and fruiting in 'Earlingrow' strawberry. J. Amer. Soc. Hort. Sci. 113:322–327.

Fischer, R.A. 1975. Yield potential in a dwarf spring wheat and the effect of shading. Crop Sci. 15:607–613.

Knight, S.L. and C.A. Mitchell. 1983a. Enhancement of lettuce yield by manipulation of light and nitrogen nutrition. J. Amer. Soc. Hort. Sci. 108:750–754.

Knight, S.L. and C.A. Mitchell. 1983b. Stimulation of lettuce productivity by manipulation of diurnal temperature and light. HortScience 18:462–463.

Madariaga, F.J. and J.E. Knott. 1951. Temperature summations in relation to lettuce growth. Proc. Amer. Soc. Hort. Sci. 58:147–152.

Pendleton, J.W. and R.O. Weibel. 1965. Shading studies on winter wheat. Agron. J. 5:292–293.

Salisbury, F.B. and C.W. Ross. 1978. Plant physiology. Wadsworth, Belmont, Calif.

SAS Institute, Inc. 1982. SAS user's guide: Statistics. 1982 ed. SAS Institute, Inc., Cary, N.C.

Scaife, M.A. 1973. The early growth rates of six lettuce cultivars as affected by temperature. Ann. Applied Biol. 74:119–128.

Schaffer, B., L. Ramos, and S.P. Lara. 1987. Effect of fruit removal on net gas exchange of avocado leaves. HortScience 22:925–927.

Teskey, R.O. and R.B. Shrestha. 1985. A relationship between carbon dioxide, photosynthetic efficiency and shade tolerance. Physiol. Plant. 63:126–132.

Thomas, F.H. 1970. Sampling and methods used for analysis of soils in the soil testing laboratory of the Everglades experiment station. Everglades Sta. Res. Rpt. EV65–18.

Thompson, H.C. and J.E. Knott. 1934. The effect of temperature and photoperiod on the growth of lettuce. Proc. Amer. Soc. Hort. Sci. 30:507–509.

Tibbitts, T.W. and T.T. Kozlowski. 1980. Growth of crop plants under high levels of HID irradiation in the Wisconsin biotron. Phytotron Nwsl. 21:68–74.

USDA. 1973. USDA standards for grades of lettuce. USDA Agr. Mktg. Serv. Washington, D.C.

Verkerk, K, and C.J.Th. Spitters. 1973. Effects of light and temperature on lettuce seedlings. Neth. J. Agr. Sci. 21:102–109.

Whitaker, T.W., E.J. Ryder, V.E. Rubatsky, and P.V. Vail. 1974. Lettuce production in the United States. USDA Hdbk. 221.

Wiebe, H.J. and J.P. Lorenz. 1977. Influence of changing temperature and light-dependent temperature control on the growth of lettuce. Gartenbauwissenschaft 42:42–45.

Zink, F.W. and M. Yamaguchi. 1962. Studies on the growth rate and nutrient absorption of head lettuce. Hilgardia. p. 471–485.

J. AMER. SOC. HORT. SCI. 114(6):890–893. 1989.

Solution Depth Affects Root Morphology and Growth of Cucumber Plants Grown in Circulating Nutrient Solution

Gap C. Chung[1], Richard N. Rowe[2], and Roger J. Field[3]
Lincoln University College, Christchurch, New Zealand

Additional index words. *Cucumis sativus*, nutrient film technique, shoot : root ratio, root number : root length ratio, hydroponics, Richards function

Abstract. **Defruited cucumber (*Cucumis sativus* L.) plants were grown hydroponically for 28 days in containers with 4.5 liters of capacity, in which constant solution depths of 1, 5, 50, and 170 mm were maintained. The plants grown in the 1- and 5-mm-deep solutions grew more slowly than those in the deeper solutions. Both root and shoot growth were reduced at the shallow depths, but shoot growth was affected more than root growth. Thus, the shoot : root ratios were considerably smaller in the shallower than in the deeper solutions. The root systems in the shallower solutions, initially, were relatively more branched than in the deeper solutions. The shallow solutions caused the plants to allocate a higher proportion of their photosynthetic resources to the root at the expense of leaf growth. In the shallow solutions, a progressively higher proportion of this root growth became exposed above the solution, and, therefore, could not contribute to the absorption of water and nutrients. Control of solution depth may be a useful tool for controlling the vigor of the shoots of cucumber and the data presented may explain why growth problems have been experienced with this crop, particularly where a very thin film of nutrient is used, as in nutrient film technique.**

One of the main physical characteristics of the nutrient film technique (NFT) is the shallow depth of the circulating nutrient solution (Cooper, 1975). Unlike plants grown in soil or in conventional hydroponics, the proportion of the root system immersed in the solution becomes progressively smaller with time, and a higher proportion of roots becomes exposed to the air. With time, the increased exposure of roots to air in plants grown in NFT would be expected to be accentuated where the physical dimensions of the troughs and the growth of competing plants confine the volume of solution available to each plant grown in the system. It would be expected, therefore, that the depth of solution would affect the proportion of the root system directly involved in the absorption of water and mineral ions.

In the case of cucumber, it is generally recommended that more care be given to plants growing in NFT compared to other greenhouse production methods (Winsor, 1978). Graves (1983) suggested that some of the difficulties experienced in growing cucumber in NFT might be due to a fast growth rate of the root system, which blocks the flow of nutrient solution and causes partial root death and subsequent poor shoot growth. However, the literature does not reveal any work that attempts to examine

---

Received for publication 11 Oct. 1988. A portion of a thesis submitted by G.C.C. as partial fulfillment of the requirements for the PhD at the Lincoln Univ. College. We appreciate the computer program supplied by David R. Causton (Dept. of Botany and Microbiology, University College of Wales, Aberystwyth), for curve fitting. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

[1] Present address : Dept. of Horticulture, College of Agr., Chonnam National Univ., Kwangju, Chonnam, Korea.

[2] Professor and Head, Dept. of Horticulture.

[3] Professor, Dept. of Plant Science.

the effects of solution depth or how it might contribute to the growth of cucumber under this system. The objective of this study was to describe the effect of different solution depths on the growth of cucumber and the associated morphological changes when grown in circulating nutrient solution.

Materials and Methods

'Special Hybrid No. 2' cucumber was used in this experiment because preliminary experiments had shown that the growth rate of shoot and roots was high. About 5 m^2 of leaf area, 10 km of root length, and a total plant dry weight of 400 g was achieved in 2 months. Therefore, the effects of solution depth on plant growth could be established rapidly. Growth was restricted to the vegetative cycle by removing female flowers as they appeared.

Plants were grown in a temperature-controlled glasshouse maintained at 18C night and 30C day (Fig. 1). Nutrient solution (Cooper, 1975) was continuously circulated by a submersible pump inside the header tank. Black polyethylene pipe (50 mm internal diameter) was laid on the ground as the main delivery system into which lateral pipes (14 mm in diameter) were connected. Plastic fittings were used to connect the laterals to each pot. Forty pots were arranged in two rows in each closed system. Spacing within and between the rows was 0.6 × 0.9 m. Each pot was about 175 mm^2 in cross-sectional area and had a capacity of 4.5 liters. There were 250 liters of solution in each closed system. Supplementary lighting was not provided, but air movement was facilitated by air heating and ventilation. Oxygen was supplied by continuous aeration of each pot. The level of nutrient solution in every pot along a row was kept constant by the simple device of monitoring the level in the header tank by a ballcock and water intake control valve. Accurate depth control for each depth treatment was achieved by stainless steel mesh trays that fit in each pot and that could be adjusted to the required depth below the solution surface by threaded metal rods.

The pH of the solution was maintained between 6.0 and 6.5. Conductivity of the solution was monitored throughout the experiment and more nutrients were added when deemed necessary. In general, the solution was replaced at weekly intervals to avoid the excessive depletion of any particular ion.

Root length was measured immediately at harvest, whereas the subsamples used for counting the root number were stored in a 5% formalin solution for measurement at a later date.

A modification of Newman's (1966) method adapted by Evans (1970) and Goubran and Richards (1979) was used to determine the root length and root number. Since cucumber roots were predominantly in the very fine class, the thick (2-mm-diameter) and suberized roots were not separated out of the measured subsamples.

Seedlings were initially grown in sand up to the first true leaf stage and then transferred to hydroponic pots containing full strength Cooper's (1975) solution. Treatments were imposed 1 week after transplanting when seedling growth was re-established. Solution depths of 1, 5, 50, and 170 mm were randomly allocated in each closed system.

Plants were harvested four times at weekly intervals. At each harvest, seven plants for each depth treatment were randomly chosen for measurements of shoot and root weight and morphology.

A FORTRAN program to fit Richards functions (1959) developed by Causton (1969) was used to fit progress curves to the shoot : root and root number : root length ratios. Data from time zero were included in the analysis to meet the requirements as set out by Causton et al. (1978).

Results and Discussion

Despite the fact that there was a 170-fold difference in solution volume bathing root system, shoot and root dry weights

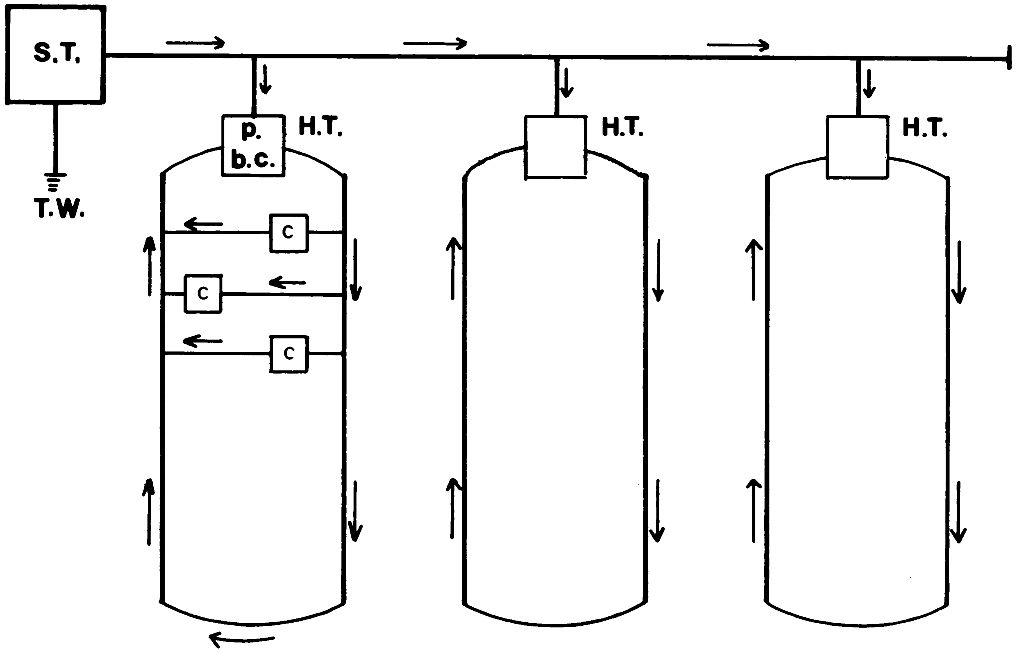

Fig. 1. Diagram indicating the layout of the nutrient solution circulating system. T.W. = tap water; S.T. = storage tank for water; p = submersible pump; H.T. = header tank; b.c. = ballcock controlling water inlet; c = container for individual plant. (Arrows indicate the flow of water and nutrient solution.)

Table 1. Shoot and root dry weight of cucumber plants grown at various solution depths in a nutrient film technique experiment.

Treatment duration (days)	Plant part	Solution depth (mm) 170	50	5	1	Dunnet's *t* value at 5%
		Dry wt (g)^z				
7	Shoot	5.0	5.4	5.0	4.5	2.1
	Root	0.9	1.0	1.1	1.1	0.4
14	Shoot	15.8	17.0	14.0	12.3	5.0
	Root	2.6	2.9	3.6	3.6	1.4
21	Shoot	41.0	37.2	31.5	24.4	14.1
	Root	7.3	6.4	8.7	7.0	2.7
28	Shoot	63.6	74.3	44.6	43.8	18.5
	Root	11.9	17.5	15.5	13.2	5.1

^{z}Each value represents the mean of seven replicates.

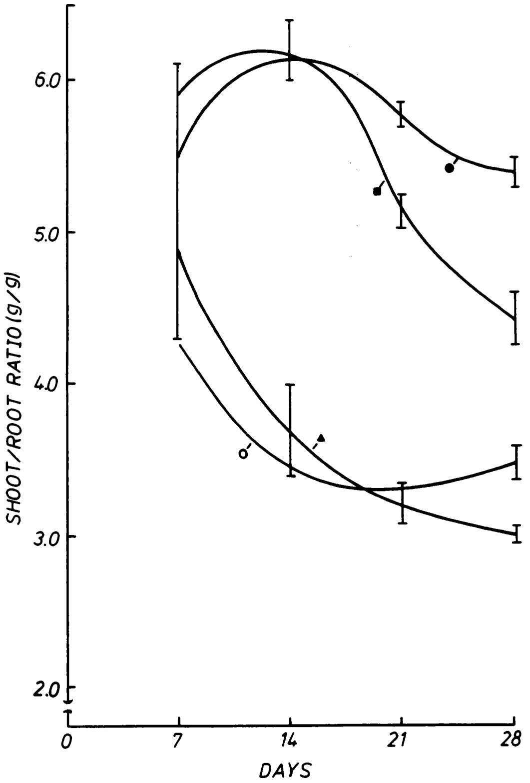

Fig. 2. Effect of solution depth on the shoot : root mass ratio. Fitted values derived from Richards function are plotted with 95% confidence limits. Depths (mm): ● = 170, ■ = 50, ▲ = 5, ○ = 1.

were not affected until 14 days of treatment (Table 1). Later, however, the shoot dry weight was reduced by the shallow treatments (1 and 5 mm), while root dry weight was not affected to the same extent. This difference is reflected by shoot : root ratios showing plants grown in shallow solutions to have allocated a higher proportion of dry weight to the root (Fig. 2). The sudden decrease in the shoot: root ratio in the 50-mm treatment near the final harvest date of the plants is interesting because it occurred after the root system filled the tray used to control the solution depth and the upper part of the root system started to be exposed to air; this situation was achieved much earlier with the shallow solution depths.

Measurement of root morphology expressed in terms of root number per centimeter of root length treated with different depths of solution showed that the shallow solutions enhanced root production relative to root elongation (Fig. 3). Plants grown in deep solution (50 and 170 mm) showed initially low ratios, followed by a gradual increase.

The dynamics of dry weight distribution between the shoot and root and changes in the morphology of roots as affected by solution depth (or, more correctly, solution volume) with time are illustrated in Figs. 2 and 3. The plants in the two shallow solutions showed a rapid decrease in the shoot : root mass ratio, accompanied by an increase in the root number : root length ratio between days 0 and 7. Similar trends occurred with plants in the 50-mm solution depth between days 14 and 21. The smaller solution volume represented by the shallower solutions rapidly stimulated adaptive responses in the plant involving a reallocation of dry weight to root growth at the expense of shoot growth and the development of a relatively branched root system. As time progressed, there was a strong tendency for the root number : root length ratios of all treatments to approach one another. Although not as striking, a similar trend occurred with shoot : root mass ratios. The differences in the total growth of plants at different solution depths, therefore, are a reflection of the growth made by plants up to the time that the solution depth was effectively occupied by roots. Before the solution was occupied by roots, allocation of dry weight to the shoot was dominant. Although the data do not permit one to distinguish between root length or numbers in or out of the solution, we deduce from the data in Fig. 3 that once the solution was completely occupied by the roots, the number of roots existing in the solution reached a maximum determined by their size and the constraints of the solution volume available. The fall in the root number : root length ratio in the 1-mm solution as time progressed may indicate the extreme situation, in which case only root length could increase once the volume had been fully

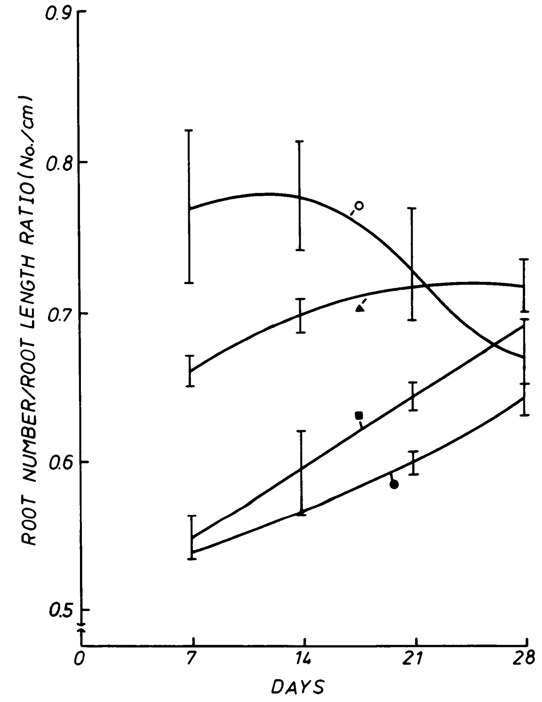

Fig. 3. Effect of solution depths on the root number : root length ratio. Fitted values derived from Richards function are plotted with 95% confidence limits. Depths (mm): ● = 170, ■ = 50, ▲ = 5, ○ = 1.

exploited. Resources continue to be committed to root length, most of which is ultimately carried above the solution as the result of growth at the distal ends of the root system. In deeper solutions, this effect would occur later in plant development.

It might be expected that continued commitment of photosynthetic resources to root growth, without increasing the amount of root tissue available to absorb water and nutrients, would ultimately be at the expense of leaf area, the total photosynthetic capacity of the plant, and total growth.

The surprising result in this work is that, by the 28th day of the experiment, the plants grown in the 50-mm deep solution produced the greatest amount of shoot dry weight (Table 1). It is possible that, between day 14 and 21, the redirection of dry weight to the root and the increase in the root number relative to root length (Figs. 2 and 3) may have conferred some temporary growth advantage relative to the plants in the 170-mm depth.

It is clear that the solution depth or volume available to the plant influences both its dry weight and its distribution and the form of the root system. It is clear that the depth of the solution, and the number of plants competing for space, have a major effect on plant performance. These factors should be taken into account when interpreting results obtained from experiments with NFT or hydroponics where the root system is not totally confined to the solution volume.

Our results suggested that control of solution depth in NFT could be used as a means of regulating plant growth rate in cucumbers.

Literature Cited

Causton, D.R. 1969. A computer program for fitting the Richards function. Biometrics 25:401–409.

Causton, D.R., C.O. Elias, and P. Nordley. 1978. Biometrical studies on plant growth: 1. The Richards function and its application in analyzing the effects of temperature on leaf growth. Plant Cell Environ. 1:163–184.

Cooper, A.J. 1975. Crop production in recirculating nutrient solution. Scientia Hort. 3:251–258.

Evans, P.S. 1970. Root growth of *Lolium Perenne* L.: 1. Effect of plant age, seed weight, and nutrient concentration on root weight, length, and number of apices. New Zealand J. Bot. 8:344–356.

Goubran, F.H. and D. Richards, 1979. The estimation of root length in samples and sub-samples. Comparison of a visual and an automatic method. Plant & Soil 52:77–83.

Graves, C.J. 1983. The nutrient film technique. Hort. Rev. 5:1–43.

Newman, E.J. 1966. A method of estimating the total length of root in a sample. J. Applied Ecol. 3:139–145.

Richards, F.J. 1959. A flexible growth function for empirical use. J. Expt. Bot. 10:290–300.

Winsor, G.W. 1978. Nutrient film culture: an appraisal of its progress and prospects for crop production under glass. Glasshouse Crops Res. Inst. Annu. Rpt. 1977. p. 185–195.

J. AMER. SOC. HORT. SCI. 114(6):893–898. 1989.

Translocation of Triazole Growth Retardants in Plant Tissues

A.N. Reed[1], E.A. Curry[1], and M.W. Williams[1]

U.S. Department of Agriculture, Agricultural Research Service, Tree Fruit Research Laboratory, 1104 North Western Avenue, Wenatchee, WA 98801

Additional index words. paclobutrazol, PP333, triapenthenol, RSW0411, BAS111, gibberellin biosynthesis inhibitors, *Malus domestica, Helianthus annuus*

Abstract. **Translocation patterns of the triazole plant growth retardants paclobutrazol, triapenthenol, and BAS111 were found to be similar when applied as a trunk paint, soil drench, or in hydroponic systems. Chemical degradation studies indicate that the greatest percentage of parent compound is translocated to roots and mature leaves following soil drench and hydroponic treatments. Generally, residue levels of BAS111 were significantly lower than those of paclobutrazol and triapenthenol. Data from trunk paint applications indicate triapenthenol and BAS111, even at concentrations 5 times greater than paclobutrazol, are not as effective in controlling shoot growth. Significant negative correlations were found between shoot growth and foliar residue levels of paclobutrazol and triapenthenol 13 weeks after trunk paint application. Chemical names used: (2*RS*,3*RS*)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)-pentan-3-ol (paclobutrazol); (*E*)-(*RS*)-1-cyclohexyl-4,4-dimethyl-2-(1H-1,2,4-triazol-1-yl)-pent-1-en-3-ol (triapenthenol); 1-phenoxy-5,5-dimethyl-3-(1,2,4-triazol-1-yl)-hexan-5-ol] (BAS111); trimethylonylpolyethoxyethanol (WK surfactant).**

Triazole derivatives have been explored extensively for use as regulators of vegetative growth in fruit trees (1). The common mechanisms of action of the triazoles are the inhibition of gibberellin (5, 6) and sterol biosynthesis (3, 7). Some triazoles, such as paclobutrazol, are very potent and their effects can be very persistent. Curry and Reed (2) have demonstrated the relative efficacy of triazoles in soil drench applications to young apple seedlings. Conclusions based on the results of that study were: 1) differential uptake and translocation patterns, 2) different half-lives, and/or 3) different rates of metabolism within the plant. A few reports have been made concerning translocation of ^{14}C-labeled triazoles (4, 9–11), translocation of paclobutrazol in apple seedlings (12), and persistence of paclobutrazol in soil (13). Reported in our paper are the results of experiments designed to compare translocation patterns of paclobutrazol, triapenthenol, and BAS111 and relate these patterns to various

---

Received for publication 12 Dec. 1988. We are grateful to K.J. Gausman for expert technical assistance. This research was supported in part by a grant (1-779-84) from the U.S.–Israel Binational Agricultural Research and Development Fund (BARD). Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

[1] Plant Physiologist.