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A METHOD FOR DENSITY CONTROL OF FOREST PLANTATIONS

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Abstract. The main approach to examine the density control regime of forest plantations in Bulgaria has resulted in a partial solution of the problem of plantation management. The main methodological approaches in the world forestry literature to examine the density control are based on studies on the competition among trees and the self-thinning of the stands, and have resulted in important scientific rules, which are the basis of the Stand Density Control Diagram (SDCD). The purpose of this paper is to present the theoretical foundation, the main elements and the application of the SDCD as an integral methodology for density control and plantation management.

Key words: plantation density, stand self-thinning, Competition-Density effect, Stand Density Control Diagram (SDCD)

Stand density is of major importance in establishment and management course of forest plantations. In Bulgaria there have been numerous discussions on the subject leading to conclusions and recommendations for practical silvicultural application in plantation management but they have been based mainly on the empirical experience (Kostov, 1985; Zahariev, 1967, 1974, 1975). The main scientific approach to examine the density control regime of plantations has been practiced through experimental plantations or sample plots in industrial plantations with different planting schemes. They have been subjected to repetitive measurements of the major growth traits of the stands such as diameter at breast height (DBH), height, volume, increment and biomass, as well as measurements and estimations of parameters related to stem quality like crown diameter, branch diameter at the live crown base period of canopy closing, degree of canopy closure, stem quality class. Such kind of studies in Bulgaria have been performed for Scotch pine (Atanasov, 1964; Lyapova, 1984; Zhelev, 1975), Austrian black pine (Bachvarov, Petkov, 1972; Kostadinov, 1980, 1985), oak (Kostov, 1960, 1963), beech (Botev, 1989, 1990a, 1990b), some other tree species (Lyapova, 1990) and various clones of Euroamerican black poplars and black locust. The allometric relationships between spacing and growth traits and among growth characteristics have been established to determine the optimal planting density in order to achieve particular management objectives (Bachvarov, 1965, 1980; Dimitrov et al., 1986, 1992; Kostov et al., 1978, 1992; Lyapova, Palashev, 1980; Popov, 1994; Popov, Kolev, 1994; Zhelev, 1971, 1976). Significant progress toward integral solution of the problem of density could be found in studies by Shikov (1973, 1974a,b) who defined the optimal stand stocking rate (with its corresponding density) through the rate of maximal productivity. On the basis of the defined criterion and using still empirical formulae, the author attempted to recommend a procedure for density control. These approaches, however, have derived a partial solution to the density control of plantations because the observations have been restricted to relatively short periods in comparison with the life span of the tree species, and the conclusions can be used only for the limited range of densities and growth conditions where the studies have been conducted.

There are other methodological approaches in the world forestry literature to examine the density control. They are based on studies of the competition among trees and self-thinning, which are major ecological processes in plant population dynamics. In investigations on growth of plant populations with various densities, the competition effect on the dynamics of the relationship between plant growth and density has been examined and formulated (Shinozaki, Kira, 1956, 1961; Yoda et al., 1963). Shinozaki, Kira (1956) derived the reciprocal equation of the Competition-Density (C-D) effect for even-aged pure plant populations using four assumptions, main of which are the general logistic growth equation as a function of time with two coefficients (the intrinsic growth rate and the upper limit of main plant mass) and the constant final yield per unit area independent of the initial density (Kira et al., 1953). It represents the biomass and/or volume at a given time as a hyperbolic function of density:

$$\frac{1}{w} = AN + B, \qquad (1)$$

where w and N are mean plant mass and density, respectively, and A and B are coefficients. For the total biomass per unit area, the following equation is obtained:

$$\frac{1}{y} = A + \frac{B}{N}, \qquad (2)$$

where y is total biomass and/or yield per unit area ($y = wN$).

In the theory by Shinozaki, Kira (1956), the population density does not decrease with plant growth, i.e. the population grows without self-thinning. The reciprocal equation holds for populations at the same growth stage, and the parameters A and B are dependent on time. By substituting $N \to 0$ in Equation 1, the value of the parameter B is obtained as a reciprocal of the mean plant mass in populations without competition:

$$\frac{1}{w_{N\to 0}} = B.$$

On the other hand, the biological meaning of the parameter A can be derived by substituting $N\to\infty$ in Equation 2:

$$\frac{1}{y_{N\to\infty}} = A.$$

Namely, the parameter A is a reciprocal of the theoretical maximum biomass at a given time or growth stage.

Yoda et al. (1963) studied self-thinning in overcrowded pure stands under cultivated and natural conditions. Experiments with herbaceous (fast growing) populations with very high initial densities have been designed to examine a decrease in density in relation to an increase in mean plant mass. They found that for each density there is a maximal possible (upper-most) mean plant mass, among populations of a species with various initial densities and growth conditions, and it is expressed as a power function of density. According to Yoda et al.'s notation,

$$w = KN^{-\alpha} \qquad (3)$$

and

$$y = KN^{1-\alpha}, \qquad (4)$$

where K and α are constants. These relationships are independent of stand age and growth conditions within a species, and the value of the power α tends to be around 3/2 for all plant species (Yoda et al., 1963). Therefore, this empirically derived relationship is known as Yoda's 3/2 power law of self-thinning.

These two main theories developed in Japan were followed by many re-examinations and supplementary tests. At present, the C-D theory by Shinozaki, Kira (1956) is accepted world-wide. Similar investigations have been made in Europe but the diameter as the growth trait (instead of biomass or volume) was related to density (Reineke, 1933; Sterba, 1987; Sterba, Monserud, 1993). Yoda's 3/2 power law has been more often subjected to criticism and discussions. The law has been argued about the universality of the power constant for all plant species (Smith, Hann, 1984; Osawa, 1995), the value of power constant, 3/2 (Franco, Kelly, 1998), and its constancy in the time (West, Borough, 1983; Zeide, 1987). As a result, this law is accepted in more general form, i. e. the values of the power α and the intercept K are considered species-dependent constants (Jack, Long, 1996). It has also been found that the power constant tends to be around 3/2 for shade-intolerant tree species, and exceeds 3/2 for shade-tolerant ones (Tadaki, 1963).

On the other hand, natural thinning (i.e. mortality) usually occurs in many plant populations growing at wider spacing, in which case the thinning process differs from Yoda's 3/2 power law. This process has been approximated by a reciprocal equation of density in relation to mean plant mass (Tadaki, 1963):

$$\frac{1}{N} = aw + b, \qquad (5)$$

where a and b are constants specific to a stand. Many other, either more complicated and explicit (Aikman, Watkinson, 1980; Puettmann et al., 1992; Tang et al., 1994, 1995) or more practically applicable models (Shibuya, 1995; Hagihara, 1998, 2000; Kikuzawa, 1999) of natural thinning have been proposed afterwards.

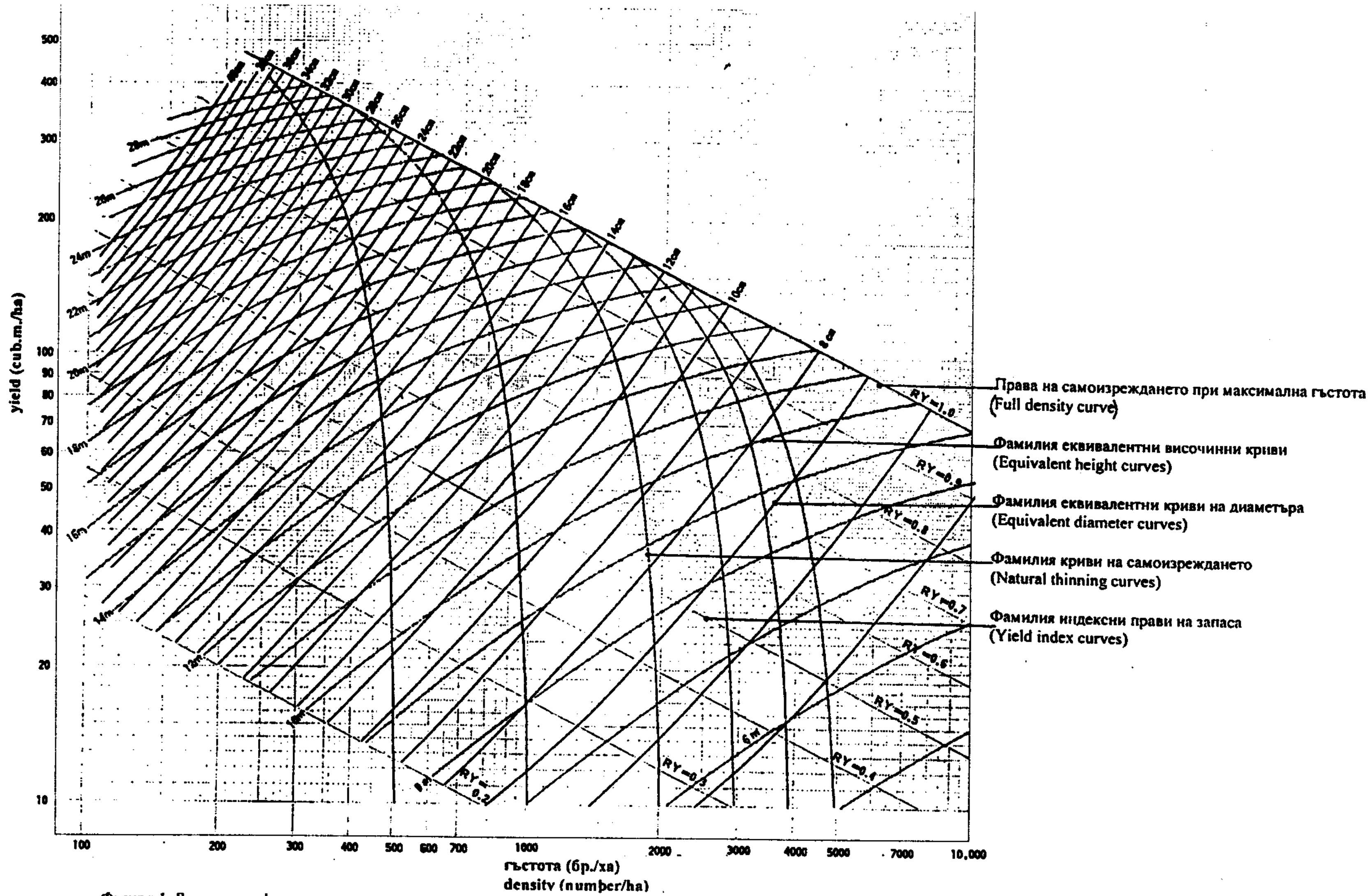
There have been few attempts trying to unify the two theories, the C-D theory and Yoda's power law (Hozumi, 1983; Kikuzawa, 1999; Hagihara, 2000). Hagihara (1999) proposed a model and derived a new reciprocal equation of the Competition-Density effect applicable to both self-thinning and non-selfthinning populations.

The C-D theory and Yoda's power law are the main postulates on which the Stand Density Control Diagram (SDCD) is founded (Ando, 1962; Tadaki, 1964). The theories are applied to two significant components of the Diagram: the Equivalent height curves by growth stage (Equation 2) and the Full density curve (Equation 4) which is presented by a straight line on the double logarithmic scale. An important feature of the Diagram is that the growth stage is presented by the dominant height, not by the physical age because the dominant height is considered to be more stable and less influenced by growth conditions indicator of growth stage. The other important elements of the SDCD (Fig. 1) are Natural-thinning curves expressing density decreasing process of populations of a given initial density (Equation 5 or other models proved to be more appropriate), Equivalent diameter curves connecting stands of the same mean DBH and Yield index curves. Yield index is estimated as a ratio of the yield per hectare of a given stand to the yield of a stand on the Full density curve in the same dominant height class. On the double logarithmic scale, the Yield index curves are presented by lines parallel to the Full density curve (Fig. 1), i.e. they are determined by an equation

$$y = K' N^{1-\alpha} \qquad (6)$$

where K' is a constant.

The Equivalent diameter curves are determined from stand form height, basal area, stand stock (yield), dominant height, diameter and density. The stand form height (*HF*) is defined as a ratio of the stand stock to



Фигура 1. Диаграма за контролиране на гъстотата на естествени насаждения от *Betula ermanii*, Япония.
(по *Inose et al.*, Научен институт по горско стопанство и горски продукти (НИГСГП) – Сапоро, Хокайдо, Япония)
Figure 1. Stand Density Control Diagram for natural stands of *Betula ermanii*, Japan.
(by *Inose et al.*, Forestry and Forest products Research Institute (FFPRI)- Sapporo, Hokkaido, Japan)

the basal area (Equation 7) and is related linearly to the dominant height (Equation 8). From these equations and Equation 9, quadratic mean diameter (d_g) of a stand on a given equivalent height curve is obtained, and the quadratic mean diameter is converted to the arithmetic mean diameter (d) by empirically established equation (Equation 10):

$$HF = \frac{y}{G}, \qquad (7)$$

$$HF = a_1 + b_1 H_D, \qquad (8)$$

$$d_g = 200\sqrt{\frac{G}{\pi N}}, \qquad (9)$$

and

$$d = a_2 + b_2 d_g, \qquad (10)$$

where HF is stand form height, G is basal area, y is stand stock, d_g is quadratic mean diameter, H_D is dominant height, d is mean diameter, and a_1, a_2, b_1 and b_2 are constants.

After successive substitution of Equations 7-10, we obtain the following relationships for the Equivalent diameter curves:

$$y = \frac{HF \pi N d_g^{2}}{40000} \qquad (11)$$

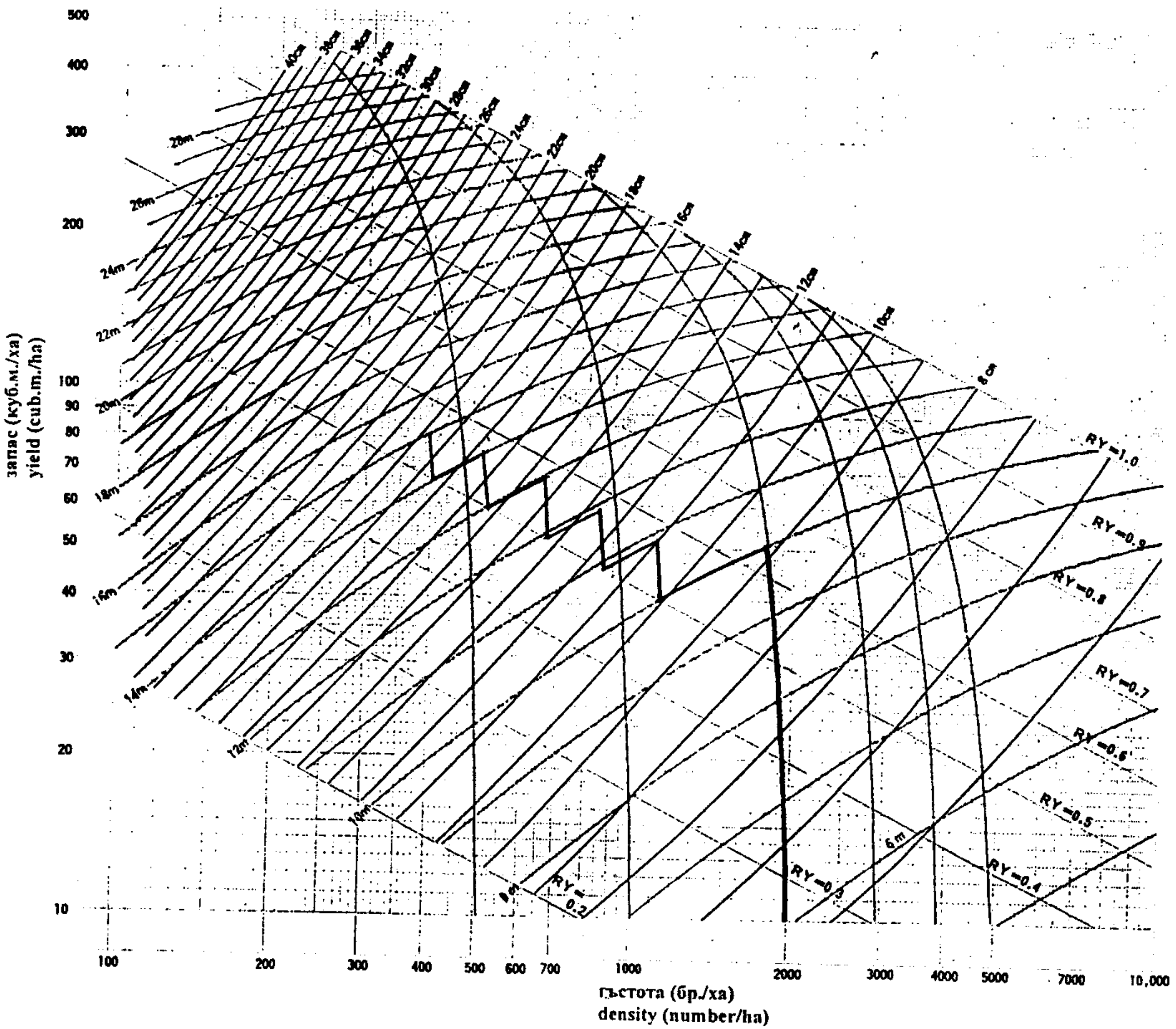
or

$$y = \left(\frac{d - a_2}{b_2}\right)^2 \frac{\pi N}{40000}\left(a_1 + b_1 \overline{H_D}\right), \qquad (12)$$

where $\overline{H_D}$ is dominant height class.

The SDCD is based on ecological rules and is sufficiently accurate as a practical model applicable to simulation of the growth and density dynamics of even-aged pure natural or man-made forest stands under a broad range of growth conditions. The SDCD is applied in three directions. First, it is used to evaluate stand growth. If dominant height and density of a stand are known, the expected stand stock (yield), mean diameter and basal area can be found on the Diagram. If the stand stock is less than the expected one the diameter growth is supposed to be small relative to height growth, and the reasons for this result, e.g. inappropriate growth conditions, abiotic and biotic injuries, can be examined. If the observed stand stock-density relationship differs significantly from the expected one, it is recommended that a correction factor should be applied.

Second application of the SDCD is to simulate various thinning regimes from the establishment to final harvesting of a plantation and to



Фигура 2. Пример за моделиране на режим на отгледни сечи със свеждане на индекса на запаса по време на сечта до Ry=0.5 (Диаграма за контролиране на гъстотата на насаждения от *B.ermanii* по *Inose et al.*, НИГСГП-Сапоро, Япония)

Figure 2. An example of a thinning course. Ry after thinning is kept to be constant. (SDCD for natural stands of *B.ermanii* by *Inose et al.*, FFPRI – Sapporo, Japan)

estimate the total yield and the corresponding profit. Thinning from below and thinning intensity less than 40% are assumed in modeling the management regime. For the shade-tolerant tree species in Japan, stands of yield index 0.8 are considered under the dense management situation, those of yield index 0.7 under the moderate situation and those of yield index 0.6 under the sparse management situation. Usually, three types of thinning models are simulated using the yield index as a criterion in Japan. The first type is that the yield index before a thinning is fixed. In the second type, the yield index after a thinning is fixed (Fig. 2), while yield indices before and after a thinning are fixed in the third type.

The third direction of the application of the SDCD is to determine the optimal initial density of forest plantations in accordance with the preferred management objective and thinning regime.

Besides Japan, SDCD is being constructed and used in some East Asian countries, USA and Canada (Drew, Flewelling, 1979; Smith, 1989; Newton, 1998; Sturtevant et al., 1998; Wilson et al., 1999). The application of SDCD in Bulgaria would be useful for the forest plantations. Because of the large variation in growth conditions (i.e. site quality), the forest plantations of a particular tree species can be presented by one to three SDCDs applicable to the whole country. The main difficulty in constructing the diagram is to collect sufficient stand data, which would allow building of a representative and reliable model. However, once it has been established, SDCD can be used by the Forest Inventory Organizations for planning activities of establishment, management and harvesting of forest stands. Some of the main modeled regimes could be further summarised in a table form, which could be used as a manual in the practical forestry.

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МЕТОД ЗА КОНТРОЛИРАНЕ ГЪСТОТИТЕ НА ГОРСКИТЕ КУЛТУРИ

Татяна Станкова, Масато Шибуя, Акио Хагихара

(Резюме)

Главният научен подход за решаване на въпроса за контролиране на гъстотите на горските култури, използван досега в България, е давал частично решение на проблема. Наблюденията са били относително краткосрочни във времето, в сравнение с жизнения цикъл на дървесните видове и изводите от тях са валидни само за ограничения спектър гъстоти и условия на месторастене, където са провеждани изучаванията. Основните методологични похвати в световната лесовъдска литература по контрола на гъстотите се основават на проучвания върху конкуренцията и самоизреждането, които са основни екологични механизми в динамиката на растителните популации. Тези проучвания са довели до създаването на два важни научни постулата, формиращи основите на диаграмите за контролиране на гъстотата (ДКГ). Първият постулат се изразява

с реципрочното уравнение за конкуренцията и гъстотата, изведено за едновъзрастни чисти растителни популации и представящо масата/обема в даден момент от времето като хиперболична функция от гъстотата. Вторият постулат е Законът на Йода за самоизреждането, според който за популациите от даден растителен вид, създадени с различни начални гъстоти и при разнообразни растежни условия, за всяка гъстота съществува максимално възможно, асимптотично средно тегло, което се изразява като степенна функция от нея.

ДКГ са достатъчно представителен за нуждите на лесовъдската практика модел за динамиката на относително едновъзрастни чисти горски насаждения с естествен или изкуствен произход, при широк обхват растежни условия. ДКГ има 5 основни компонента: фамилията еквивалентни височинни криви, изградени на основата на Реципрочното уравнение за конкуренцията и гъстотата и построени по растежни стадии, представени чрез доминантно-височинни класове; правата на самоизреждане при максимална гъстота, която се представя чрез степенната функция на Йода за самоизреждането (на двойната логаритмична скала приема формата на права); фамилията криви на естественото изреждане, представящи процеса на естествено изреждане на популации с различни начални гъстоти; фамилията еквивалентни криви на диаметъра, свързващи насаждения с еднакъв среден диаметър и фамилията индексни прави на запаса, свързващи точките с еднакъв индекс на запаса. ДКГ имат три основни приложения. Те могат да се използват за оценка растежа на насажденията. Второто им приложение е за симулиране различни режими на стопанисване през целия турнусен период на културите, от създаването им до главната сеч, с оценка на общото ползване от тях. Третата насока на приложение на ДКГ е да се определи оптималната начална гъстота на горските култури в зависимост от целта и начина на стопанисването им. ДКГ в България могат да се създадат и използват за горските култури, като културите от един дървесен вид ще бъдат представени с 1 до 3 диаграми, в зависимост от разнообразието в месторастенията, където са разпространени, и тези диаграми ще бъдат приложими за цялата страна. Веднъж създадени, ДКГ могат да бъдат използвани от Лесоустройствените организации при планиране на създаването, стопанисването и ползването на горските насаждения.

Ключови думи: гъстота на горските култури, естествено изреждане на насажденията, ефект на конкуренцията и гъстотата, диаграми за контролиране на гъстотата (ДКГ)