The Theoretical Fundamentals of Forming of the most Productive Stands

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Abstract

The paper deals with the development of the theory of the most productive *Picea abies* Karst., *Pinus sylvestris* L., *Quercus robus* L., *Fraxinus excelsior* L., *Betula pendula* L., pure and mixed stands, the utilization of solar energy by trees and storeys, the interaction between trees, their productivity, optimal stand density, the influence of intermediate fellings on the increment of trees and stands. Also the construction of the models of the most productive stands and the development of the standards of intermediate fellings are analysed. For this the data gleaned over 30 years in more than 500 permanent experimental plots have been used.

The revealed new phenomenon of the stress effect of trees while forming ecosystem enabled the density of forming young stands to be optimized according to the critical limit of crowns approach while the density of stands according to the maximally possible projection area of a storey and an optimal degree of crown overlapping. It ensures the largest increment of the most valuable wood in ontogenesis of ecosystem.

It has been determined that the more the surface of a storey resembles the stairs, the more the solar energy penetrates into the stand. The most productive trees (class A) use the solar energy most effectively for the increment of wood. The most significant productivity of stands is achieved in case the stocking of a storey is maximal, the trees in the storey are maximally productive and the distance between them (crown overlapping) is optimal.

In the paper tree prototype – models of the most productive stands and the standards of their forming by intermediate fellings are presented. It has been ascertained that at a certain interval of stand age and thinning intensities the increment of thinned stands exceeds that of stands where thinnings have not been applied. With increasing age of stands the feasibility to enlarge stand increment by regulating density is more seldom noted because stocking augments, up to which it is feasible to thin stands without diminishing their increment, in comparison to the increment of stands where thinnings have not been applied.

Key words: critical limit of crown approach, the effect of stress, maximal stand productivity, use of solar energy, optimal stand density, intermediate fellings, thinning intensity.

Introduction

The increasing of forest productivity and sustainability is one of the most important tasks in forest management. It has been determined that naturally growing stands are not most productive since, along with productive trees using solar energy and space best, there is 40–60% of trees of average and low productivity (Kairiūkštis 1973). In most cases stand structure and density are not optimal nor do they ensure the largest volume increment of stands and their highest total productivity.

In the given soil and climatic conditions it is feasible to form most productive stands in natural forests and in sufficiently dense plantations by systematic and qualitative regulating quantity, quality and spacing of trees for example by thinning and intermediate fellings carried out in time. This is of paramount importance particularly in the last decade when the requirements of wood quality for industry have increased and acceleration of wood use for energy purposes is increased and their effect by many ecological and socio–economic aspects have enlarged (Kairiukstis *et al.* 2001, 2003, 2005). Foresters of the whole world have done much in developing theoretical assumptions of intermediate fellings and practical ways of carrying out them (Becking 1954, Mitcherlich 1957, Георгиевский 1957, Assmann 1961, Давидов 1971, Казимиров 1972, Кожевников 1971, Marquis *et al.* 1991). They are done from time to time as a means of forest management, which decrease too high density of stands. However intermediate fellings did not become an expedient system of forming stands from the most productive trees of desirable species composition. Moreover, in some countries particularly where conifer forests prevail, for the sake of short–term benefit, intermediate fellings are simplified. Forest is thinned without special selection of trees and intermediate fellings are divided only into precommercial and commercial. The main qualitative criterion of such intermediate fellings remains thinning intensity. The investigations (Kairiūkštis 1964, Kairiūkštis, Juodvalkis 1985) have shown that stand productivity largely depends upon the quantity of solar energy received in the stand effectiveness of their utilization by trees and storey, quality, number and distribution (spacing) of trees left for growing.

In order to achieve more significant effect of intermediate fellings the authors of the paper had the following tasks: 1) to investigate thoroughly intra– and interspecific regularities of the interaction between trees in the process of creation of ecosystem and formation of natural stands or plantations; 2) to perceive the factors crucially affecting penetration and utilization of solar energy in storey, differentiation of trees, their increment and stand productivity; 3) to create a common theory of forming of the most productive forest and on this basis to prepare the standards for thinning and intermediate fellings in stands of the main tree species and their combination. Application of such standards would ensure maximally possible increment of wood of the best quality and significant sustainability in the whole ontogenesis of a stand.

Methods and the scope of research

For determination of intra– and interspecific regularities of the interaction between trees more than 500 stationary experimental plots have been set up by the authors and followed up from 5 to 25 years. In the plots all trees have been numbered and their biometric and actinometric measurements have been repeated 2–5 times. For spruce, birch, pine and asp some physiological investigations of leaves and needles have been conducted. In more than 300 experimental plots intermediate fellings of different intensity have been carried out 2–5 times. Besides, the data on many other experimental plots have been used. The plots have been delineated in stands of different species composition, structure and age, where different soils prevail. The investigations have been conducted along the following directions:

1. The influence of solar energy use in storeys of stands on productivity has been analysed. The investigations have been conducted experimentally on how to decrease the quantity of solar energy reflected from the stand and increase that getting into the stand. The effectiveness of solar energy use by trees of different classes has been studied.

2. Analysis has been conducted on the spatial structure of pure and mixed spruce, pine, oak, birch and aspen stands. The regularities of stocking of stand with increasing age, the parameters of crowns of trees of different classes, the use of occupied space have been determined. Also the most productive area of horizontal projection of crowns in stands of different age has been searched. Interspecific relations between the crown horizontal projection area, stem diameter and age, optimal crown structure and its change with age have been ascertained. For this purpose for 116 experimental plots the plans of tree distribution and crown horizontal projection have been drawn. Crown horizontal projection area for more than 41 thousand trees, stem diameter and its current increment have been determined.

3. The investigation has been conducted on the rate of tree growth, the peculiarities of crown forming, the productivity if the space occupied by trees as well as on their volume. Inter– and intraspecific relations of trees in the process of crown approach in stands of different density have been analysed. Also such investigations have been carried out annually in specially (identical spacing) established spruce and pine plantations covering density variants 100, 50, 25, 12.5, 6, 3, 1.5 and 0.86 thousand trees per hectare.

4. Analysis has been conducted on the peculiarities of mixed stand growth, on the regularities of formation of their composition and structure. For this the data on 47 permanent experimental plots have been applied.

5. Ecological and phytocoenotic conditions of the growth of oaks, ashes and spruces in mixed stands have been determined. The investigation has been conducted on the changes in daylight illumination of crowns and under them by allowing for the growing stock of a storey. The dependence of the growth in height of oaks, ashes and spruces on daylight intensity, the position of a tree in stand and on the growing stock of the storey of broad–leaved species has been investigated. For this purpose more than 29 thousand measurements of daylight have been made and the height increment of more than 3.700 model oaks, ashes and spruces has been measured.

6. The influence of thinnings and intermediate fellings on the growth of different trees and on the productivity of the whole stand has been investigated. Also the reaction of trees of different classes to the thinning of stands has been clarified. The dependence of volume and the current increment on intermediate felling intensity, growing stock, class structure of trees left after fellings has been determined. Optimal and critical stand thinning and optimal regime

of intermediate fellings in stands of different species composition, structure and age has been ascertained. In order to resolve this issue the data on 309 experimental plots have been used in which recurrent measurements every 5 years have been made from 2 to 5 times and intermediate fellings of different intensity have been carried out also from 2 to 5 times.

The methods used for the whole scale of investigation have been described in detail (Kairiukstis 1961, 1968, 1969, 1972, 1973, Kairiukstis, Juodvalkis 1975, 1976, 1980, 1985, 1986).

Results and discussion

With the aid of investigations it has been determined that the productivity of stand of investigated tree species (*Picea abies* Karst., *Pinus sylvestris* L., *Quercus robur* L., *Fraxinus excelsior* L., *Betula pendula* L., *Populus tremula* L.) in given soil capacity is conditioned by the quantity of solar energy getting into the stand, the effectiveness of its use in trees and storeys, by the quality (class) and productivity of trees forming the stand, by its optimal number and their distribution on an area unit.

While investigating the use of solar energy in storeys (Kairiūkštis 1967, 1968) it has been established that the quantity of the solar energy reflected from the stand (albedo) directly depends upon the inequality (depth) of crown surface: the more the storey surface resembles the stairs, the less the solar energy is reflected and the more of it gets into the stand, at the same time more solar energy is used for creating wood. In case the extent of depth of crowns resembling stairs increases from 1–2 to 7–8 metres albedo diminishes from 16 to 8%. Thus additionally nearly 8% of solar energy penetrates into the stand.

While investigating the effectiveness of the use of solar energy it has been found that the use of solar energy by trees of different classes*) is different (Kairiūkštis 1972). The more productive the assimilation part of trees is, the more wood is produced per unit of absorbed energy. In case the coefficient of sum radiation and beneficial energy use of FAR is equal to 1.0 for trees developing well (class A), for trees weak developing (class B) it is equal 0.8–0.7 while for suppressed trees (class C) 0.7–0.5 (Figure 1). Therefore with the aid of intermediate fellings vigorously developed trees (class AI) that use the solar energy nonproductively, suppressed and weak developed trees (C and B) must be eliminated. By forming the stand from trees of A class it is feasible more economically to use solar energy for producing wood increment. Then less solar energy is used for the upper storey and more favourable lighting conditions are created for the second storey and underwood (Kairiūkštis 1973).

In resolving the issues of forming the most productive forest one of the main problems was to find the method of determining the optimal number of trees or stand density. Under identical conditions stands can attain the highest productivity only at optimal density (Kairiūkštis 1972).

A great deal of different methods optimizing density and the growing stock have been suggested in the special forestry literature. In old times stand density was determined on the bases of investigations (Тимофеев 1957, 1959, Кондратьев 1959, Wiksten 1965, Дитикин 1967, Kazimirov 1972 *et al.*) conducted on the regularities of the growth and forming of plantations established at different density as well as on these of self regenerated stands of different density. Other researchers made an attempt to ascertain stand density on the basis of the correlation between the number of trees, spacing between trees, the area of nutrition different inventory indexes of trees, such as stem diameter, height of a tree, crown diameter etc. (Kohler 1929, Reinecke 1933, Шустов 1933, Beck-

*) A[1] *Vigorously developed trees which are relatively stable*; grow under excessive environmental conditions always of the upper story, fully lighted, having the thickest stems, gnarled, strongly tapered, not of high technical quality; broad, deep crowns with round-tops, the assimilative mass covering area of the crown is high, the foliage of the type grown in full light and low humidity; medium productivity, with a comparatively high coefficient of profitable utilization of solar energy (CPUSE).

A. Well-developed trees, medium stability; grow under optimal environmental conditions deciduous trees of the 1st (upper) storey, spruce of the 1st-2nd storeys; the upper part of the crowns is lighted; medium and thick stems, with normal taper, of high technical quality; compact crowns with pointed tops; the assimilative mass covering area of the crown is the highest one; foliage of the type grown in shade and medium humidity; high productivity, the highest CPUSE: fast growth in the growing season, and long period of the growth.

B. Weakly developed trees, very unstable; grow under minimum environmental conditions deciduous trees of the 1st-2nd, spruce of the 2nd-3rd storeys, moderately shaded; stems of medium thickness; with little taper and of satisfactory technical quality; crowns of medium length, the assimilative mass covering area of the crown is decreased; foliage of the type grown in shade and high humidity; reduced productivity, low CPUSE; the trees have a medium rate of the growth.

C. Suppressed trees, unstable; grow under insufficient environmental conditions, always in the lower part of the stand, strongly shaded; thin stems, with very little taper, of inferior technical quality; short crowns that are comparatively broad, round-tops; the assimilative mass covering area of the crown is the lowest one; foliage of the type grown in deep shade and very high humidity; low productivity and very low CPUSE; poor rate of the growth in a growing season and short period of the growth.

ing 1954, 1972, 1995 *et al.*). Attempts were made to determine density by allowing for the dependence of the current increment of stand volume on nutrition area of a tree (Томазиус 1978 *et al.*).

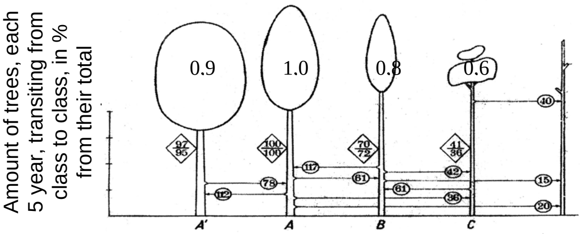

Figure 1. Trees transiting from class to class, their comparative productivity in % from the trees of A class productivity in thinned stands

Indices: in crowns – Coefficient of Profitable Utilization of Solar Energy (CPUSE);
in rhomb: in the numerator comparative productivity of stable trees;
in the denominator comparative productivity of all trees during 5 years, which at the beginning belonged to this class including the productivity of the trees which had transited to other classes over the same period;
in circulars the productivity of trees which have transited from one class to another is shown in the indicated direction. The vertical position of the directional marker indicates the % of trees having transited from one class to another during 5 years

The analysis of the available methods of determining optimal stand density has shown that most of the suggested methods are of theoretical nature. With the aid of them an attempt is made to optimize different constituent parts of a stand while the structure of tree distribution in classes in the stand and its productivity are not taken into consideration. On the other hand, the investigation conducted on a full cycle of ontogenesis (from stand creation process till its maturity) have indicated that density indexes in terms of stand productivity are not univocal. The investigation has been conducted on the growth of plantations established at different initial density as well as on crown approach in the process of coenosis forming. It resulted in revealing a new biological law which we called stress effect of trees in the process of coenosis forming (Kairiūkštis, Juodvalkis 1975). The law enabled us to look newly at density optimization of stands at different stages of their growth and development. It has been clarified that significant changes occur in the mutual relations of trees during the formation of one kind of coenosis. It appeared that the critical limit of crown approach exists. Depending upon generative maturity of given tree species and the height of a tree this limit approximately ranges from 10 to 70 cm. For instance, for spruce it is calculated according to the formula:

$$y = 73{,}2 - \frac{24{,}8}{x}; \quad (\eta = 0{,}979)$$

here y – distance between crowns, cm;
x – height of a tree (from 0.5 to 5.0), m.

In case the limit is exceeded the trees are submitted to stress of mutual interaction. Then intensive mutual suppression starts, which reveals itself by a decrease in the increment in all points of the growth (Figure 2). The younger the trees overstep this critical limit of crown approach, the more significant mutual suppression is. Later, when the crowns of trees start closing mutual suppression weakens and the increment of trees again conditionally starts increasing (trees differentiate). It implies that trees already make up coenosis which from the sum of former individuals forms unified homeostatic sustainability of the system.

Such a change in the mutual relations of trees during the creation of coenosis enabled us to infer that it is infeasible to guide by univocal perception of optimal stand density at different stages of stand forming. It appeared that during the creation of young stand optimal density is such when trees do not approach up to the critical limit and there is no negative interaction between individuals, the height and diameter increments of most of the saplings are largest. It poses an assumption to attain the culmination of stand productivity at pole stand age. Thus, optimal young stand density is such when maximal diameter and height increment are ensured for a possibly larger number of individuals. It is calculated according to the formula:

$$N_{opt} = \frac{Q}{S};$$

here Q – the most significant stocking of a storey during crown closing, m^2/ha, S – nutrition area (m^2) per one tree when there is critical distance between crowns.

After finding the law of stress effect in the process of crown approach and after optimizing density of trees in the phase of young stand forming the onset of forest (as coenosis or an ecosystem) functioning has been determined (Kairiūkštis 1992). It appeared that prior to the critical crown approach trees do not affect each other nor do they make up coenosis (ecosystem) or forest.

There was a possibility to prepare a method of determining stand density for already established stands which enables all the constituent parts of stand to be optimized in the rest ontogenesis of forest. The method was created relying on the spatial parameters of tree crowns and on optimal space norm conditioning optimal increment of trees and maximal increment of the whole stand. Crown of trees was taken as the basis of stand density optimization because it is the most informative index. Crown indicates the degree (class) of the development of a tree, its productivity and position in the stand. On the other hand, our investigations have shown that the correlation between the current increment of tree volume and the area of crown horizontal projection is closer (r=0.75) than the area of tree nutrition (r=0.47) or the average distance between trees (r=0.26), i.e. the indexes which for a comparison have been also applied for determining optimal stand density.

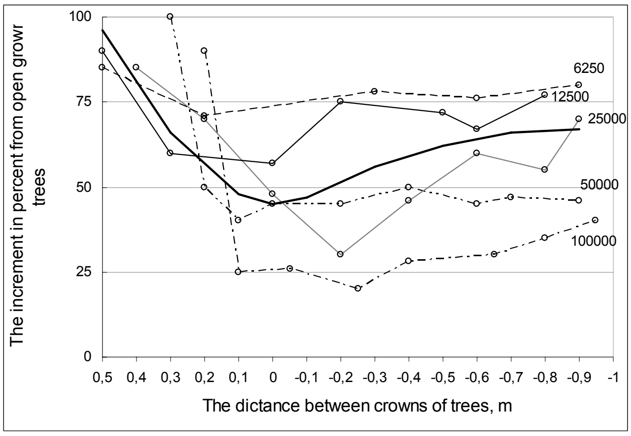

Figure 2. A change in the growth in height of spruces in different phases of crown closing 6250, 2500 etc. tree density, trees/ha

Having investigated the laws of changes in stocking with increasing age of stands (Kairiūkštis, Juodvalkis 1973, 1985) we have ascertained that self–forming stands attain neither maximally possible stocking nor productivity. In stands there are always larger or smaller openings that are not occupied by tree crowns. A part of these openings consists of the areas where trees might grow. However, for some reasons they are absent there another part of these gaps consists of so called inevitable clear spaces which depending upon the species and age comprise from 9 to 30% of the stand area. Thus, in case we deny inevitable clear spaces and artificially insert trees in larger spaces it is possible to calculate maximal storey area and maximally possible crown projection sum (Figure 3) of trees. It has been determined that depending upon species and age maximal storey area makes up from 6.8 to 9.1 thousand m¸/ha while maximal projection sum from 7.4 to 14.2 thousand m¸/ha. Of course, the largest storey area and crown projection sum has been found in spruce stands and the least in aspen and birch stands.

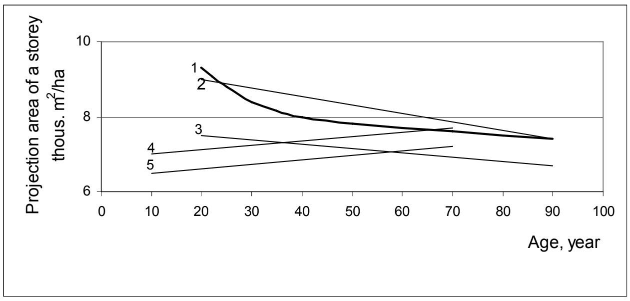

Figure 3. A change in the projection area of a storey according to age in closed natural oak (1), spruce (2), ash (3), aspen (4) and birch (5) stands

While constructing the theoretical model of the most productive forest we have established experimentally the classes of trees and their crown parameters that must occupy maximally possible crown area of a storey in order the stand could give maximal increment. Every stand consists of trees differing in not only in crown parameters but in their productivity. While measuring trees in long–term stationaries over several decades it has been found (Kairiūkštis, Juodvalkis 1980) that within every stand by going from suppressed and weakly developed trees up to well and vigorously developing trees relative crown productivity increases. At a certain size of crown its productivity attains maximum and with further enlargement of crown the productivity starts diminishing (Figure 4). Hence, at a certain age in a stand of every species there is an optimal area of horizontal crown projection. It has been clarified that the parameters of an optimal crown are very similar to the average crown parameters of trees of class A of that stand. It means that in order to achieve maximal stand productivity it is imperative that maximally possible area of a storey be occupied only by crowns of trees of class A.

After determining maximally possible stocking of a storey and optimal parameters of the most productive crowns of trees it was necessary to clarify the spacing between trees, at which the most productive ones should grow, in order maximal stand productivity might be ensured. The investigations conducted on the optimal spacing between trees showed that it was expressed best by crown overlapping. It appeared that with increasing degree of crown overlapping the increment of an individual tree gradually diminishes while that of a stand increases till reaches maximum at a certain degree of crown overlapping. After that stand increment starts diminishing (Figure 5). It means that in every stand there exists a certain degree of overlapping at which maximal stand productivity is attained. Depending upon the species and age it ranges from 4 to 25%. It appeared that optimal degree of crown overlapping is rather similar to the average degree of crown overlapping of trees of class A.

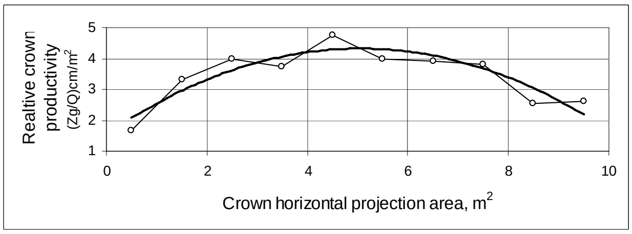

Figure 4. The dependence of relative crown productivity on its size in the stand aged 22 years

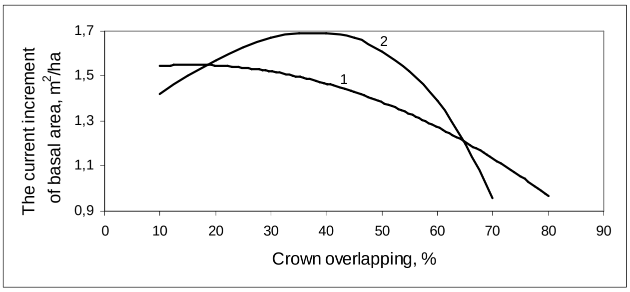

Figure 5. The dependence of the current increment of a tree (1) and stand (2) on percent of crown overlapping in oak stands (*Aegopodio Quercetum*) aged 30 years

$$N_{opt.} = \frac{Q_{max}}{S_{opt}\left(1 - \frac{P_{opt}}{100}\right)};$$

here Q_{max} – refers to the maximal stocking of a storey, m²/ha, S_{opt} – optimal area (m²) of crown horizontal projection of a tree, P_{opt} – optimal crown overlapping, %.

Optimal density determined according to this formula at the given moment allows maximal volume increment and maximal stand productivity also comparative hight but not highest stand stability to be achieved.

On the basis of the determined regularities of the growth of stands and their spatial structure forming the prototypes (models) of the most productive stands were constructed for the main tree species growing in the Baltic sea region according to the prevailing site types and species composition as, for example, shown in Table 1. For practical use optimal number of trees are expressed not from stand age but from the mean height of well developed trees (class A). This enabled to reduce the influence of soil–ecological conditions on the change in inventory indexes and use one model for forest site types similar according to productivity. It allowed us to simplify practical use of standard tables (optimal number of trees) as shown in Table 2.

Table 1. The model of the most productive *myrtillus* spruce stands

Stand age	Stem diameter, cm	Height, m	Crown horizontal projection area of a tree, m²	Sum of crown projection areas, m²/ha	Optimal inventory indexes			
					Number of trees, trees/ha	Sum basal area, m²/ha	Volume, m³/ha	The average distance between trees, m
10	2.0	2.6	1.4	4360	3113	.0	3	1.9
15	4.5	5.1	1.9	4590	2416	3.9	10	2.2
20	6.9	7.5	2.5	5320	2130	8.1	34	2.3
25	9.1	9.5	3.2	6530	2040	13.3	69	2.4
30	11.2	11.3	3.9	7610	1950	19.3	118	2.4
35	13.2	13.0	4.7	8790	1870	25.6	178	2.5
40	15.2	14.5	5.6	9490	1702	30.8	240	2.6
45	17.0	15.8	6.3	9360	1486	33.7	278	2.8
50	18.8	17.1	7.1	9230	1300	36.1	318	3.0
55	20.5	18.3	7.9	9110	1153	38.0	356	3.2
60	22.1	19.3	8.7	8990	1033	39.7	390	3.3
65	23.7	20.3	9.5	8870	934	41.2	420	3.5
70	25.1	21.1	10.3	8760	850	42.1	445	3.7
75	26.4	21.8	11.1	8660	780	42.7	464	3.8
80	27.7	22.5	11.9	8540	718	43.3	480	4.0

Table 2. An optimal number of trees in birch stands of different site types

Height, m	Forest type				
	Myrtillus	Myrtillum–oxalis	Oxalis	Aegopodium oxalido nemorosa	On average all forest types
6	6000	6470	6840	7530	6750
7	5410	5810	6160	6680	6010
8	4880	5220	5540	5920	5350
9	4390	4680	4980	5240	4760
10	3940	4190	4460	4640	4230
11	3540	3750	4000	4110	3760
12	3170	3350	3580	3640	3340
13	2830	2990	3200	3220	2960
14	2530	2660	2860	2850	2630
15	2250	2370	2540	2520	2330
16	1990	2100	2260	2230	2060
17	1760	1860	2000	1970	1820
18	1550	1640	1770	1740	1600
19	1360	1440	560	1530	1410
20	1180	1260	1360	1350	1240
21	1020	1100	1190	1190	1090
22	880	950	1030	1050	950
23	740	820	890	920	830
24	620	700	760	810	720
25	510	590	640	710	620
26		490	530	620	530
27			430	540	450
28				470	380
29				410	320

As illustrated in Table 2, for instance, for all forest sites of birch stands it is feasible to use the average standard (for instance, *Oxalis* type) of an optimal number of trees or three standards (*myrtillus*, *myrtillum Oxalis* and *Oxalis*) at the most because *Aegopodium–oxalido nemorosus* was assigned to *Oxalis* site type.

The peculiarities of mixed stand forming, the dependence of the growth in height of the main tree species on lighting have been investigated. Also the intensity of lighting in different parts of a storey of soft broadleaved stands has been determined. It resulted in constructing the models of the most productive mixed stands (Kairiūkštis, Juodvalkis 1981, 1985). While designing the models the stocking of stands has been allowed for. The optimizing of the structure of trees in mixed forest has been based on the factor of light, namely, that for the main tree species optimal conditions of lighting might be created without reducing the total stand productivity. The models have been constructed for different composition groups of mixed stands.

In all the models (50) optimal inventory indexes of stands are indicated at different stages of their growth and development. However, the optimum is a dynamic concept. What is found to be optimal at the given moment will not be optimal after some time. Therefore in a natural forest practically it is difficult to find a stand in which composition, structure and density might be optimal at the given moment. The most productive stands can be formed by systematically regulating the number of trees. The long term experience of thinnings shows that in terms of stand productivity the regulation of the number of trees has the greatest effect in case thinnings recur optimally and the trees for felling are selected correctly.

After investigating the regularities of the growth and formation of stands thinned by removing trees of different classes and different growth intensity the possibilities were found to increase stand increment by intermediate fellings (Kairiūkštis 1969, Kairiūkštis, Juodvalkis 1986). While analysing a response of trees to different thinning intensities it was noticed that the duration of response of trees left after fellings and additional increment depended on stand age, the extent of thinning and on the stocking of the stand prior to thinning. **The younger the stand, the more intensive the thinning and the more dense the initial growing stock, the more considerable response of trees to thinning and the increment of fostered trees for a longer time exceeds** that a trees growing in stands which were not thinned (Figure 6).

A response of trees to better conditions of the growth is not proportional to the enlargement of the area of the growth nor to a decrease in the stocking of stands. Depending upon tree species and age the diameter increment of trees increases when the stocking of stands decreases only up to 0.6–0.3 (Figure 7). **The stocking below which trees no larger respond to thinning is called minimal stocking phytocoenosis, beyond which the functioning of forest as coenosis or ecosystem as well as the effect of its homeostatic forces cease.** Minimal stocking in young stands is 0.3–0.4, in middle–aged 0.4–0.5 whilst in maturing stands 0.5–0.6. The reducing of the stocking below this limit is not expedient neither from the stand point of biology nor forest management.

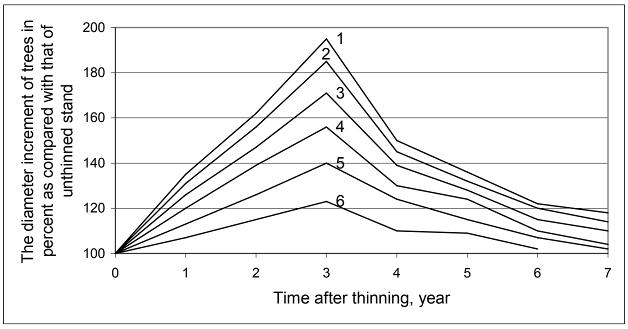

Figure 6. The diameter increment of well developed trees in the thinned 22–year–old oak stand depending upon thinning intensity and the time spare after thinning. Stand volume felled comprised: (1)–60%, (2)–50%, (3)–40%, (4)–30%, (5)–20%, (6)–10%

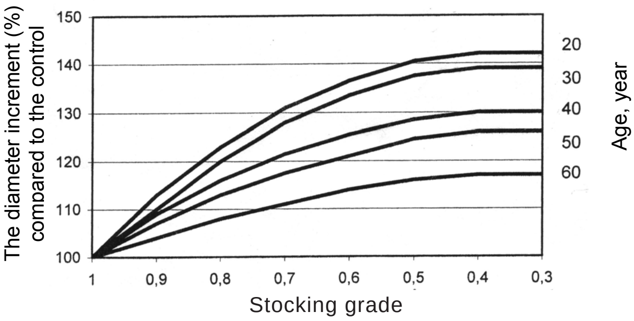

Figure 7. The influence of thinning intensities on the diameter increment of stands aged between 20–60 years

Having determined a response of trees to thinning and to an increase in their increment we investigated: (1) kinds of current increment after thinning and (2) whether the increased increment of trees left after felling can compensate loss of the increment, which the stand incurs after eliminating a part of trees that are increment producers. It has been found that in case stand basal area or their stocking before thinning are identical the increment of thinned stands consisting of soil–lighting and pure additional increment, which result from fellings, will be always larger than the increment of stands where thinnings have not been applied (Figure 8). Depending upon the species and age this difference constitutes from 10 to 85%.

The essence of pure additional increment lies in the fact that the magnitude of the increment of thinned stands depends upon correct selection of trees for felling. In case first nonproductive trees (class C, B, A^1) are eliminated (felled) stand productivity after felling may be up to 12% larger than the productivity of stand from which at the same thinning intensities proportionally to class structure will be eliminated trees (Figure 9) of all classes. Vici versa, if productive trees (class A) are felled first the stand increment by the same thinning intensity may be reduced up to 20% (Kairiūkštis 1969).

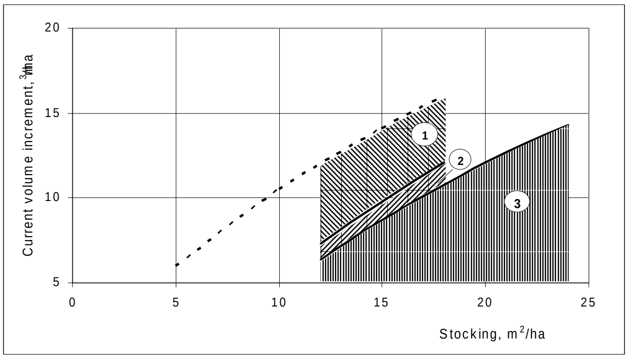

Figure 8. Increment induced by soil–lighting (1), pure additional increment (2) and (3) increment of self–forming stands

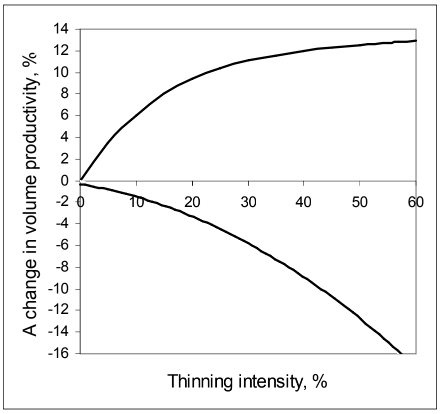

Figure 9. The limits of an increase or a decrease in the current productivity of a storey depending upon the selection of trees for felling

It has been ascertained that if the selection of trees for felling is correct in most cases the increments (pure additional and soil–lighting increment) of thinned stands (even if the stocking of these stands is less than that in self–forming stands) are larger than the increment of stands where thinnings have not been applied (Figure 10).

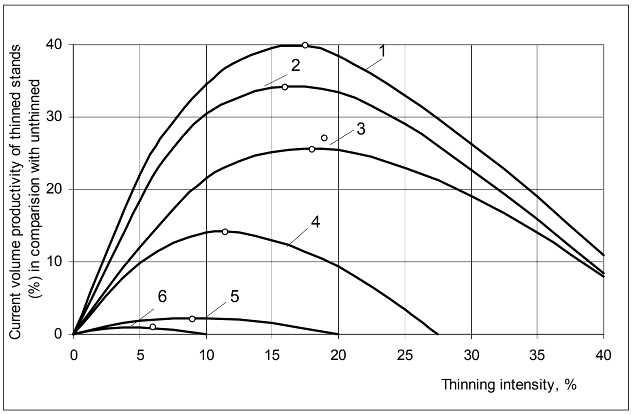

Figure 10. A change in the volume increment (%) of Oxalis spruce stands thinned at different intensities in comparison to that of self–forming (unthinned) stands, 1 – stand aged 24 years; 2 – 27 years; 3 – 25 years; 4 – 36 years; 5 – 56 years; 6 – 58 years; 0 – optimal thinning intensity

It has been determined that under similar other conditions the magnitude of additional increment largely depends upon stand age and thinning intensities. In every age category there exists optimal thinning intensity at which maximal fostering effect is attained (Kairiūkštis, Juodvalkis 1985). With increasing age optimal thinning intensity diminishes (Figure 11). Also the effect of intermediate fellings lessens (Figure 12). In stands older than 60–70 years intermediate fellings are no longer effective. Therefore, any thinning of stands older than 60–70 years reduces their increment, in comparison to that of self–forming – unthinned stands. With increasing stand age not only optimal thinning intensity and the effect of intermediate fellings diminish but also the stocking increases, up to which thinning of stands is feasible without decreasing their increment compared to that of stands which are not thinned. Consequently, in stands older than 60–70 years any regulation of the number of trees for maintaining the largest increment is senseless.

Based on the results of long–term stationary investigations the theory of the most productive forest has been developed. According to the theory also the programmes of forming maximum productive: *Picea abies* Karsten, *Pinus sylvestris* L., *Quercus robur* L., *Fraxinus excelsior* L., *Betula pendula* Roth., *Populus tremula* L. pure and mixed stands according to the prevailing sites in the Baltic region have been created. For practical thinning perposes special tables for each above mentioned species have been established. As one example (Table 3) shows the number of most productive (class A) trees, the distance between them, the basal area and volume of stand to be left after thinning in each table are given. Such tables adopted by the government currently are widely used in Lithuania. They served also for objective quality control of thinnings and intermediate cuttings.

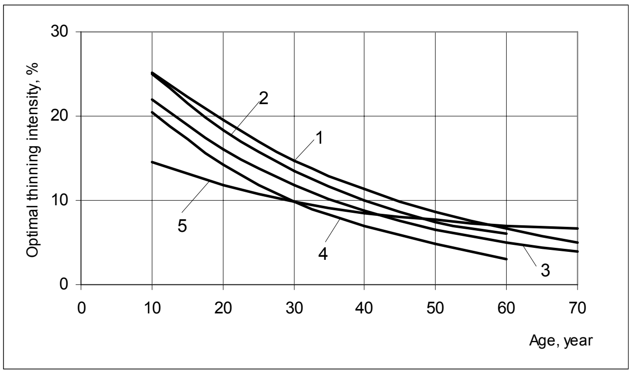

Figure 11. The dependence of optimal thinning intensity on age of different tree species: 1 – spruce stands, 2 – aspen stands, 3 – ash stands, 4 – birch stands, 5 – oak stands

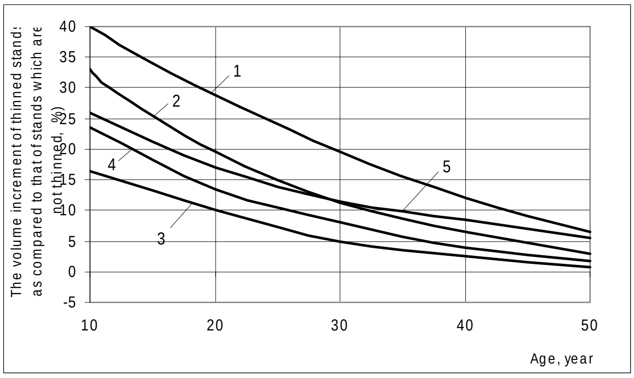

Figure 12. Maximal positive effect of intermediate fellings in different stands. 1 – spruce stands, 2 – aspen stands, 3 – ash stands, 4 – birch stands, 5 – oak stands

General conclusions

The theory of the most productive forest is based on the following determined regularities:

1. In any period of time the largest productivity (the stem increment) of forest (where this or that species grows) depends upon the largest quantity of the energy (least albedo) getting into the stand, the effectiveness of energy consumption in trees and storeys, upon the conformity of tree species for the type of site conditions, upon the quality of trees (classes of tree development) forming the stand, upon their productivity and optimal number of trees properly distributed in the area.

2. The quantity of solar energy reflected from the forest directly depends on the depth of crown surface of a storey: the more stepped the surface of a storey is, the less albedo and the more energy gets into the stand and the more of it is used for producing wood. Trees of different classes use the solar energy differently for creating production. The more productive is the assimilation part of trees (a larger part of light needles and leaves), the larger the increment per volume unit of a stem of a growing tree, the more wood is produced per absorbed energy unit (well developed trees – class A 100%, vigorously developing trees – class A′ 95–97%, weakly developing trees – class B 70–72%, suppressed trees – class C 36–41%). In case the relative coefficient of useful energy use for well developing trees (class A) is equal to 1.0, that for weakly developing trees (class B) is equal to 0.8–0.7 while the relative coefficient of trees of suppressed development (class C) is 0.7–0.5.

Table 3. The number (N) of trees left after felling, the distance between them (1), Basal area (Σg) and the volume in spruce stands when thinnings are repeated every 5 years while intermediate cuttings every 10 years

The height of well developed trees, m	Groups of site types: Myrtillus, oxalido–nemorosus, aegopodius				Oxalis–myrtillus, oxalis–hepaticus, Oxalis			
	N, tree/ha	l, m	Σg, m^3/ha	V, m^3/ha	N, tree/ha	l, m	Σg, m^2/ha	V, m^3/ha
2	2320	2,2	0,3	3	2410	2,2	0,2	2
3	2310	2,2	0,9	5	2400	2,2	0,7	3
4	2290	2,2	2,0	6	2390	2,2	1,5	4
5	2250	2,3	3,2	9	2370	2,2	2,6	7
6	2200	2,3	4,8	15	2320	2,2	4,1	14
7	2140	2,3	6,6	25	2270	2,3	5,9	24
8	2080	2,4	8,8	40	2210	2,3	7,9	35
9	2000	2,4	11,4	59	2140	2,3	10,0	51
10	1920	2,5	13,9	78	2070	2,4	12,4	68
11	1830	2,5	16,5	101	1980	2,4	14,6	89
12	1740	2,6	19,2	128	1890	2,5	17,1	112
13	1640	2,7	22,1	158	1800	2,5	20,0	139
14	1540	2,7	24,9	188	1700	2,6	22,6	165
15	1430	2,8	27,7	222	1590	2,7	25,1	196
16	1330	2,9	30,0	255	1490	2,8	27,2	228
17	1220	3,1	32,4	287	1380	2,9	29,5	256
18	1120	3,2	34,5	321	1280	3,0	31,3	289
19	1020	3,4	36,3	352	1180	3,1	33,5	320
20	920	3,5	37,9	384	1080	3,3	34,7	352
21	830	3,7	39,2	415	980	3,4	35,9	380
22	740	4,0	40,3	443	890	3,6	37,4	410
23	650	4,2	41,1	470	800	3,8	38,3	435
24	580	4,5	42,0	493	720	4,0	39,3	458
25	510	4,8	42,8	517	650	4,2	40,2	485
26	450	5,1	43,6	540	590	4,4	41,0	510
27					540	4,6	41,7	534

3. During intermediate fellings due to elimination of trees using the solar energy non–productively and by forming the stand from the most productive trees of class A energy capacity of a storey is enlarged and the effectiveness of energy use increased. Energy economy (up to 8% from complete lighting of an open place) results in additional (lighting) increment of the remaining trees and creates more favourable conditions for lower storeys and for the growth of underwood.

4. The critical limit of crown approach has been found in the process of forest (ecosystem) forming. Crowns overstepping this limit induce too early the effect of stress on trees (response, suppression, tolerance) during mutual interaction. In case in young age (the phase of vegetative growth) the overstepping of the critical limit of crown approach is not allowed the density of forest ecosystem (young stand) being formed is optimized. It ensures maximal growth in height and diameter for a maximal number of individuals that can grow on the given area (Invention No. 409677).

5. In self–formed or regenerated stands the largest increment of stems is attained in case the stocking of a storey is maximal (depending upon tree species 68–91% of the stand area) and in case maximally productive (class A) trees grow in the storey at an optimal distance from each other. Optimal stand density is determined according to the spatial parameters of the crowns of well developed trees (class A), according to the maximally possible area of storey projection for the given species, optimal crown overlapping degree and according to the space standards indispensable for trees left till the next thinning, which condition optimal volume increment of trees and maximal volume increment of the whole stand.

6. Having optimized the process of forest ecosystem forming (young stand) as well as the density of closed stands (spatial structure, number of trees, quality, distribution) we designed the prototypes (models) of the most productive stands for pure stands of the prevailing tree species growing in the Baltic region. The site types were allowed for. The models of the most productive stands for mixed forests had been constructed according to the principle that it was indispensable to create optimal (or close to the optimum) daylight illumination conditions for the main tree species without reducing the total stand productivity. For this, the dependence of the growth in height of the main species of trees on daylight illumination in mixed stands and lighting intensity in different parts of a storey of mixed stand was determined taking into consideration the stocking of stand. The models were designed for different groups of mixture of stand composition. All the models incorporate optimal stand inventory indexes when the volume increment is largest at this stage of stand growth and development.

7. In a self–regenerated or planted forest practically it is difficult to find a stand which at the given moment completely would meet the requirements of the most productive forest – standard (optimal density, class structure of trees, distribution) since in the growing forest the optimum of indexes is only for a short time. Optimal parameters (assumption of the largest increment) in stand can be maintained by systematical regulation (partial regeneration, intermediate fellings) of them.

8. Due to a positive change in class structure (leaving trees of class A), which results from thinnings and intermediate fellings, pure additional increment is noted. Its maximal magnitude attains 12%, as compared with that when fellings of the same intensity are carried out without changing class structure of trees. Depending upon stand age and stocking positive magnitude of soil–lighting induced increment after thinnings is found to be 40% of the base increment. Depending upon the sum of these increments the increment of thinned stands is usually larger than that of stands where the stocking is less and the thinnings have not been done.

9. In every age and height category there is an optimal thinning intensity at which the sum increment and fostering effect are most significant. With increasing age optimal thinning intensity and the effect of intermediate fellings lessen. In stands older than 60–70 years any regulation of stand density and structure does not result in enlargement of the increment. With increasing age the stocking augments up to which thinning of stands is feasible without diminishing their increment, as compared with that of stands where thinnings have not been done.

The revealed regularities of pure and mixed stand formation (natural and artificial) make up the theory of the most productive forest forming. It defines the conditions necessary to enlarge the increment and total productivity of forests. On the basis of this theory the models (standards) of the most productive forest were designed and the programmes of constructing such models for pure and mixed stands in forests were developed. In accordance with it (a) the beginning of stand density regulation is the onset of ecosystem (coenosis) forming; (b) after stand closing the most productive (class A) trees are left; (c) for limited intervals of time intermediate felling intensity is optimized by diminishing it with increasing age.

The theory of the most productive forest and clarified regularities provided the foundation for developing the programmes and normatives of thinning and intermediate fellings. The normatives are applied in Lithuania and positively affect the forest productivity and sustainability of stands. These normatives are applicable for forests of North East Europe in carrying out thinnings and intermediate fellings.

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ТЕОРЕТИЧЕСКИЕ ОСНОВЫ ФОРМИРОВАНИЯ МАКСИМАЛЬНО ПРОДУКТИВНОГО НАСАЖДЕНИЯ

Л. Кайрюкштис, А. Юодвалкис

Резюме

В статье рассматривается развитие теории максимально прлдуктивного леса и ее применение в практике лесного хозяйства применительно к чистым древостоям: ели, сосны, дуба, ясеня, березы а также применительно к различным типам их смешения. В основу теории положены долговременные (30–50 лет) исследования естественного и искуственного формирования чистых и смешаных насаждений различной первоначальной густоты (100–0,8 тыс. деревьев на 1 га), растущих на более чем 500 постоянных пробных площадях (с нумерированными деревьями, на многих и с зарисовкой планов площадей проекции крон) на которых переучет проводился каждые 5 лет.

В исследованиях открыто новое явление – эффект стресса деревьев наступающий по мере сближения их крон и образования древесного ценоза (экосистемы). Установлена критическая граница сближения крон, по которой оптимизируется первоначальная густота образующегося леса, тогда как оптимальная густота древостоя (возникшего леса) определяется по максимально возможной для данной породы площади яруса состоявшего из хорошо развитых деревьев и оптимальному проценту перекрытия крон.

Установлено что чем большая ступинчатость древесного полога тем меньше альбедо и тем больше солнечной энергии поступает в экосистему. Постоянный переход деревьев из класса в класс определяет различную степень их развития, различную продолжительность их роста в течении вегетационного периода и различную эффективность использования солнечной энергии на образования единицы (1 куб. м) древесины. Максимальная продуктивность древостоя достигается при условии, когда площадь яруса является максимальной, а ярус состоит из равномерно распределенных по площади деревьев с оптимальным перекрытием их крон в данный момент отличающихся максимальной продуктивностью. В чистых насаждениях это деревья класса II по Крафту, в смешанных – класса A по Кайрюкштису, включая деревья переходящих в указанные классы из менее развитых.

Посредством рубок ухода и другими несплошными рубками регулирование оптимальной густоты, качества деревьев и перекрытия их крон при максимально равномерном их распределении на площади, обеспечивает максимальный прирост древесины лучшего качества по всему циклу онтогенеза чистого леса. При этом также достигается высокая, но не максимальная устойчивость насаждения. В смешанных насаждениях при этом учитывается световое довольствие главной породы и разница высот между ней и второстепенными породами.

В статье приводится основные закономерности формирования чистых и смешанных древостоев, даны некоторые прототипы – модели максимального продуктивных древостоев и програмы рубок ухода, которые обеспечивают максимальный прирост. Установлено, что на определенном возрастном интервале древостоя регулирование рубками ухода густоты и качества древостоя позволяет за счет почвено–светового и чистого дополнительного прироста значительно повысить текущую продуктивность древостоя по сравнении с контрольным насаждением (без ухода). По мере старения древостоя возможность повышения прироста посредством регулирования густоты и качества деревьев резко снижается, так как критическая полнота до которой можно разредить древостой, получая дополнительный прирост, резко повышается.

Ключевые слова: эффект стресса, образование ценоза, оптимизация густоты, продуктивность класса дерева, прирост, рубки ухода.