MOISTURE-NUTRIENT INTERRELATIONSHIP

H. Brix

ABSTRACT

Effects of rainfall and soil moisture on availability of native and applied soil nitrogen to trees are discussed, including effects on loss of nitrogen through ammonia volatilization, denitrification, leaching and surface runoff, and mineralization of organic matter and movement of nitrogen to the roots. The important interrelationship of water and nitrogen in tree physiology is pointed out. On this basis, one would expect a different tree growth response to nitrogen fertilization, depending on rainfall and soil moisture conditions, but this interaction has not been well explored and has been demonstrated in only a few studies.

INTRODUCTION

Moisture and N are two of the most important factors limiting tree growth in the Pacific Northwest. Though the individual role of each has received considerable attention, their combined effect has not been clarified. For the purpose of site selection for fertilizer application and explaining responses in different years and sites, the forest manager would like to know whether fertilizer has more effect at one soil moisture condition than at another; i.e., whether or not an interaction between the two factors exists.

In agriculture, it is well recognized that soil moisture can be an important factor in soil nutrition and in crop response to fertilization (Black 1966). Conversely, improvement in soil nutrition often increases the efficiency of water used, i.e., gives a higher crop production per unit of water used (Viets 1962).

I shall briefly discuss the various ways in which moisture can influence N availability by affecting N loss through volatilization, leaching and surface runoff, mineralization of organic material, and movement to roots, together with moisture-nitrogen interrelationship in tree physiology. This will provide a background for understanding how an interaction between the two factors may arise. The few studies in which this interaction in growth has been examined will be presented, and mention will be made of possibilities for influencing soil moisture conditions.

While the discussion will be limited to N, since this is the only fertilizer applied in this region, it should be realized that water has different effects on the behavior of other nutrient elements.

MOISTURE EFFECT ON NITROGEN AVAILABILITY

NITROGEN LOSSES

Volatilization

Nitrogen losses by ammonia volatilization are affected by soil and atmospheric moisture conditions soon after fertilization (Crane 1972, Cole et al. 1975). Formation of ammonia is favored by high soil pH. With urea, the soil pH increases as a result of urea hydrolysis and losses may be substantial, but with ammonium nitrate soil pH is not elevated and ammonia losses with this fertilizer are insignificant. Estimation of amounts of urea-N lost under unfavorable warm and dry weather vary considerably from 5% (Overrein 1969, Cole et al. 1975) to as much as one-half of the applied dose (Watkins et al. 1972, Carrier and Bernier 1971).

Moisture is important in several ways. A dry litter surface at time of fertilization may be favorable initially by slowing down the rate of urea hydrolysis for litter layers, which are not readily infiltrated by urea pellets (Derome 1979). Rainfall occurring shortly after fertilization can leach urea into deeper soil horizons, thus reducing losses of ammonia (Crane 1972). Leaching rain must fall, however, before urea is hydrolyzed to the less mobile ammonium cation state. The soil moisture content is also important since this will affect the capacity of the soil to retain ammonia (Crane 1972). Evaporation of soil moisture provides the diffusion pathway for escape of aqueous ammonia, and factors affecting rate of evaporation such as air humidity, temperature, and wind conditions therefore influence volatilization losses.

Evidence of the importance of rainfall in ammonia volatilization loss has been provided in several irrigation experiments. Crane (1972), working with a Douglas-fir soil in Washington, found that the ammonia loss was reduced from 11.6 to 1.1 kg/N/ha after application of 224 kg/N/ha when irrigation was increased from a light regime, starting 9 days after fertilization, to a heavy regime, starting immediately after fertilization. An irrigation of only 12 mm of water applied 4 days after a 220 kg/N/ha urea fertilization reduced volatilization losses drastically from 18% to 9% of the applied N in a Douglas-fir site on Vancouver Island (Marshall, Pacific Forest Research Centre, per. commun. August 1979). Amount, as well as timing, of irrigation was shown to be important in ammonia losses in a study on jack pine soil in Quebec (Carrier and Bernier 1971). The loss was about 30% of the urea-N applied at a rate of 224 kg/N/ha without irrigation, about 22% with either 50.8 mm water applied 3 days after fertilization or 3.2 mm applied after 1 day, and about 8% with a 25-mm irrigation applied after 1 day. A warm soil during fertilization in August accounted for a rapid urea hydrolysis, which was virtually completed between days 3 and 5, and explained the importance of irrigation within a day of fertilization.

Significant losses of N can also result from reduction of nitrate anion to N gases by denitrifying bacteria (Broadbent and Clark 1965). This process takes place in the presence of organic material under an O deficient condition such as in water-saturated soils, even when this condition exists only for a few days (Will 1977). Nömmik and Thorin (1972) considered denitrification losses to be of minor importance on acidic raw humus soils but losses were as much as 70% of the added nitrate-N when the pH was increased to 6 or 7. Volatilization of gaseous N compounds other than ammonia appeared to be high in a study by Marshall and DeBell (Marshall, Pacific Forest Research Centre, pers. commun. August 1979).

Leaching

Loss of N through leaching has not been considered serious following urea fertilization (Cole and Gessel 1965, Cole et al. 1975). Although urea in the nonionic form is readily leached in mass flow with water in well-drained soil, the enzymatic hydrolysis of urea to the less mobile ammonium cation state is rapid in coniferous forest soils, requiring from 10 to 20 days (Crane 1972) or less (Roberge and Knowles 1966, Johnson 1979). The subsequent nitrification of ammonium cation to the mobile nitrate anion has been, at least under some conditions, too slow to cause appreciable leaching losses (Cole et al. 1975), though there are reports of more significant productions of nitrate, especially with repeated applications of urea (Heilman 1974, Otchere-Boateng and Ballard 1978). Substantial N losses can be expected, and have been found (Overrein 1971), when a nitrate source of fertilizer is applied. In cold soils and with fertilization on snow, urea hydrolysis may be slowed sufficiently to cause urea losses, but this has yet to be demonstrated.

Surface Runoff

Other fertilizer losses influenced by water can occur through surface runoff. This is significant on agricultural lands, but is not likely to be serious in most forestry situations, where a humus layer and a better soil structure facilitate fertilizer infiltration (Neary and Leonard 1977). In a study by Moore (1975), only minor increases of N were recorded in streams adjacent to urea-fertilized watersheds in western Washington and Oregon and these increases were attributed more to direct application to the streams than to leaching and surface runoff.

MINERALIZATION OF ORGANIC MATERIAL

A continuous supply of native soil N in a form available to trees depends on mineralization of organic material. For some low-site Douglas-fir soils, the pool of available soil N has been shown to be so small that it has to turn over many times a year to meet normal tree requirement (Johnson 1979). The transformation from organic to inorganic N forms is therefore very important for tree growth. This biological activity, carried out by soil microflora and aided by the soil fauna, is highly influenced by soil moisture and temperature (Black 1966, Bollen 1974). At the Canadian Forestry Service Shawnigan site, populations of soil microflora and soil respiration rates declined drastically during the dry summer periods (Dangerfield, Pacific Forest Research Centre, pers. commun. August 1979). Johnson (1979) did find a depression in soil ammonium cation level during the summer, but felt that this was not caused by moisture limiting the mineralization rate since the study was done in an unusually wet summer. Since most of the organic matter is in a soil surface layer, which can dry out quickly in the summer, deficiency of N may occur sooner than deficiency of moisture, which can be supplied from deeper soil horizons.

NITROGEN MOVEMENT TO ROOTS

Following urea fertilization, the rate of N movement is determined by soil-water flow (rainfall) and by the rate of ureolysis, as urea is more mobile than the transformation product ammonium cation. This was demonstrated in an irrigation study in which heavy irrigation resulted in a deeper distribution of urea-N and a faster rate of ureolysis than light irrigation (Crane 1972). In addition to this initial role of water in downward leaching of N, water serves as the medium for diffusion and mass flow of nutrients to tree roots. In mass flow, nutrients move with water as it is being absorbed by the roots. Nutrient movement may be seriously limited in soils with a low moisture content, since that reduces hydraulic conductivity and thereby the mass flow, and also the pathways for nutrient diffusion (Ballard and Cole 1974, Viets 1972). Of the annual N uptake of a Douglas-fir stand, it was estimated that less than 22% was supplied by mass flow and the rest by diffusion or a mixture of the two processes (Ballard and Cole 1974).

TREE PHYSIOLOGY

NITROGEN UPTAKE AND TRANSLOCATION IN TREES

A continuous supply to the trees of moisture and soil nutrients depends not only on their movement in the soil but also on root extension, i.e., root interception (Barber 1966), and that in turn is highly dependent on soil moisture conditions (Zahner 1968). Excessive soil moisture, which creates poor soil aeration, can be as detrimental as a deficiency. Actively growing, unsuberized roots are also needed for efficient nutrient uptake. The direct role of water in nutrient uptake has been the subject of much controversy in which uptake by mass flow with water is considered nonexistent by some (Crafts 1968) but of importance by others (Kramer 1969), though active uptake and diffusion along an electrochemical gradient are regarded as the principal mechanisms. Translocation from roots to foliage, however, takes place by mass flow in the transpiration stream in the xylem, but it is doubtful that the flow rate becomes critical for nutrient supply. Tree moisture stress has been shown to decrease nutrient translocation in the phloem (Crafts 1968).

METABOLISM

Moisture deficiency affects N metabolism of trees directly and indirectly in many complex ways, as reviewed by Naylor (1972), and suffice it to say that this could conceivably result in a moisture-N interaction in growth.

Rate of photosynthesis was studied over a wide range of shoot moisture deficits for branches from N-fertilized and unfertilized Douglas-fir trees (Brix 1972). Moisture stress reduced the rate of photosynthesis similarly for these two groups of trees.

NITROGEN SUPPLY AND DEMAND

An interaction of moisture and nutrients in tree growth depends on whether moisture changes affect the relation of nutrient supply and demand by the trees. Though there is much evidence to show that soil moisture affects soil nutrient availability, we know little as to what extent growth is limited by low nutrient availability during periods of soil moisture deficiency, since demand for nutrients also changes. It is conceivable that demand is reduced more than availability, thus improving the mineral nutrient status of plants (Viets 1972). Also, nutrient storage within trees may overcome brief periods of limitations in nutrient uptake. This, then, could provide a clear case of a fertilizer-moisture interaction in which fertilization would affect growth under favorable soil moisture but not when moisture becomes deficient.

Experiments at Shawnigan Lake and elsewhere have not shown this distinct difference, since Douglas-fir stem growth benefited from N fertilization even during periods of prolonged summer drought (Brix 1972). Production of xylem cells was also increased throughout the growing season by fertilization even though the soil moisture potential in some periods was -20 bars and lower (Brix and Mitchell, unpubl. data). The demand for N apparently still exceeded the supply during drought as was the case under moist conditions. Less drastic moisture effect on nutrient supply-demand relationship must therefore be investigated.

TREE GROWTH

Only one study was found in which tree growth response to N fertilization had been related to the natural site moisture conditions (Fiedler et al. 1978). In this study in Germany, good volume growth response of Norway spruce was obtained over a 10-yr period where the climate was favorable, but no response was detected on sites where the May-August precipitation was below 300 mm. Fertilizer studies in the Pacific Northwest have related growth response only to overall natural site productivity, and with contrasting results. Steinbrenner (1968) found the best actual and relative response of Douglas-fir on Weyerhaeuser Company land on high sites, whereas such response generally occurred on low sites in the trials of the Regional Forest Nutrition Research Project (RFNRP) in Oregon and Washington (Univ. Washington 1977). There is an obvious need to relate growth response to important site productivity factors including moisture, and studies are underway in RFNRP (Univ. Washington 1977). As stated by Hermann et al. (1974), it is tempting to hypothesize that the best response would be obtained on sites low in available N and high in available moisture, but supporting experimental evidence is needed.

Some studies in the Pacific Northwest have investigated N fertilization effect on Douglas-fir growth with and without supplementary irrigation. In a study with two Douglas-fir stands in Oregon, 20 and 30 yr old, Strand (1964) found only an additive effect and no interaction of irrigation and N fertilization in stem radial growth over a 3-yr period. In one of the stands, growth increased 20% with fertilization, 45% with irrigation, and 60% with the two treatments combined.

An experiment at Pack Forest, Washington, showed no evidence of an irrigation-fertilization interaction in basal area and volume growth over a period of 8 yr, but data interpretation was made difficult by a large within-treatment plot variation (Gessel et al. 1969). A study in a 23-yr-old Douglas-fir stand near Victoria, B.C., provided evidence of an interaction with an increase in diameter growth of 15% with irrigation, 16% with N fertilization, and 59% when treatments were combined (Brix 1972). This, therefore, indicated that N fertilization would have most effect on stem diameter growth in years and on sites with favorable soil moisture conditions.

An explanation for the above interaction was sought by studying rates of photosynthesis, shoot moisture stress, and foliage nutrient (N, P, K) concentrations for untreated trees and for trees that had been irrigated, fertilized, or both (Brix 1972). The rate of photosynthesis was reduced similarly by shoot moisture stress whether or not the trees had been fertilized, so that did not provide an explanation. Trees that had been fertilized and irrigated had the lowest shoot moisture stress throughout the growing season and this may have contributed to the interaction. The most likely explanation, however, was the irrigation influenced N availability for fertilized trees since foliage N concentration was highest with irrigation plus fertilization and irrigation alone had no effect on foliage N status.

REGULATION OF SOIL MOISTURE

If a moisture-nutrient interaction in tree growth can be documented, it will provide an additional incentive for further studies on improvement of moisture conditions of forest soils by means such as irrigation, thinning, and better soil management practices. Irrigation is the obvious way of improving soil moisture and has been investigated and discussed in several reports (Kraus and Bengtson 1959, Hermann et al. 1974, Woodman 1971, 1972), but there are many problems of technical, legal, economic, and long-term ecological natures to be considered and it will probably become feasible only on limited areas.

Thinning has greatly improved soil moisture during summer drought periods in our Shawnigan experiment and thus benefited the remaining trees, but it is not a practice that will increase site productivity. Better soil management practices should be emphasized and further explored. For instance, practices employed in site preparation and logging are likely to have a profound effect, temporary or permanent, by removal, redistribution, or compaction of organic matter and mineral soil. This can lead to changes in water infiltration, water pathways in the soil, and in their water-holding capacity. Critical soil disturbances can also result from methods of slash disposal during piling and burning, and low fire temperatures can lead to production of gases that condense in the soil and cause water repellency for many years (DeBano and Rice 1973).

CONCLUSIONS

Moisture influences the behavior of N in soil and trees in many complex ways that may give rise to an interaction between them in tree growth. Following N fertilization, moisture conditions affect losses of N by volatilization of ammonia and of other nitrogenous gases arising from denitrification, and by leaching below the rooting zone. Timing and amount of rainfall after fertilization are critical for losses, as are soil type and source and rate of fertilizer application. Season of application is therefore important, as discussed elsewhere by Heilman (this volume). Though losses have been considered minor and unimportant in some studies, they have been considerable in others. Technical difficulties in their measurement have contributed to the variation. Moisture effect on N loss provides a distinct cause for a moisture-fertilizer interaction in tree growth.

Moisture and N interrelate in other aspects of N availability, i.e., mineralization of organic matter and N movement to roots, as well as in tree physiology. Whether or not these factors also lead to an interaction in growth has not been shown and has been the subject of only a few studies. Further studies of this aspect and field trials relating fertilizer response to natural and induced moisture conditions are warranted to clarify this important question.

LITERATURE CITED

Ballard, T. M., and D. W. Cole.
1974. Transport of nutrients to tree root systems. Can. J. For. Res. 4:563–565.

Barber, S. A.
1966. The role of root interception, mass flow and diffusion relating the uptake of ions by plants from soil. Atom. Energy Ag. Tech. Rep. Ser. 65. p. 39–45. International Atomic Energy Agency, Vienna.

Black, C. A.
1966. Crop yield in relation to water supply and soil fertility. *IN* Plant environment and efficient water use. W. H. Pierre et al., eds. p. 177–206. American Society of Agronomy, Inc., and Soil Science Society of America, Madison, Wisc.

Bollen, W. B.
1974. Soil microbes. *IN* Environmental effects of forest residues management in the Pacific Northwest. USDA For. Serv. Gen. Tech. Rep. PNW-24. Owen P. Cramer, ed. p. B1–B41. USDA Forest Service, Portland, Oreg.

Brix, H.
1972. Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. Can. J. For. Res. 2:467–478.

Broadbent, R. E., and F. Clark.
1965. Denitrification. *IN* Soil nitrogen. W. V. Bartholomew and F. E Clark, eds. p. 344–359. American Society of Agronomy, Inc., Madison, Wisc.

Carrier, D., and B. Bernier.
1971. Pertes d'azote par volitilisation ammoniacale aprés fertilisation en forêt de pin gris. Can. J. For. Res. 1:69–79.

Cole, D. W., and S. P. Gessel.
1965. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. *IN* Forest-soil relations in North America. C. T. Youngberg, ed. p. 95–104. Oregon State Univ. Press, Corvallis.

Cole, D. W., W. J. B. Crane, and C. C. Grier. The effect of forest management practices on water chemistry in a second-growth Douglas-fir ecosystem. *IN* Forest soils and forest land management. B. Bernier and C. J. Winget, eds. p. 195–207. (Proc. Fourth North Am. For. Solls Conf., Quebec 1973.) Laval Univ. Press, Quebec.

Crafts, A. S.
1968. Water deficits and physiological processes. *IN* Water deficits and plant growth. Vol. 2. Plant water consumption and response. T. T. Kozlowski, ed. p. 85–133. Academic Press, Inc., New York.

Crane, W. J. B.
1972. Urea-nitrogen transformations, soil reactions, and elemental movement via leaching and volatilization, in a coniferous forest ecosystem following fertilization. Ph.D. thesis, Univ. Washington, Seattle. 285 p.

DeBano, L. F., and R. M. Rice.
1973. Water-repellent soils: Their implications in forestry. J. For. 71:220–223.

Derome, J. R.
1979. Urea hydrolysis and ammonia volatilization from urea pellets spread on top of the litter layer. Commun. Inst. For. Fenn. 97:1–22.

Fiedler, H. J., W. Nebe, W. Hofmann, and W. Hunger.
1978. Intensivierung der Holzerzeugung durch Stickstoffdüngung in älteren Fichtenbestanden auf grund- und stauwasserfreien Standorten. Beitr. Forstwirtsch. 12(1):16–24.

Gessel, S. P., T. N. Stoate, and K. J. Turnbull.
1969. The growth behavior of Douglas-fir with nitrogenous fertilizer in western Washington. 2nd rep., Univ. Wash., Inst. For. Prod. Cont. No. 7. College of Forest Resources, Univ. Washington, Seattle.

Heilman, P.
1974. Effect of urea fertilization on nitrification in forest soils of the Pacific Northwest. Soil Sci. Soc. Am. Proc. 38:664–667.

Hermann, R. K., D. P. Lavender, and J. B. Zaerr.
1974. Role of physiology in young-growth management: Nutrition, fertilization, irrigation, and growth regulators. *IN* Managing young forests in the Douglas-fir region. A. B. Berg, ed. p. 77–104. Oregon State Univ., Corvallis.

Johnson, D. W.
1979. Some nitrogen fractions in two forest soils and their changes in response to urea fertilization. Northwest Sci. 53:22–32.

Kramer, P. J.
1969. Plant and soil water relationships: A modern synthesis. 482 p. McGraw-Hill, Inc., New York.

Kraus, J. F., and G. W. Bengtson.
1959. The use of irrigation in forestry. *IN* Southern forest soils. (Eighth Annual Forestry Symposium, Baton Rouge, La. p. 96–105). Louisiana State Univ. Press, Baton Rouge.

Moore, D. G.
1975. Impact of forest fertilization on water quality in the Douglas-fir region—A summary of monitoring studies. p. 209–219. *IN* Forestry issues in urban forestry (Proc. 1974 Natl. Conv., Soc. Am. For.).

Naylor, A. W.
1972. Water deficits and nitrogen metabolism. *IN* Water deficit and plant growth. Vol. 3. Plant responses and control of water balance. T. T. Kozlowski, ed. p. 241–254. Academic Press Inc., New York.

Neary, D. G., and J. H. Leonard.
1977. Environmental aspects of forest fertilization. *IN* Use of fertilizers in New Zealand forestry. R. Ballard, compiler. p. 247–266. N.Z. For. Serv. FRI Symp. 19. New Zealand Forest Service, Forestry Research Institute, Rotorua.

Nömmik, H., and J. Thorin.
1972. Transformation of ^{15}N-labelled nitrite and nitrate in forest raw humus during anaerobic incubation. *IN* Isotopes and radiation in soil-plant relationships including forestry. p. 369–382. International Atomic Energy Agency, Vienna.

Otchere-Boateng, J., and T. M. Ballard.
1978. Urea fertilizer effects on dissolved nutrient concentrations in some forest soils. Soil Sci. Soc. Am. J. 42:503–508.

Overrein, L. N.
1971. Isotope studies on nitrogen in forest soil: I. Relative losses of nitrogen through leaching during a period of forty months. Medd. Nor. Skogforsöksves. 29:261–280.

Overrein, L. N.
1969. Lysimeter studies on tracer nitrogen ln forest soil: 2. Comparative losses of nitrogen through leaching and volatilization after the addition of urea-, ammonium- and nitrate-N^{15}. Soil Sci. 107:149–159.

Roberge, M. R., and R. Knowles.
1966. Ureolysis, immobilization and nitrification in black spruce (*Picea mariana* Mill.) humus. Soil Sci. Soc. Am. Proc. 30:201–204.

Steinbrenner, E. C.
1968. Research in forest fertilization at Weyerhaeuser Company in the Pacific Northwest. *IN* Forest fertilization—Theory and practice. G. W. Bengtson, ed. p. 209–215. Tennessee Valley Authority National Fertilizer Devel. Centre., Muscle Shoals, Ala.

Strand, R. F.
1964. Soil and growth studies in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands near Molalla, Oregon. Ph.D. thesis, Oregon State Univ., Corvallis.

University of Washington, College of Forest Resources.
1977. Regional forest nutrition research project, Biennial Report 1974–76. Univ. Wash. Inst. For. Prod. Cont. No. 25. 67 p. Univ. Washington, Seattle.

Viets, F. G., Jr.
1962. Fertilizers and efficient use of water. Adv. Agron. 14:223–264.

Viets, F. G., Jr.
1972. Water deficits and nutrient availability. *IN* Water deficits and plant growth. Vol. 3. Plant responses and control of water balance. T. T. Kozlowski, ed. p. 217–239. Academic Press, Inc. New York.

Watkins, S. H., R. F. Strand, D. S. DeBell, and J. Esch, Jr.
1972. Factors influencing ammonia losses from urea applied to northwestern forest soils. Soil Sci. Soc. Am. Proc. 36:354–357.

Will, G. M.
1977. The fate of fertilizers applied to forest soils. *IN* Use of fertilizers in New Zealand Forestry. N.Z. For. Serv., FRI Symposium no. 19. New Zealand Forest Service, Forest Research Institute, Rotorua.

Woodman, J. N.
1971. Is there a future for irrigation in the management of forests? Am. Soc. Agric. Eng., Pap. P. p. 171–179.

Woodman, J. N.
1972. Forest irrigation. *IN* Perm. Assoc. Comm. Proc., 1972, p. 143–145. Western Forestry & Conservation Assoc., Ann. Meet., Seattle, Washington.

Zahner, R.
1968. Water deficits and growth of trees. *IN* Water deficits and plant growth. Vol. 2. Plant water consumption and response. T. T. Kozlowski, ed. p. 191–254. Academic Press Inc., New York.