry should consider that the feasibility and extent of forest utilization, as well as its response within a specific environment, are influenced by internal factors such as environmental conditions, forest health, and management practices, as well as stochastic factors associated with environmental impacts (Stępień, 1998).

Stands of a specific age exhibit distinct structures and characteristics assessable by reference to various metrics like tree density per unit area, average diameter at breast height and height, and current growth rate. The status of these attributes helps determine the susceptibility of stands to both biotic and abiotic factors (Macias-Fauria and Johnson, 2008; Bruchwald and Dmyterko, 2012; van Lierop *et al.*, 2015; Brodrick *et al.*, 2019). Climate change and stand-specific traits serve as primary factors influencing stand development on a broader scale (Zhang *et al.*, 2019).

Disturbances are key processes of forest-ecosystem dynamics that affect the structure and functioning of forest ecosystems significantly (Franklin *et al.*, 2002), often also determining the spatial distribution of forests in the landscape. The combined effects of environmental factors on forest result in changes in the survival and mortality of stands within age classes (Poznański, 2003; Kanabus and Miścicki, 2022).

Europe's forest management systems – as long oriented towards uniformity of utilisation – have often failed to take account of disturbance dynamics – as is reflected in yield tables, for example. Equally, around the world the paradigm of forest management based on Normal or Intentional/Intended Forests models has receded, and knowledge of disturbances such as wind, fire or pests is being used very widely in forest management (Franklin *et al.*, 2002; Prestemon and Holmes, 2004).

Disturbances and economic decisions both give rise to changes in stand age-class distributions, and these distributions included in the so-called age class table then constitute an indispensable element of the decision-making process in forest management planning. They are a source of knowledge about the size and structure of timber resources; and currently – with stand calculations using the felling maturity method – they allow for a division involving two major categories (of mature or pre-mature stands). Each of these categories has its separate and independent regulatory system, with the current situation in Poland being that the final yield for mature stands is determined as the maximum volume of timber to be harvested under the forest management plan, even as the mandatory yield in the case of pre-mature stands is area-based.

Pursuit of an idea of forest sustainability through the adoption of forest management methods appropriate to condition and function was an aspect expressed long ago – in the theory of the Normal Forest Model presented by J. Ch. Hundeshagen in 1826, and developed further by G. Hayer in 1841 (Oesten and Roeder, 2002). In practice, the shares of age classes in Forest Districts vary, and are different from those present in the theoretical model of the Normal Forest. This circumstance can lead to serious disturbances in the replacement process involving successive generations of stands, with a periodic lack of systematic harvesting or change in the level of growth in biomass. In commercial forests, the effects of disturbance prove far-reaching and difficult to correct.

As the assumptions of the Normal Forest (not least the maintenance of constant stocking without time limitation, as well as equal proportions in all age classes; Fig. 1) proved impossible to achieve, further developments entailed models for the Intentional Forest (Fig. 2) (Lucas and Anders, 1978) and the real forest (Rutkowski, 1971; Poznański, 2000) (Table 1).

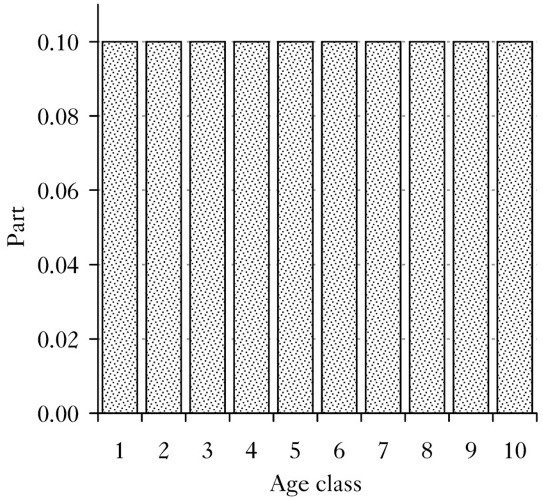

Fig. 1.
The share of age classes in the Normal Forest model
survival rate=1, cutting age=100 years

Fig. 2.
The share of age classes in the Intentional Forest model
survival rate=0.8, cutting age=100 years

Table 1.
Comparison of the main assumptions of the Normal, Intentional, Real and Desired forest models (Poznański, 2000, modified)

Normal Forest Model	Intentional Forest Model	Real Forest Model	Desired Forest Model
No influence of random factors on the forest	Based on a reductionist approach to studying the impact of random environmental factors on the forest	Based on a holistic approach to studying the impact of all identifiable environmental factors on the forest	Based on a holistic approach to studying the impact of all identifiable environmental factors on the forest
Lack of research	Theoretical nature of the research	Empirical nature of the research	Empirical nature of the research
The aim is to harvest a constant yield	The aim is to achieve the targeted forest age structure	The aim is to maintain the sustainable and balanced development of the forest by pursuing strategic, tactical and operational objectives through various methods: forecasting, programming and planning	The aim is to move continually towards an optimal age structure, even as uniformity of yield is maintained
The development process is seen as a finite technical process	The development process is seen as a finite technical process	The process of forest development is treated as a continuous process of a biological nature	The forest development process is treated as a continuous process of a technical and biological nature
The development and structure of the forest is constant and reproducible	The development and structure of the forest depends solely on the current state of the forest stands	The development of the forest and its structure depends on its past and present development	The development of the forest and its structure depends on the past and present development of the forest and on future actions taken
Forest development is predetermined	The development of the forest is expressed in a probabilistic but defined way	Forest development is expressed in a probabilistic but unknown way	Forest development is expressed in a probabilistic manner on the based of evidence
The probability of survival of the stands is constant at 1 until the cutting age is reached	The interpretation of stand survival in age classes is narrowed (predetermined)	A full interpretation of the probability of survival of stands in age classes is encompassed	A full interpretation of the probability of survival of stands in age classes is included
The stand survival probability matrix is constant	The stand survival probability matrix is constant	The stand survival probability matrix is variable over time	The stand survival probability matrix is variable over time, and updated in line with new data
Basic idea of uniformity of forest use	The idea of a Normal Forest is made more real	It is completely contrary to the assumptions of the Normal Forest	Effect is given to the idea of the Intentional Forest model
Regulation is based on a yield being taken only from stands that have reached cutting age	Regulation involves the selection of methods to achieve the target forest structure	Regulation is understood as actions that eliminate disturbances making it difficult or impossible to keep the forest alive and therefore sustainable	Regulation involves selecting methods that will allow the actual age structure to approach the desired age model structure

Desired Forest Model

The aim of the work detailed here is then to present a concept for a new forest model; and to use it in developing model age structures of forest management units in respect of Poland's six main forest-forming tree species, *i.e.* pine, spruce, birch, oak, beech and alder; with account also being taken of management method ('clear-cutting' versus 'shelterwood'), as well as cutting ages and adopted regeneration periods.

The new forest model is called 'Desired Forest'. This new concept draws on the assumptions of both the Intentional and Real forest models. In the Table 1 the model was characterized using several features and simultaneously compared to the previous forest models: Normal, Intentional and Real, using the work prepared by Poznański (2000).

Thus, in the case of the so-called 'desired' forest, reference is made to a 'desired' stand age structure model, as developed on the basis of empirical data. However, the process of pursuit of a model often makes actual achievement difficult, since a random factor is also taken account (Table 1). In a Desired Forest, the core aim entails a constant yield around which permitted fluctuations are limited. However, the model structure of stand age classes is not one to be pursued using all available methods. Correction of that structure is a long-term process, with changes in the natural and economic environment being frequent (where the length of the production cycle is concerned), to the extent that *de novo* determination of the age structure of the forest unit is necessitated, with account needing to be taken of the latest data, often in advance of the desired form being achieved. On the other hand, through the making of cuts of the right size, a model age structure for the unit should be approached, and this offers the basis upon which to determine the desired final yield, which – if applied consistently – will lead to the desired (model) age structure in regulatory units, and consequently within an entire Forest District (or even country). A model of the age-class structure of stands in FMUs is needed in order for the desired area of regeneration in a given period to be determined, and thus also the area over which cutting is to take place.

The model of the Desired Forest is based on a holistic approach being taken in investigating the impact on forest of all determinable environmental factors, with account taken of mortality due to disturbance and management activities, but also the abandonment of such activities. This is therefore a matter for managed stands that does not apply to forests under a protection regime. Information as to the influence of factors leading to distributions across age classes is then as confirmed by empirical study.

The objective of a model like the one presented being applied is steady convergence in the direction of an optimal age structure, even as uniformity of use over the long term (covering the length of the production cycle) is maintained (Table 1).

The development of forest is viewed as a continuous process influenced by both technical and biological factors, including natural events and management operations (Table 1). The stand survival probability matrix is time-varying, and so requires regular updates if there is to be accurate reflection of the probabilistic nature of forest development. Such a process of updating relies on best-available data to facilitate comprehensive understanding of the likelihood of forest development across age classes. Regulation in FMUs involves the selection of methods that steer forest development towards a desired age structure, ensuring sustainable use of the forest over the long term, even as the target age-class distribution continues to be approached gradually.

Materials and methods

Data on the survival rates of stands within different age classes were utilized to develop model structures representing stand age distributions. This information was used subsequently in determining areas of initial cuts necessary to maintain the desired model structure. In a clear-cutting system, only a portion of the area occupied by stands in a particular age class transitions to the next class at the end of the 10-year management period. The proportion involved in this transition is under the influence of core factors that are:

– natural (pertaining to destructive elements present in nature),
– economic (pertaining to cutting age, the feasibility of cuts based around spatial organization being conducted, and decisions as regards cuts being accelerated or postponed).

Such an approach ensures that forest stand management aligns with objectives of both an ecological and economic nature.

However, as data that would distinguish between the two types of survival are not available, the holistic approach adopted worked to integrate stand-survival data, so as to encompass both survival in relation to natural-disturbance factors and economic survival in line with either the harvesting of forest or decisions taken not to harvest. The study utilized stand survival data developed by Kanabus and Miścicki (2022), which determine the probabilities of a stand transitioning to the next 10-year age class, and from group B (without regeneration) to group A (with regeneration). Those probabilities was estimated using logistic regression in line with silvicultural method and the presence or absence of shelterwood cutting, and clear-cutting), as well as in respect of the six main tree species in Polish forestry. The data used to do this were collected by the Forest Management and Geodesy Bureau in respect of 64 Polish forest districts located within 14 regional directorates of the State Forests, and with a view to forest management plans being developed and made available by the State Forests General Directorate. Specifically, data from forest management plans elaborated in 2009 and 2010 were used, as were in essence repeat data (from Plans elaborated for the same Districts 10 years later – in 2019 and 2020). The empirical survival of stands in ten-year age classes was estimated by overlapping the vector map of stands of Forest Districts with a 100×100 m grid of sample plots.

Furthermore, the probability of a stand transitioning from group A after regeneration to the corresponding group-B age class was referenced in characterizing the age classes in shelterwood FMUs. Information as regards these probabilities is as detailed in Kanabus and Miścicki (2023), and was now employed in developing model age structures that account for different (*i.e.* uniform, group and stepwise) shelterwood practices; as well as two scenarios for regeneration periods of duration 10 years or more than 10 years. It was assumed that, with a regeneration period exceeding 10 years, the probability of the regeneration process being completed more than 10 years after the assumed period is equal to 1. Those probabilities was also estimated using logistic regression and the empirical data was also collected by Poland's Forest Management and Geodesy Bureau in line with the Forest Management Instruction, in respect of 64 Forest Districts located within 14 of Poland's 17 State Forests' Regional Directorates.

Elucidation of the process further entailed stands in Group A being described dually, by reference to both the age (age class) of the mature tree layer and the age of the regeneration layer. The model age-class structure for stands in clear-cutting FMUs was then determined via steps as follows:

– an initial area of 100 ha was assumed for the first (10-year) age class;
– the area of subsequent age classes was calculated by reference to the survival rate over 10 years;

- the areal fractions accounted for by each age class were determined using the relevant proportions by area;
- the fraction of the initial cuts area (of the area of the first age class) was then calculated.

In turn, the calculation of the model age-class structure for stands in the shelterwood FMU was achieved as follows:

- the initial area of the first age class in group B of stands, to which the area of stands after regeneration no longer passes, was assumed to be 100 ha;
- the areas taken by the next age classes were calculated in line with the survival rate in 10-year age classes or the transition to group A of the respective classes, following the start of the regeneration process (from group B to A) or the end of regeneration (from A to B), taking into account the regeneration age class;
- the sum of the areas of stands where restocking initiation cuts are undertaken within 10 years was calculated;
- the area of clear cuts resulting from unsuccessful regeneration, clearing of stands that are too old, and natural disturbances that cause the stand area to move to the first age class were calculated.

For clear-cutting FMUs, the proportion of age classes was calculated using the formula:

$$kw_j = kw_{j-1} \cdot q_j \tag{1}$$

where:

kwj is the area accounted for by the given age class *j*,
qj is the probability of survival.

For shelterwood FMUs, the share of an age class was calculated from the formula:

$$kw_j = kw_{j-1} \cdot q_j + kw_o \cdot q_{jo} \tag{2}$$

where:

kwj is the area accounted for by the given age class *j*,
qj is the probability of survival,
kwo is the area accounted for by the regeneration class at any given age of regeneration,
qjo is the probability of completion of the regeneration process in the regeneration class at a given regeneration age.

Case examples of model age structures and desired fractions of initiation cuts were developed for the FMUs:

1. Clear-cutting system:
   - for Scots pine *Pinus sylvestris* L. with a cutting age of 100 years,
   - for Norway spruce *Picea abies* (L.) H.Karst with a cutting age of 90 years,
   - for silver birch *Betula pendula* Roth, and black alder *Alnus glutinosa* (L.) Gaertn. with cutting ages of 80 years.
2. Shelterwood system:
   - for oak *Quercus* sp.: a cutting age of 140 years and a regeneration period of 20 years, managed using the uniform shelterwood system,
   - for European beech *Fagus sylvatica* L.: a cutting age of 120 years and a regeneration period of 30 years, managed using the stepwise shelterwood system,
   - for Scots pine *Pinus sylvestris*: a cutting age of 120 years and a regeneration period of 10 years, managed using the group shelterwood system,

- for Norway spruce *Picea abies*: a cutting age of 90 years and a regeneration period of 30 years, managed using the uniform shelterwood system.

These examples provide a framework by which to understand the age structures and desired initiation cut fractions for different forest management units.

Results

CLEAR-CUTTING FOREST MANAGEMENT UNITS. In the clear-cutting FMUs, the shares by area accounted for different age classes – as determined by the model developed – were seen to differ from those obtained in line with the Normal Forest model (Figs. 3-6). The share of the area accounted for by stands in the younger age classes was the largest; lowering with greater age. Age classes older than the cutting age accounted for the least area. In the spruce FMU, the share by area taken by stands in the middle age classes was smaller than that taken by the youngest

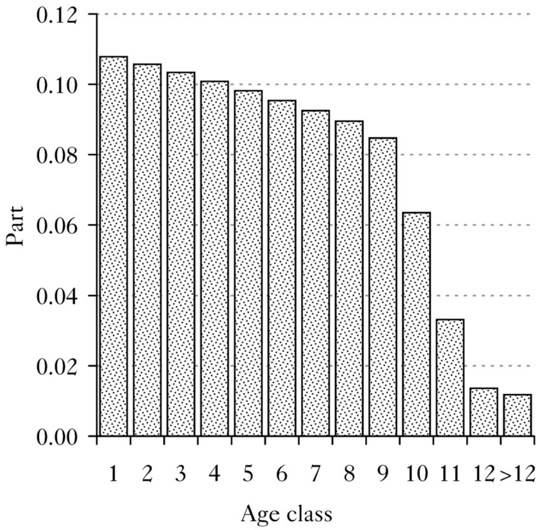

Fig. 3.

The forest age-structure model in the Scots pine FMU managed using the clear-cutting system
cutting age=100 years

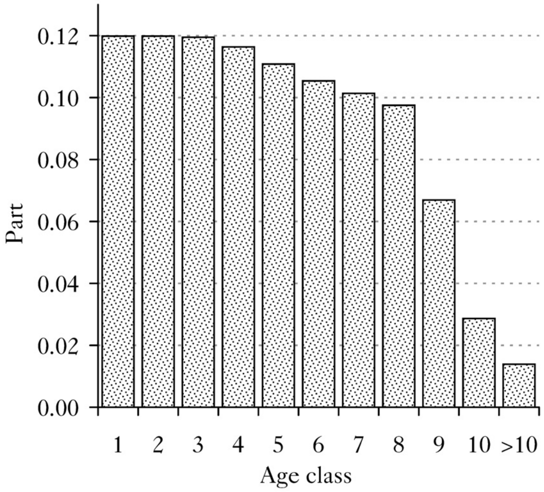

Fig. 4.

The forest age-structure model in the Norway spruce FMU managed using the clear-cutting system
cutting age=90 years

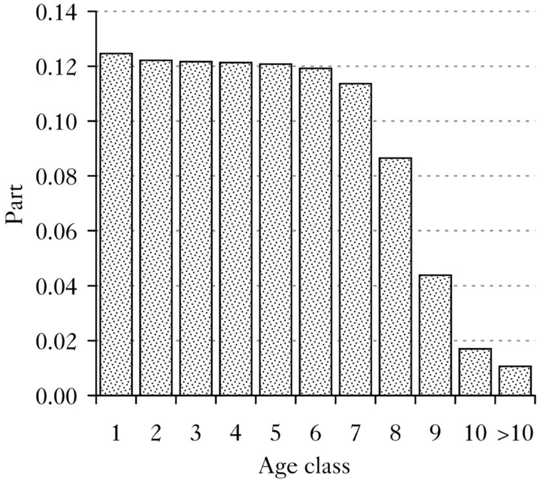

Fig. 5.
The forest age-structure model in the silver birch FMU managed using the clear-cutting system
cutting age=80 years

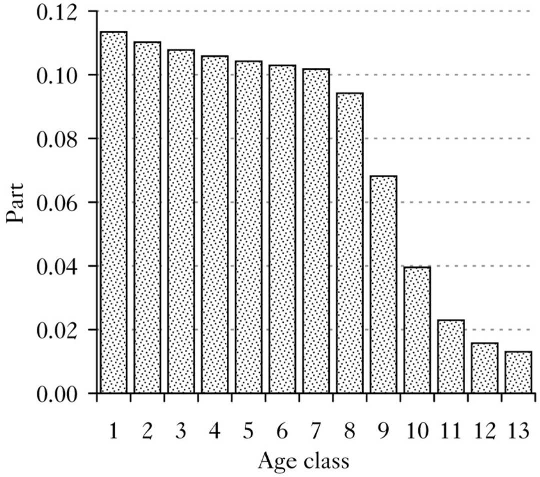

Fig. 6.
The forest age-structure model in the black alder FMU managed using the clear-cutting system; cutting age
cutting age=80 years

classes, in association with rather high mortality of spruce stands sensitive to environmental conditions. In the black alder FMUs, there was a high share of the area of stands assigned to the first age class, and a relatively high share of overmature stands – their fraction being about 0.16. Irrespective of the dominant species in the FMU, there was a group of stands that exceeded the assumed cutting age.

SHELTERWOOD FOREST MANAGEMENT SYSTEMS. In the shelterwood FMUs, the structure by area associated with different age classes was seen to depend on the cutting age adopted, as well as (to an even greater extent) on the assumed regeneration period. In the Scots pine FMUs, the share of the area accounted for by the first age class was the smallest (Fig. 7). The presence of this class was due to unsuccessful regeneration, but also to incidental cuts in Group B stands. The shares of the area present within stands assigned to the second and third age classes were high, reflecting the probability of regeneration processes being completed. At the same time, the regeneration might have been 'held' under the cover of the upper tree layer. The longer the regeneration period, the more limited the fraction of stands present in the youngest age classes.

The fraction of overmature oak stands was 0.01 in Group B. In the oak stands with a regeneration period of 20 years, the share taken by age class 3 proved to be the largest, while the fractions taken by the first and second classes were about 0.02 and 0.05 respectively (Fig. 8). A rather large share of overmatured stands included in both Groups B and A was evident. Stands that were 40 years younger than the cutting age already had regeneration layers within them (denoting a Group A classification). In the beech FMU with a regeneration period of 30 years, the proportions in the third and fourth age classes were highest, while the fraction taken by the first three classes combined was about 0.15 (Fig. 9). Stands in Group A were even present in the middle age classes, but a significant proportion of them appeared in age class 10 only, meaning the one 20 years before cutting age. The fraction of overmature stands was considerable in this FMU too. In the spruce FMU with a regeneration period of 30 years and a cutting age of 90 years, the age structure proved to be uneven (Fig. 10). The largest area was assigned to the fourth age class, the most limited area to the first. The shares of stand area accounted for were significantly lower from the fifth age class onwards. The structure of this FMU was associated with a long regeneration period and significant stand mortality in the middle age classes.

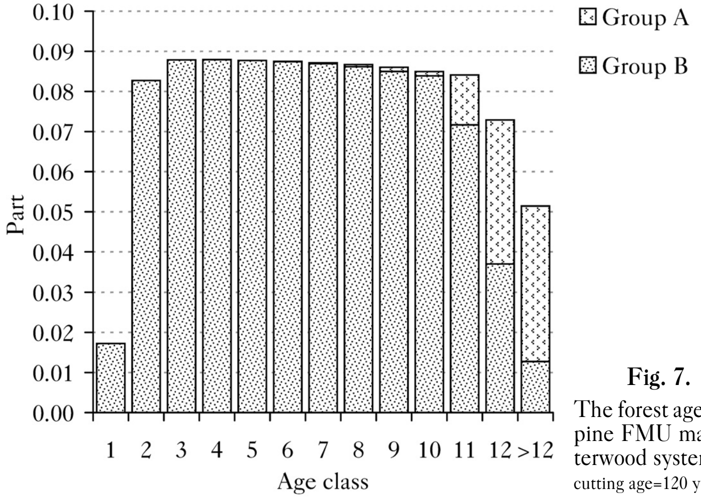

Fig. 7.

The forest age-structure model in the Scots pine FMU managed using the group shelterwood system

cutting age=120 years, regeneration period=10 years

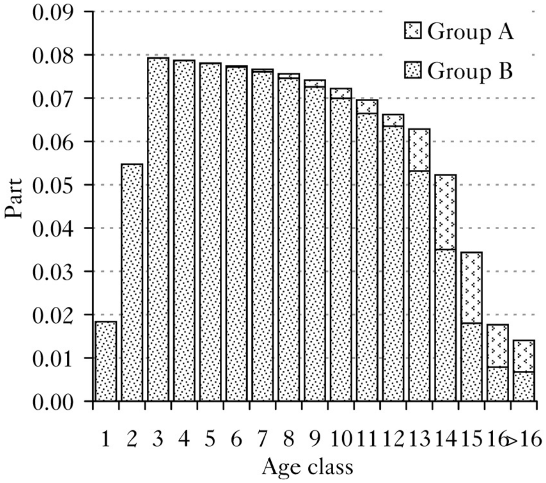

Fig. 8.

The forest age-structure model in the oak FMU managed using the uniform shelterwood system

cutting age=140 years, regeneration period=20 years

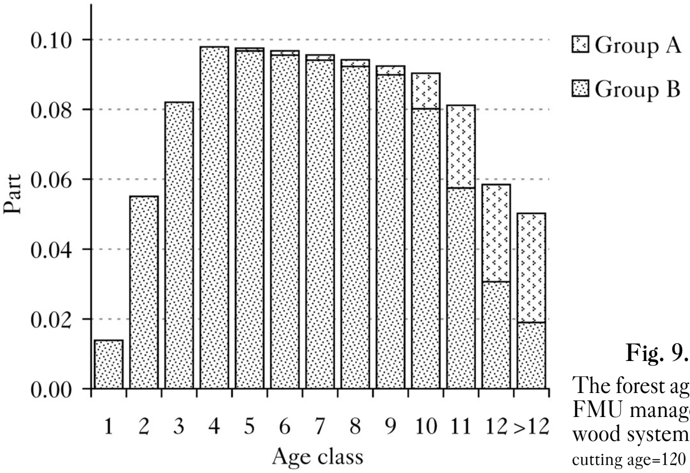

Fig. 9.

The forest age-structure model in the beech FMU managed using the stepwise shelterwood system

cutting age=120 years, regeneration period=30 years

Fig. 10.

The forest age-structure model in the Norway spruce FMU managed using the uniform shelterwood system

cutting age=90 years, regeneration period=30 years

In each of the shelterwood FMUs, there was both a fraction of overmatured stands and stands in the regeneration process at an age class significantly lower than the cutting age. This situation may have resulted from disturbances leading to decisions to manage stands actively at an earlier stage, using methods other than clear-cutting.

The cutting size fractions in the clear-cutting FMUs ranged from less than 0.11 in the pine FMU with a cutting age of 100 years, to more than 0.12 in the silver birch FMU with a cutting age of 80 years (Fig. 11). The lower the cutting age, the higher the cutting fraction should have been. The exception was the alder FMU, which had an initiation cut size fraction of just over 0.11.

The fraction of initiating cuts in the shelterwood FMUs ranged from about 0.09 in the oak FMU with a cutting age of 140 years to about 0.14 in the spruce FMU with a cutting age of 90 years and a regeneration period of 30 years (Fig. 12). The proportion of clear-cutting (including unsuccessful regeneration) was lowest in the beech FMU at 12%, and highest in the spruce FMU at 23%.

Discussion

Forecasting of the development of forest resources by reference to various theoretical assumptions and models has been engaged in many times in Poland. Models of tree and stand growth have

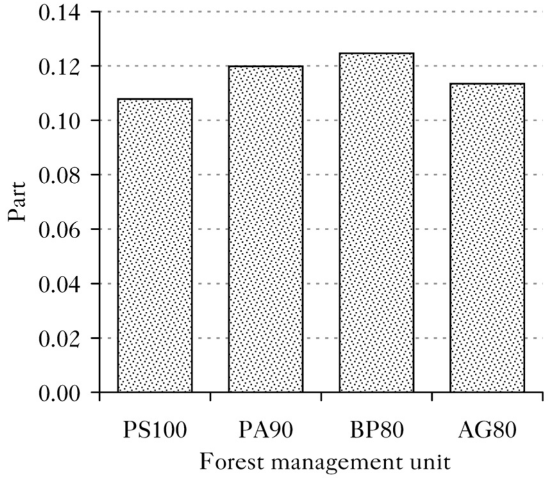

Fig. 11.

The cutting size fractions in the clear-cutting FMU's

PS100 – Scots pine, cutting age=100 years; PA90 – Norway spruce, cutting age=90 years; BP80 – Silver birch, cutting age=80 years; AG80 – Black alder, cutting age=80 years

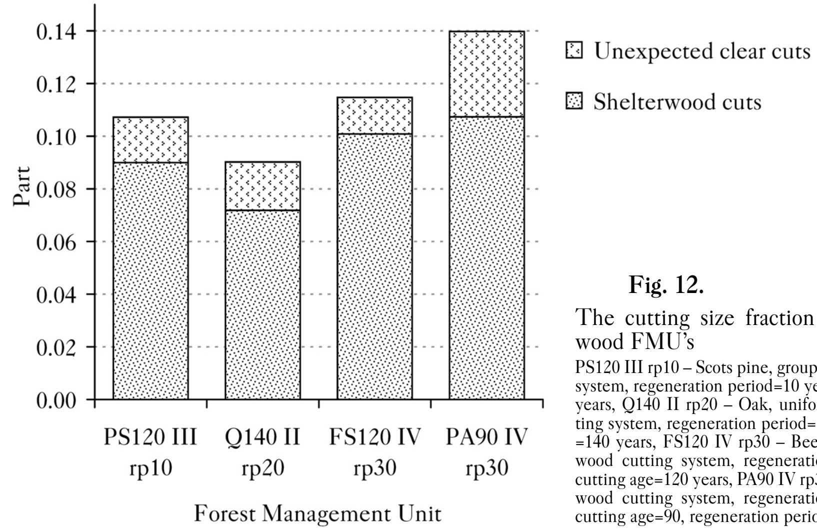

Fig. 12.

The cutting size fraction in the shelterwood FMU's

PS120 III rp10 – Scots pine, group shelterwood cutting system, regeneration period=10 years, cutting age=100 years, Q140 II rp20 – Oak, uniform shelterwood cutting system, regeneration period=20 years, cutting age =140 years, FS120 IV rp30 – Beech, uniform shelterwood cutting system, regeneration period=30 years, cutting age=120 years, PA90 IV rp30 – uniform shelterwood cutting system, regeneration period=30 years, cutting age=90, regeneration period=30 years

been developed (Bruchwald *et al.*, 2003; Drozdowski, 2006; Bruchwald and Zasada, 2010), but there are no models on larger scales, such as that of the forest management unit.

The methodology for forecasting the development of forest resources based on the theory of the Intentional Forest – indicated by Stępień (1998) as the basis for control and regulation in forestry in the 21st century – has for example gained presentation in studies by Poznański (1973, 1999), Klocek and Borowski (1990), and Klocek and Oesten (1992). On the other hand, the forecasts made by Głaz (1997) based themselves on the Normal Forest model. Kanabus and Miścicki (2022, 2023) determined the probabilities of transitioning of stands in given age classes taking place, and the probabilities of regeneration processes being completed in stands in the course of being regenerated, with this also affecting the proportionate representation of particular age classes.

Forecasts of the development of timber resources and of possibilities for harvesting (be that final or pre-mature) are also present in the work of Dawidziuk (2012), Dawidziuk and Zajączkowski (2015), and Zajączkowski and Neroj (2019), with the indication being that possibilities will increase in Poland in the long term. Though based on a variety of methodological assumptions and input data, both historical and current studies show that the forecasting of forest trends is important in the pursuit of sustainable and balanced forest management. However, it is necessary to conduct a comprehensive analysis of the cause-and-effect relationships between characterisations of a forest's current state and its past management, with this allowing former approaches to be verified, even as strategies for the future are developed. Information on the extent of use in particular age classes, or on the survival rate of stands, can serve as a basis upon which to forecast the development of timber resources as assumptions in line with different policies are made (*e.g.* in the European Union, in the context of the National Forestry Accounting Plan (NFAP, 2018)).

In forestry, the concept of an optimal age structure refers to the ideal distribution of different age classes within a forest to achieve sustainable management objectives. This issue has long been recognized, as an optimal age structure ensures continuous forest productivity, biodiversity conservation, and ecological balance. However, the literature lacks specific references to what an optimal age structure should precisely look like. This knowledge gap is primarily due to the complexity and variability of factors that influence forest dynamics, including species composition, site conditions, management goals, and disturbances.

One of the key considerations in determining the optimal age structure is the probability of stand survival. This involves understanding the life expectancy of different tree species and the factors that affect their longevity, such as disease, pest outbreaks, climatic conditions, natural disasters, and harvesting. Effective forest management must account for these probabilities to maintain a balanced age distribution. Additionally, the transition of stands into regeneration classes is crucial. The timing and methods of regeneration practices must be aligned with the natural dynamics of the forest and the specific management objectives. Ultimately, achieving the optimal age structure for a forest management unit requires a comprehensive understanding of ecological processes, careful planning, and adaptive management. It involves balancing short-term economic benefits with long-term sustainability goals.

The study of different forest management units employing shelterwood and clear-cutting systems offers valuable insights into the complexities of achieving an optimal age structure for an FMU. The optimal age structure is crucial for sustainable forest management, as it ensures continuous productivity, biodiversity, and ecological balance. However, defining what constitutes an optimal age structure is challenging due to the various factors at play, such as species composition, site conditions, and management goals.

The results presented in this work showed that the desired (optimal) forest age structure of an FMU is always far from the regular structure typical of the Normal Forest model. For example, spruce FMUs exhibit an uneven age structure, reflecting the impact of longer regeneration periods and significant stand mortality. This highlights the need for targeted interventions to manage mortality rates and ensure a balanced distribution of forest stands in different age classes. Beech FMUs, with a longer regeneration period, demonstrate the challenges of balancing age classes. The dominance of middle age classes and the presence of overmature stands suggest that delayed harvesting can disrupt the desired age structure. Effective forest management should aim to optimize regeneration timing to maintain ecological balance and avoid the overrepresentation of older stands.

The clear-cutting system presents different scenarios, with the fraction of cut areas varying depending on the cutting age. For example, pine FMUs with higher cutting ages have lower fractions of cut areas, while species like silver birch with lower cutting ages show higher fractions.

This indicates that shorter cutting cycles can lead to a quicker transition of stands, potentially aiding in maintaining a balanced age structure if regeneration is managed effectively.

The optimal forest age structure was presented by Tahvonen (2004) who invoked the Faustmann equation in developing assumptions regarding an age structure that would permit uniformity of utilisation of forest stands in so doing pointing to the need for a high share to be accounted for by the youngest age classes (with about 50% up to age 20, in the circumstances of a 100-year production cycle). Structure of this kind could be used to determine the optimum yield in a single age class. Bettinger *et al.* (2016) only pointed to the need for the Normal Forest paradigm to be maintained as a model worth aspiring to … but actually impossible to achieve.

Forecasting of the development of wood resources serves as the foundational framework for more-detailed forecasts in related domains. This leaves it critical that a straightforward yet highly accurate method should be devised to project the development of timber resources and forest ecosystems. As Strigul *et al.* (2012) emphasized, the adoption of a holistic approach enhances the prognostic reliability of forecasts significantly. Over the short and medium terms (5-20 years), forecasts can be utilized reliably, as prevailing disturbance regimes typically remain unaffected by climate change, and land-use practices exhibit relative stability. However, as long-term forest dynamics are anticipated amidst transformation on the global scale, it becomes imperative to refine models and projections continually with updated data, so as to reflect the latest insights into disturbance patterns. This ensures robust integration of multi-scale changes and evolving environmental conditions into predictive frameworks, in line with contemporary scientific understanding.

There is an extent to which insects, fungi and industrial emissions are classified as gradual factors affecting forest ecosystems. Conversely, a distinct group of factors impacting upon the distribution of stands across age classes consists of unpredictable, episodic events termed ‘spike’ random occurrences. These include hurricanes, snowstorms, frosts, floods, and forest fires. While these events are inevitable, their frequency of occurrence has shown an upward trend in recent decades, with this largely attributable to climate change, even if that is not quite the sole factor (Hanewinkel *et al.*, 2013; Seidl *et al.*, 2017). Such factors were indirectly taken in the work, using the empirical data of the probability of the forest stand survival in different age classes obtained from Polish forest from the period of 2009-2020 (Kanabus and Miścicki, 2022).

In the set of factors influencing the distribution of stands in age classes, economic decisions to retain stands mature for harvesting also need taking into account. Most forest models associated with a particular forest-management planning method make no assumptions regarding the permanent presence of a group of overmatured stands. However, in real forests, the presence of such stands is unavoidable, given that, in most Forest Districts, certain stands are harvested before the cutting age is reached, with the converse effect that only a certain proportion of the area of mature stands can be utilized, thereby ensuring the formation of a group of overmatured stands in the short term at least. Additionally, and for a variety of reasons, not all mature stands can be harvested. Overmature stands may reflect forest management historically, *e.g.* where large areas were afforested at one time, resulting in the current accumulation of (ready-to-harvest) mature stands of uniform age over a large area. The need to uphold tenets of spatial planning prevents the harvesting of all mature stands, ensuring that some are left in place beyond the cutting age. Secondly, there is a need to reduce harvesting in mature stands when the planned size of premature cuts areas is exceeded. Thirdly, a role can also be played by the subjective decisions of forest managers, especially where there is increased public pressure for older stands to be left in place beyond cutting age (Kłapeć *et al.*, 2009).

Management practices in forestry currently focus their attention on the adaptive capacity of individual stands (Bolte *et al.*, 2010). This is correct, as it is the sum of the adaptive capacity of the smallest planning units that will influence the regulatory capacity at higher levels: the FMU, the Forest District, or the country. Assessing regulatory capacity at levels higher than the forest stand can influence forest policy-making as long-term goals are set. The replication of traditional solutions or methods, or the use of new management models and theoretical discoveries in forest policy-making should be reviewed, albeit with account taken of the adaptive capacity of forests (Paschalis-Jakubowicz, 2020). Such solutions can also help in planning the distribution of forests across the landscape, as consideration is given to the different functions they serve (Fires *et al.*, 1998). Desired age-class distribution should above all be considered as a 'beyond landscape' point of view is adopted.

Furthermore, account has to be taken of the way in which climate change might potentially change our perception of the recurrence of certain disturbances rather rapidly (Lindner *et al.*, 2010). Climate change is expected to raise the level of threat posed by insects, especially in boreal and temperate-zone forests (Battisti *et al.*, 2005; Netherer and Schopf, 2010). A higher frequency of fires in forest ecosystems may also be observed (Westerling *et al.*, 2006).

Knowledge in the modelling of natural processes is increasing, and models have been developed to account for fires, for example (Keane *et al.*, 2003, 2004; Szczygieł *et al.*, 2009), or else wind (Gardiner *et al.*, 2008; Bruchwald and Dmytertko, 2011), mass outbreaks of insect pests (Malmström and Raffa, 2000; Dukes *et al.*, 2009), or droughts (Socha *et al.*, 2023). However, such growing knowledge of individual processes and their modelling has not been enough to exert much of an impact on the actual formation of forest ecosystems. Disturbances are still neglected in the context of forest management planning, especially in the holistic dimension. And where they are taken account of, that process is selective, leaving decisions regarding the direction of forest-resource development subject to errors.

The age structures presented in this study reflect the status as regards forest development between 2009 and 2020, incorporating updated data that encompasses various disturbances affecting forests during this timeframe, as well as the corresponding economic decisions. The models offer utility in delineating the optimal regeneration area. The pursuit of harvesting operations within bounds that ensure the attainment of this regeneration area can serve in the progressive alignment of age structure in forest management units with the modelled structure, and over a period that aligns closely with the cycle of production in forest management.

Conclusions

- The desired forest model combines features of the Intentional and Real Forest models. It is based on empirical data and can be the basis for the regulation of utilization in forest FMUs, the structure of which should ensure uniformity of harvesting.
- The existence of both old-growth stands and stands subject to management before the assumed cutting age is an inherent part of sustainable FMU age structures taking into account the assumptions of the 'Desired Forest' model.
- When creating model age structures, it proves justified for account to be taken of all factors influencing the distribution of stands in age classes, with the development potential of FMUs also reflected well in this way.
- The fractions of initiating cuts in both clear-cutting and shelterwood FMUs – as calculated on the basis of model age structures – can contribute to the shaping of FMU age structures that need to be corrected where the distribution of stands across age classes is too irregular.

Authors' contributions

R.K. – conceptualisation, methodology, formal analysis, material collection, investigation, writing – original draft preparation; S.M. – conceptualisation, methodology, investigation, manuscript review and editing.

Conflicts of interest

The authors declare that potential conflicts of interest are not present.

Funding source

The research was financed from the authors' own funds.

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STRESZCZENIE

Modelowe struktury wiekowe lasu jako podstawa koncepcji Modelu Lasu Pożądanego

Celem pracy było przedstawienie koncepcji nowego modelu struktury wiekowej lasu i opracowanie modelowych struktur wiekowych gospodarstw leśnych dla 6 głównych gatunków lasotwórczych drzew Polski (sosna, świerk, brzoza, dąb, buk i olsza), z uwzględnieniem sposobu zagospodarowania (zrębowy i przerębowo-zrębowy) oraz wieków rębności i przyjętych okresów odnowienia. W pracy przedstawiono nową koncepcję modelu lasu, która uwzględnia założenia lasu celowego (ryc. 1) i rzeczywistego (ryc. 2). W nowym modelu „lasu pożądanego" wykorzystuje się model docelowej struktury wiekowej drzewostanów, opracowany na podstawie danych empirycznych dotyczących przeżywalności drzewostanów w klasach wieku. W dążeniu do postaci modelowej uwzględnia się czynnik losowy (utrudnianie dojścia do postaci modelowej). W lesie pożądanym najważniejsze jest dążenie do stałej wielkości plonu z dopuszczeniem niewielkich wahań. Korygowanie tej struktury jest procesem długotrwałym, ponadto otoczenie przyrodnicze i gospodarcze często się zmienia, stąd strukturę wiekową gospodarstwa należy kształtować od nowa, z uwzględnieniem najnowszych danych. Natomiast wykonywanie odpowiedniego rozmiaru cięć powinno prowadzić do zbliżania się do modelowej struktury wiekowej gospodarstwa (tab. 1).

Do opracowania modelowych struktur reprezentujących rozkłady klas wieku drzewostanów zostały wykorzystane dane dotyczące prawdopodobieństwa przeżycia drzewostanów w różnych klasach wieku. Następnie informacje te wykorzystano do określenia powierzchni cięć inicjujących niezbędnych do utrzymania pożądanej struktury modelu. Ze względu na brak dostępnych danych, które rozróżniałyby te rodzaje przeżywalności, przyjęto podejście holistyczne, integrujące dane dotyczące przeżywalności drzewostanów związanej z naturalnymi czynnikami zaburzającymi, jak i przeżywalność spowodowaną przez człowieka, biorąc pod uwagę użytkowanie lasów lub decyzje o zaniechaniu użytkowania. Ponadto prawdopodobieństwo przejścia drzewostanu z grupy A (z odnowieniem) po odnowieniu do odpowiedniej klasy wieku grupy B (bez odnowienia) zostało wykorzystane do scharakteryzowania klas wieku w gospodarstwach przerębowo-zrębowych. Współczynniki przeżywalności wykorzystano do opracowania modelowych struktur wiekowych dla różnych rodzajów rębni (częściowych, grupowych i stopniowych), a także 2 długości okresów odnowienia: 10 lat i ponad 10 lat. Drzewostany w klasie odnowienia zostały opisane na 2 sposoby: przez wiek (klasę wieku) warstwy drzew dojrzałych i wiek warstwy odnowienia. W celu określenia pożądanej struktury dla I klasy wieku (10-letniej) przyjęto początkową powierzchnię 100 ha. W gospodarstwie zrębowym udział powierzchni klas wieku, ustalony na podstawie opracowanego modelu, różnił się od udziału tych klas według modelu lasu normalnego

(ryc. 3-6). Udział powierzchni drzewostanów młodszych klas wieku był największy i stopniowo zmniejszał się, a klas wieku starszych niż wiek rębności był najmniejszy. Niezależnie od gatunku panującego w gospodarstwie istniała grupa drzewostanów, które przekroczyły zakładany wiek rębności. W gospodarstwie przerębowo-zrębowym struktura powierzchni klas wieku zależała od przyjętego wieku rębności, a w większym stopniu od zakładanego okresu odnowienia. W gospodarstwie sosnowym użytkowanym rębnią gniazdową udział powierzchni I klasy wieku był najmniejszy (ryc. 7). Udział powierzchni drzewostanów II i III klasy wieku był duży i wynikał z prawdopodobieństwa zakończenia procesów odnowienia. Im dłuższy był okres odnowienia, tym mniejsza była frakcja drzewostanów najmłodszych klas wieku. W gospodarstwie dębowym największy był udział III klasy wieku, a frakcje I i II klasy wynosiły odpowiednio około 0,02 i 0,05 (ryc. 8). Widoczny był dość duży udział drzewostanów przeszłorębnych zaliczonych do grupy B i grupy A. W gospodarstwie bukowym z okresem odnowienia 30 lat największy był udział III i IV klasy wieku, a frakcja pierwszych trzech klas wynosiła łącznie około 0,15 (ryc. 9). W gospodarstwie świerkowym z okresem odnowienia 30 lat i wiekiem rębności 90 lat struktura wiekowa była nierównomierna (ryc. 10). Frakcje cięć w gospodarstwie zrębowym wynosiły od niecałych 0,11 w gospodarstwie sosnowym z wiekiem rębności 100 lat do ponad 0,12 w gospodarstwie brzozowym z wiekiem rębności 80 lat (ryc. 11). Im mniejszy był wiek rębności, tym większa powinna być frakcja cięć. Wyjątek stanowiło gospodarstwo olszowe, którego frakcja cięć inicjujących wyniosła niewiele ponad 0,11.

Frakcja cięć inicjujących w gospodarstwach przerębowo-zrębowych wynosiła od około 0,09 w gospodarstwie dębowym z wiekiem rębności 140 lat do około 0,14 w gospodarstwie świerkowym z wiekiem rębności 90 lat i okresem odnowienia 30 lat. Udział cięć zupełnych (łącznie z nieudanym odnowieniem) był najmniejszy w gospodarstwie bukowym i wyniósł 12%, a największy w gospodarstwie świerkowym: 23% (ryc. 12).

Wnioski:

- Model lasu celowo-rzeczywistego łączy w sobie cechy modeli lasu celowego i rzeczywistego. Bazuje na empirycznych danych i może być podstawą regulacji użytkowania w gospodarstwach leśnych, których struktura powinna zapewniać równomierność pozyskiwania plonu.
- Trwałe występowanie zarówno drzewostanów przeszłorębnych, jak i tych użytkowanych przed wyznaczonym wiekiem rębności jest nieodłącznym elementem zrównoważonych struktur wiekowych gospodarstw leśnych uwzględniających założenia modelu lasu celowo-rzeczywistego.
- Uwzględnienie wpływu wszystkich czynników wpływających na rozmieszczenie drzewostanów w klasach wieku podczas tworzenia modelowych struktur wiekowych jest uzasadnione i w dobry sposób odzwierciedla potencjał rozwoju gospodarstw leśnych.
- Frakcje cięć inicjujących w gospodarstwie zrębowym i przerębowo-zrębowym obliczone na podstawie modelowych struktur wiekowych mogą przyczynić się do kształtowania struktur wiekowych gospodarstw, które wymagają korygowania ze względu na zbyt nierównomierny rozkład drzewostanów w klasach wieku.