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FINAL REPORT

LOSS OF ORGANIC AND INORGANIC
MATERIALS FROM ABOVE-GROUND PLANT PARTS
BY LEACHING

Contract AT(11-1)-3154

United States Atomic Energy Commission

Prepared by

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March 1, 1974

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March 1, 1974

Mr. Harold Miller, Director
Contract Management Division
U.S. Atomic Energy Commission
Chicago Operations Office
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Mr. Miller:

Attached is the Final Report of Atomic Energy Commission Contract AT(11-1)-3154 covering the period of 1960 to 1973. Statements of Actual Costs are in preparation and will be forwarded shortly.

Let me express my appreciation to the Atomic Energy Commission for its support for the 13 years. We have had fine assistance from your office and from the New York Operations Office in former years. The group at Germantown, especially Dr. Reitemeier, were helpful in all aspects of the project.

We have enjoyed the association with the Atomic Energy Commission. It has been a productive project, we have gained information about decontamination of food plants from fallout, there have been several practical adaptations currently in use in the commercial horticultural industries, and we have developed a completely new concept of an important environmental factor in horticulture and plant physiology, namely, the influence of rainfall on plant growth. For this, we are pleased, and we are grateful for the financial and other support over the years.

Sincerely,

H.B. Tukey, Jr.
Professor

HBT:prl
ENC.

Yearly accomplishments of Atomic Energy Commission Contract AT(11-1)-3154 (formerly AT(11-1)-2595) has been summarized in the annual progress reports, from which this summary report is developed. The significant accomplishments are:

A. LEACHING CHARACTERIZED

1. Leaching is the loss of organic and inorganic substances from plant, stems, foliage, flowers, fruit, branches, and roots, by the action of rain, dew, mist, fog, overhead irrigation, and other water solutions. Although leaching has been discussed since 1804, only after the use of radioisotopes could it be demonstrated conclusively that labeled materials introduced into plants could be leached from them, and the process could be studied efficiently.

Tukey, H.B. Jr., H.B. Tukey and S.H. Wittwer. Loss of nutrients by foliar leaching as determined by radioisotopes. Proc. Amer. Soc. Hort. Sci. 71:496-506. 1958.

Tukey, H.B., S.H. Wittwer and H.B. Tukey, Jr. Leaching of nutrients from plant foliage as determined by radio-isotopes. In: "Radioisotopes and Scientific Research" 4:304-322. (Proc. 1st UNESCO Intern. Conf. Paris, 1957). Pergamon Press, London. 1958.

Tukey, H.B. Jr. and H.B. Tukey. The loss of organic and inorganic materials by leaching from leaves and other above-ground plant parts. In: "Radioisotopes In Soil Plant Nutrition Studies". pp. 289-302. Intern. Atomic Energy Agency, Vienna, 1962.

2. A great diversity of both organic and inorganic substances can be leached from plants. All of the minerals commonly found in plants can be leached, including boron, calcium, chlorine, iron, magnesium, manganese, nitrogen, phosphorus, potassium, sodium, strontium, sulphur, and zinc, with losses ranging up to 50-90% of the mineral content of tissues in 24 hours of rain. Large amounts of carbohydrates are also leached, including free sugars, pectic substances, and other polysaccharides, totaling up to 800 pounds per acre per year from cultivated crops. All of the common amino acids and derivatives, many organic acids, alkaloids, phenolic substances, pigments, vitamins, phytotoxins and growth regulating substances such as auxins, co-factors, gibberellins, and abscisic acid are leached.

Hemphill, D.D. Jr. and H.B. Tukey, Jr. The effect of intermittent mist on abscisic acid contact of Euonymus alatus Sieb. 'Compactus'. J. Amer. Soc. Hort. Sci. 98:416-420. 1973.

Kozel, P.C. and H.B. Tukey, Jr. Loss of gibberellins by leaching from stems and foliage of Chrysanthemum morifolium 'Princess Anne'. Amer. Jour. Bot. 55:1184-1189. 1968.

Lee, Choong Il and H.B. Tukey, Jr. Induction of root-promoting substances in Euonymus alatus 'Compactus' by intermittent mist. J. Amer. Soc. Hort. Sci. 96:731-736. 1971.

Morgan, J.V. and H.B. Tukey, Jr. Characterization of leachates from plant foliage. Plant Physiol. 39:590-593. 1964.

Tukey, H.B. Jr. and J.V. Morgan. The occurrence of leaching from above-ground plant parts and the nature of the material leached. Proc. XVI Intern. Hort. Cong. 4:153-160. 1964.

Zondag, R.J. The levels of rooting cofactor 4 in Chrysanthemum morifolium during propagation. M.S. thesis, Cornell University, Ithaca, N.Y. 1972.

3. Leaching is an important natural phenomenon occurring in all geographical areas involving a wide range of plant species including coniferous and deciduous forest and shade trees, tree fruits, small fruits, grapes, tropical and sub-tropical plants, vegetable crops, grains, grasses, forage crops, woody and herbaceous ornamentals, plantation crops, and foliage and conservatory plants.

Tukey, H.B. Jr. and J.V. Morgan. The occurrence of leaching from above-ground plant parts and the nature of the material leached. Proc. XVI Intern. Hort. Cong. 4:153-160. 1964.

Tukey, H.B. Jr. Leaching of metabolites from foliage and its implication in the tropical rainforest. In: "A Tropical Rainforest", Ed. by H.T. Odum, Atomic Energy Commission, Division of Technical Information, Washington, D.C. 1969.

4. Many factors, both external and internal to the plant, have an influence upon leaching.

Tukey, H.B. Jr., H.B. Tukey and S.H. Wittwer. Loss of nutrients by foliar leaching as determined by radioisotopes. Proc. Amer. Soc. Hort. Sci. 71:496-506. 1958.

Tukey, H.B., S.H. Wittwer and H.B. Tukey, Jr. Leaching of nutrients from plant foliage as determined by radio-isotopes. In: "Radioisotopes and Scientific Research". 4:304-322. (Proc. 1st UNESCO Intern. Conf. Paris, 1957). Pergamon Press, London. 1958.

Tukey, H.B. Jr. and H.B. Tukey. The loss of organic and inorganic materials by leaching from leaves and other above-ground plant parts. In: "Radioisotopes In Soil Plant Nutrition Studies". pp. 289-302. Intern. Atomic Energy Agency, Vienna. 1962.

a. Physiological age. Mature tissues approaching senescence are much more susceptible to leaching than are young tissues. For example, 80-90 percent of the potassium in a mature leaf can be leached in 24 hours whereas only 5 percent can be leached from an immature leaf.

Good, G.L. and H.B. Tukey, Jr. Leaching of metabolites from cuttings propagated under intermittent mist. Proc. Amer. Soc. Hort. Sci. 89:727-733. 1966.

b. Plant morphology. There are differences in leachability among plants and parts of the same plant, due in large measure to leaf characteristics such as wettability, continuity of the cuticle, pubescence, and presence of hydathodes. Leaching is a specific phenomenon and some plants are more susceptible to leaching than are others.

c. Metabolites. Mineral elements, such as calcium, potassium, and sodium, are leached with ease, whereas other elements, such as zinc and phosphorus are leached with difficulty. Carbohydrates are the most easily leached of the organic substances. Differences in leachability of substances are directly related to their metabolism within the plant.

d. Plant nutrient status. As the supply of nutrients to the plant is increased, the amount of nutrients capable of being leached is also increased.

Mecklenburg, R.A. and H.B. Tukey, Jr. The influence of foliar leaching on root uptake and translocation of calcium-45 to the stems and foliage of Phaseolus vulgaris. Plant Physiol. 39:533-536. 1964.

e. Nature of the leaching solution. Salts in the leaching solution will increase losses of mineral nutrients. As rain drips down through leaves of a plant, the substances leached from the upper leaves will have an effect on leaching from the lower leaves.

f. Environmental effects. Light and temperature have little direct influence on leaching of mineral elements. However, an increase in temperature and light intensity will increase losses by leaching of organic substances, due perhaps to changes in metabolism rather than leaching.

Mitchell, C.A. Detection of carbohydrates leached from above-ground plant parts. M.S. thesis, Cornell University, Ithaca, New York. 1968.

Tukey, H.B. Jr., S.H. Wittwer and H.B. Tukey. Leaching of carbohydrates from plant foliage as related to light intensity. Science 126:120-121. 1957.

g. Duration of leaching period and intensity of rain. Losses of substances are increased with the duration of the leaching period. Stems and foliage need only be wetted to be leached, and, in fact, a small amount of moisture over a long period of time such as fog and dew will leach considerably more metabolites than with a heavy, but brief rain shower.

Tukey, H.B. Jr., R.A. Mecklenburg and J.V. Morgan. A mechanism for the leaching of metabolites from foliage. In: "Isotopes and Radiation in Soil-Plant Nutrition Studies", pp. 371-385. Intern. Atomic Energy Agency, Vienna, 1965.

h. Injury. Injury of any kind to plant tissue will greatly increase the loss by leaching, whether the injury be by pathological, entomological, physiological, environmental, or physical means.

Tukey, H.B. Jr. and J.V. Morgan. Injury to foliage and its effect upon the leaching of nutrients from above-ground plant parts. *Physiologia Plantarum*. 16:557-565. 1963.

5. The mechanism for leaching of cations such as calcium, potassium, strontium, and rubidium involves (a) exchange of hydrogen in the leaching solutions for cations on the cell wall and cuticle exchange sites, (b) diffusion of cations within the leaves to the leaf surface, and (c) a combination of both exchange and diffusion. Cations are leached from the exchangeable cation pool in plants and not from within the cells or within cell walls. This explains why young tissues are more difficult to leach than are older tissues; in that leaching competes with cellular metabolism for exchangeable ions. All factors which influence exchange reactions, root uptake of nutrients, and translocation have an influence upon the leaching of substances from above-ground plant parts.

Mecklenburg, R.A. and H.B. Tukey, Jr. The influence of foliar leaching on root uptake and translocation of calcium-45 to the stems and foliage of Phaseolus vulgaris. *Plant Physiol.* 39:533-536. 1964.

Mecklenburg, R.A., H.B. Tukey and J.V. Morgan. A mechanism for the leaching of calcium from foliage. *Plant Physiol.* 41:610-613. 1966.

Tukey, H.B. Jr., R.A. Mecklenburg and J.V. Morgan. A mechanism for the leaching of metabolites from foliage. In: "Isotopes and Radiation in Soil-Plant Nutrition Studies", pp. 371-385. Intern. Atomic Energy Agency, Vienna, 1965.

6. Cycling of leached substances.

Substances which are leached from one plant can be absorbed by the roots and foliage of the same and other nearby plants and reutilized in growth. Such cycling of substances from one plant to another is now well documented and has important implications in plant nutrition, stimulation and suppression of plants beneath the spread of other plants in both natural and landscape plantings, plant competition, development of plant associations and ecosystems, and susceptibility of plants to diseases and insects. Certain basipetally immobile nutrients such as calcium and strontium can be redistributed from older leaves to new leaves of the same plant, in part outside the plant, by leaching and root absorption of the leachates. Use of radio-isotopes has contributed considerably to the evaluation of nutrient cycling.

Tukey, H.B. Jr. Leaching of metabolites from above-ground plant parts and its implications. *Bull. Torrey Bot. Club.* 93:385-401. 1966.

Tukey, H.B. Jr. and R.A. Mecklenburg. Leaching of metabolites from foliage and subsequent reabsorption and redistribution of the leachate in the plant. *Amer. Jour. Bot.* 51:737-742. 1964.

Tukey, H.B. Jr., R.A. Mecklenburg and J.V. Morgan. A mechanism for the leaching of metabolites from foliage. In: "Isotopes and Radiation in Soil-Plant Nutrition Studies", pp. 371-385. Intern. Atomic Energy Agency, Vienna, 1965.

7. Leaching in the tropics.

a. Leaching of substances from plants is of particular importance in the warm humid tropics, as shown by our experiments in the rainforest of Puerto Rico. Apparently, species adapted to the heavy rainfall of the rainforest have developed mechanisms to withstand leaching, in that only small quantities of mineral nutrients were leached from plants of these species. In contrast, larger amounts of mineral nutrients were leached from important agricultural crops of the tropics, banana (Musa sp.), sugar cane (Saccharum officinalis), and coffee (Coffea arabica) which are not adapted to the high rainfall occurring in the rainforest.

Thus, leaching is one of the important overlooked factors in crop production in tropical areas with heavy rainfall. Some preliminary experiments have shown that protection of plants from rain, as by roofs or sprays of waxes onto the foliage, may significantly improve crop yields.

Tukey, H.B. Jr. Leaching of metabolites from foliage and its implication in the tropical rain forest. In: "A Tropical Rainforest", Ed. by H.T. Odum, Atomic Energy Commission, Washington, D.C. pp. H155-160. 1970.

b. Cycling of leached metabolites in the tropical rainforest is much slower than in temperate zone forests. When cesium-137, manganese-56, and strontium-85 were sprayed on to the forest floor of the Luguillo rainforest, due to the high exchange capacity of the organic fraction on the forest floor, almost all of the radioisotopes were tightly fixed by the organic fraction and were rendered unavailable or only slowly available to plants. Such tenacious retention is of ecological importance to maintenance of the rainforest, and is also of great significance in the retention of fallout products, such as might be distributed by use of atomic devices in tropical regions.

c. Nutrition of epiphytes in the rainforest. Bromeliads growing on the trunks of many trees in the rainforest trap leachates from the overhead canopy in a natural catch-basin formed by the diverging leaf bases, from which nutrients are absorbed efficiently by the foliage. Other epiphytes growing on leaf surfaces in the rainforest also trap nutrients leached from the overhead canopy and use them in their own growth and also that of the host plant. These results have importance in both ecology and in distribution of fallout products, and these relationships are being studied in many other natural ecosystems.

Tukey, H.B. Jr. Leaching of metabolites from foliage and its implication in the tropical rainforest. In: "A Tropical Rainforest", Ed. by H.T. Odum, Atomic Energy Commission, Washington, D.C. pp. H155-160. 1970.

Tukey, H.B. Jr. Implications of allelopathy in agricultural plant science. Bot. Rev. 35:1-16. 1969.

B. IMPLICATIONS, PRACTICAL APPLICATIONS AND SPECIAL CONSIDERATIONS OF LEACHING

8. Leaching and decontamination of food plants.

With the mechanism of leaching now established, it is possible to apply this knowledge to the decontamination of food plants from radioactive fallout. Those plants which had been tested extensively include bean (Phaseolus vulgaris), corn (Zea mays), lettuce (Lactuca sativa), pea (Pisum sativum), parsley (Petroselinum crispum), and tomato (Lycopersicon esculentum). Other food plants had been used to a lesser degree. Root absorption and translocation of ^{89}Sr into the fruit of bean, pea, and tomato was noted only if contamination occurred after the onset of flowering. If contamination occurred previous to the development of inflorescence, or late in fruit development, the fruit was not contaminated.

However when radioactive contaminants were incorporated into tissues, they ordinarily were not removed, since cellular contents are not easily leached. Only those contaminants which are being translocated or are in the exchangeable ion pool can be leached. Since leaching is a process involving exchange at the surface of tissues, leaves are much easier to decontaminate than are thick fleshy storage organs and fruit, and any factor which favors ion exchange will favor decontamination. Substances including radioactive materials, which are deposited on leaf surfaces are easier to leach than are materials which are root absorbed and incorporated within plant parts.

Mechling, W.H. III. Decontamination of selected vegetable crops by leaching with reference to strontium. M.S. thesis, Cornell University, Ithaca, New York. 1966.

Mecklenburg, R.A. The influence of foliar leaching upon plant nutrition with special reference to root uptake, translocation, and loss of calcium. Ph.D. thesis, Cornell University, Ithaca, New York. 1964.

Tukey, H.B. Jr., R.A. Mecklenburg and J.V. Morgan. A mechanism for the leaching of metabolites from foliage. In: "Isotopes and Radiation in Soil-Plant Nutrition Studies", pp. 371-385. Intern. Atomic Energy Agency, Vienna, 1965.

Since strontium is not normally transported basipetally in plants, it was once thought that underground storage organs, such as fleshy roots and underground stems, would be free from radioactive contamination by fallout ^{90}Sr . However, this is not the case. Radioactive strontium is deposited onto leaf surfaces from where it can be leached to the soil by rain, absorbed by the roots and translocated acropetally into the storage organs and above-ground plant parts. We have demonstrated this phenomenon with potato (Solanum tuberosum) and the results are applicable to many other crops and other contaminants. Such a redistribution is important in the translocation of fallout materials and in the contamination of plants and plant parts not contaminated originally.

9. Leaching of growth regulating substances (plant hormones).

a. Gibberellins, effect upon flowering.

When Easter lilies (Lilium longiflorum) were grown under intermittent water mist, stem length was reduced in direct proportion to increasing amounts of water mist, although leaf number, flower number, date of flowering and dry weight remained the same. Similarly, stem length of lilies can be controlled by changing the length of day (photoperiod) under which the plants were growing, suggesting that growth regulators involved in the photoperiod reaction can also be leached.

We have shown that gibberellins are leached from the foliage of Chrysanthemum morifolium and Pharbitis nil, gibberellins A₁₋₃ and GA₅ leached from vegetative, non-flowering plants, and GA₁₋₃ and GA₆ from flowering plants. When Chrysanthemum and Pharbitis, both of which require short day (long night) conditions to flower, were leached prior to and following a photoinductive period, subsequent flowering was delayed and even completely inhibited, especially in Pharbitis. Carbohydrate levels in the plant are not responsible directly for these results, for when Pharbitis plants were vegetative, the flowering response to mist was the same. Rather, it appears that the substances or balance of substances necessary for flowering in these plants were removed or modified by leaching.

Kozel, P.C. and H.B. Tukey, Jr. Loss of gibberellins by leaching from stems and foliage of Chrysanthemum morifolium 'Princess Anne'. Amer. Jour. Bot. 55:1184-1189. 1968.

Kimura, K. and H.B. Tukey, Jr. Influence of mist on floral initiation of Pharbitis nil. Ber. Ohara Inst. Landwirts. Biol. 15:61-67. 1971.

NYO-2598-52

Progress Report, 1970-71

b. Auxins

Other growth regulating substances can be leached from plants including auxins, chlorogenic acid, and many phenolic and flavanoid substances. Leaching of these materials has effects upon senescence, dormancy, leaf abscission, root initiation and development, and fall coloration in leaves.

Lee, Choong Il and H.B. Tukey, Jr. Induction of root-promoting substances in Euonymus alatus 'Compactus' by intermittent mist. J. Amer. Soc. Hort. Sci. 96:731-736. 1971.

Lee, Choong Il and H.B. Tukey, Jr. Effect of intermittent mist on development of fall color in foliage of Euonymus alatus 'Compactus'. J. Amer. Soc. Hort. Sci. 97:97-101. 1972.

c. Rooting cofactors.

Rooting cofactors are 4 partially characterized compounds or groups of compounds which act synergistically with auxins to improve root initiation. Their exact function is not clear. Cofactors 1-4 were leached from cuttings of Chrysanthemum morifolium and Euonymus alatus 'Compactus', but we were unable to note any definite correlation with root initiation in these plants when propagated under mist. It adds further evidence to our suggestion that many other compounds, other than auxins and rooting cofactors are involved in root initiation and should be considered more fully.

Mecklenburg, R.A. and H.B. Tukey, Jr. Uptake by the root and subsequent distribution within the potato plant of strontium-89 leached from the foliage. *Nature*. 198:552-553. 1963.

Tukey, H.B. Jr. and H.B. Tukey. The loss of organic and inorganic materials by leaching from leaves and other above-ground plant parts. In: "Radioisotopes and Soil Plant Nutrition Studies". pp. 289-302. Intern. Atomic Energy Agency, Vienna, 1962.

It was once thought that dormant plants would not absorb appreciable amounts of radioactive contamination presumably because foliage might be absent and translocation inhibited. However, we have shown that the roots of woody plants do not become dormant during the winter season as do the above-ground portions, but continue to grow throughout the winter season in direct proportion to the soil temperature. Growing roots absorb nutrients from the soil which are translocated to the above-ground parts, even though these parts are completely dormant. Thus, a dormant plant in the winter season can become contaminated as during the growing season, and the same principles of decontamination hold true for these plants as well.

Good, G.L. The influence of shoot and root zone temperature on the root uptake and translocation of nutrients in dormant woody plants. Ph.D. thesis, Cornell University, Ithaca, New York. 1969.

Good, G.L. and H.B. Tukey, Jr. Root growth and nutrient uptake by dormant Ligustrum ibolium and Euonymus alatus 'Compactus'. *J. Amer. Soc. Hort. Sci.* 94:324-326. 1969.

Meyer, M.M. Jr. The influence of nutrition in root temperature on the dormant season nutrient content and spring growth of Taxus media and Forsythia intermedia. Ph.D. thesis, Cornell University, Ithaca, New York. 1965.

Meyer, M.M. Jr. and H.B. Tukey, Jr. Influence of root temperature and nutrient applications on root growth and mineral nutrient content of Taxus and Forsythia plants during the dormant season. *Proc. Amer. Soc. Hort. Sci.* 90:440-446. 1967.

Surface contamination of the aerial parts of plants can easily be removed by leaching within a short time after contamination. However, as the time period between contamination and leaching increases, the amount of contaminants leached is greatly decreased. Once contaminants have been incorporated within cells, they are difficult to leach.

Mechling, W.H. Decontamination of selected vegetable crops by leaching with reference to strontium. M.S. thesis, Cornell University, Ithaca, New York. 1966.

Zondag, R.J. The levels of rooting cofactor 4 in Chrysanthemum morifolium during propagation. M.S. thesis, Cornell University, Ithaca, New York. 1972.

d. Abscissic acid and dormancy.

When Euonymus alatus 'Compactus', a deciduous ornamental shrub, was grown under intermittent mist, plants failed to develop anthocyanins, leaves did not abscise, and senescence and dormancy were delayed for up to 1 year, as long as plants remained under the mist. When the plants were removed from the mist, immediately anthocyanins developed, leaves abscised, and the plants became dormant. This is in contrast to control plants (non-misted) which developed leaf pigmentation and became dormant in the fall, requiring 6 weeks of cold before growth resumed in spring.

Levels of abscissic acid (ABA), a growth regulator associated with dormancy, were correlated directly with dormancy, being high in control plants (non-misted) which became dormant, and less in misted plants that were not dormant. In addition, ABA was detected in the leachates. This suggests that ABA can be leached and that natural dormancy in plants can be altered by rainfall.

Hemphill, D.D. Jr. and H.B. Tukey, Jr. The effect of intermittent mist on abscissic acid content of Euonymus alatus Sieb. 'Compactus'. J. Amer. Soc. Hort. Sci. 98:416-420. 1973.

10. Chemical Ecology - chemical interactions among plants.

Chemical substances liberated by one plant can have a significant reaction upon another plant. Crop rotations and seeding mixtures have been developed, in part, to avoid the toxic influence of crop residues. Certain species cannot grow in association with other species in landscape and agricultural plantings; some weeds compete successfully with crop plants and plant successions develop, in part, because of inhibitory chemical effects of one plant on another, called allelopathy.

Leaching is important in chemical ecology since it is one of the major mechanisms by which substances from plants are released into the surrounding area and since it occurs throughout the growing season. Although the inhibiting effects of plant leachates has received the most attention, we have long suggested that the promotive effects of substances from one plant on growth of another may prove ultimately to be of greater significance. Since such a wide range of plant substances are leached, including minerals, carbohydrates, organic acids, amino acids, and most important growth regulating substances, it is not difficult to speculate on the importance of this process in plant interactions, both in natural conditions and in controlled agriculture.

Tukey, H.B. Jr. Leaching of metabolites from above-ground plant parts and its implications. Bull. Torrey Bot. Club. 93:385-401. 1966.

Tukey, H.B. Jr. Implications of allelopathy in agricultural plant science. Bot. Rev. 35:1-16. 1969.

Tukey, H.B. Jr. Leaching of substances from plants. In: "Bio-chemical Interactions Among Plants" National Academy of Sciences, Washington, D.C. 1971. pp. 25-32.

11. Leaching and nutrition of cuttings propagated under intermittent mist.

In commercial plant propagation, cuttings are placed under an intermittent water mist which cools the leaves, thus reducing transpiration (water loss) and respiration in the cuttings, enabling root formation to occur more rapidly. The mist continually bathes the stems and foliage of the cuttings and leaches substances from the cuttings. Hardwood cuttings taken from mature wood are particularly susceptible to leaching, whereas softwood and herbaceous cuttings taken from new succulent growth are less susceptible to leaching.

Good, G.L. and H.B. Tukey, Jr. Leaching of nutrients from cuttings under mist. Proc. Intern. Plant Propagators' Soc. 14:138-142. 1964.

Good, G.L. and H.B. Tukey, Jr. The influence of intermittent mist on the mineral nutrient content of cuttings during propagation. Proc. Intern. Plant Propagators' Soc. 15:78-86. 1965.

Good, G.L. and H.B. Tukey, Jr. Leaching of metabolites from cuttings propagated under intermittent mist. Proc. Amer. Soc. Hort. Sci. 89:727-733. 1966.

Tukey, H.B. Jr. Leaching of metabolites from above-ground plant parts with special reference to cuttings used for propagation. Proc. Intern. Plant Propagators' Soc. 12:63-70. 1962.

To replace the leached nutrients and to provide nutrients for new growth of the cuttings during propagation, mineral nutrients can be added directly to the cuttings through the water mist. Cuttings propagated under nutrient mist are improved in that: (a) the nutrient content of the cuttings is greatly increased, stimulating more growth during propagation, (b) rooting is speeded and the numbers and length of roots are greatly increased, (c) development of side branches is greatly increased, producing heavier, bushier cuttings, (d) cuttings propagated under nutrient mist continue to grow at a faster rate following transplanting, and are less susceptible to injury.

Good, G.L. and H.B. Tukey, Jr. Redistribution of mineral nutrients in Chrysanthemum morifolium during propagation. Proc. Amer. Soc. Hort. Sci. 90:384-388. 1967.

Wott, J.A. and H.B. Tukey, Jr. Propagation of cuttings under nutrient mist. Proc. Intern. Plant Propagators' Soc. 15:86-94. 1965.

Wott, J.A. and H.B. Tukey, Jr. Influence of nutrient mist and the propagation of cuttings. Proc. Amer. Soc. Hort. Sci. 90:454-461. 1967.

Use of ³²P has shown that more than 95% of the phosphorus absorbed by cuttings from the nutrient mist was absorbed by the above-ground leaves and stems and only 5% was absorbed through the below-ground portion of the cut stems and the new developing roots. Nutrient mist and uptake of nutrients through the foliage is a much more efficient method of applying nutrients to cuttings than are applications applied to the root medium.

Wott, J.A. and H.B. Tukey, Jr. Absorption of phosphorus by Chrysanthemum morifolium cuttings propagated under nutrient mist. Jour. Amer. Soc. Hort. Sci. 94:382-384. 1969.

Recommendations have been developed for the use of nutrient mist by commercial nurserymen, including optimum concentrations for particular plants, equipment and methods of application, timing of applications for greatest benefit, and sanitation methods necessary in the program. These results have made an important contribution to the plant propagation industry, and use of nutrient mist is now a common commercial practice throughout the country, particularly by the large concerns which annually propagate millions of plants.

Wott, J.A. and H.B. Tukey, Jr. Cutting size and nutrient mist affect rooting of chrysanthemums. N.Y. State Flower Growers Bull. 284. July, 1969.

Wott, J.A. and H.B. Tukey, Jr. Propagation of chrysanthemums under nutrient mist. Proc. Intern. Plant Propagators' Soc. 18. 1968.

12. Root growth and nutrient uptake by dormant plants.

Roots of dormant woody plants in winter continue to grow throughout the dormant period, as long as root temperatures are above freezing. Root growth at 35°F is small, and is greatly increased as the temperature increases to 55°F. This may be one reason why roots are injured so easily by winter cold in that they do not become completely dormant. Growing roots of dormant plants absorb ^{32}P in direct proportion to the root temperature above freezing. Translocation of ^{32}P from the roots to the above-ground stems is influenced primarily by air temperature. At air temperatures of 45 and 55°F, translocation from the roots is appreciable, even though the plants remain completely dormant.

In the case of Taxus media and Forsythia intermedia, 50 to 80% of the mineral nutrient requirement for spring growth came from nutrient reserves present in the plant during the dormant season, whereas nutrients absorbed from the soil during the spring growth were much less important. Radioactive isotopes were used to great advantage in this experiment.

It is now a common practice of commercial nurserymen throughout the United States to apply nutrients to woody plants in the fall season of the year, commonly September to December in New York State, when plants are dormant, but when soil temperatures are warm and roots are growing. This allows four months in which nutrients can be absorbed and translocated into the above-ground parts of the plant, increasing the winter hardiness of plants and producing greater amounts of nutrient reserves for increased spring growth the following year. Not only does this improve growth and make more efficient use of labor, but the utilization of nutrient applications is more efficient, and application rates can be reduced thus helping to reduce environmental pollution by fertilizers.

Good, G.L. and H.B. Tukey, Jr. Root growth and nutrient uptake by dormant Ligustrum ibolium and Euonymus alatus 'Compactus'. J. Amer. Soc. Hort. Sci. 94:324-326. 1969.

Meyer, M.M. Jr. and H.B. Tukey, Jr. Nitrogen, phosphorus, and potassium reserves in the spring growth of Taxus and Forsythia. Proc. Amer. Soc. Hort. Sci. 87:537-544. 1965.

Meyer, M.M. Jr. and H.B. Tukey, Jr. Influence of root temperature and nutrient applications on root growth and mineral nutrient content of Taxus and Forsythia plants during the dormant season. Proc. Amer. Soc. Hort. Sci. 90:440-446. 1967.

Tukey, H.B. Jr. and M.M. Meyer, Jr. Nutrient applications during the dormant season. Proc. Intern. Plant Propagators' Soc. 16:306-310. 1966.

13. Role of stomata in loss of nutrients by leaching.

Stomata of several species, particularly Chrysanthemum morifolium, were closed by applications of phenylmercuric acetate, and reductions of transpiration rates were observed. However, the use of phenylmercuric acetate to control transpiration in commercial chrysanthemum crops is not recommended because of the toxicity of the chemical to both man and plants. Thus, the technique did not prove to be practicable in studies of leaching.

Cocking, W.D. and H.B. Tukey, Jr. Reduction of water loss from Chrysanthemum morifolium following foliar applications of phenylmercuric acetate. J. Amer. Soc. Hort. Sci. 95:382-384. 1970.

C. NEW CONCEPT OF RAIN AND MIST IN PLANT GROWTH

14. Effect upon dormancy.

Abscisic acid, a plant hormone associated with dormancy is leached from plants, directly influencing dormancy. (see section 9d).

15. Effect upon fall color.

Euonymus alatus, noted for its brilliant red fall color, failed to develop anthocyanins when grown under intermittent mist.

Mist affects anthocyanin synthesis in three ways. First, substances involved directly in the syntheses of anthocyanins (carbohydrates, potassium, flavanoid compounds) can be leached, thus reducing red coloration. When these leached substances are added back to plants, anthocyanin synthesis proceeds. Second, mist apparently delays dormancy due to leaching of abscisic acid and maintains plants in the vegetative state. Proteins continue to develop, sugars are changed to starch, and tricarboxylic acid activity increases, all of which compete for the substrates used in anthocyanin synthesis, again reducing red coloration. Third, the metabolic pathways of anthocyanin precursors are changed. Phenolic substances other than those directly involved in anthocyanin synthesis are formed, such as leucoanthocyanins and certain flavans which are colorless. In effect, mist reduces the amount of precursors of anthocyanin by leaching and also conditions the plant to produce substances other than anthocyanins. This explains why in seasons of prolonged rainfall in late summer and early fall, development of red foliage color due to anthocyanin formation is inhibited.

Lee, Choong Il and H.B. Tukey, Jr. Induction of root-promoting substances in Euonymus alatus 'Compactus' by intermittent mist. J. Amer. Soc. Hort. Sci. 96:731-736. 1971.

Lee, Choong Il and H.B. Tukey, Jr. Effect of intermittent mist on development of fall color in foliage of Euonymus alatus 'Compactus'. J. Amer. Soc. Hort. Sci. 97:97-101. 1972.

16. Effect upon root-inducing substances.

Intermittent mist has been used with great success by commercial nurserymen in propagation of cuttings by reducing transpiration and respiration in the cuttings. In Euonymus plants grown under intermittent mist, vegetative growth was promoted, dormancy inhibited, and phenolic and flavanoid substances accumulated in the leaves. These included specific phenolic compounds important in root initiation such as chlorogenic acid, flavans, flavonols, auxin-like substances, and rooting cofactors, as well as carbohydrates and phenylalanine ammonia lyase, an enzyme important in synthesis of phenolic compounds and total phenolic compounds. Thus, it was no surprise that cuttings taken from misted plants rooted more rapidly and more profusely than did cuttings from non-misted plants. Further, when root-promoting substances which accumulate in misted plants are added to non-misted plants, rooting is improved.

These results offer an additional explanation for the success of mist propagation. Not only does intermittent mist cool the cuttings, but also it induces the production of root-promoting substances which cause cuttings to root more easily in mist.

Lee, Choong Il and H.B. Tukey, Jr. Induction of root-promoting substances in Euonymus alatus 'Compactus' by intermittent mist. J. Amer. Soc. Hort. Sci. 96:731-736. 1971.

Tukey, H.B. and Choong Il Lee. Stimulation of rooting substances by mist. New York Food and Life Sciences Quart. 4(2,3):31-33. 1971.

Lee, Choong Il and H.B. Tukey, Jr. Development of root-promoting substances in Euonymus alatus 'Compactus' under intermittent mist. Proc. Int. Plant Prop. Soc. 21:343-350. 1971.

17. Influence of mist and leaching on incidence of disease

Incidence of disease is much reduced in cuttings under mist as compared with cuttings grown without mist. This has been explained on the basis that fungus spores are washed from the cuttings by the mist. However, the changes in metabolism observed in plants under mist may be associated with improved resistance to some diseases. We have suggested that leachates from plants could have an effect upon pathogens, both by conditioning the host or by providing a nutrient medium for spore germination and growth. This has now been shown experimentally and is being investigated by plant pathologists in several laboratories.

Tukey, H.B. Jr. Leaching of substances from plants. In: Preece, T.F. and C.H. Dickinson (ed) "Ecology of Leaf Surface Micro-organism". Academic Press, New York. pp. 57-80. 1971.

18. A new concept of rainfall in plant growth.

Traditionally, rainfall has been associated with moisture requirements of plants and with the development of plant pathogens in moist conditions. However, our research has indicated some additional effects of rainfall which may be of even greater significance. Large quantities of materials can be leached from plants, with effects on growth, yield, quality, nutritive value, and ecology. The metabolism of plants is changed when grown under mist, having an effect upon flowering, development of fall color, and root initiation, all of which we have reported.

In explanation when plants are grown under rain and mist, mineral substances are leached out, which decreases the osmotic concentration of the cell sap. Apparently, carbohydrates are put into the cell sap by mechanisms which we do not understand, which maintains the osmotic concentration in misted plants and in plants grown under irrigation and rainy climates. With carbohydrates available, growth regulating substances are manufactured, such as auxins, cofactors and other metabolites which in turn affects growth processes of many kinds.

Perhaps the large amount of growth associated with areas of high rainfall such as the humid tropics, British Isles, and Pacific Northwest should be thought of in terms of metabolic change induced by the rain, mist, and fog, as well as moisture. Vegetable crops, grapes, tree fruits, ornamental plants, and agronomic crops are now being produced commercially under overhead mist systems with large increases in yield and quality. These increases have been attributed to cooler leaf temperatures with less transpiration and respiration. This is exactly what we have observed in our experiments, especially with cuttings, and we suggest that leaching and induction of growth regulating substances in plants under mist should be considered to explain the benefits of mist in plant production. Further, we suggest that the whole influence of rain on crop development needs reevaluation.

Tukey, H.B. Jr. Rain, Dew, and Mist-Significance to Plant Growth. Longwood Garden Lectures, Kennett Square, Pennsylvania. February 16, 1972.

PERSONNEL

One of the most important contributions of the Contract has been the development of graduate students, who contributed significantly to the success of the project and who have continued to serve with distinction in the horticultural community. Their names and current assignments are listed as follows:

1. W. Dean Cocking, Assistant Professor, Department of Biology, Madison College, Harrisonburg, Virginia.
2. G.L. Good, Assistant Professor, Department of Floriculture and Ornamental Horticulture, Cornell University, Ithaca, New York.
3. Philip C. Kozel, Associate Professor, Department of Horticulture, Ohio State University, Columbus, Ohio.
4. Choong Il Lee, Postdoctoral Fellow, Department of Environmental Horticulture, University of California, Davis, California
5. William Mechling III, Biology teacher, Towson, Maryland.
6. Roy A. Mecklenburg, Associate Professor, Department of Horticulture, Michigan State University, East Lansing, Michigan.
7. Martin M. Meyer, Jr., Associate Professor, Department of Horticulture, University of Illinois, Urbana, Illinois.
8. Cary A. Mitchell, Assistant Professor, Department of Horticulture, Purdue University, Lafayette, Indiana.
9. J.V. Morgan, Professor of Horticulture, Faculty of Agriculture, University College, Dublin, Ireland.
10. John A. Wott, Associate Professor, Department of Horticulture, Purdue University, Lafayette, Indiana.
11. Richard Zondag, Manager, J.W. Jung Seed Company, Randolph, Wisconsin.

Mrs. M.C. Ophardt, completing M.S. program, Cornell University.

Ms. M.E. Oster, completing M.S. program at Cornell University.

PUBLICATIONS

The project has produced many scientific publications of interest to scientific horticulture, plant physiology, ecology, plant pathology, and the commercial horticulture industries. The complete list of journal articles, abstracts, popular articles and theses follows:

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