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PRODUCTION OF ENERGY MATERIAL BY FOREST STANDS AS RELATED TO SUPPLY OF SOIL WATER[1]

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SELOSTE:
METSIKÖIDEN ENERGIA-AINEEN TUOTTO SUHTEESSA MAAN VESIMÄÄRÄÄN

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Introduction

On several occasions students of environment have made attempts to evaluate the growth of different plant and animal communities in terms of calorific values and to relate the production of energy material to the incident solar radiation (LINDEMAN, 1942; WASSING, 1959; OVINGTON and HEITKAMP, 1960; OVINGTON, 1961).

In some sectors of biology this approach promises certain advantages, but in the realm of timber production it encounters obstacles of both practical and theoretical nature. An estimate of the radiation is hindered by inadequate records of sunlight, the difference in the effect of the short- and long-wave radiation, and uncertainty about the value of the reflection coefficient. At best, the use of proximate formulae (PENMAN, 1956) can provide only general information for

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a broad area, not individual stand. The forests entrap only a very small fraction of the sun's energy and the importance of radiation as a growth factor in silviculture is largely confined to uneven-aged stands, such as found in practice of »everlasting forests» (Dauerwald). Under such a method of management, a considerable fraction of the increment is often lost due to the failure of the forester to timely remove the senile members of the overstory which deprive the light to the young trees of the high growth potential. On the other hand, an increase of radiation by partial cuttings of even-aged stands as a rule does not produce the slightest increase of the volume.

Another important detail is that available sunlight plays in photosynthesis a very minor part in comparison with the soil's supply of water, air, and nutrients. Depending on the state of these critical factors, the annual biomass increment of forest ecosystems, receiving the same amount of radiation, varies within an enormous range from a few hundred to more than 15 000 kg per hectare. A few studies of energy relations in forest stands, reported to date, were conducted with no consideration of the productive capacity of soils and are of limited practical significance.

This study was undertaken with the intention of outlining the role of soil water in accumulation of energy material by forest cover. For this purpose, soil and growing stock of a 32-year-old plantation of red pine, *Pinus resinosa* Ait., were subjected to analysis. The determination of statistically significant averages was considerably facilitated by the nature of the red pine stand and its sandy soil of glacial outwash; both of these show a remarkable uniformity in their external as well as internal features (shape of trunks, specific gravity of wood; texture, bulk density, permeability, and water retaining capacity of the soil). Both aeration and fertility of the soil in this case were more than adequate for the requirements of red pine stands. Soil and timber analyses were performed by methods described by Wilde *et al.* (1964).

Water as a Factor of Forest Growth

Water, be it in the form of soil constituent, measurable or nonmeasurable precipitation, or air humidity, more often than not determines the increment of forest stands. Water available for transpiration exerts direct influence on photosynthesis; together with temperature it delineates the duration of root activity or the actual period of tree growth. An adequate content of soil water greatly augments the supply of available soil nutrients through extended activity of rhizospheric organisms and increased breakdown of silicate minerals. As recent studies have shown (Wilde and Iyer, 1963), the presence of ground water at a depth between 4 and 9 feet extends the *de facto* growing season of pine plantations from 6 or 7 to nearly 14 weeks thereby doubling the increment of trees.

Even high air humidity, leading to reduced evaporation and occasional »intra-sylvan rain», or a drip of water condensed on tree crowns (Kittredge, 1948; Remezov and Pogrebniak, 1965), appreciably increases the rate of forest growth. For example, Wisconsin forest plantations in the fog belt of Lake Superior yield about 30% higher increment than that given by regression equations for stands in the continental parts of the State (Wilde *et al.*, 1965).

Production of Biomass by Red Pine Stands as Related to Water Supply of Sandy Soils

The composition of soil and growing stock of the object of this study, Keshena red pine plantation, was reported previously by Wilde *et al.* (1965, plantation No. 98). This 32-year-old stand of an excellent rate of growth was established in the former Menominee Indian Reservation (Figure 1). It is supported by non-podzolic Plainfield (Omega) sand of glacial outwash enriched in silicate minerals and exhibiting a higher than average level of fertility for this soil type (pH 5,2, fine separates — 10,0%, organic matter — 2,0%, exchange capacity — 4,1 meq/100 g, available P_2O_5 — 80 kg/ha., available K_2O — 200 kg/ha., exchangeable Ca — 1,40 meq/100 g, and exchangeable Mg — 0,29 meq/100 g).

According to the regression equation, $-26{,}8 + 8{,}7$ pH $+ 0{,}55$ p.ct. fine separates $+ 6{,}25$ p.ct. org. matter $+ 0{,}17$ kg $P_2O^5 + 0{,}02$ kg K_2O, the height increment of 54 cm. per year indicates the growth potential exceeding site index 65.

Figure 1. A view of a sample plot in the 32-year-old red pine Keshena plantation.
Kuva 1. Näkymä koealalta 32-vuotiaassa Pinus resinosa-viljelymetsikössä.

The stand has the following average growth features on a per hectare basis: height — 14,4 m., DBH — 15,5 cm., number of stems — 2 175, basal area — 39 m^2, total volume — 243 m^3, average increment — 7,6 m^3, current annual increment — 10,2 m^3. The last figure would be regarded with a degree of respect by many foresters.

The volume and weight of merchantable and non-merchantable wood was determined by measuring trees on two 0,25 ha plots and by analysis of several trees of average height and diameter. No laborious separation of branches and foliage was attempted. The excavation of roots by hand presented particular difficulties, in part because of the occasional inter-grafting of root systems. This task, however, eventually was greatly facilitated by the use of hydraulic jets, provided by the fire control division of the Wisconsin Conservation Department (Figure 2). The oven dry weight was determined by subsampling small parts of the air-dry material. The weight of the annual »leaf fall», or fall out of dead tree fragments, such as needles, cones, and twigs, was determined by collecting material in 60 by 60 cm. wooden traps provided with 15 cm. legs and screen bottoms. The fact that the weight of the discharged organs of trees approaches, and at times even exceeds, the weight of the annual increment of merchantable

Figure 2. Excavation of the root system of red pine by means of a hydraulic jet of a 2,000 gallon capacity.

Kuva 2. Männyn juuriston paljastamista vesisuihkun avulla.

timber is a significant detail from the standpoint of both soil fertility and forest management.

Considering that the non-merchantable material of the forest stand has the same increment as the merchantable timber, the annual production of dry matter per hectare is as follows:

Merchantable timber, 10,2 solid cubic meters with specific gravity of 0,38	3 876 kg
Tops below 7,5 cm. diameter	400 »
Branches and foliage	960 »
One-foot stumps	410 »
Roots	1 190 »
Leaf fall	3 260 »
Total, about	10 100 kg

The determination of the calorific values of different parts of trees, such as boles, branches, and roots, by the use of an oxygen bomb calorimeter was not performed because of the questionable significance of this analysis. The energy content in terms of calories is related to the oven dry weight of tissues and, for practical purposes, can be easily obtained by the use of a suitable conversion coefficient, such as $0{,}016 \times 10^5$ cal. per gram.

The annual production of dry matter by the Keshena plantation is equal to about 162×10^5 kcal/g, and is near the maximum attainable on this soil type.

The water supply of non-phreatic soils effective in the wood production comprises largely the balance between the following components: gains from winter storage, summer precipitation, and water of condensation; losses due to interception and evaporation by trees and ground cover plants, evaporation from bare soil, and gravitational discharge. In the case of outwash sandy soils supporting fully stocked stands without competing vegetation, the supply of water available for transpiration can be estimated with a fair degree of accuracy, as given in the following paragraphs.

According to many years' observations, the interior of Wisconsin receives during the growing season (May to September) about 350 mm. of rain water. Considering the perennial nature of forest crops, the average data have considerable reliability and the error of estimate in this case should not exceed 5%.

The soils of central Wisconsin are not influenced by the proximity of large bodies of water or subjected to extremes of day and night temperature. In localities of this type, the summer condensation of water does not contribute more than 25 mm. to the moisture supply of the 1,20 m. surface layer of forested soils (MOLCHANOV, 1960).

Nuclear probe analyses of several years' duration have established that the 1,20 m. root zone of coarse sandy soils retains against percolation and evaporation about 8% by volume or 100 mm. of water. With this low field or evapo-percolation capacity, nearly half of the 60 mm. of winter stored water is drained from the root zone prior to the initiation of tree growth (DE VRIES and WILDE, 1962).

Thus, the total supply received by the sandy soils during the growing season is in the proximity of 400 mm.

The dense coniferous plantations, such as those of red pine, intercept by their crowns and evaporate back at least 30% of the rainfall or 100 mm. of water (KITTREDGE, 1948). On the other hand, studies employing tension lysimeters (KRAUSE, 1960; KRAUSE and WILDE, 1960; HABERLAND and WILDE, 1961) disclosed that the 1,20 m. surface layers of outwash sand supporting dense plantations lose by gravitational discharge during the summer months about 25 mm. of rainfall.

Therefore, the balance of water available for active growth of fully stocked stands is about 275 mm., constituting 2 750 cubic meters or metric tons (2 750 000 kg) per hectare.

Because the annual biomass increment of the Keshena plantation (10 100 kg/ha.) was obtained with 2 750 000 kg of water, it required 272 kg to produce 1 kg of dry matter, or 1 000 kg of water per 3,7 kg of energy material. The corresponding transpiration coefficient of 0,37 % is considerably higher than the average of the estimates made for the Great Plains of North America (STOCKER,

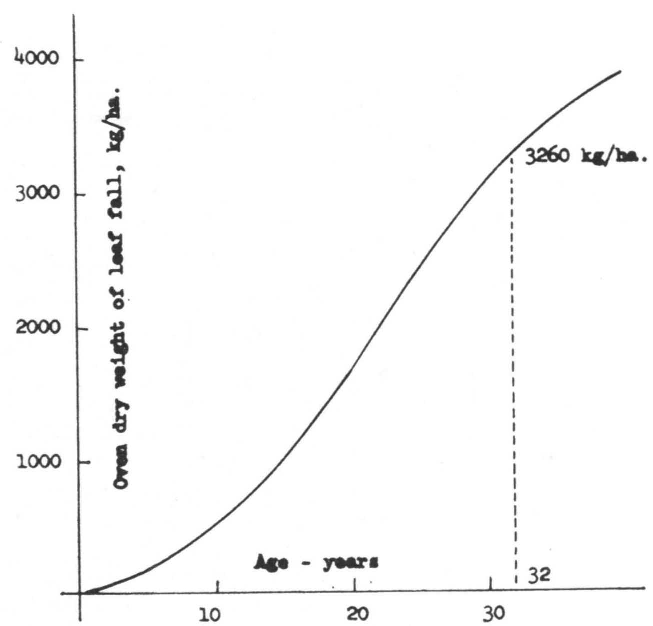

Figure 3. Weight of leaf fall in the 32-year-old Keshena red pine plantation. The estimate is made on the basis of yield curve for the corresponding site index 65; the total weight of 43 960 kg per hectare of discarded tree material is equal to the sum of annual ordinates.
Kuva 3. Karikesadon paino 32-vuotiaassa Pinus resinosa-viljelymetsikössä. Käyrä perustuu arvioon, joka on tehty vastaavan boniteetin (valtapituus 65 jalkaa 50 vuoden iällä) tuottokäyrän mukaan; 43 960 kg/ha karikkeen kokonaispaino on sama kuin vuosittaisten ordinaattojen summa. (Vaaka-akseli: ikä — vuosia; pystyakseli: uunikuivan lehtikarikesadon paino kg/ha.)

1929). However, it is in agreement with the productive efficiency of well stocked red pine stands during the period of their growth culmination. A part of the biomass increment, particularly leaf fall, is not a result of a single year performance of the crop, but in a large part a cumulative product of many years of the previous growth of trees. An efficiency higher than 0,4% was obtained only with artificial control of irrigation in the field and in greenhouse trials (TUMANOV, 1927; MAXIMOV, 1929).

The current increment of 10,2 m³/ha. is very close to the maximum for this particular ecosystem with its coarse-textured non-phreatic soil. Consequently, the transpiration coefficient of 0,37% delineates the upper limit of dry matter production for this tree species and soils of 7 to 9% field capacity, the high fertility level notwithstanding.

Analysis of the biomass, produced during the entire period of the plantation's growth, provides a somewhat different picture of water economy.

To obtain the total amount of leaf fall deposited by the plantation during its lifetime, the weight of collected litter was plotted against the age of the plantation to serve as the apex of the curve expressing the yield of wood for corresponding site index. The annual ordinates then were integrated (Figure 3). This approach appeared to be the most plausible for obtaining the weight of the total litter deposited by the stand.

The entire production of dry matter per hectare by the Keshena plantation ia as follows:

Merchantable timber, 243 solid cubic meters with specific gravity 0,38	91 340 kg
Tops below 7,5 cm. diameter	10 880 »
Branches and foliage	29 100 »
One-foot stumps	7 770 »
Roots	28 070 »
Leaf fall	43 960 »
Total	211 120 kg

The merchantable wood comprises 43% of the total production of energy material.

During their early growth, forest stands intercept very little rainfall and theoretically the amount of precipitation trapped by tree crowns should be correlated with the sigmoid curve expressing the yield of stands. On this basis, the volume of precipitation intercepted during the lifetime of the Keshena plantation would be slightly less than one-half of the maximum interception, let us say 15% instead of 35%, i.e., about 50 mm. Actually, however, the reduction of the canopy provides only a small increase in the supply of soil moisture; a large share of unintercepted water is lost by evaporation from the bare land or foliage of ground cover plants and by gravitational discharge. According to analyses of DE VRIES and WILDE (1962), the net gain of sandy soils during the first 20 years of growth of pine plantations seldom exceeds 2 per cent or 25 mm.

of water per 1,20 m. zone. Consequently, the maximum supply of transpiration water for the 32-year-old Keshena stand can be estimated at 300 mm. or 3 000 metric tons per hectare and growing season, or 96 000 tons for the 32 year period. In turn, the production of one kilogram of wood required 455 kg of water with corresponding respiration coefficient of about 0,22%.

The difference in the efficiency of dry matter production by the fully stocked plantation during the 32nd year of its life and during the entire 32 years (272 kg vs. 455 kg of water per kg of energy material), constituting about 40%, is due to the evapogravitational loss during the early stages of the stand's growth.

Extension of the Relationship

These findings suggest a possibility of establishing several hydrological relationships pertinent to forest culture. The most significant of these would be as follows: (a) determination of the maximum rate of forest growth permitted by the available supply of transpiration water irrespective of the high level of natural or artificially augmented soil fertility; (b) estimate of the content of available water in fertile fine textured soils of high tension capacity; (c) appraisal of the contribution to the supply of soil water rendered by subirrigation, seepage, or condensation of atmospheric water; (d) appraisal of the growth depressing effect of weeds. These relationships are illustrated by pertinent examples.

The most conspicuous manifestation of the critical deficiency of soil moisture is observed on sand dunes of *Cladonia* type, such as occur in central Wisconsin. Soils of these aeolian deposits possess the field capacity of mere 4% (Watterston, 1966). In consequence, they have no effective winter storage of water and lose a better half of precipitation by gravitational discharge. The interception of some 20% of rainfall by stands of advanced age reduces the seasonal supply of transpiration water to less than 1 000 metric tons per hectare. This amount is sufficient to produce an annual biomass increment of only 2 200 kg/ha of which only 2,5 m³ are merchantable timber. This is one example of soils whose productive capacity cannot be augmented by the use of fertilizers.

Outside of the fog belt of Lake Superior and with exclusion of subirrigated soils, the very maximum annual supply of transpiration water in soils of Wisconsin is in the proximity of 340 mm. or 3 400 metric tons per hectare. With this amount of water the biomass of a 32-year-old red pine plantation may attain on fertile soils a total weight of about 246 000 kg. A stand of this productive capacity would have about 270 m³/ha of merchantable timber and the current increment close to 14 m³. Plantations of this rate of growth are encountered in Wisconsin only on a few subirrigated and fine textured soils, e.g., Ockley silt loam and Superior clay loam (Wilde *et al.*, 1965, stands No. 112 and 151).

Fine textured soils of southern Wisconsin, such as Miami silt loams, possess high content of colloids and supply of nutrients; they receive annually about

Figure 4. Typical forest cover of fine-textured soils of southern Wisconsin illustrating condition of transpiration unfavorable for trees. This indigenous oak-hickory stand has a volume of mere 118 m³/ha at the average of 90 years; it is supported by Miami silt loam, one of the most productive farming soils of North America yielding as much as 250 centners per ha of *Zea mays* grain.

Kuva 4. Tyypillistä etelä-Wisconsinin hienorakeisten maiden puustoa; transpiraatio-olosuhteet ovat puille epäedulliset. Tämän luontaisen tammi-hikkori-metsikön kuutiotilavuus on 90 vuoden keskimääräisellä iällä vain 118 m³/ha; maa on Miami-hiesusavea, Pohjois-Amerikan parhaita viljelysmaita, joka tuottaa jopa 250 sentneriä maissinjyviä hehtaarilla vuodessa.

800 mm of precipitation water. Yet, the yield of oaks and other native hardwoods on most of these soils does not exceed 125 m³/ha at the age of 50 years (Figure 4). This volume corresponds approximately to the average annual biomass increment of 2 000 kg/ha. The production of this amount of dry matter would consume some 900 metric tons of water. Consequently, a larger share of transpiration water in these soils, comprising nearly 2 000 metric tons, is not available to trees because of a delayed spring thawing, decreased aeration due to prolonged overlogging of soil with melt water, a high percentage of inner-capillary and inter-rhizal moisture, and consumption of water by weeds. This is another example of soil conditions which make the use of fertilizers totally ineffectual.

As previously observed (Wilde and Iyer, 1963), the presence of ground water accessible to roots radically modifies the physical and nutritional aspects of soil productivity. This relationship is illustrated by the 28-year-old red pine plantation on a subirrigated coarse sandy soil, reported by Wilde *et al.* (1965,

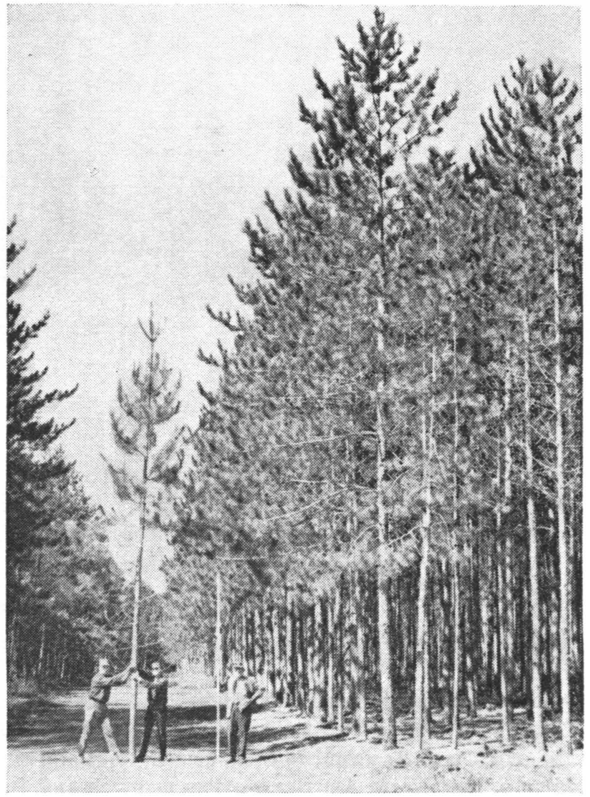

Figure 5. Average sample tree of 20,2 cm. diameter and 8,7 m. height from 31-year-old McNaughton red pine plantation on uncultivated Hiawatha sandy soil in the center of similar age adjacent plantation on cultivated soil with average trees of 13,5 cm. diameter and 14 m. height.

Kuva 5. Keskimääräinen näytepuu — läpimitta 10,2 cm, korkeus 8,7 m — 31-vuotiaasta Pinus-resinosa-metsiköstä muokkaamattomalta Hiawatha hiekkakankaalta viereisellä muokatulla viljelyalalla, jossa puiden keskimääräinen läpimitta on 13,5 cm ja pituus 14 m.

plantation No. 25). This soil with its 7,0% of fine separates and field capacity of three inches should have produced maximum 150 m^3/ha of merchantable wood or 120 000 kg of total dry matter per hectare. However, this stand actually yielded 225 m^3 of timber and total weight of 190 000 kg. This suggests that the capillary fringe contributed during the 28 years of the stand growth about 30 000 metric tons of water per hectare.

The outlined analyses may also be helpful in evaluation of the growth depressing effect of weeds. While forest stands consume water for continuous production of energy material, weeds maintain in the course of years the same weight of their biomass. In a way, the cover of weeds is not unsimilar to the legendary dragon devouring its own tail. At the same time, transpiration and evaporation of intercepted rainfall by ground vegetation diverts from the soil

body a large fraction of available water. An example of this relationship is provided by the McNaughton plantations of red pine supported by cultivated and uncultivated soils (Wittenkamp and Wilde, 1964). In the latter stand the cover of heath plants and bracken fern evapotranspired at an approximate average rate of 88 kg of water per kg of dry tissues (tops and roots). During 31 years of plantation growth the weeds consumed nearly 50 000 metric tons of water out of the total supply of 85 000 metric tons per hectare. The growth of the weed-invaded plantation was proportionally reduced from 160,0 to 57,5 m^3 per hectare (Figure 5).

Discussion

The supply of water for use in photosynthesis is equivalent to the algebraic sum of many variables, such as amount of precipitation, energy of radiation, velocity of winds, loss by evaporation, condensation of atmospheric moisture, interception and transpiration of rainfall by vegetative cover, and permeability and water-retaining capacity of the soil. In some localities the effect of all these factors is radically modified by the presence of ground water or an extended capillary fringe.

The determination of the supply of available water can be approached by the use of instrumental analyses, i.e., by measuring intensity of radiation, evaporation, fluctuation of ground water table, content of water in soil profile, etc. All these analyses require nearly continuous observation of photometers, evaporimeters, nuclear probes, and other recording gauges. Yet, the sum of all these variable factors, *per se*, provides only the first approximation to the actuality because a considerable fraction of water evades exact analytical recording. This is especially true of water of condensation, water ectracted by deep-rooted plants from inaccessible lower horizons, water rendered unavailable by tension forces of soil colloids or by deficient aeration, and water stored in the inter-rhizal spaces. The chances, therefore, to obtain by instrumental analyses meaningless series of noncontextural figures are indeed very great.

Fortunately, nature often provides a valuable analytical tool in the form of vegetative cover, particularly that of forest stands. Among these, the uniform fully stocked plantations of conifers during the period of their growth culmination are especially well adopted to serve as gauges of the supply of moisture available for transpiration. In forest stands, supported by well aerated soils with fertility satisfying the requirements of the given tree species, the site index or »bonitet» serves as a reliable indicator of the actually consumed supply of water. Thus, the array of climatic and soil variables or constants is supplemented by a concrete numerical value that considerably facilitates the hydrological appraisal, at least that of the given site.

Furthermore, uniform forest stands provide additional important information.

The diameter growth, automatically recorded by circumferencial tension bands, usually manifests the cessation of the active photosynthesis, or the end of the actual growing season coinciding with the survival minimum of soil moisture; the latter in sandy soils exceeds by 2 or 3% by volume the wilting coefficient, and by a higher content in fine textured soils. One of the principal reasons for the discrepancy between the wilting point and the survival minimum rests in the water of the interrhizal spaces which cannot reach root systems because of a too limited or a too slow capillary transfer.

Summary

This study estimates the supply of soil water required for the annual and total production of energy material by the biomass of 32-year-old plantation of red pine, *Pinus resinosa* AIT.

The supply of transpiration water was determined as the sum of summer precipitation, winter stored water, and condensed vapor, minus gravitational discharge and evaporation of intercepted rainfall. On the average, the 1,20 m root zone of coarse sandy soils of central Wisconsin receives 2750 M.T. of water per hectare. During the 32nd year of plantation growth, the increment of biomass, including 43% of merchantable timber, was 10 100 kg/ha, or 162 × 10^5 kcal/g. At this time of the culminating growth, the production of 1 kg of wood material consumed 272 kg of water. The corresponding transpiration coefficient 0,37% is near the maximum for the ecosystem of hard pines — sandy soils of glacial outwash with field capacity between 7 and 9%. On the weight basis, the annual leaf fall constituted 32% of the biomass and over 80% of merchantable timber.

The entire supply of water of 96 000 M.T./ha produced in 32 years 211 120 kg of total dry matter at a rate of 1 kg of wood per 455 kg of water, with corresponding transpiration coefficient of 0,22%. The evapogravitational losses during the early stages of the stand's growth decreased the water utilization efficiency of trees about 40%.

The information obtained permitted to outline several hydrological relationships pertinent to forest culture, namely: maximum rate of forest growth as delineated by the supply of available transpiration water; content of available moisture in soils of high tension capacity; contribution to soil water rendered by natural subirrigation and condensation of atmospheric vapor; growth depressing effect of weeds.

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SELOSTE:

METSIKÖIDEN ENERGIA-AINEEN TUOTTO SUHTEESSA MAAN VESIMÄÄRÄÄN

Tutkimuksessa arvioidaan se maan vesimäärä, joka tarvitaan 32-vuotiaan *Pinus resinosa* AIT. viljelymetsikön orgaanisen aineen vuosittain ja kokonaisuudessaan tuottamaa energia-ainemäärää varten.

Transpiraatioon käytettävän veden määrä laskettiin laskemalla yhteen kesäsateiden, talven vesivaraston ja tiivistyneen vesihöyryn määrä ja vähentämällä tästä maahan painuva vesi ja metsikköpidännän haihtuma. Keski-Wisconsinin karkearakeisten hiekkamaiden 120 cm:n juurivyöhyke vastaanottaa vuosittain keskimäärin 2 750 tonnia vettä hehtaarille. Viljelymetsikön 32:na vuonna orgaanisen aineen kasvu (tästä 43 % myytäväksi kelpaavaa puuta) oli 10 100 kg/ha eli 162 × 10^5 kcal/g. Tänä aikana, jolloin metsikön kasvu oli saavuttanut käännekohtansa, yhden puukilon tuotto vaati 272 kiloa vettä. Vastaava transpiraatiokerroin 0,37 % on suurimpia sille ekosysteemille, jonka muodostavat kovat männyt ja jääkauden seurauksena kerrostuneet hiekkamaat, joiden kenttäkapasiteetti on 7 % ja 9 % välillä. Vuotuinen karikesato oli 32 % orgaanisen aineen ja yli 80 % myytäväksi kelpaavan puun painosta.

Koko 96 000 tonnin vesimäärä tuotti 32 vuodessa 211 120 kg kuiva-ainetta, suhteessa 1 kg puuta 455 kg vettä kohti; vastaava transpiraatiokerroin on 0,22 %. Haihdunta ja veden painuminen maahan metsikön varhaisessa kasvuvaiheessa vähensivät puiden vedenkäyttötehokkuutta noin 40 %.

Saadut tulokset antoivat mahdollisuuden määritellä useita vesitaloudellisia metsänviljelylle tärkeitä suhteita: transpiraatioon saatavissa olevan veden rajoitukset metsän maksimikasvulle; saatavissa olevan veden määrä maissa, joissa on suuri jännityskapasiteetti; luonnollisia teitä maan alla kulkevan valuman ja ilman höyryn tiivistymisen tuottaman veden määrä; rikkaruohojen kasvua vähentävä vaikutus.