Trees as a water transport system

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TIIVISTELMÄ: PUUN RAKENNE VEDENKULJETUSSYSTEEMINÄ


The structure of 20 Scots pine (Pinus sylvestris L.) trees was analyzed as a water transport system. There is a tight linear regression between the cross-sectional area of the stem at the height of its lowest living branch and the cross-sectional area of its roots, between the cross-sectional area of the stem at the height of its lowest living branch and the total cross-sectional area of its branches, and between the cross-sectional area at the base of a main branch and the total cross-sectional area of its subsidiary branches. The capacity of successive organs, measured as cross-sectional areas, to transport water was thus found to be regular within a tree.


Keywords: cross-sectional area, stem, corse roots, branches, water transport system, Pinus sylvestris

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Introduction

Establishing whether or not regularities exist in the structure of trees represents a valuable tool for estimating the current state and growth of tree stands. Such relationships have often been derived on a purely empirical basis, for example the allometric power laws (Ledig 1969). It seems reasonable to assume, however, that if structural regularities exist, they should be associated with functional systems that are dependent upon such structures. A balance between structure and function makes the system more efficient from the point of view of energy and material consumption, and can hence be expected to have increased in proportion during the course of evolution. If this is true, then it would appear that structural regularities are derived from the requirements of metabolic function. There is a lot of empirical evidence to indicate that the cross-sectional area of tree stems is correlated with the leaf area, i.e. the transpiring tissue (e.g. Rogers & Hinckley 1979, Waring et al. 1980, Kaufman & Troedde 1981, Waring et al. 1982). A theoretical basis for this relationship has been suggested in the pipe model theory presented by Shinozaki et al. (1964a, 1964b).

Both empirical and theoretical considerations emphasize that trees have a balanced structure in which the size of the transporting tissue is related to that of the consuming tissue. The present paper is a further development of the idea. We examine the relationship between the size of different transporting tissues. The cross-sectional areas of the coarse roots, the branches and the stem of Scots pine (Pinus sylvestris L.) are considered within the framework of a physical analog model.

Theory and model

The water transporting tissue in the stem and branches of coniferous trees is formed of elongated tracheid cells. Water movement between tracheids is facilitated by numerous pits in the tracheid walls. The water transporting part of the tracheids, as well as the water transporting capacity of the pits, is smaller in latitudinal than in earlywood (Bauch et al. 1972). Compared with the vertical water flow, the horizontal flows between growth rings are negligible. The velocity of the water flow in confers is less than 1 m/h (Huber 1956). This means that the flow of water is non-turbulent.

A physical model of water flow in the stem and branches can be derived by forming hydrodynamical equations describing the flow through the tracheids and pits between the tracheids. The macroscopic properties of the water flow can then be derived from the microscopic model. Many difficulties will, however, arise because of the complicated structure of the conducting system. A different approach to modelling the physical situation is adopted in this paper. The main physical properties of the water flow are described by means of an approximate model.

Compared with the outside dimensions of pine, the tracheids are so small that fluctuations in the flow between single tracheids can be neglected. The process is approximated by a steady, laminar flow, i.e. there are no oscillations in the flow over time. The water is running in sheaths arranged inside one another. A sheath thus describes a growth ring. It is assumed that there is no movement of water between the sheaths.

The essence of the above assumptions is that the storage of water in the stem remains constant and that the dimensions of the growth rings do not change. It is therefore a question of an analogy model which is applicable to long-term considerations only. The velocity of the steady flow could be interpreted as the mean annual velocity of water flow through the growth rings, but the analysis below is not confined to any particular interpretation.

Let $dA$ be an infinitesimal area in a sheath. Let $v$ be the velocity of the water moving along the sheath. The water volume $dQ$ flowing through the area $dA$ in unit time is

$$dQ = v \cdot dA.$$  \hspace{1cm} (1)

The mean velocity of the flow over the cross section of a sheath is defined as

$$v = \frac{Q}{A} = \frac{1}{A} \int v \cdot dA,$$  \hspace{1cm} (2)

where $A$ is the cross-sectional area of the sheath.

Consider the flow of water at two heights $h_i$ and $h_o$. Denote the cross-sectional areas with $A_i$ and $A_o$, velocities with $v_i$, $v_o$, and mean velocities $v_i^m$, $v_o^m$ correspondingly. It follows from the conservation of mass that

$$\int v_i \cdot dA_i = \int v_o \cdot dA_o.$$  \hspace{1cm} (3)

Eqs. (2) and (3) yield, when combined,

$$v_i^m \cdot A_i = \text{constant}.$$  \hspace{1cm} (4)

Let $A_i$ be the cross-sectional area of a growth ring in the stem and $v_i^m$ the corresponding mean velocity of flow. Let $A_i$, where $i = 1, \ldots, n$, be the cross-sectional areas of the same growth ring in the main branches above the point in the stem where $A_i$ is measured. Let $v_i$ be the corresponding mean velocities in the branches.

Using the conservation of mass, the amount of water flowing through the stem and through the branches, are obtained

$$A_o = \frac{1}{v_o^m} \int v_o \cdot dA_o.$$  \hspace{1cm} (5)

This equation can be generalized to a set of sheaths one inside the other, i.e. to the whole cross-sectional areas of the stem and main branches.

If it is assumed that the mean velocity of the water flow is the same in all the main branches, then the model predicts that there is a linear regression between the cross-sectional area of the stem and the sum of the cross-sectional areas of the main branches above this part of the stem, i.e.

$$A_i = \frac{v_i^m}{v_o^m} \cdot A_o.$$  \hspace{1cm} (6)

$v_o^m$ is the mean velocity of water in the branches.

The present article analyses the structure of a number of Scots pine trees within the framework of Eq. (6). The objective is to examine whether or not such a correlation exists, whereas the interpretation of the correlation coefficients in terms of real water flow velocities is not attempted. The relationship between the stem and the branches is analysed as indicated above, and the analysis is further extended to the analogous case of the stem and the coarse roots.

Methods and material

The study was carried out in a 40-year-old Scots pine (Pinus sylvestris) stand situated near the field station of the Forest Institute of the Karelian branch of the Academy of Science, USSR, 50 kilometres from Petrozawodsk. The stand had regenerated naturally after a forest fire. The soil at the site consisted of sand, and the site was of the Calluna site type according to the classification of Cajander (1946). The variation in the size, age and density of the stand was rather large. The mean diameter was 4.5 cm, the mean height was 5.7 m, and the volume was 75 m$^3$ ha$^{-1}$.

The diameters of the large roots, stem, main branches and intermediate branches were measured under bark to an accuracy of 0.2 mm. The stems and branches were measured near to the mid-point between successive whorls. The diameter of the roots was measured at the point where the rapid tapering of the roots ceased and the root attained a stable diameter. The location of each measuring point was determined subjectively.
Results

As the large roots supply water to the stem, the cross-sectional area of the water transporting tissues in the stem and in the large roots should follow Eq. (6). The regression between the total cross-sectional area of the roots and the cross-sectional area of the stem at the height of the lowest living branch is shown in Fig. (1). The amount of water flowing in the stem is the same as that flowing through the branches. Thus Eq. (6) should also hold for the cross-sectional area of the stem and the sum of the cross-sectional area of the branches. The regression between the cross-sectional area of the stem at the height of the lowest living branch and the total cross-sectional area of the branches in a tree is shown in Fig. (2). A pine branch and a whole pine tree have the same geometrical structure: the leading shoot of a branch corresponding to the stem and the subsidiary branches of a branch corresponding to the main branches extending from the stem. The regression between the cross-sectional area at the base of a main branch and the total cross-sectional area of its subsidiary branches is close (Fig. (3)).

The cross-sectional area of a stem and the total cross-sectional area of the main branches above a point can also be analyzed within a tree. As the observations are no longer independent of each other, a high degree of inter correlation can be expected. For this reason, the main interest should be focused on the form of the regression. The regression for an example tree is presented in Fig. (4). Laasanenaho (1982) has reported the cross-sectional area of the stem and the sum of the cross-sectional area of the branches as a function of height in three trees. The results are in agreement with the close linear regression found in this study between the cross-sectional areas. The same type of regression can also be determined for a main branch and its subsidiary branches (Fig. (5)).

Discussion

It is clearly apparent from Figs. (1) – (5) that the relationships between the cross-sectional areas tend to be linear. The lower measuring accuracy of the roots is reflected as a greater degree of variance in Fig. (1) than in Figs. (2) and (3), which are based on more exact measurements. There are two points in Fig. (2) which lie outside the general regression lines. The general shape of these trees differed from the norm for the stand: one had very short and the other very long branches. The regressions within a tree also seem to be linear in Figs. (4) and (5).

According to the hypothesis, the slopes of the straight lines in Figs. (1) – (5) are determined by the mean velocity of the water flow. The water transport capacity of the wood in the different parts of a tree is determined to a
great extent by the cross-sectional area of the pores of the tracheids. The area of pores is closely associated with wood density, such that wood of low density has more pores than wood with a high density. The density of wood increases on moving from the roots to the stem, and again from the stem to the branches. The cross-sectional area of water-transporting wood (Figs. (1) and (2)) increases on moving from the roots to the stem, and again from the stem to the branches.

The strength properties, which undoubtedly affect the shape of a tree, are not considered in this model. It is evident that the forks of branches are affected by strength requirements and also that the shape of the base of a stem is affected by the mechanical strength requirement (Vilen 1952).

The results support the hypothesis that the structure of the transporting tissue of Scots pine is in balance with the water transport requirements. The systematically collected empirical material is so far limited only to a single stand. The results should be confirmed by measuring additional stands representative of stands growing on different site types and of different origin. The correlations between the cross-sectional area of the stem and the amount of leaves or needles could be generated by a balanced system of water transport and transpirative demand. Thus the observations of Kaufman and Troeddel (1981), Waring et al. (1982) and Albrektson (1984) suggest that the result can be extended to cover several tree species.

References


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Männyn puuaineen laadun ja tuotoksen vaihtelu suomalaisessa proveniensskojesarjassa

Pirkko Velling & Gérard Nepveu

SUMMARY: VARIATION OF WOOD QUALITY AND YIELD IN A FINNISH SERIES OF PROVENANCE TRIALS ON SCOTS PINE

RESUME: VARIABILITÉ DE LA QUALITÉ DU BOIS ET DU RENDEMENT EN MATIÈRE SECHE DANS UN TEST MULTISTATIONNEL DE PROVENANCES DE PIN SYLVESTRE D’ORIGINE FINLANDEISE.


The purpose of the study was to determine the effects of the origin of seeds and the location of cultivation of Scots pine on certain properties particularly important to the pulp industry. The research material consisted of six parallel trials of the same 12 provenances. Increment cores were taken of a total of 1267 sample trees, 19 years old. The location of the trial site generally affected the properties to a larger extent than the origin of the seed. The effect of the variation of wood density and fiber yield on the cultivation values of the provenances was only a few percentages of average; however, at most the effect was nearly 10%. Eastern Finnish provenances adapted well to western Finnish conditions.

L’objet de l’étude a été de déterminer les effets de l’origine de la graine et de sa localisation de plantation sur certaines propriétés importantes, en particulier pour l’industrie de la pâte à papier sont examinés dans cette étude. L’échantillonnage provenait de six dispositifs expérimentaux parallèles dans le cadre desquels étaient étudiées les mêmes 12 provenances. L’étude rentrait 1267 arbres âgés de 19 ans sur lesquels des carottes de sondage étaient prélèvées. La localisation de la plantation influait en général sur les caractéristiques du bois plus que l’origine de la graine. L’effet de la variabilité de la densité du bois et du rendement en fibres sur les valeurs de reboisement des provenances n’était en moyenne que de quelques pour-cent, les plus fortes valeurs approchant néanmoins 10%. Les provenances de Finlàndie orientale se comportaient bien en Finlande occidentale.

Key words: Pinus sylvestris, geographical variation, increment cores

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