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ORIGINAL PAPER

Forest stands in a regeneration class – a management-planning point of view

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ABSTRACT

A forest management unit (FMU) is a management-planning unit containing stands distinguished in terms of their similar production possibilities (*e.g.* on account of site type). In Polish forestry, the shelterwood FMU category groups together stands managed using a uniform shelterwood cutting system, group cutting, and a stepwise cutting system (with a regeneration period of up to 40 years). However, the forecasting of stand development in FMUs of this type proves more difficult than in clear-cutting FMUs, due to the presence of stands with young-generation trees (formally assigned to classes 'in regeneration' or 'with regeneration to be improved'). Such stands transition into one of the lower age classes depending on the age of regeneration after the clear-up cuts, but thus far there has been uncertainty as to the probability of the regeneration process completion (when the last cut is completed and regeneration layer covers presumed area), and as to the aspects that might make such completion more or less likely. Hence the work detailed here, which has sought to determine the nature of influences on the probability of the regeneration process being completed, as well as the dependence of that on type of cutting. The data put to this use were 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, and with a view to forest management plans being developed and made available by the Directorate General of the State Forests . More specifically, data from 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 degree to which regeneration processes could be considered completed was then estimated empirically by overlaying the vector map of stands of Forest Districts with a 100×100 m grid of sample plots. Probabilities were calculated using logistic regression in line with type of cutting applied (uniform, group or stepwise), and the mean age or mean height of trees in the regeneration layer, along with assumed regeneration periods (of up to or more than 10 years). The relationship between the mean heights and mean ages of trees in the regeneration layer was checked, with the calculated probability then used to develop theoretical distributions of stands in age classes of the regeneration layer and height classes of young trees, with these then set against the distributions determined empirically. In the event, no correlation was found between the maximum age/height of trees in the regeneration layer or the age/height of the dominant tree species in the regeneration layer (where dominant means those present in the highest proportion), on the one hand; and the probability of the regen-

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eration process being completed, on the other. Also looked for, though not confirmed, was an influence on completion of the regeneration process exerted by closure and dominant tree species in the upper storey, and degree of cover of the stand area achieved by the regeneration layer. In turn, completion of the regeneration process was shown to be influenced by the average age and height of trees in the regeneration layer. Fairly strong relationships between these characteristics were obtained – of R^2=0.79 in the case of stands in FMUs subject to uniform shelterwood cutting, 0.72 in FMUs with group cutting, and 0.73 in those cut in stepwise fashion. The probability of the regeneration process being completed also differed between types of shelterwood FMU, differing in the stands with an assigned regeneration period of up to or else over 10 years. With a regeneration period of up to 10 years, this was initially a value of around 0.23 for FMUs with group cutting, not shown to depend on average age. In turn, for FMUs subject to uniform shelterwood cutting, the figure was again of about 0.23 at an average age of 1 year, though was at 0.52 where the average age was 40. Likewise, in the FMUs featuring stepwise cutting, the values initially and where average age equalled 40 were of 0.13 and 0.74 respectively.

KEY WORDS

cutting, group, layer, shelterwood, stepwise, tree, unit, young

Introduction

In Polish forestry, a forest management unit (FMU) is defined as a territorial unit of management planning, distinguished on the basis of equal or similar production possibilities resulting from similar habitat characteristics and the same forest functions. By function, a distinction is made between FMUs of special purpose, conservation FMUs and multi-functional managed-forest FMUs. The latter have been divided into smaller units in line with felling regime, and so are clear-cutting FMUs (comprising stands managed using that system), shelterwood FMUs (of stands managed using a uniform, group or stepwise shelterwood system of maximum regeneration period equal to 40 years), and continuous-cover FMUs (which include stands managed using individual tree selection, or else a stepwise shelterwood system of regeneration period exceeding 40 years) (IUL, 2012).

Although a range of cutting systems indeed gain application within the shelterwood FMUs, the description is of a unit managed using a periodically uneven-aged silvicultural lead-method. There are thus two types of forest stand in shelterwood FMUs, *i.e.* those lacking a young-tree (regeneration) layer (designated as the B-group) or those with such a regeneration layer (designated as the A-group). Over the 1967-2021 period, the area with stands in this category increased from 200,000 to almost 700,000 ha (Forests in Poland, 2022).

The growing stock volume of a stand belonging to the B-group increases with stand age, and the dynamics of such an FMU gain description by reference to the share of stands of a given age class that progress into another age class over a given period (usually 10 years). One element of this dynamic relates to the way certain B-group stands re-enter the youngest age class – usually following unplanned and unwanted cuts, *e.g.* in the wake of disasters of different kinds. In turn, some stands (generally the oldest) acquire the status of A-group stands as a result of planned shelterwood cutting (Poznański, 2003; Kanabus and Miścicki, 2022).

The achievement of correct proportionality between stands of the two groups is key to successful management in a shelterwood FMU, even as the mutual relations over time between the groups is of fundamental importance to forest sustainability (Banaś, 1996a). As the condition of young-generation trees affects the sustainability of forest, quantity and quality should also be reflected as criteria are determined to programme wood-resource development, as well as the regulation process, in shelterwood FMUs (Poznański, 1999). The complexity of form assumed by such stands does much to complicate economic decision-making and silvicultural planning, especially where a compromise between different forest functions is sought (Drozdowski, 2006). This makes it necessary for such stands to be the subject of effective planning, forecasting and regulation tools (Poznański, 1999; Poznański and Jaworski, 2000).

As forest management plans are prepared, age estimation of A-group stands proves ambiguous. Traditionally, it was confined to the ages of trees of the species dominant in the upper storey, though Banaś *et al.* (2015) found such age estimation of stands inappropriate, and so proposed another method. They pointed out that the age of the regeneration layer is not taken into account as the age of A-group stands is determined, yet information of that kind is important, since young trees forming the regeneration layer in the shelterwood FMU remain under the canopy, and – depending on the length of the regeneration period – completion of the regeneration process is followed by a stand being reassigned to the age-class corresponding with the age of the uncovered young-generation trees (usually of the dominant species).

Poznański (1993) found no relationship between the age of A-group stands and the probability of the regeneration process being completed. Nor did the length of the regeneration period affect the intensity of cutting in the Forest Districts of southern Poland or cover by the young-tree generation layer affect the intensity of cutting in these stands. This denoted schematic pursuit of silvicultural measures relating to stands containing a young-tree (regeneration) layer. Knowledge has also been lacking when it comes to characteristics of the regeneration layer that influence the decision to undertake final cutting.

The regeneration period is an indicator of management method in itself, supplying information on the complexity of age structure of a given FMU. If this is equal to zero, the FMU is managed using a clear-cutting system, while its being equal to the rotation period denotes an FMU in a continuous cover system. In the periodically uneven-aged silvicultural lead-method (*i.e.* the shelterwood cutting system), the ratio of the regeneration period to felling age is in the range (0, 1).

It would thus seem that the ages of trees of the regeneration layer (or perhaps better their heights) should be basic information when it comes to deciding the point at which the regeneration process should be considered completed; *i.e.* when clean-up (final) cuts are to be conducted. Additional criteria for the taking of a decision that the regeneration process is complete should relate to adequate coverage by the layer of young-generation trees, as well as the quality thereof.

Research on stand regeneration has so far focused on determining the importance of such environmental parameters as the edaphic or insolation-related (Resenvalt *et al.*, 2020). Yet these must be viewed as less-relevant parameters from a management-planning point of view. Meanwhile, regeneration period is assigned to a stand in the context of a field survey. And, apart from a relationship with the type of shelterwood FMU, the indication that survey supplies fails to base itself on such empirical considerations as ages or heights in the existing layer of young-generation trees. Polish forest-management planning rather confines itself to the cover and quality of regeneration-layer trees, as a basis by which to distinguish between a forest stand 'in regeneration' or 'with regeneration to be improved'. There is anyway no influence on the decision to continue with or bring an end to the regeneration process.

The implementation of the clean-up cut in a certain stand of a shelterwood FMU should be linked to several characteristics, such as the quality of stems and crowns, disease symptoms on trees, vitality, cover by the layer of trees of the young generation and the mean height of those trees. The total height of trees in the regeneration layer can also offer a reflection of condition where regeneration is concerned, with the parameter being used to assess the development of regeneration (Miścicki, 2016); as well as to forecast changes in forest conditions (Gazda and Miścicki, 2016). The state of the regeneration layer should therefore start to be used in forecasting the development of stands of the 'in regeneration' class.

Against that background, research detailed here sought to note the identities and intensities of forest-survey characteristics actually influencing completion of the regeneration process in stands of the 'in regeneration' or 'with regeneration to be improved' classes (where both categories were treated jointly as stands in which a young-tree (regeneration) layer was present).

Materials and methods

Relevant data were as made available by the Directorate General of the State Forests in Poland. Their preparation and processing have already been described, in Kanabus and Miścicki (2022). Data from 2009 and 2010 forest management plans were used, as set against plans for the same Forest Districts drawn up 10 years later, *i.e.* in 2019 and 2020. These encompassed 64 Forest Districts grouped within 14 (out of the total of 17) Regional Directorates through which Poland's State Forests are managed. The development of regeneration-class stands was checked upon empirically, with a 100×100 m grid of sample points being placed on a vector map of the Forest District stands from the first (2009-2010) period. Each point was then assigned attributes as regards: (1) the dominant tree species in the upper storey (dbh=7.0 cm) and the regeneration layer, *i.e.* the sapling layer (trees of dbh<7 cm or height h=0.5-1.3 m), the layer of seedlings and/or underplanted trees (of h<0.5 m); (2) the age of each tree species present in the regeneration layer and achieving a share of at least 5%; and (3) coverage attributable to the regeneration layer (*i.e.* the portion of stand area covered by young-generation trees), and the assigned regeneration period.

In order for calculations to be performed, two groups of FMU were founded, of which the first included those with a regeneration period of up to 10 years. A-group stands in such an FMU require a decision (silvicultural advice) regarding completion of the regeneration process (implementation of final cutting). The second group comprised FMUs in which the regeneration period is of more than 10 years – most often 20 years, as a longer regeneration period is only indicated quite rarely.

A total dataset of 44,722 sample points was used, and for each drawn point average ages and heights of trees in the regeneration layer were estimated using data for the forest stand in which the given point was located virtually. Data for individual stands were gathered in the form of the stand description – as a recognised part of the forest management plan. As each layer may have contained tree species of different ages or heights, the first calculation involved a weighted average age for each layer or height for saplings (*i.e.* the taller part of the regeneration layer). In this calculation, the proportion of the latter the given tree species accounted for was used in weighting, albeit with exclusion of species accounting for less than 5% of cover. The height of seedlings and/or underplanted trees (lower part of the regeneration layer) was assumed to be 0.3 m, because the height of the trees of this layer is not given in stand descriptions yet, under the Forest Management Instructions (IUL, 2003, 2012), does not exceed 0.5 m. The average age (a), or height (h) in the layer was calculated using the formula:

$$a_i, h_i = \sum \frac{M \cdot Part\ [1;10]}{10}$$

where:

i is a layer of saplings, seedlings and/or underplanted trees,

M is the age/height of the tree species in the layer,

Part [1;10] is the portion of a given layer accounted for by a tree species, as expressed in the range (1;10); with the total for the portions of all species always equal to 10.

The weight of a given layer (*Uw*) was calculated as its ratio (expressed in terms of cover) to the sum of the coverage of all young-tree (regeneration) layers, in line with the formula:

$$U_w = \frac{Pw_i}{\sum Pw}$$

where:

Pw is the areal coverage achieved by a given layer,

i is a layer of saplings, seedlings and/or underplanted trees.

The averages for age of regeneration (AGE) and height of regeneration (H) were calculated as weighted averages referencing the sapling, seedling and/or underplanted tree layers, where the weighting was taken as the proportion of the respective layer, in line with the formula:

$$P_{fin} = 1/(1 + \exp(b_0 + b_1 \cdot (\ln(\text{AGE, H}))^1 + \ldots + b_n \cdot (\ln(\text{AGE, H}))^n)) \quad (3)$$

where:

b_0, b_1, b_n are coefficients of the equation calculated using a forward step-wise logistic regression model.

It was also examined whether the probability of the regeneration process being completed might be affected by such characteristics of the young-tree (regeneration) layer as average age/height, maximum age/height, age/height of the dominant tree species, dominant tree species, share of the overall area covered by trees, and species present in the upper storey. The alternative was for a stand to remain assigned to the class of stands with a young-tree (regeneration) layer.

The Chi^2-test was used to compare the distribution of stands in age classes (heights) of the regeneration layer obtained from empirical distribution with that determined from the calculated probability of completion of the regeneration process in a stand of the A-group for each type of cutting method (*i.e.* group cut, uniform shelterwood cut or stepwise cut). The theoretical distribution was calculated presuming that the initial number of cases (in the youngest age class or the lowest height class) was the same as at the beginning of the analysed period. The abundance of the next age class was calculated using the formula:

$$N_{k(\text{a,H})} = N_{k-1} \cdot (1 - P_{fin}) \quad (4)$$

where:

N_k is the number of observations for a given age or regeneration class,

P_{fin} is the probability of the regeneration process being completed for a given age- or height--class of young trees (for stands in which uniform shelterwood or stepwise felling were carried out, this probability was estimated for a regeneration period of more than 10 years, whereas for stands with the group cutting method that period was 10 years exactly).

A linear relationship was determined between a stand regeneration layer's mean age and its mean height. The Statistica ver. 13 programme was used for the calculations (StatSoft, 2017).

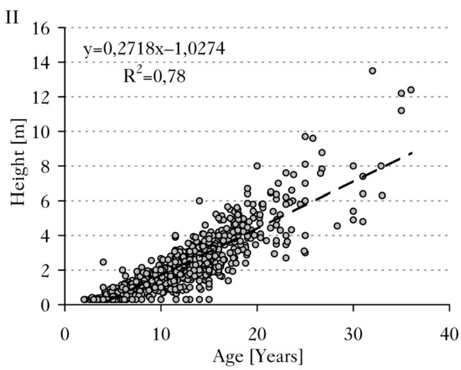
Results

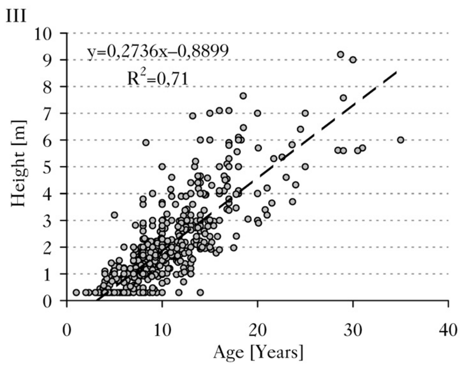
There was no correlation found between the maximum age/height of the young-tree (regeneration) layer, or else the age/height of that layer's dominant species (that accounting for the highest share), and the probability of the regeneration process being completed. Neither were stocking degree or the identity of the dominant species in the upper storey, or else coverage by the young--tree layer, found to be exerting a significant influence on completion of the regeneration process.

However, there proved to be a quite strong relationship between the average height of trees in the regeneration layer and their age. A figure of R^2=0.79 was obtained for stands in FMUs subject to uniform shelterwood cutting, while R^2=0.72 and 0.73 respectively were obtained for FMUs with the group or else stepwise cutting (Fig. 1).

The probability that a stand will remain among A-group stands (of the 'in regeneration' or else 'with regeneration to be improved' classes) was found to vary with cutting system and assigned regeneration period – whether reference was made to either average ages or average heights of trees in the regeneration layer.

The probability of completion of the regeneration process in stands subject to uniform shelterwood cutting, and with an assigned regeneration period of more than 10 years, was found to be greater in circumstances of higher average ages and heights of the young-generation tree layer. The figures were 0.23 where the average age of trees was 1 year, 0.29 where it was 10 years, and 0.52 where it was 40 years (Fig. 2). In stands with a regeneration period of up to 10 years, the probability of the regeneration process being completed was 0.82, though with no demonstrated dependence on the average age of young-generation trees (Fig. 3). The result was similar whether it was average tree height or average age of young trees that was referred to. The prob-





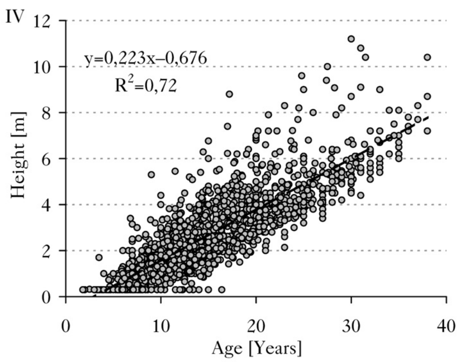


Fig. 1.

Relationships between average ages and average heights in the regeneration layer under different shelterwood cutting systems

II=uniform, III=group, IV=stepwise

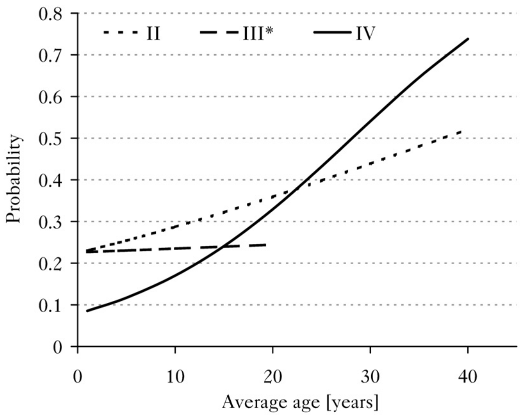


Fig. 2.
Probability of the regeneration process being completed in a stand under different shelterwood cutting systems by reference to average age in the regeneration layer

II=uniform, III=group, IV=stepwise; reconstruction period >10 years; *not achieving statistical significance

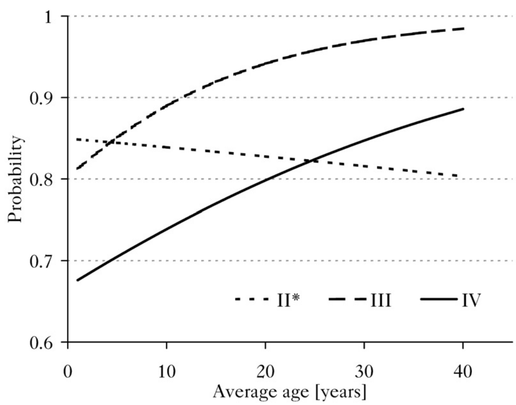


Fig. 3.
Probability of the regeneration process being completed in a stand under different cutting shelterwood cutting systems, by reference to average age in the regeneration layer

II=uniform, III=group, IV=stepwise), reconstruction period 10 years; *not achieving statistical significance

ability of completion of the regeneration process was 0.23 where an average height of 0.3 m characterised an area with seedlings and underplanted trees, even as it was of 0.64 where average height equalled 10 m, where the regeneration period was of over 10 years (Fig. 4). In turn, when that period was below 10 years, the mean height of trees in the regeneration layer was not found to exert an effect on the probability (at 0.82) that a stand would remain in the 'in regeneration' class.

In stands of FMUs managed by way of a group cutting system, the probability of the regeneration process reaching completion (where the regeneration period was 10+ years) proved to be 0.25, irrespective of the average ages or heights of trees in the regeneration layer. In stands with an assumed regeneration period of up to 10 years, this probability was 0.81, with the average age of trees equal to 1 year; as well as 0.86 in the case of seedlings and underplanted trees. Among trees of greater age and height, the values recorded came close to 1 (Fig. 5).

For stands in FMUs managed with stepwise cutting systems and a regeneration period of more than 10 years, the probability of the regeneration process reaching completion varied, being below 0.1 for the average age of young-generation trees equal to 1 year, as compared with 0.13 for trees less than a metre in height, but up to 0.74 for an average age of young-generation trees equal to 40, as well as where trees were of average height equal to 10 m. In stands with an assigned regeneration period of up to 10 years (notwithstanding the lack of applicability to step-

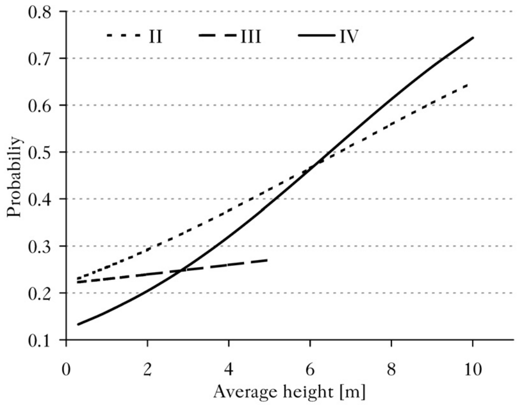


Fig. 4.
Probability of the regeneration process being completed in a stand under different shelterwood cutting systems

II=uniform, III=group, IV=stepwise; reconstruction period >10 years

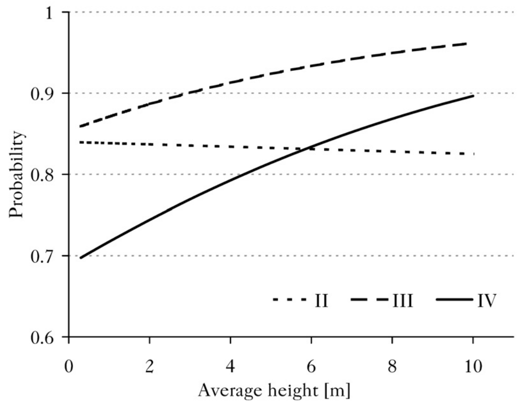


Fig. 5.
Probability of the regeneration process being completed in a stand under different shelterwood cutting systems

II=uniform, III=group, IV=stepwise), reconstruction period 10 years

wise cutting), the probability of the regeneration process being completed was successively greater with progressively-greater ages and heights of young-generation trees, being 0.67 where trees of the layer were 1 year old, 0.86 where that age was 40 years, and 0.7 in the case of a regeneration layer in which trees were of average height below a metre, plus 0.90 by the time average height had reached 10 m (Fig. 5).

It proved possible to note similar theoretical and empirical distributions as regards shares of stands assigned to height classes in the regeneration layer under uniform shelterwood cutting systems (Chi^2=0.054, p=1). The largest shares of stands were in the height class up to 1 m, with values of 30 and 36% respectively being noted (Fig. 6). The share was also lower where the average height of trees in the regeneration layer was greater. The empirically-determined distribution of shares of stands by average age in the young-generation tree layer did not differ from the distribution estimated by reference to survival of trees in this layer as determined empirically (Chi^2=0.220, p=0.99). In the case of the empirical distribution, 47% of stands had regeneration layers in which trees were of an average age not exceeding 10 years, even as stands with a regeneration layer of trees aged over 25 years on average only accounted for about 2% of the total (Fig. 7).

Distributions for shares of stands managed using the group shelterwood cutting system in age classes of the young-tree layer proved to be similar (Chi^2=0.161, p=0.98). In contrast, a difference was noted where tree height classes were concerned (Chi^2=24.75, p<0.001). The largest group of stands was characterised by an average height of the young-tree layer under 1 m and by an

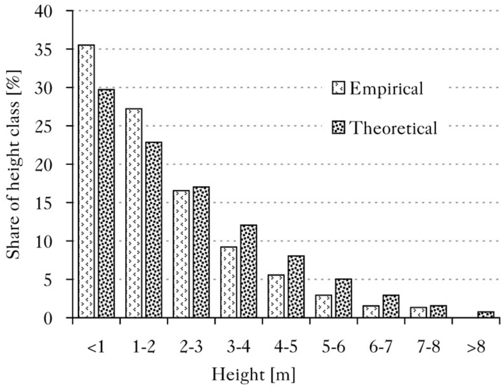


Fig. 6.
Comparison of theoretical height structure in the regeneration layer of forest stands – based on the accounted probability of the regeneration process being completed, as well as structure derived empirically by reference to data for the uniform shelterwood cutting system

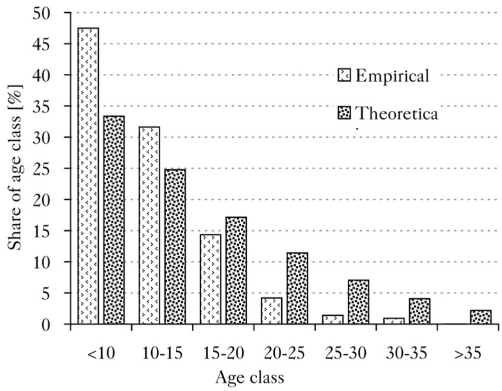


Fig. 7.
Comparison of theoretical age structure in the regeneration layer of forest stands – based on accounted probability of the regeneration process being completed, as well as structure determined empirically for data characterising the uniform shelterwood cutting system

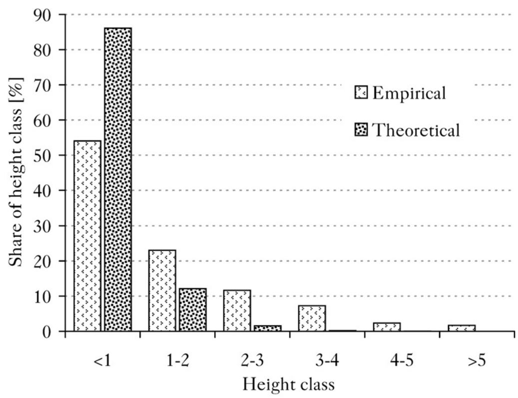


Fig. 8.
Comparison of theoretical height structure of the regeneration layer in forest stands – based on the accounted probability of the regeneration process being completed, as well as structure determined empirically for data characterising group shelterwood cutting system

average age of these trees of under 10 years (Figs. 8, 9). Only a small proportion of all stands had a young-generation tree layer of height greater than 4 m or age equal to 15 years.

In the case of the stepwise cutting system, the theoretical distribution of the proportions of stands in the height classes characterising the young-generation tree layer proved to be closely similar to the empirical distribution (Chi^2=0.059, p=1) (Fig. 10). The empirically-derived distribution noted for the portions of stands in the different age classes of young tree was also seen to be closely similar to the theoretical distribution (Chi^2=0.143, p=0.99) (Fig. 11).

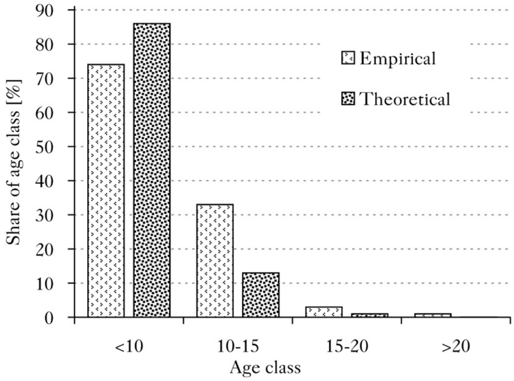


Fig. 9.
Comparison of the theoretical age structure of the regeneration layer in forest stands – as based on accounted probability of completion of the regeneration process and empirical structure based on the obtained data in the group shelterwood cutting system

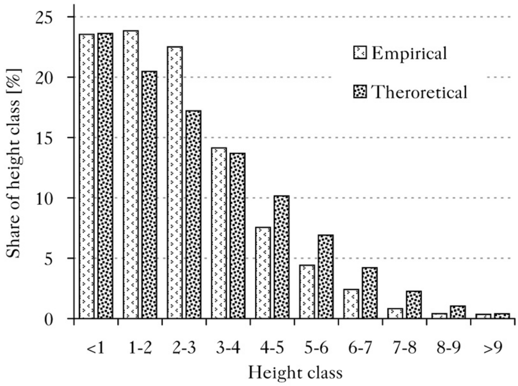


Fig. 10.
Comparison of theoretical height structure in the regeneration layer of forest stands – as based on accounted probability of the regeneration process being completed, as well as empirical structure based on the obtained data for the stepwise shelterwood cutting system

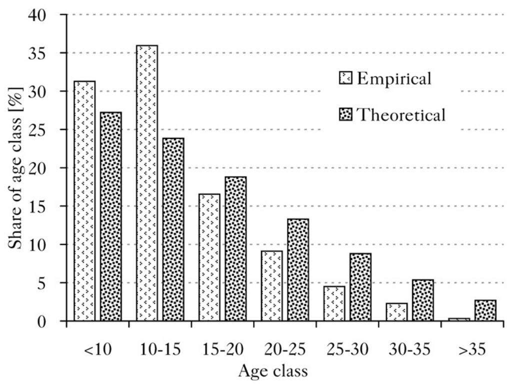


Fig. 11.
Comparison of theoretical age structure in the regeneration layer of forest stands – as based on accounted probability of the regeneration process being completed, as well as empirical structure based on obtained data for the stepwise shelterwood cutting system

Discussion

Classically, the objectives of forest-management planning are perceived to reflect the need for comprehensive identification – first, of factors of forest production, such as climate, soil and stand (with all the characteristics thereof); and then of objectives and ways in which they can be achieved (Pukkala, 2002; Borecki and Stępień, 2017). Originally, it was the production function of forests that was seen as most important, even as forest management in line with that was viewed as serving social and protection functions at the same time. However, recent years have brought a re-evaluation necessitating change in forest management practices, including in Poland.

The area within forest management units assigned for clear-cutting has been decreasing steadily here, while the area comprising shelterwood FMUs has been increasing (especially in forests where the lead function is social). *In extremis*, the abandonment of forest management is even expected by society, despite the steady increase in demand for timber (Gołos and Kaliszewski, 2016); while there is a general recognition that planning in managed forests needs to become more flexible (Borecki *et al*., 2017). The changes to come in Polish forests will transform the age structure, doing much to affect the presence of multi-aged stands. In 2021, stands 'in regeneration' or 'with regeneration to be improved' accounted for approximately 4.5% of those under State Forests management (where stands subject to the individual tree-selection method are also included). But in the years to come that share is likely to increase, as Polish stand age structure will prove favourable to higher levels of utilisation (WISL, 2022). That change is likely to force an adaptation of existing rules and regulations in the direction of stands 'in regeneration' having a greater role to play in forest management generally, and planned use in particular, as in the case of the aforementioned forests whose lead function is social (Zarządzenie, 2022).

The subject literature has only extended marginal treatment to the A-group stands (of the classes 'in regeneration' or 'with regeneration to be improved'). Therefore, as Poznański *et al*. (1999) pointed out, there is little information on the condition these are in, or their potential for development. From a regulatory (forest-management planning) point of view, the length of the regeneration period is key, along with the amount of regeneration (extent of cover), and the intensity of projected cuts. However, these are all matters of a purely technical nature, deriving from the theory of the normal forest, in which all that happens reflects forester decision-making. In practice, the process of stand regeneration may sometimes fail, with the effects being a range of complications resolved by silvicultural and forest-protection measures, and as the forest management plan is prepared. Elaboration of the latter, along with forecasting of wood-resource development, should then take more account of the established regeneration period, with the clean-up period being linked to what is known about the layer of young-generation trees and the range of probabilities for the regeneration process to be completed which that insight offers.

Silvicultural and forest-protection decisions are limited to potentially facilitated completion of the regeneration process through the removal (or thinning) of remaining trees in a stand's upper storey, with possible planting of young trees leading into protection of the regeneration layer. Established layers of young trees therefore lack homogeneity of age and height, and also differ in regard to location within the stand. There is also a problem with mixing tall trees of the regeneration layer and trees of the old generation layer. In long regeneration periods, it could be an obstacle to harvesting work and greater need to pay attention to the occurrence and distribution of young trees, thus there is a need for planning technical routes which can help in avoiding damage in regeneration layers. There is also the problem of forest management planning, how to estimate in mature stands the volume of trees that will be felled, but excluding the volume of trees that already belong to the new generation layer.

As the work detailed here makes clear, the regeneration period *per se* is important information influencing completion of the regeneration process – regardless of the condition the regeneration may be in. Following clean-up cuts, a stand transfers to an age class appropriate to the age of the dominant species in the regeneration layer (usually 11-20 or 21-40 years, rarely 1-10). However, our results fail to sustain the idea of the age of the dominant species in the regeneration layer being crucial to completion of regeneration, with all the questions that raises for decision-making by the forest surveyor. Where a surveyor indicated a regeneration period of 10 years, there was a high probability of the regeneration process needing to be completed by the time of elaboration of the next forest management plan, even in stands managed through the stepwise cutting theoretically demanding a much longer period of regeneration. Keeping forest stands in regeneration process more than presumed regeneration period could prompted by foresters decisions with regard to unexpected issues.

Such results are obviously of practical relevance, where they offer a basis on which to forecast stand development in shelterwood FMUs. Thus far, such forecast development of wood resources has taken insufficient account of stands of the 'in regeneration' or 'with regeneration to be improved' classes, with consideration limited to the age of the upper storey, as opposed to the condition of the layer of young-generation trees (Poznański, 1993; Banaś, 1996b; Banaś *et al*., 2015). The result has been limited forecasting of development in shelterwood FMUs, whose long term prognoses should be elaborated with account taken of the probability of an A- to B-group transition, as well as the condition of the regeneration layer. The results of the present study also speak for a change in the method of estimating the age of a new forest stand established upon the regeneration process being completed. It is shown here that stand-age estimation based around the ages of trees of the dominant species may fail to offer an adequate reflection of stand structure and condition.

The Forest Management Instruction (IUL, 2012) provides that the age of a stand (as later used to calculate the prescribed cut or forecast wood-resource development) shall be determined by reference to the age of that stand's dominant tree species, with no age estimation at all where stands are 'in regeneration' or 'with regeneration to be improved'. Forecasts to date have thus predicated the development of such stands on age of the dominant tree species in the upper storey. This is shown to be inappropriate, as the course of time sees this layer utilised while further cuts are performed. Each layer has its own role to play in the development of stands 'in regeneration' or 'with regeneration to be improved'. And each layer has different tree species of different ages and heights, whose states influence decision-making when it comes to completion of the regeneration process. Estimation of the age of the regeneration layer in the manner advocated by this study can be seen to supply information of value as the development of wood resources in shelterwood FMUs is forecast.

Estimation of the final yield is another issue. Where shelterwood FMUs are concerned, the current Forest Management Instruction (IUL, 2012) provides for that to be done in line with 'silvicultural needs', but there are no guidelines on determining cutting intensity. The forest surveyor uses the forest description (in advance of the elaborated management plan) to indicate wood volume to be harvested. Here, information on the average age or height of the regeneration layer might be well-used, as, with a given probability of the regeneration process coming to an end, it is possible (though not easy) to estimate how long a stand will retain its upper storey. However, forecasting of the development of shelterwood FMUs looks more realistic where there is full insight into the probability of stand development, *i.e.* of the survival of stands in younger age classes, and of the onset and completion of the regeneration process.

Conclusions

- The characteristics found to best describe the probability of a tree-regeneration process being completed were average height and age in the young-tree generation. Such characteristics take account of the complexity of the young-tree layer.
- The most important information indicative of a regeneration process potentially reaching completion is the length of the regeneration period.
- For the stepwise shelterwood cutting system, even short regeneration periods of up to 10 years were found to have been assigned, despite accepted rules providing that long and very long periods of over 40 years should be applied.

- The average age of regeneration often exceeded the presumed regeneration period, and this was above all the case for forest management units subject to a more complex method of felling (*i.e.* stepwise shelterwood cutting). It is likely that patches of young-tree generation appeared even prior to initiation of the regeneration process.
- As the height of young trees in stands of the 'in regeneration' or 'with regeneration to be improved' classes may sometimes have exceeded 10 m, there is a potential for problems with estimating tree ages in a next-generation stand.
- More attention should be paid to the presence of a young-tree generation as a forest survey is being carried out; and this would be especially true of stands managed by way of shelterwood felling. A possibility of achieving rapid recalculation of the ages of trees in given layers – in the direction of the average age in a whole forest stand – could improve and facilitate decision-making among forest surveyors as regards the possibility of the regeneration process achieving completion.

Authors' contributions

R.K. – conceptualisation, methodology, formal analysis, material collection, statistical analyses, 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.

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STRESZCZENIE

Drzewostany w procesie odnowienia – kontekst planowania urządzeniowego

W gospodarstwach przerębowo-zrębowych wyodrębnianych podczas tworzenia planów urządzenia lasu występują dwa typy drzewostanów: bez warstwy odnowienia (oznaczane jako B) oraz z warstwą odnowienia, które są jednocześnie poddawane użytkowaniu (oznaczane jako A). W toku rozwoju takiego gospodarstwa drzewostany z grupy B w miarę starzenia się zwiększają swój zapas. Część z nich w następstwie działania różnych czynników (na ogół nieplanowanych i niepożądanych) przechodzi bezpośrednio do najmłodszej klasy wieku, a część – zazwyczaj najstarszych – po wykonaniu cięć przechodzi do grupy A. Właściwy udział drzewostanów tych dwóch grup w gospodarstwie oraz wzajemne relacje zachodzące pomiędzy nimi wraz z upływem czasu mają podstawowe znaczenie dla trwałości lasu. Celem pracy było określenie, w jaki sposób moment zakończenia procesu odnowienia jest uzależniony od cech taksacyjnych drzewostanu. Wykorzystano dane z planów urządzenia lasu z lat 2009 i 2010 oraz planów dla tych samych nadleśnictw przygotowanych 10 lat później: w latach 2019 oraz 2020. Dotyczyły one 64 nadleśnictw skupionych w 14 dyrekcjach regionalnych Lasów Państwowych. Rozwój drzewostanów w klasie odnowienia został sprawdzony w sposób empiryczny. Na mapę wektorową drzewostanów nadleśnictw z pierwszego okresu (2009-2010) nałożono siatkę punktów próbnych w więźbie 100×100 m. Każdemu punktowi przypisano atrybuty: gatunek panujący w warstwie drzew, warstwie podrostu oraz warstwach nalotu

i podsadzeń, wiek każdego gatunku w warstwie odnowienia, którego udział (wg pokrycia) wynosił co najmniej 5%, a także przypisany okres odnowienia. W obliczeniach zostały uwzględnione dwie grupy gospodarstw: w pierwszej ujęto gospodarstwa z okresem odnowienia do 10 lat, a w drugiej gospodarstwa z okresem odnowienia powyżej 10 lat, najczęściej 20 lat. Dla każdego wylosowanego punktu (na podstawie danych taksacyjnych drzewostanu, w którym był zlokalizowany ten punkt) obliczono średni wiek i wysokość odnowienia. W związku z tym, że w każdej warstwie mogły znajdować się gatunki drzew o różnym wieku lub wysokości, obliczono średnią ważoną wieku lub wysokości dla każdej warstwy. Średnie ważone wieku odnowienia oraz wysokości odnowienia obliczono na podstawie danych dla warstw podrostu, nalotu i podsadzeń, gdzie za wagę przyjęto udział danej warstwy. W celu określenia prawdopodobieństwa zakończenia procesu odnowienia drzewostanu zaliczonego do grupy A obliczono regresję logistyczną dla 3 rodzajów rębni: częściowych, gniazdowych i stopniowych, z uwzględnieniem okresów odnowienia do 10 lat i powyżej 10 lat. Przy użyciu testu χ^2 wykonano porównanie rozkładów empirycznych drzewostanów w klasach wieku i klasach wysokości z rozkładem ustalonym na podstawie obliczonego prawdopodobieństwa zakończenia procesu odnowienia drzewostanu w grupie A dla każdej grupy rębni.

Nie stwierdzono zależności między maksymalnym wiekiem/wysokością odnowienia lub wiekiem/wysokością gatunku panującego w odnowieniu (o największym udziale) a prawdopodobieństwem zakończenia procesu odnowienia. Również zwarcie i gatunek panujący drzewostanu macierzystego oraz stopień pokrycia powierzchni przez odnowienie nie miały wpływu na zakończenie procesu odnowienia. Dość silna była zależność między średnią wysokością odnowienia a jego wiekiem. Dla rębni częściowych wynosiła ona R^2=0,79, dla rębni gniazdowych R^2=0,72, a dla rębni stopniowych R^2=0,73 (ryc. 1).

Prawdopodobieństwo zakończenia procesu odnowienia w drzewostanach użytkowanych rębnią częściową, z przypisanym okresem odnowienia powyżej 10 lat, zwiększało się wraz ze średnim wiekiem oraz wysokością drzew odnowienia. Wynosiło ono 0,23 przy średnim wieku odnowienia 1 rok, 0,29 przy średnim wieku 10 lat i 0,52 przy średnim wieku 40 lat (ryc. 2). W drzewostanach z okresem odnowienia do 10 lat prawdopodobieństwo zakończenia odnowienia wynosiło 0,82, jednak nie zależało od średniego wieku drzew odnowienia (ryc. 3). Prawdopodobieństwo zakończenia procesu odnowienia wynosiło 0,23 przy średniej wysokości poniżej 0,5 m i zwiększało się do 0,64 dla średniej wysokości 10 m w przypadku okresu odnowienia powyżej 10 lat (ryc. 4). Gdy okres odnowienia był mniejszy niż 10 lat, średnia wysokość odnowienia nie miała wpływu na prawdopodobieństwo pozostania drzewostanu w klasie odnowienia, które wynosiło 0,82.

W drzewostanach użytkowanych rębniami gniazdowymi prawdopodobieństwo zakończenia procesu odnowienia, gdy okres odnowienia był większy niż 10 lat, wynosiło 0,25 bez względu na średni wiek czy wysokość drzew warstwy odnowienia. W drzewostanach, w których założony okres odnowienia był mniejszy niż 10 lat, prawdopodobieństwo to wynosiło 0,81 przy średnim wieku odnowienia wynoszącym 1 rok, 0,86 przy wysokości poniżej 0,5 m i zwiększało się prawie do wartości 1 wraz ze zwiększaniem się wieku i wysokości drzew (ryc. 5). W przypadku drzewostanów użytkowanych rębniami stopniowymi, przy okresie odnowienia powyżej 10 lat, prawdopodobieństwo zakończenia procesu odnowienia było zróżnicowane i wynosiło poniżej 0,1 dla średniego wieku drzew odnowienia 1 rok i 0,13 dla wysokości drzew poniżej 1 m, a następnie zwiększało się do 0,74 dla średniego wieku odnowienia 40 lat i do 0,74 dla średniej wysokości 10 m. W drzewostanach z przypisanym okresem odnowienia poniżej 10 lat (choć taki fakt nie powinien mieć miejsca w przypadku rębni stopniowych) prawdopodobieństwo zakończenia procesu odnowienia zwiększało się wraz z wiekiem oraz wysokością odnowienia i wynosiło 0,67, gdy wiek drzew warstwy odnowienia wynosił 1 rok i 0,86, gdy ten wiek wynosił 40 lat oraz 0,7 przy średniej wysokości drzew poniżej 1 m i 0,90, gdy ich średnia wysokość wynosiła 10 m (ryc. 5).

Rozkład teoretyczny i empiryczny udziału drzewostanów w klasach wysokości odnowienia w rębniach częściowych były do siebie podobne (χ^2=0,054, p=1). Najwięcej było drzewostanów w klasie wysokości drzew odnowienia do 1 m, odpowiednio 30 i 36% (ryc. 6). Ich udział zmniejszał się wraz ze średnią wysokością odnowienia. Rozkład empiryczny drzewostanów ze względu na średni wiek odnowienia nie różnił się od obliczonego na podstawie empirycznie określonej przeżywalności tej warstwy drzewostanu (χ^2=0,220, p=0,99). W przypadku rozkładu empirycznego 47% drzewostanów cechowało odnowienie, którego średni wiek nie przekraczał 10 lat, a drzewostany z odnowieniem o średnim wieku powyżej 25 lat stanowiły około 2% (ryc. 7).

Rozkłady udziału drzewostanów użytkowanych rębniami gniazdowymi w klasach wieku odnowienia były zbliżone (χ^2=0,161, p=0,98), jednak przy uwzględnieniu klasy wysokości odnowienia różniły się od siebie (χ^2=24,75, p<0,001). Przeważała grupa drzewostanów ze średnią wysokością poniżej 1 m i ze średnim wiekiem odnowienia do 10 lat (ryc. 8 i 9). Udział drzewostanów z odnowieniem o wysokości powyżej 4 m lub wieku 15 lat był niewielki.

W przypadku rębni stopniowych teoretyczny rozkład udziału drzewostanów w klasach wysokości drzew warstwy odnowienia był zbliżony do rozkładu empirycznego (χ^2=0,059, p=1) (ryc. 10). Rozkład empiryczny udziału drzewostanów w klasach wieku odnowienia był zbliżony do rozkładu teoretycznego (χ^2=0,143, p=0,99) (ryc. 11).

Wnioski

- Cechami najlepiej opisującymi prawdopodobieństwo zakończenia procesu regeneracji drzew były średnia wysokość i wiek młodego pokolenia. Takie cechy uwzględniają złożoność warstwy młodych drzew: nalotu, podsadzeń i podrostów. Najważniejszą cechą wpływającą na zakończenie procesu odnowienia był przyjęty okres odnowienia.
- Średni wiek odnowienia często przekraczał zakładany okres odnowienia i dotyczyło to przede wszystkim rębni stopniowej. Prawdopodobnie wynikało to z obecności odnowienia przed rozpoczęciem wykonywania cięć.
- Podczas prac taksacyjnych należy zwrócić uwagę na obecność młodego pokolenia drzew, w szczególności w drzewostanach w klasie odnowienia i w klasie do odnowienia. Umożliwi to poznanie pełnego potencjału tych drzewostanów do wykorzystania w procesie odnowienia oraz ułatwi planowanie urządzeniowe.