

Microclimate in the Establishment, Growth, and Development of Man-Made Forests

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Abstract

The man-made forest that we create after initial harvest will generally be established in a microclimate that may be considerably different from that which was present when the harvested trees were started. Good regeneration, survival and optimum growth in this man-made forest will depend on the selection of phenotypes genetically capable of favorable response under the physiological stress conditions imposed by that microclimate.

Research to achieve regeneration and optimum growth must be related to the organism that we wish to grow under the conditions that we expect it to grow. Simulation models relating plant-water relations and the photosynthetic response of an organism to the microclimate and soil water conditions of the site are one possible research tool. We should try to match species, rotation, and product to the anticipated recurrence probability of catastrophic events. Lastly, our harvesting practices should be designed to tailor site conditions to provide the best microclimate possible within the range of overall climate that we have to work with.

Résumé

La forêt que l'homme crée après la récolte initiale s'établira généralement dans un microclimat qui risque d'être fort différent de celui qui existait au moment du développement des arbres qu'on vient de récolter. La qualité de la régénération, la survie et la croissance optimale de cette forêt anthropique dépendent de la sélection de phénotypes génétiquement capables de réagir favorablement aux conditions de stress physiologique imposées par le microclimat.

La recherche sur la régénération et la croissance optimale doit tenir compte de l'organisme qu'on veut utiliser dans des conditions où on prévoit qu'il se développera. Les modèles de simulation établissant les rapports plante-eau et la réaction photosynthétique d'un organisme aux conditions microclimatiques et édaphiques du site constituent un outil possible de recherche. On doit tenter d'assortir les espèces, la rotation et les produits aux probabilités de manifestation périodique des désastres. Enfin, les méthodes de récolte doivent être adaptées aux conditions du terrain pour produire le meilleur microclimat possible dans les limites du régime climatique régional.

Introduction

Canada's natural forests are ours to use and perpetuate for future generations. As we harvest the trees from a forest, our desire should be to replace it with a man-made forest containing trees of equal or greater value for the next harvest. If a forest site is clear-cut, regeneration and subsequent growth will generally occur in a microclimate considerably different from that which was present during the establishment of the harvested stand, that is one with a greater light intensity, higher winds, higher surface and soil temperatures, and higher potential evaporation. Reforestation with the harvested species may be difficult; even more so with selected indigenous or exotic species to improve productivity. Successful reforestation and the achievement of optimum growth will likely depend on matching of phenotype and microclimate, and should receive careful consideration before any harvest takes place.

General classifications of climate and vegetation are not sufficient to prescribe species and practices to reforest or to maximize the productivity of a forest site, although there is certainly a close association between climate and the natural occurrence of a particular type of forest. Most bioclimatic classifications rely on a close association between the heat and water economy of an area and the vegetation found there (Daubenmire 1956). The vegetation on a site is thought to integrate all environmental factors important to a plant (Daubenmire 1976). However, it is my contention that classifications based on the interaction of natural vegetation with local climate provide a poor basis for predicting the behavior of other species on that site or even the behavior of the same species on that site if the microclimate departs dramatically from that of initial establishment.

A TALE OF TWO TREES

To illustrate the importance of a proper species/microclimate match, I draw on the experience of early plantings of Monterey pine and coastal redwood in New Zealand. Monterey pine occurs along several off-shore islands and the coast of California from San Francisco southward in the Mediterranean climate type. Annual precipitation varies between 430 and 890 mm, and occurs mostly as rain during the winter. The months of July and August are frequently rainless but foggy. The species can survive temperatures to -8°C during the winter when it is dormant, and summer temperatures as high as 41°C (Scott 60).

The range of coastal redwood in California extends northward along the coast from Monterey, just south of San Francisco where its range overlaps with that of Monterey pine, to the Oregon-California border. Annual precipitation varies from 630 to 2000 mm and occurs mostly as winter rain. Minimum temperatures rarely fall below -10°C and maximums rarely exceed 38°C. The natural range of this tree is limited to areas with heavy summer fog (Fowells 1965).

During the 1850s and '60s, both Monterey pine and coastal redwood were planted on sites with climate similar to that of Monterey, California, throughout the North Island of New Zealand. By 1912, only 1% of the plantations of redwood had survived. By 1960, Monterey pine had become the major exotic planted in New Zealand; redwood was confined to shelterbelts, small plantations and specimen trees (Streets 1962).

The poorer survival of the redwoods in an environment and climate generally similar to that near Monterey has been attributed to insufficient summer fog in New Zealand. The frequent presence of dense summer fog along the coast of

California decreases water loss from the trees and may add to the soil water supply. It is apparently more important to the tree's survival than is the total amount of precipitation (Fowells 1965).

OPERATIONAL ENVIRONMENT OF AN ORGANISM

From the foregoing account, it should be evident to those who would use climatic data to describe growing conditions that such data must be related to the organism that one wishes to grow. The operational environment of a particular organism consists of the organism, all physical phenomena that enter into a significant relationship with the organism, and the relationships between the organism and these phenomena (Mason and Langenheim 1957). If climate and microclimate studies are to have a meaningful impact on increasing the productivity of forests, then the focus of such studies must be on the response of physiological parameters that effect tree growth to climatic parameters pertinent to growth. In the case of coastal redwood, it would have been necessary to determine the relationship between its physiological reactions to the presence of fog at all stages of the trees development; that is, how and when is the presence of fog operationally significant to the growth or survival of redwood?

Genetic Content of Natural Versus Man-Made Forests

SURVIVORS VERSUS GROWERS

It is impossible to discuss climate and tree growth without mentioning genetics. The trees that we see in a present day forest have been selected by natural climatic and biological forces over many generations. Daubenmire (1976) states that "Natural vegetation reflects the algebraic sum of all environmental factors important to a plant." I would modify Daubenmire's statement to read "... important to the survival of a plant." Naturally occurring forests can be considered as "living bodies . . . programmed by genes who have *survived*" (Dawkins 1978). As Staebler (1974) put it, "Nature's ruling criterion has only been the survival of its fittest forms." The evolutionary strategy of any species must be survival; any aspect of the phenotype's form that is useful to man is purely coincidental.

The differing strategies that trees use to survive are important to our understanding and management of them to optimize wood production. The strategy that we desire for the trees of a man-made forest must be one that maximizes growth within the constraints of the local climate.

To illustrate, the mechanism by which most of our trees survive the temperature extremes of the Canadian climate is dormancy. Dormancy may be induced by temperature, day length, or drought. In the Rocky Mountain region and in the much more favorable climate of New Zealand, lodgepole pine often ceases to photosynthesize in response to water stress, and can become physiologically quiescent even though temperatures are warm and day lengths are sufficiently long for growth. If the stress condition is maintained for a long time period, then true dormancy may occur, and even the reestablishment of favorable soil moisture conditions will not restore photosynthetic activity (Salisbury and Ross 1978). The Monterey pine that has been so successful in New Zealand never really becomes dormant there. It stops photosynthesizing under severe drought stress, but resumes

root growth and photosynthesis within a day or so after rewatering (Rook et al. 1976).

Monterey pine thus exemplifies a type of response to precipitation that we should seek for optimum growth. However, if a tree does resume physiological activity, it faces the possibility of being unprepared (not hardened) when our harsh winter conditions demand that it be truly dormant to survive. As Bunting (1976) puts it, "To succeed in a climate where the season favorable to plant growth is limited by extremes of temperature, a provenance must either have an inbuilt timetable of appropriate length, or be able to endure the extremes." A good growing tree in the Rocky Mountain region would be responsive to summer precipitation and possess a timetable that prepares it for winter.

I think we should design forests in somewhat the same manner that hydrologists design dams, that is, to survive probable catastrophic events. Canadian forests are long-lived. They developed over several centuries and the trees have survived climatic events that occur with probabilities of 1:100 or even 1:1000. The trees we replace them with need only to be capable of surviving the events that are most likely to occur within their operational lifetime. If the forest we want will be operated on a 100-yr rotation, then the trees must be capable of surviving events that occur at somewhat longer intervals, perhaps the 500- or 1000-yr event. However, if we can operate a forest within a 20-yr rotation, then the trees may need only to survive the 100-yr event. To ensure the survival of the man-made forest, man would have to impose the "appropriate timetable" (Bunting 1976), that is, a rotation period within which disastrous climatic events would have a low probability of occurrence, and maintain seed and planting stock to replace both the trees harvested and those that didn't survive an untimely event that occurred within their rotation period.

Linkage Between Climate and Growth

There is no single climatic parameter that can be linked with growth to provide us with an easy way to prescribe the climate-growth links necessary to produce the man-made forest. Most growth and yield models have been derived from regression analyses (e.g., Ek and Monserud 1979, Fries 1974) of yield data which integrate all elements of the climatic and genetic composition that have shaped the stand. Models that integrate site and species characteristics may be advantageous for use in managing natural stands, where, for the most part, the site and species are considered constants (Curtis 1972), but such models are not advantageous to those of us who would like to change either site conditions or species.

NET PHOTOSYNTHESIS — THE ULTIMATE LINK BETWEEN CLIMATE AND GROWTH

Researchers are using photosynthetic variables increasingly to describe site productivity (Emmingham and Waring 1977, Reed 1980, Running 1984a). The bulk of tree growth is derived from the fixation of CO₂ during photosynthesis (Ledig 1976). Photosynthesis is a light-driven process of plants that combines CO₂ from the atmosphere with water taken up from the soil in the transpiration stream to make organic compounds. The uptake of CO₂ is controlled by the openness of the stomata through which the water of transpiration also escapes. Respiration is a temperature-driven process

that converts some of the organic compounds created during photosynthesis into heat. Some of the heat energy of respiration is lost to the atmosphere; however, the more important part is trapped as energy in compounds that are used later in growth and differentiation (Salisbury and Ross 1978). Gross photosynthesis minus respiration equals net photosynthesis (PSN). Most models of photosynthesis require leaf temperature and leaf conductance in addition to the more commonly measured light intensity, air temperature, and atmospheric humidity (Helms 1976, Tenhunen et al. 1980).

MODELS — A WAY TO LINK MICROCLIMATE AND GROWTH

Emmingham and Waring (1977) postulated that the microclimate of forest sites that affects photosynthesis should show a close relationship with the productivity of those sites. Their model for net photosynthesis combined the effects of light, temperature, drought, and cold soils. They measured day length, average day and night temperature measured at 20 cm below and 1 m above ground, and total radiation as site-specific climatic parameters; leaf conductance and xylem water potential were the site-specific plant parameters linking microclimate to photosynthesis. This model was used as an index to seasonal and annual net carbon assimilation, and was successful in explaining productivity differences found on four forest microclimates.

Reed (1980) proposed a somewhat simpler model based on ecological, meteorological, and physiological variables. He derived a set of growth response functions that were in turn defined as indexes of air and soil temperature, solar radiation, soil water availability, and atmospheric moisture demand. Leaf biomass was used as the on-site indicator of photosynthetic productivity.

Running (1984a,b) developed a model to calculate the net photosynthesis of a tree species on a homogeneous site in response to microclimate variables. The plant water stress variables that influence photosynthesis were simulated with a daily transpiration model. The model was calibrated on real data from the Lubrecht Experimental Forest in Montana, and then used with climatic data from 42 different sites to estimate net photosynthesis on them.

There are some obvious advantages of process modeling approaches, such as Running's (1984a,b), over those using site-specific water stress measurements. The first is that we have a fair base of hydrological/climatological evapotranspiration models to draw from, which simulate plant water stress in response to climatic and soil variables (Federer 1979, Goldstein and Mankin 1972, Luxmore et al. 1981, Running 1984b, Running et al. 1975). The second advantage is that it may be possible to link the output from this type of physiological model with more traditional growth and yield models through modification of site indices to estimate the performance of other species and changes in site climatic conditions (Running 1981). Anyone who has tried to estimate the effect of soil moisture, which can be altered by various silviculture practices, on growth in models based on site indices knows how difficult this is (Swanson 1985).

The third and perhaps most important advantage of photosynthetic models such as Running's (1984a) is that they provide a framework that can be used to incorporate the

results of various photosynthesis studies (e.g., Brix 1962 and 1967, Helms 1965, Schultz and Gatherum 1971, Sweet and Wareing 1968, Zavitkovski and Farrell 1968) to estimate integrated growth responses to microclimate parameters over several years. It is important that we be able to try various combinations of genotypes with the climate in question to see how they will perform under the range of conditions expected within a rotation. Such simulations will also provide new questions to which we can direct research to fill knowledge gaps that prevent us from applying physiological/climatological models to management problems.

TRANSPIRATION — THE LINK BETWEEN PLANT AND CLIMATOLOGIST

An understanding and physical description of the transpiration process, particularly the functioning of the stomata (Hall 1982, Running 1980, Schulze and Hall 1982), is fundamental to all of these attempts to link climatic or microclimatic variables and photosynthetic production. Transpiration is normally the major component of evapotranspiration (ET). The hydrological and climatological literature is replete with various models that describe ET solely from the atmospheric viewpoint in various environments (e.g., Monteith 1973, Morton 1975, Penman 1963). Most of the models originated by hydrologists or climatologists do not deal with the effect of plant water stress on stomatal conductance, although Monteith's (1973) does contain a stomatal resistance term that must be determined separately for use in the model. Monteith's model is often used as the transpiration submodel in those more physiologically based.

The transpiration models most useful in the study or prediction of microclimatic effects on photosynthesis are those that describe the water relations of a single tree. From a climatological standpoint there are disadvantages to single tree models, the most obvious being that water vapor transfer across a three-dimensional boundary layer surrounding a single leaf or tree is not describable with one-dimensional theory. However, at least two methods exist that provide direct measures or estimates of transpiration and do not depend on mass transfer theory — cuvettes and in-stem tracers.

Cuvettes, with controlled microclimates, can be placed on individual leaves, twigs, or branches to obtain direct measures of both transpiration and CO₂ exchange (Swanson et al. 1979). These data must be taken at locations that are representative of the whole tree crown and must be extrapolated to the whole plant. This is a serious but not insurmountable limitation on using the cuvette method with large trees.

The transpiration process in large trees can be studied with tracer techniques that measure the rate of sap flow (e.g., radioactive tracers: Kline et al. 1976; heat pulse: Lassoie et al. 1977, Swanson and Whitfield 1981, Swanson 1983). Of these, the heat pulse technique is the least destructive and most advanced theoretically (Swanson 1983) and it can be used to measure the rate of sap flow in branches or stems of coniferous trees (or hardwood trees with diffuse porous wood structure) with diameters greater than 4–5 cm. Sap flow data can be used as: (1) an independent measure of transpiration for comparison against data from cuvette and micrometeorological methods; (2) an indirect means of

determining bulk vapor transfer coefficients in conjunction with micrometeorological methods; and (3) a means of extrapolating cuvette data to an entire tree.

WAYS IN WHICH MICROCLIMATE CAN BE CHANGED TO INFLUENCE GROWTH

Snow Accumulation and Loss — One effect of snow accumulation and/or loss on tree growth is on the amount of soil water on a site at the start of the growing season. The distribution and ultimate disposition of snow is profoundly affected by forest clear-cutting (Troendle and Leaf 1981). Up to 1.5 times more snow accumulates in clearings two tree heights across than under the uncut canopy (Golding and Swanson 1978) and gains in accumulation continue through time until the regrowth is at least 75% of the height of the surrounding canopy (Gary 1979).

Not all clear-cutting can be considered advantageous for growth. Gains in snow accumulation become progressively less as clear-cut size is increased, especially in windy climates where sublimation losses during long-distance transport and in situ evaporation can reduce accumulations to zero (Tabler and Schmidt 1973, Swanson and Bernier 1986). Snow loss also occurs along the south-facing edge of clearings greater than two tree heights across (N-S direction) due to the high energy input to the south-facing canopy from direct solar radiation and that reflected from the snow surface (Golding and Swanson 1986).

Running (1984a) simulated the effect of various soil moisture regimes on photosynthesis of lodgepole pine. He found that summer rains in the Rocky Mountain region were almost all lost as evaporation from interception on the canopy and were not effective in replenishing soil moisture and that almost all of the moisture for growth must be supplied from the snowpack. If Running's (1984a) simulations are indicative of what we could expect in Alberta, then the extra snow that accumulates in a two-tree wide clearing would allow a significantly longer spring growth period, and if the surrounding forest were not removed, this effect would continue for several decades until the new growth was almost as tall as the surrounding trees. Conversely, snow lost to evaporation during the winter would have an adverse effect on tree growth.

Wind — Wind has a direct effect on evaporation from snow and transpiration from leaves, with direct effect on soil moisture. The wind speed at the surface of small clearings 1–6 tree heights across is generally less than one-tenth the speed of that found above the canopy or in clear-cuts greater than 20 tree heights across (Swanson 1980). Evaporation from the snow in these small clearings averaged less than 50% that from a clearing 20 tree heights across. (The "red belting" that occurs in the portion of Alberta's foothills where chinook winds are prevalent is thought to be caused by evaporative water loss from the foliage, which cannot be replenished from the frozen soil [Henson 1952]. Damage is most severe on the windward side of trees, and those sheltered from the wind are undamaged [MacHattie 1963].)

Drainage — Drainage of peatlands directly modifies the near-surface microclimate by alteration of soil thermal and hydraulic properties. The surface soil temperature is generally increased, soil moisture decreased, and near-surface air temperature increased by draining water from peatland sites (Pessi 1958). Kaunisto and Päivänen (1985) indicate that water availability and soil temperature for tree growth are generally improved by drainage. Root growth (Tryon and

Chapin 1983) and root resistance (Running and Reid 1980) are both influenced by temperature. While it is true that tree growth generally improves (Payandeh 1973), both the site and the trees on it may undergo an adjustment period before any improvement in growth will occur (Liefers and Rothwell 1987). Models such as PROSPER (Goldstein and Mankin 1972) and DAYTRANS/PSN (Running 1984a, 1984b), which link plant functions to microclimatic parameters and soil water availability, should be useful for studying the time trend of the effects of various drainage strategies on tree growth.

Purposeful Modification of Microclimate

Staebler (1974) says we should dare to be different and innovative. Therefore, I would like to suggest some clear-cutting practices that would produce relatively permanent changes in microclimate and possibly improve tree growth. My experience is all with forests where snow is the dominant precipitation. However, some of these ideas might apply in areas where rain predominates as well.

Anderson (1966) suggested a wall and step type of forest manipulation, with cutting progressing from north to south. Such an arrangement would maximize shading to retard snowmelt. Anderson's purpose was to augment late season streamflow. However, the delayed snowmelt might also be advantageous for tree growth since the site would retain snow (possibly prolonging the period during which soil moisture is available) for about 2 wk longer than those less shaded. The increased snow accumulation and shading conditions could be maintained throughout the period of regeneration and juvenile growth by maintaining the leave strips for one-half the rotation duration.

It might be possible to establish a "nurse" forest to create and maintain a more moist and low evapotranspiration microclimate to increase growth. For instance, we have observed significantly faster growth of lodgepole pine in a 1 tree height wide, east-west oriented strip, than in either small circular openings less than 6 tree heights across or in 15-ha square clear-cut, approximately 20 tree heights across. One could create a series of 1 tree height wide clear-cut and uncut strips in a mature forest. The uncut strips might be managed on a 100-yr rotation for saw logs and the cut strips on a 20-yr rotation for pulp. Such a system would maintain the microclimate change in perpetuity to provide shade and the aerodynamic conditions for snow accumulation and retention in the intervening clear-cut strips.

Drainage is already a well-established practice in Finland (Päivänen 1984) and is becoming more prevalent in Canada. The recommended spacing for drainage ditches ranges from 25 to 50 m depending on the type of peatland site (Päivänen 1984). The creation of such a drainage network is a major alteration of the existing topography. It would therefore be interesting to look at the possibility of restructuring the landscape by deliberate orientation and spacing of the ditch network, during the implementation of the drainage network, to increase the solar radiation and wind regimes of the drained site in addition to the alteration of the soil water conditions.

Summary

Optimum growth in the man-made forest will not occur about accidentally. We must be careful that we select species

for their growth as well as their survival attributes. Research to achieve optimum growth must be related to the organism that we wish to grow under the conditions that we expect it to grow. Physical models relating plant-water relations and the photosynthetic response of an organism to the microclimate and soil water conditions of the site are one possible research tool. We should try to match species, rotation, and product to the anticipated recurrence probability of catastrophic events. Lastly, we should seek to tailor site conditions to provide the best microclimate conditions for growth that are possible within the range of overall climate that we have to work with.

References

- ANDERSON, H.W. 1966. Integrating snow zone management with basin management, p. 355-373, in *Water Research*, A.V. Kneese and S.C. Smith (eds.). John Hopkins Press, Baltimore, Maryland.
- BRIX, H. 1962. The effect of water stress on the rate of photosynthesis and respiration in tomato plants and loblolly pine seedlings. *Physiologica Plantarum*, 15:10-20.
- BRIX, H. 1967. An analysis of dry matter production of Douglas-fir seedlings in relation to temperature and light intensity. *Can. J. Bot.* 45:2063-2072.
- BUNTING, A.H. 1976. Maximizing the product, or how to have it both ways, p. 1-20, in *Tree Physiology and Yield Improvement*, M.G.R. Cannell and F.T. Last (eds.). Academic Press, London. 567 p.
- CURTIS, R.O. 1972. Yield tables past and present. *J. For.* 70(1):28-32.
- DAUBENMIRE, R. 1956. Climate as a determinant of vegetation distribution in eastern Washington and northern Idaho. *Ecological Monographs* 26(2):131-154.
- DAUBENMIRE, R. 1976. The use of vegetation in assessing the productivity of forest lands. *The Botanical Review* 42(2):115-143.
- DAWKINS, R. 1978. The selfish gene. Granada Publishing, Toronto. 224 p.
- EK, A.R., AND R.A. MONSERUD. 1979. Performance and comparison of stand growth models based on individual tree and diameter-class growth. *Can. J. For. Res.* 9:231-244.
- EMMINGHAM, W.H., AND R.H. WARING. 1977. An index of photosynthesis for comparing forest sites in western Oregon. *Can. J. For. Res.* 7:165-174.
- FEDERER, C.A. 1979. A soil-plant-atmosphere model for transpiration and availability of soil water. *Water Resour. Res.* 15(3):555-562.
- FOWELLS, H.A. 1965. Silvics of forest trees of the United States. USDA For. Serv., Washington, D.C. Agriculture Handbook No. 271. 762 p.
- FRIES, J., ed. 1974. Growth models for tree and stand simulation. Royal College of Forestry, Department of Forest Yield Research, Uppsala, Sweden. Research Notes No. 30. 379 p.
- GARY, H.L. 1979. Duration of snow accumulation increases after harvesting in lodgepole pine in Wyoming and Colorado. USDA For. Serv., Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, Research Note RM-366. 7 p.
- GOLDING, D.L., AND R.H. SWANSON. 1978. Snow accumulation and melt in small forest openings in Alberta. *Can. J. For. Res.* 8(4):380-388.
- GOLDING, D.L., AND R.H. SWANSON. 1986. Snow distribution patterns in clearings and adjacent forest. *Water Resour. Res.* 22(13):1931-1940.
- GOLDSTEIN, R.A., AND J.B. MANKIN. 1972. PROSPER: a model of atmosphere-soil-plant water flow, in *Summer Computer Simulation Conference Proceedings*, June 14-16, 1972, San Diego, California.
- HALL, A.E. 1982. Mathematical models of plant water loss and plant water relations, p. 231-261, in *Encyclopedia of Plant Physiology*, New Series, Volume 12B, Physiological Plant Ecology II, Water Relations and Carbon Assimilation, O.L. Lange, P.S. Nobel, C.B. Osmond and H. Ziegler (eds.). Springer-Verlag, Berlin. 747 p.
- HELMS, J.A. 1965. Diurnal and seasonal patterns of net assimilation in Douglas fir, *Pseudotsuga menziesii* (Mirb) Franco, as influenced by environment. *Ecology* 46:698-708.
- HELMS, J.A. 1976. Factors influencing net photosynthesis in trees: an ecological viewpoint, p. 57-58, in *Tree Physiology and Yield Improvement*, M.G.R. Cannell and F.T. Last (eds.). Academic Press, London. 567 p.
- HENSON, W.R. 1952. Chinook winds and red belt injury to lodgepole pine in the Rocky Mountain parks area of Canada. *For. Chron.* 28(1): 62-64.
- KAUNISTO, S., AND J. PÄIVÄNEN. 1985. Metsänuudistaminen ja metsittäminen ojitetuilla turvemaidilla. Summary: Forest regeneration and afforestation on drained peatlands. A literature review. The Finnish Forest Research Institute, Helsinki, *Folia Forestalia* 625:1-75.
- KLINE, J.R., K.L. REED, R.H. WARING, AND M.L. STEWART. 1976. Field measurements of transpiration in Douglas-fir. *J. Appl. Ecol.* 13:273-283.
- LASSOIE, J.P., D.R.M. SCOTT, AND L.J. FRITSCHEN. 1977. Transpiration studies in Douglas-fir using the heat pulse technique. *For. Sci.* 23:377-390.
- LEDIG, F.T. 1976. Physiological genetics, photosynthesis and growth models, p. 21-54, in *Tree Physiology and Yield Improvement*, M.G.R. Cannell and F.T. Last (eds.). Academic Press, London. 567 p.
- LIEFFERS, V.J., AND R.L. ROTHWELL. 1987. Effects of drainage on substrate temperature and phenology of trees and shrubs in an Alberta peatland. *Can. J. For. Res.* 17:97-104.
- LUXMOORE, R.J., J.L. STOLZY, AND J.T. HOLDEMAN. 1981. Sensitivity of a soil-plant-atmosphere model to changes in air temperature, dew point temperature, and solar radiation. *Agric. Meteorol.* 23:115-129.
- MACHATTIE, L.B. 1963. Winter injury of lodgepole pine foliage. *Weather* 18(10):301-307.
- MASON, H.L., AND J.H. LANGENHEIM. 1957. Language analysis and the concept environment. *Ecology*, 38(2):325-340.
- MONTEITH, J.L. 1973. Principles of environmental physics. American Elsevier Publishing Company, New York. 241 p.
- MORTON, F.I. 1975. Estimating evaporation and transpiration from climatological observations. *J. Appl. Meteorol.* 14(4):488-497.
- PÄIVÄNEN, J. 1984. Increasing the land base and yield through drainage. The University of Alberta, Faculty of Agriculture and Forestry, Edmonton, Forest Industry Lecture Series No. 13. 22 p.
- PAYANDEH, B. 1973. Analyses of a forest drainage experiment in Northern Ontario. I: Growth analysis. *Can. J. For. Res.* 3:387-398.
- PENMAN, H.L. 1963. Vegetation and Hydrology. Commonwealth Bureau of Soils, Harpenden, Technical Communication No. 53. 124 p.
- PESSI, Yrj. 1958. On the influence of bog draining upon thermal conditions in the soil and air near the ground. *Acta Agriculturae Scandinavica* 24:359-374.
- REED, K.L. 1980. An ecological approach to modeling growth of forest trees. *For. Sci.* 26(1):33-50.
- ROOK, D.A., R.H. SWANSON, AND A.M. CRANSWICK. 1976. Reaction of radiata pine to drought, p. 55-68, in *Proc. Soil and Plant Water Symp.*, Palmerston North, New Zealand, May 25-27, 1976.
- RUNNING, S.W. 1980. Environmental and physiological control of water flux through *Pinus contorta*. *Can. J. For. Res.* 10:82-91.
- RUNNING, S.W. 1981. The influence of microclimate on forest

- productivity: a system to predict the biophysical site quality of forest land, p. 297-316, *in* Computer techniques and meteorological data applied to problems of agriculture and forestry: a workshop. March 29-30, 1981, Anaheim, California. Am. Meteorol. Soc. Boston, Mass.
- RUNNING, S.W. 1984a. Microclimate control of forest productivity: analysis by computer simulation of annual photosynthesis/transpiration balance in different environments. *Agric. For. Meteorol.* 32:267-288.
- RUNNING, S.W. 1984b. Documentation and preliminary validation of H2OTRANS and DAYTRANS, two models for predicting transpiration and water stress in western coniferous forests. USDA For. Serv., Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, Research Paper RM-252. 45 p.
- RUNNING, S.W., AND C.P. REID. 1980. Soil temperature influences on root resistance of *Pinus contorta* seedlings. *Plant Physiol.* 65:635-640.
- RUNNING, S.W., R.H. WARING, AND R.A. RYDELL. 1975. Physiological control of water flux in conifers: a computer simulation model. *Oecologia (Berlin)*, 18:1-16.
- SALISBURY, F.B., AND C.W. ROSS. 1978. *Plant physiology*, second edition. Wadsworth Publishing Company, Belmont, California. 436 p.
- SCHULTZ, R.C., AND G.E. GATHERUM. 1971. Photosynthesis and distribution of assimilate in Scotch pine seedlings in relation to soil moisture and provenance. *Botanical Gazette*, 132:91-96.
- SCHULZE, E.D., AND A.E. HALL. 1982. Stomatal responses, water loss and CO₂ assimilation rates of plants in contrasting environments, p. 181-230, *in* Encyclopedia of Plant Physiology, New Series, Volume 12B, Physiological Plant Ecology II, Water Relations and Carbon Assimilation, O.L. Lange, P.S. Nobel, C.B. Osmond, and H. Ziegler (eds.). Springer-Verlag, Berlin. 747 p.
- SCOTT, C.W. 1960. *Pinus radiata*. Food and Agriculture Organization of the United Nations, Rome. FAO Forestry and Forest Products Studies No. 14. 328 p.
- STAEBLER, G.R. 1974. Dare to be different: the case for innovation in forestry. *For. Chron.* 50(6):280-285.
- STREETS, R.J. 1962. Exotic forest trees in the British Commonwealth. Clarendon Press, Oxford. 765 p.
- SWANSON, R.H. 1980. Surface wind structure in forest clearings during a chinook, p. 26-30, *in* Proc. Western Snow Conf. 48th Annual Meeting, April 15-17, 1980, Laramie, Wyoming.
- SWANSON, R.H. 1983. Numerical and experimental analyses of implanted-probe heat pulse velocity theory. Unpublished PhD thesis, The University of Alberta, Edmonton. 298 p.
- SWANSON, R.H. 1985. Managing lodgepole pine ecosystems as watersheds, p. 305-313, *in* Symposium Proceedings, Lodgepole pine — the species and its management, D.M. Baumgartner, R.G. Krebill, J.T. Arnott, and G.F. Weetman (eds.). May 8-10, 1984, Spokane, Washington, and May 14-16, 1984, Vancouver, British Columbia. Published by Cooperative Extension, Washington State University, Pullman, Washington.
- SWANSON, R.H., U. BENEKE, AND W.M. HAVRANEK. 1979. Transpiration in mountain beech estimated simultaneously by heat-pulse velocity and climatized cuvette. *N. Z. J. For. Sci.* 9(2):170-176.
- SWANSON, R.H., AND P.Y. BERNIER. 1986. The potential for increasing water supply in the Saskatchewan River system through watershed management, p. 485-496, *in* Proc. Can. Hydrol. Symp. No. 16, 1986. Drought: The Impending Crisis?, June 3-6, 1986, Regina, Saskatchewan. National Research Council of Canada, Ottawa, No. 25524.
- SWANSON, R.H., AND D.W.A. WHITFIELD. 1981. A numerical analysis of heat pulse velocity theory and practice. *J. Exp. Bot.* 32:221-239.
- SWEET, G.B., AND P.F. WAREING. 1968. A comparison of the rate of growth and photosynthesis in first year seedlings of four provenances of *Pinus contorta* Dougl. *Ann. Bot.* 32:735-751.
- TABLER, R.D., AND R.A. SCHMIDT. 1973. Weather conditions that determine snow transport distances at a site in Wyoming, p. 118-127, *in* The Role of Snow and Ice in Hydrology, Volume I, Proc. Banff Symp., Sept. 6-20, 1972, Banff, Alberta. Unesco/WMO/IAHS.
- TENHUNEN, J.D., A. MEYER, O.L. LANGE, AND D.M. GATES. 1980. Development of a photosynthesis model with emphasis on ecological applications. V. Test of the applicability of a steady-state model to description of net photosynthesis of *Prunus amereniaca* under field conditions. *Oecologia (Berlin)*, 45:147-155.
- TROENDLE, C.A., AND C.F. LEAF. 1981. Effects of timber harvest in the snow zone on volume and timing of water yield, p. 131-143, *in* Interior West Watershed Management, Symp. Proc., April 8-10, 1980, Spokane, Washington, D.M. Baumgartner (ed.). Washington State University, Cooperative Extension, Pullman, Washington.
- TRYON, P.R., AND F.S. CHAPIN III. 1983. Temperature control over root growth and root biomass in taiga forest trees. *Can. J. For. Res.* 13:827-833.
- ZAVITKOVSKI, J., AND W.K. FARRELL. 1968. Effect of drought upon rates of photosynthesis, respiration and transpiration of seedlings of two ecotypes of Douglas fir. *Botanical Gazette*, 129:346-350.

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