

© S. P. AREFYEV, A. A. KONOVALOV

sp_arefyev@mail.ru, konov7@rambler.ru

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ON THE DEFORMATION MODEL OF WOODY PLANTS RADIAL GROWTH

SUMMARY. The deformation concept of ecogeosystem evolution is developed as exemplified in the woody plants radial growth. Similar to all natural systems, a tree passes through four stages during its growth: an implicit stage ("antenatal") and three explicit ones: the early (juvenile) stage, the mature stage, and the late (senile) stage. The stages form two semiperiods — hardening and weakening. They correspond with two annual zones on a cross-section cut of a trunk — on its peripheral and central parts. We give typical examples of a long-term dependence of growth for the trees aged 200-400 years in various bioclimatic conditions of the Tyumen Region and other regions, and determine the quantitative regularities of tree radial growth. The curves representing the dependence of a tree radius on its age are well-described by a polynomial of degree 2. The universal formula of radial tree growth speed is developed. The physical sense of the coefficients of this dependence is found out, which allows us to identify biological survival time of various woody plants species. The role of the phase transfer of wood moisture in the annual ring formation and its structural insulation is described.

KEY WORDS. Deformation, model, natural system, cycles, woody plants, wood, annual rings, radial growth.

Introduction. The study of tree morphogenesis regulations has a long history [1-8]. It is commonly known [7] that there are two complementary approaches to the explanation of tree growth and morphogenesis — the physiological and mechanical ones. The first one, emphasizing the role of physiological processes (photosynthesis, transpiration, assimilation, etc.), is mainly oriented to the tree crown; the trunk is considered as an intermediate link between the root system and the leaf apparatus. In the second one, the target of analysis is the trunk, its size, as well as its physical and mechanical properties determining crown parameters (phytomass in particular) and the whole tree functioning. Analyzing pros and cons of mentioned approaches (recognizing the mechanical approach), H.B. Kofman says [7; 81]: "...as opposed to quality physiological theories, all mechanical ones are more constructive, they are carried off to the number and allow implementing their adequacy check to the full extent."

This paper, the purpose of which is to reveal tree radial growth regularities (quantitative ones, first of all) applies the mechanical approach. A solid body deformation model is used as a basis of the analysis [9-10].

The layered tree structure, especially noticeable in the temperate climatic zone with seasonal transitions of temperature over 0°C, reflects the variations of environmental conditions and their succession [11]. Annually, the forming layer can

be considered as the trunk deformation j_r , which will be generally expressed in relative (non-dimensional) form: $j_r = (r - r_n) / (r_m - r_n)$, where r_n , r_m and r are initial, terminal (maximum) and any intermediate trunk radii, respectively [12]. The data analysis demonstrated that starting from about 10-15 years of tree age, its radius stops depending on the initial size, and j_r -value becomes $j_r \approx r / r_m$.

As opposed to mechanically loaded rigid systems, the radial growth is accompanied by the increase in mass. However, it does not affect the general, visible regularities of the body form change occurring under various impacts, including the increase in mass which can theoretically be replaced by a tensile load. By this approach, the progressive accumulation of inner entropy ("fatigue") inherent in every mature system and leading to gradual structure breakdown appears in trees in stable reduction of an absolute and a relative annual ring widths, down to zero, which means the biological death of a tree.

The data and methods of the research. In Fig. 1, we present typical examples of the trunk circle relative radius ($j_r = r / r_m$) and the area ($j_q = (r / r_m)^2$) increasing with time (τ , years), for comparatively long-lived (more than one hundred years) trees in different climatic and biotopical conditions of the Tyumen Region (the town of Labytngi in the forest-tundra zone, the settlement of Numto in the northern taiga zone, the banks of lakes Kuchak and Shaitanskoye in the subtaiga zone) according to S.P. Arefyev's data, and also in Alaska [13]. The trend (approximated) graphs and formulae with their reliability estimate R^2 (the EXCEL software) and trees dating are marked with a thin line. The annual rings width was measured under the microscope on the cylindrical cores 4 mm in diameter, drilled out radially through the center of the trunk at the height of 1.3 m. Therefore, hereinafter, when the trunk parameters are mentioned, we always mean their values on this cross section.

A tree, similar to all nature systems, passes through four stages during its growth: an implicit stage ("antenatal") and three explicit ones: the early (juvenile) stage, the mature (stationary) stage, and the late (senile) stage [12], or, in less detail and more obviously, two semi-periods — consolidation (hardening) and weakening, the border between them falls on the middle of the 2nd stage, the peak of maturity (Fig. 1). On the cross section, these semi-periods are represented by similarly-named zones, the first one lies on the trunk circle periphery, the second one is in its central part. Explicit degradation and decay firstly appear in the center of a trunk and then gradually spread to the periphery. The graphs in the left part of Fig. 1 refer to light-demanding pine (*Pinus silvestris*) and larch (*Larix sibirica*), which cannot tolerate light inhibition and grow intensively from the very beginning. The graphs on the right part of Fig. 1 refer to shade-tolerant spruce (*Picea obovata*) and fir (*Abies sibirica*), which suffer light inhibition from quick-growing woods at the beginning of the growth and enter the intensive growth phase after the latter fall out of the forest stand.

The curves in Fig. 1 are well-described with a polynomial of degree 2: $j_r = ar \pm br^2$ (a and b are numerical coefficients), whence the relative growth speed is $v = d_r / d\tau = a \pm 2br$. In the speed formula, the physical sense of a and b coefficients is clarified: a is the initial speed of growth; b is the acceleration. The b -value depends on the habitat conditions and age: it is more often positive for old trees and negative for young ones.

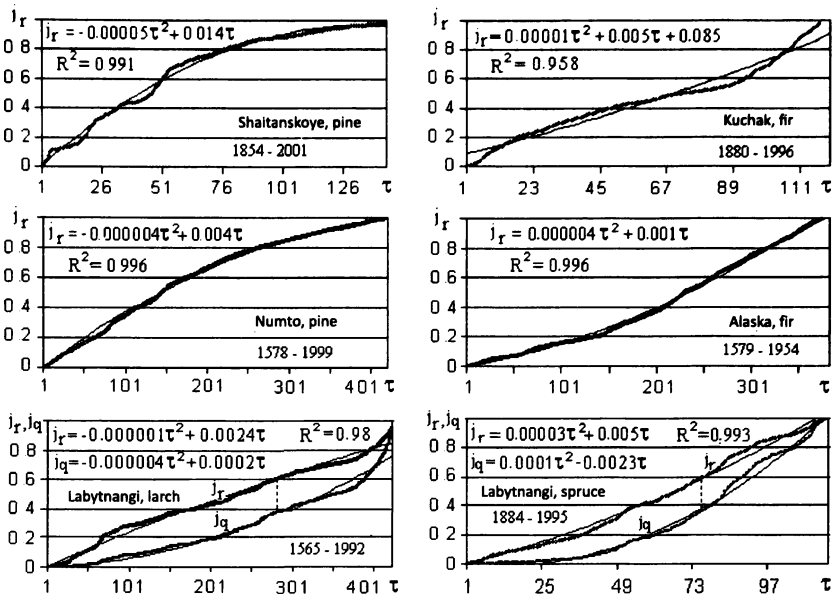


Fig. 1. Typical examples of the j -variation in absolute (τ , years) and relative (j_i) time

The variation graphs j_r and j_q do not essentially differ, but the second ones have the more clearly expressed profile (convexity or concavity). On the time axis, the specific point is marked out, where $j_r + j_q = j_r + j_r^2 = 1$. It characterizes the balance between the increment in closing trunk circumference length ($1 - j_r$), responsible for the surface tension force, and the increasing trunk circle area in a growing tree j_r^2 , responsible for the inner pressure on closing circumference. The balance between them (their equality) is possible only if $j_r = 0.618$ and $j_r^2 = 0.382$, respectively. The number of 0.618 is nothing but a golden section [14] that provides two-component systems of any nature with maximum harmony and stability. Apparently, when the trunk radius reaches this value, the balance between the surface tension and the inner pressure is disrupted and the hardening period goes into the weakening one.

The age features of woody plants (staging) are strongly shaded with long-term fluctuations of heat and moisture. Under these conditions, as it can be observed in Fig. 1, the impact of the genetic properties of the tree species (their susceptibility to light (warmth) or shade tolerance, in particular), on the deformation character increases.

Results and discussion. The modeling data interpretation. The area of a trunk circle can be interpreted as a conventional energy capacity or as a conventional internal energy (they are relatively similar) consisting of two parts: already used, or bound ($j_r = r/r_m$) and free ($j_z = 1 - j_r$).

Their sum equals 1 and their product, understood as the *production* of their interaction product, is $C = j_r j_z$.

In Fig. 2, the graphs representing variations of these parameters are given. They are generally designated as j_i in time (the “complete” graph for Numto and the bisection ones, within the limits $j_i \leq 0.5$, for other locations); they are constructed according to the data presented in Fig. 1. The curve consisting of the segments of the dependence curves $j_r(\tau)$ and $j_z(\tau)$ below $j_i = 0.5$ is the dependence of the

reversible deformation j_y , which, as the C -parameter dependence, adds a cyclic character to the development. The calculations demonstrate that $j_y > C$, but in the beginning and in the end, their graphs practically merge. Both parameters represent the interaction between the real-valued part of the system, which is marked with slanting lines in Fig. 2, and the "hallow". The difference $(j_y - C) = j_{rp}$ can be interpreted as part of reversible energy, which is responsible only for reproductive (seed-producing, "fertile") function of a tree (the upper part of the C -area in Fig. 2 is marked with dots). This function is inherent only in the tree crown, moving upward during the tree growth. It runs out earlier than the other part of reversible energy (C), which is responsible for annual growth of the tree thickness. We should mention that, like all organisms, including the higher ones, the reproductive function and its substance (pollen, spores, etc.) have a strict purpose and are regularly (periodically) secreted even if there is no possibility of fertilization, i.e. in most cases it is excessive and useless for self-reproduction.

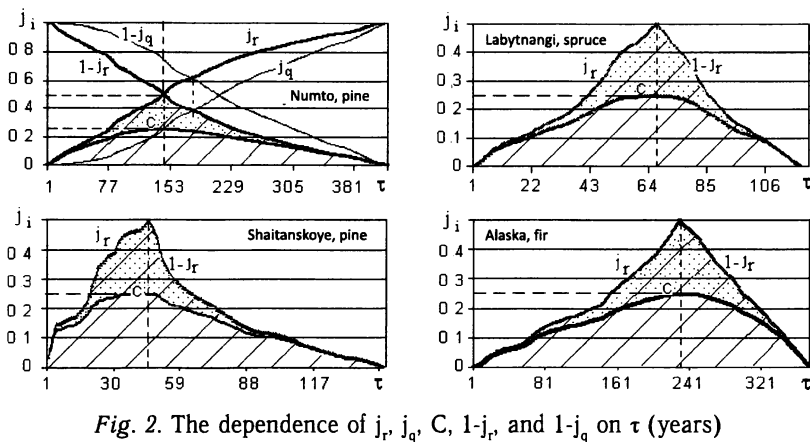


Fig. 2. The dependence of j_r , j_q , C , $1-j_r$, and $1-j_q$ on τ (years)

Within the deformation model, the formation of a tree crown (or a single shrub) is explained by the fact that the stretching force is largely concentrated in one or several points rather than applied to the whole trunk circumference, and the radial growth energy is mainly spent on forming spurs (branches), rather than the ring. Then these spurs develop like the main trunk.

As for the pine in Numto in Fig. 2, in addition to the time dependence of the current relative inner ring length j_r and outer ring thickness $1-j_r$, the dependences of the current relative inner ring area $j_q = j_r^2$ and outer ring area $1-j_q$ are presented. The calculations and graphs demonstrate that always $j_q = j_r^2 = j_r - C$, and the golden section $j_r = 1-j_q = 0.618$ is located at the crossing point of the curves j_r and $1-j_q$ (see also the graphs in Fig. 1 for the fir and spruce in Labytngangi).

The graphs for deformation, attributed to the deformation at the moment of observation, like those presented in Fig. 1-2, represent the actual correlations between j_i -parameters only for 1) an old tree with the end of life rather close to the year of observation and 2) any tree at the end of the vegetation period, if the growth of the annual ring is observed as the one of a separate plant. In the other cases, they are quite arbitrary. At the same time, they give a clear idea of radial deformation components and their correlations.

The modified deformation model. Express current trunk radius and its annual growth in terms of ratio of the smaller ring radius r_1 to the larger one r_2 : $j_{r1} = r_1 / r_2$; $j_{\Delta} = 1 - j_{r1} = 1 - r_1 / r_2$. Similar to j_r and j_z , these ratios vary in the interval 0...1, but while in the former ones, only the numerator is a variable, in the latter ones both the numerator and denominator (both r_1 and r_2) are variables. Thus, there appear new opportunities to research the regulations of wood plants radial growth, in particular, the long-term relative annual ring thickness dependence (j_{Δ}) and the evaluation of the biological age of a tree.

According to our observations, j_{r1} increases during life, and the increase is especially intensive in its beginning (up to 90% of the final value in the first 10-15 years of life), and j_{Δ} , on the contrary, decreases, its maximum is in the first year of life. At the top of Fig. 3, there are graphs of the time dependence of relative 5-year moving averages of the current trunk radius j_{r1} , the annual ring width $1 - j_{r1} = j_{\Delta}$, and the elasticity factor $C = j_{r1} \cdot j_{\Delta}$ for two old trees (according to Fig. 1 and 2) — a light-demanding pine in Numto and a shade-tolerant fir in Alaska during the first 20 years of life; for the pine in Numto, there is also the dependence of the current trunk circle area j_{q1} and the annual ring area ($1 - j_{q1}$). In y direction of the graphs (the ordinate), these parameters are denoted with the same symbol — j_{ii} . As in Fig. 2, the shaded area limited with the segments of curves j_{r1} and j_{Δ} below the horizontal line $j_{ii} = 0.5$ represents the “life energy” (elasticity), but not that of the whole tree (as in Fig. 2), but only of the current annual ring j_{yr} . Its reproductive part $j_{rpl} = j_{yr} - C$ is marked with dots. As it can be seen in Fig. 3, on the given cross section (1.3 m), the elasticity is already exhausted in the 6th-12th year of life, which is indicated by the merging of the curves j_{Δ} and C . As in Fig. 2, the trunk circle area $j_{q1} = j_{r1}^2 = j_{r1} - C$, and the annual ring area $j_{z1} = 1 - j_{q1}$. The observation proves that the average time dependencies of all but C deformation indicators of both light-demanding and shade-tolerant plants are well-described with a homomorphous power function, and with time they smooth out to such an extent that in about 100...150 years turn into linear ones. For example, at the bottom of Fig. 3, the dependence of the annual ring width values j_{Δ} averaged according to the current coordinates r and τ during the 100 years before the observation, as well as its approximation, are presented for the same trees. The linear character of the dependence of j_{Δ} on τ allows us to give the approximate estimation of the biological tree lifetime, i.e. its maximal survival time τ_m in the absence of fires, storm damage, and other disasters.

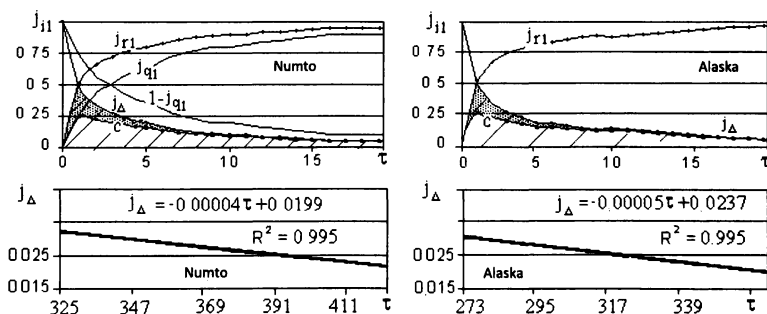


Fig. 3. Dependence of j_{r1} , j_{q1} , C , $1 - j_{r1}$ and j_{Δ} on τ (years) during the first 20 years of life and the dependence of j_{Δ} on τ during 100 years before the measurement

Biological survival time τ_m . The biological death of a tree occurs when its ring width reaches critically small, close to zero value and the ring becomes obstructive, making metabolism impossible. Substituting $j_A = 0$ into the straight-line formulas in the bottom graphs of Fig. 3, get the $\tau_m = 273 + 0.024 / 0.00005 = 753$ (years); $\tau_m = 273 + 0.023 / 0.00006 = 656$ (years) for the pine in Numto and the fir in Alaska, respectively.

The role of the temperature dependence of water density. The annual ring formation, deformation, and structural insulation are sufficiently determined by the phase transfers of the wood moisture, or water-supply properties. In Fig. 4a, there is a graph that represents the dependence of water density ρ_w on temperature t °C [6], and there is also its approximation formula.

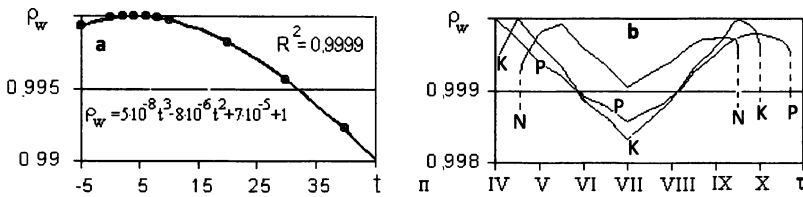


Fig. 4. The dependence of ρ_w on t and τ (months), n is for Numto, k is for Krasnoyarsk, p is for Podmoskovye (the Moscow Region)

When wood moisture crystallizes in the beginning of winter, its volume sharply increases, creating tension. When the latter exceeds the ultimate rupture strength of tracheide or bark walls, frost clefts appear. Moreover, ice crystals obstruct the water-conducting tissues, interrupting the metabolism. The moisture decrystallization, which occurs in the temperate climatic zone in April-May and in the subarctic one in May-June, cause the reduction of the volume by 8.33% and the formation of cavities in the tree body, which are oriented along the movement of the thawed moisture. As a consequence, negative pressure appears in tracheides, which have a longitudinal-canal shape and are connected into an integrated system. The negative pressure adsorbs telluric moisture, the “raw material” for wood-formation, into them until they are completely saturated. The density of moist wood is about twice lower than that of water, so its production is accompanied by the increase in volume.

In Fig. 4b, the dependence of water density ρ_w in warm months of the year in different climatic conditions (n for Numto, k for Krasnoyarsk, and p for Podmoskovye) is presented; it was calculated according to its formula (see Fig. 4a) and the data from synoptic stations. Two peaks of increased water density are registered: spring-summer on the rise and summer-autumn on the dip; they determine the morphological properties of young-growth wood and latewood. The low-density water is more mobile, this facilitates metabolism in cambium and the wood tissue formation within the time segment between the density peaks. The cell size reaches maximum values during this period. Apparently, it is the lack of density (the lack of mass with the volume increased) in the “potential pit” between these peaks that provides the physical opportunity to grow the tree skeleton mass.

Conclusion. Thus, the proposed model of woody plants radial growth based on the universal regularities of physical body deformation quite adequately explains the structural and functional dynamics of biological processes in wood bodies.

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