LIMITATIONS OF AUTO-IRRIGATORS FOR CONTROLLING SOIL MOISTURE UNDER GROWING PLANTS[1]

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(WITH FIVE FIGURES)

An accurate, convenient method for controlling soil moisture under growing plants would be of obvious advantage to the experimenter attempting to grow plants under uniform conditions, as well as to the physiologist who may wish to study the effect of varying soil moisture on plant development. Since the time of the original suggestion by LIVINGSTON in 1908 (**3**), various forms of auto-irrigators have been proposed for this purpose. Porous clay cones were later developed by LIVINGSTON (**4**) to overcome difficulties ascribed to poor contact between the soil and the porous water-supplying surface of the early cylindrical cups. LIVINGSTON, HEMMI and WILSON (**5**) used tensions up to 40 cm. of mercury and state, "The moisture conditions of the soil are now among the environmental conditions most susceptible of control and satisfactory measurement." Tensions of 60 to 65 cm. of mercury, equivalent to 8 or 9 meters of water, were considered to be maximum for satisfactory irrigator performance.

HENDRICKSON and VEIHMEYER (**1**), with an unstated water supply tension, were unable to maintain uniform moisture distribution with irrigator cones, but found a layer of moist soil near the irrigator surface filled with absorbing roots. Under such conditions growth of plants might easily give indications of controlled low soil moisture which actually were only responses to a restricted rooting zone.

A substantial improvement in apparatus design was made with the development of double-walled irrigator pots by KORNEFF (**2**), RICHARDS (**6**), WILSON (**14**) and RICHARDS and BLOOD (**7**). Compared with porous irrigator cylinders or cones, these units maintain a larger fraction of the soil mass in proximity to and in good contact with the irrigator surface.

WIGGIN (**11, 12**) has published results from a study of double-walled irrigators from the same source as those described by WILSON (**14**). He states that, "Soils can be held at an approximately constant percentage of soil moisture anywhere within a range from below the wilting point for plants to a condition of soil saturation." His data, however, hardly justify this conclusion for he reports, "The greatest difference found between the water content of the soil in the outside layer and the center of the pot was 4.2 per cent.; the greatest difference between the top and bottom layers of soil, 5.1 per cent. The variation in the water content of the soil . . . is therefore

[1] Journal Paper no. J–894, Iowa Agricultural Experiment Station, Ames, Iowa. Projects 487 and 678.

very small." A variation of 4 or 5 per cent. in as many inches, with the low percentage at or below the wilting point, would ordinarily not be considered small, and in a sandy loam soil, might represent the difference between the permanent wilting point and optimum soil moisture. Neither LIVINGSTON, HEMMI and WILSON, nor WIGGIN presents data showing that uniform pot weights were maintained.

This paper presents representative results from a series of experiments designed to test critically the usefulness and performance of improved double-walled irrigator pots under a variety of soil moisture and plant growth conditions. The results indicate definite limitations which are in-

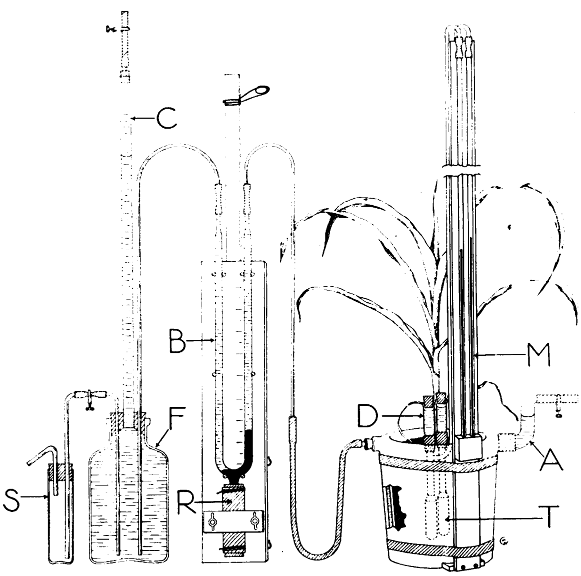

FIG. 1. Apparatus assembled for testing the performance of six-inch auto-irrigator pots. See text for description.

herent in the moisture absorbing and transmitting properties of soil and which are not likely to be overcome by further improvements in irrigator design.

Apparatus

The double-walled irrigator pots[2] used were of single piece construction having a glazed outer wall $\frac{1}{4}$-inch thick, a porous inner wall $\frac{1}{4}$-inch thick, and an inter-wall space of $\frac{1}{4}$-inch for the supply water. Two sizes of pots were available: the soil cavities being 6 inches in diameter at the top, 5 inches in diameter at the bottom, and $6\frac{3}{4}$ inches deep in the smaller unit; and 10 inches in diameter at the top, 6 inches in diameter at the bottom, and 14

[2] These pots were designed by L. A. RICHARDS and manufactured by General Ceramics Company, New York, New York.

inches deep in the larger unit. The apparatus assembly used for the small-pot experiments is shown in figure 1. Any air entering the irrigator system accumulates in and may be removed from the glass air trap A. The Mariotte flask F serves as a constant pressure source of water which moves past the mercury in the barostat B to the water cavity in the pot. The mercury reservoir R provides a convenient adjustment for the supply water tension. The water uptake by the soil in the pot is measured in the burette C, and the safety flask S prevents loss of water from back flow which occasionally takes place because of thermal expansion.

Tensiometer cups T were installed in the pots, one at 2 cm. from the edge and the other in the center, to give information on soil moisture tension within the soil mass. In use the barostat was secured to the Mariotte flask with rubber bands and the flexible rubber tube connection made it possible to transfer the plant container to a balance for weighing. In the experiments reported in this paper a mixture of paraffin and petroleum jelly was used to prevent evaporation from the soil surface so that water losses were limited to transpiration.

Experiments with six-inch pots

Twelve six-inch pots were filled with Clarion loam, planted to maize, and thinned to three plants per pot. This soil had a wilting point of 7.0 per cent. and a field percentage of 13.1 per cent. Ammonium phosphate was mixed with the soil and the plants grew vigorously with a water tension of about one centimeter of mercury at the bottom of the pot.

On May 11, when the plants were 80 to 90 cm. from the soil surface to the tip of the tallest leaf, the barostats for six pots were set at 2.8 cm. of mercury and the remaining six pots were set at 4.2 cm. of mercury. Both sets of pots lost weight rapidly and in three days the pots with the 4.2 cm. barostat setting had lost 357 gm., equivalent to a change of 12 per cent. in the soil moisture, assuming uniform distribution within the pots, and the plants were wilting badly during the day. On May 17 the barostats were emptied on the 4.2 cm. pots and the water tension adjusted to zero at the bottom of the auto-irrigators. Only one of the six pots gained weight and the plants in the others continued to wilt. On May 22 the soil masses were removed from the irrigators and sampled for soil moisture at three locations in the pot: (a) at a point just above the center; (b) the outside centimeter of soil from the top half of the pot; and (c) the bottom centimeter of soil. The outside layer of roots was removed before taking samples (b) and (c), and large roots were removed from all samples. The data are shown in table I.

The three maize plants, about 85 cm. tall with a green weight of 30 gm. each, obviously utilized more water than could be supplied by the irrigator pot and uniform soil moisture conditions were not maintained. It is apparent from the data that only one of the first six pots had wet up in the five days following complete removal of the supply water tension. This resistance of dry soil to wetting, aided in this instance by root mats and rapid transpiration, is a principal cause of failure in auto-irrigator systems. The soil moisture contents found on sampling were far below the equilibrium values of 20 to 22 per cent. that would have been maintained in the absence of plants, thus indicating definitely that the soil moisture was not being controlled by the irrigator, even with a barostat setting as low as 2.8 cm. of Hg. The literature on auto-irrigators contains no suggestion that such a barostat

TABLE I

PERCENTAGES OF "AVAILABLE"* SOIL MOISTURE UNDER MAIZE GROWING IN SIX-INCH AUTO-IRRIGATOR POTS

POT NUMBER	BAROSTAT TENSION IN CENTIMETERS HG		PERCENTAGE OF AVAILABLE MOISTURE IN THE SOIL ON MAY 22		
	MAY 13–17	MAY 17–22	CENTER OF POT	OUTSIDE TOP	OUTSIDE BOTTOM
	cm.	*cm.*	%	%	%
1	4.2	0	1.8	2.3	8.9
2	4.2	0	21.2	23.2	20.9
3	4.2	0	1.7	2.1	10.5
4	4.2	0	3.5	5.6	15.3
5	4.2	0	2.7	2.5	8.7
6	4.2	0	5.5	7.0	13.7
7	2.8	2.8	7.2	6.5	18.5
8	2.8	2.8	1.9	1.9	7.8
9	2.8	2.8	2.1	2.0	2.5
10	2.8	2.8	2.9	2.0	2.0
11	2.8	2.8	10.8	16.3	19.5
12	2.8	2.8	3.8	7.8	12.1

* Soil moisture percentage minus the wilting percentage (7.0 per cent.).

setting is excessive for successful operation under the conditions of this experiment.

In spite of the nearly complete failure of the moisture supply in the center of the soil mass, the corn plants were making a satisfactory growth on moisture absorbed from the outer layers of soil or directly from the irrigator surface, and to the casual observer the experiment might have been considered normal. The pot-weight losses, tensiometer readings, and afternoon wilting of the plants, as well as the soil moisture percentages, showed clearly, however, that the soil moisture was out of control.

A number of auto-irrigator experiments with a range of soil and plant conditions have indicated that for any given rate of moisture absorption by roots, there is a definite upper limit for the supply water tension that will permit auto-irrigators to control even approximately the soil moisture percentage. The higher the rate of water extraction by roots, *i.e.*, rate of transpiration, the lower the supply water tension must be. This reciprocal relation of course was anticipated, but the authors were surprised to find how low the tension must be kept in the case of rapidly transpiring crop plants.

The curves in figure 2 give results from an experiment conducted in the greenhouse in December with one maize plant per six-inch pot. Procedures were as before with the same Clarion loam and barostat assembly. A series of experiments with these same plants in November resulted in irrigator failure, and all pots were flooded under pressure on November 27 to insure rapid and complete wetting of the soil. Barostats were attached

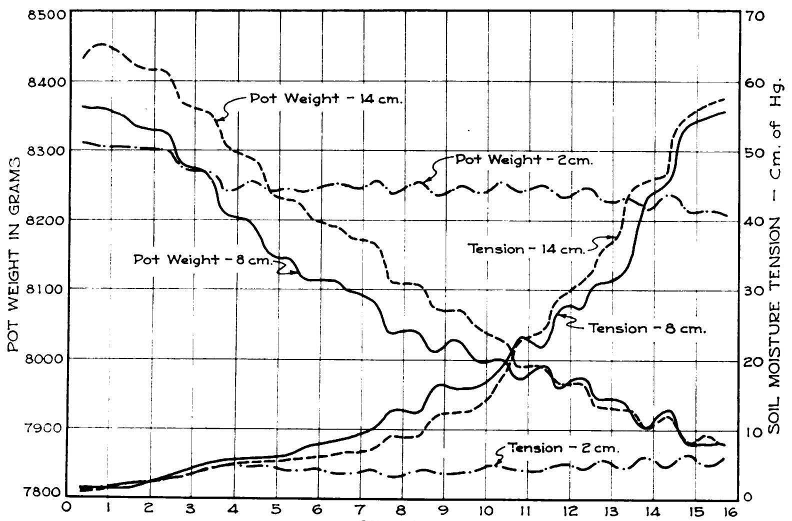

FIG. 2. Record of gross pot weight and soil moisture tension for three pots, each containing one maize plant 90 to 100 cm. tall. The barostat settings were 2, 8, and 14 cm. of mercury.

and adjusted on November 30 with four pots at each of three settings of 2 cm., 8 cm., and 14 cm. of mercury.

The curves of figure 2 show reasonably good control of pot weights with a 2.0 cm. barostat setting, with only one 30-gm. plant per pot and midwinter transpiration rates. Average weight dropped in 3 days from about 8300 to 8250 gm. and then fluctuated, losing by day and regaining by night, until December 12 when a gradual loss set in. The tensiometer curve is for the *outside* tensiometer which was placed 1.5 to 2.0 cm. from the irrigator wall. With a water supply tension of 2.0 cm. of mercury the soil moisture tension 2 cm. away varied between 4 and 6 cm. of mercury, which might be regarded as reasonably good control. At barostat settings of 8.0 and 14.0 cm. of mercury, however, the moisture content of the soil was definitely not maintained or controlled. There was a continuous decrease in pot weight and a continuous increase in soil moisture tension.

Moisture movement data for the experiment are summarized in table II. They emphasize the limitations of auto-irrigators when considerable quantities of water must be transferred. The first period, Nov. 30 to Dec. 3, may be ignored as representing adjustments to changed barostat settings. During the second period, Dec. 4 to 9, the 2.0 barostat setting may be considered to have operated successfully with a soil moisture tension drop of about 1 cm. Hg per centimeter indicated by the outer tensiometer reading of 4.1 cm. Hg on Dec. 9. The 8.0-cm. series was going out of control with a tension difference of 4 cm. Hg per cm. and the 14.0 series apparently had not reached

TABLE II

TRANSPIRATION LOSSES AND AUTO-IRRIGATOR PERFORMANCE FOR SIX-INCH POTS CONTAINING ONE 90–100 CM. MAIZE PLANT. DATA ARE GRAMS PER POT PER DAY—AVERAGE OF FOUR POTS

PERIOD AND MEASUREMENT	BAROSTAT SETTING IN CENTIMETERS OF MERCURY		
	2.0	8.0	14.0
	gm.	*gm.*	*gm.*
Nov. 30–Dec. 3			
Transpiration	95.7	147.2	151.2
Uptake from reservoir	27.3	0.0	0.5
Net loss per pot	68.4	147.2	150.7
Soil moisture tension—Dec. 3	4.8	5.9	4.7
December 4–9			
Transpiration	273.2	236.3	272.3
Uptake from reservoir	259.2	55.3	30.6
Net loss per pot	14.0	181.0	241.7
Soil moisture tension—Dec. 9	4.1	15.6	12.7
December 10–15			
Transpiration	329.2	365.1	360.1
Uptake from reservoir	289.7	221.8	170.2
Net loss per pot	39.5	143.3	189.9
Soil moisture tension—Dec. 15	6.0	55.3	57.2

equilibrium although moisture was being absorbed from the irrigator while the soil moisture tension 2 cm. away was below the barostat reading. This situation was observed on several occasions and is ascribed to rapid absorption by roots in contact with the irrigator surface and to slow equalization of tensions within the soil mass. By December 15 the 2.0 cm. series was beginning to show failure, and the pots with the higher barostat settings were obviously completely out of control with soil moisture tension gradients of more than 20 cm. Hg per centimeter of soil.

In individual pots, tensiometer readings in excees of 60 cm. of mercury were obtained 2 cm. away from a water supply under a tension of only 8 cm. of mercury. Although transpiration losses were only 40 to 60 gm. per pot per day and contact between the soil and irrigator was as good as can be obtained, the tensiometer and pot-weight readings and the soil moisture data of table III show that the soil moisture in all pots with as much as 8-cm. barostat setting was either out of control or rapidly failing.

The third column of the table labeled "static equilibrium moisture" shows the moisture content that was obtained when the soil without plants was saturated and allowed to come to equilibrium with supply water at the tensions shown in column two. Only pot no. 1 maintained this equilibrium percentage, while pots 5 to 12 showed significant moisture losses in even the bottom centimeter of soil, with other losses running above 70 per cent. of

TABLE III

AVAILABLE SOIL MOISTURE PERCENTAGES IN THE SIX-INCH POTS ON DECEMBER 15

POT NUMBER	BAROSTAT TENSION IN CM. HG	STATIC EQUILIBRIUM MOISTURE†	PERCENTAGE OF AVAILABLE SOIL MOISTURE*		
			CENTER OF POT	OUTSIDE TOP	OUTSIDE BOTTOM
	cm.	%	%	%	%
1	2.0	22.0	22.7	22.2	23.6
4	2.0	22.0	17.0	15.6	24.2
7	8.0	18.7	8.4	9.5	15.2
8	8.0	18.7	6.0	7.1	15.1
10	14.0	16.8	8.1	8.6	12.3
12	14.0	16.8	5.7	4.8	9.3

* Total moisture percentage less the wilting percentage (7.0 per cent.).
† As determined in unplanted auto-irrigator assemblies.

the theoretical values at the end of a two-week period, and with no important tendency for losses to be regained.

Experiments with ten-inch pots

Experiments with ten-inch double-walled pots likewise have shown that auto-irrigators will function successfully only when both the supply water tension and the rate of water extraction by roots is low. Detailed information on the performance of individual ten-inch irrigator pots has been obtained by means of an apparatus assembly (**8**) whereby the pot weight and the water input to the pot were automatically and continuously recorded. Continuous records were also kept of air temperature, humidity and atmometer evaporation. The curves in figure 3 show typical results for the ten-inch pots. The gross pot weight and the rate of water input to the pot are shown for three soybean plants growing in Clarion loam soil. The tension in the water at the bottom of the pot was maintained at 1.5 cm. of mercury throughout the test. It was found in this particular experiment that, except for small diurnal fluctuations, the irrigator was able to maintain constant pot weight until the transpiration rate for the three soybean plants reached about 360 ml. per day.

The seventh day shown in the figure was hot and dry and the transpiration loss from the plants exceeded the amount of moisture the soil was able to absorb from the irrigator during the following night. From this time on there was a downward trend in the pot weight, no substantial pot weight recovery being attained even after a succession of low transpiration days such as the fifteenth and sixteenth in the figure.

At the end of the period shown in figure 3 the experiment was terminated. The soybean plants growing in the pot were 82 cm. high and were making vigorous growth. The roots were well nodulated and evenly distributed throughout the pot. There was some concentration of roots at the bottom

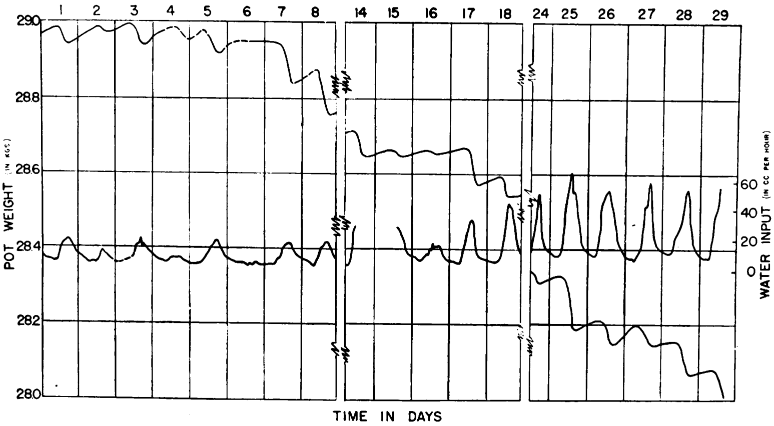

FIG. 3. Rate of water input and gross weight for 10-inch irrigator pot containing three soybean plants.

of the pot and around the side, but not sufficient to prevent excellent contact between the soil and the porous wall of the irrigator. In spite of the large moisture supplying surface and the low tension of the supply water, the steadily declining gross pot weight indicates that the moisture content of the soil was not being maintained by the irrigator. The moisture content at the center of the pot at take down was 12.9 per cent., whereas at the top-outside and bottom-outside edges of the soil mass the moisture percentages were 15.7 and 18.1 respectively.

Experiments with oats, wheat, soybeans, and maize in double walled irrigator pots using various soils were consistent in showing that when the moisture tension in the surrounding soil or the irrigator wall exceeded two or three centimeters of mercury (27 to 40 cm. of water) moisture transfer did not take place rapidly enough to prevent the soil around the roots from becoming progressively drier. This change was particularly marked when the transpiration rate was high. Better control was obtained in loam soils of medium texture than in coarser or finer soils, but the best results obtained in a dozen experiments with crop plants were decidedly disappointing.

Discussion

An auto-irrigator pot makes it possible to surround a test mass of soil with what is equivalent to a mass of soil at constant moisture content and, in addition, provides means for measuring the average content of moisture and the capillary transfer of water to the test mass in which roots are growing. The results of these experiments, which appear also to apply directly

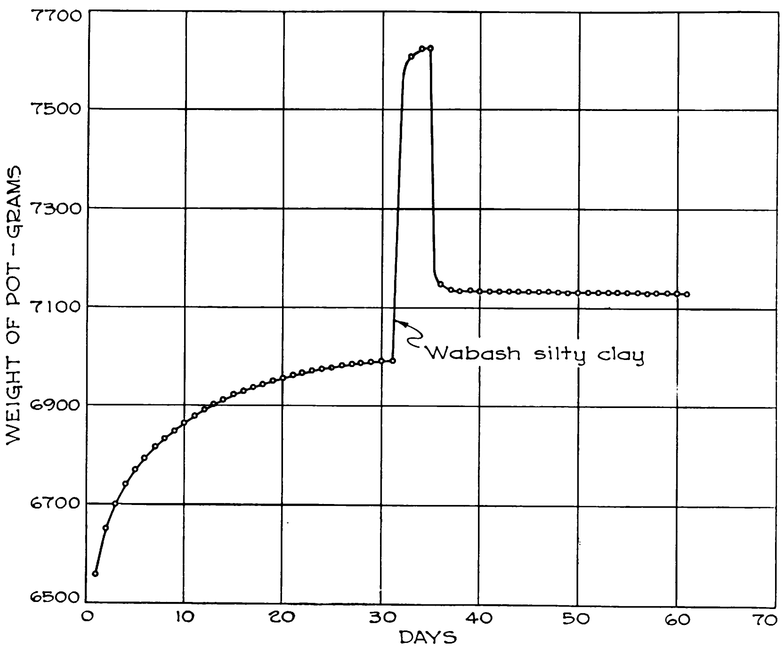

Fig. 4. Changes in pot weight show directly the moisture transfer to and from a mass of soil contained in a six-inch irrigator pot. The tensions of the supply water for the three sections of the curve were 22, 0, and 22 cm. of mercury, respectively. At the start the soil was air dry with a moisture content of 4.3 per cent.

to field conditions, indicate that if the moisture tension in the surrounding soil is more than a few centimeters of mercury, moisture transfer does not take place rapidly enough to prevent the progressive depletion of moisture from soil near the root systems of developing crop plants.

It is this slowness of transfer of water through unsaturated soil coupled with a certain "resistance" of soils to rewetting that limits the range of usefulness of double-walled irrigator pots.

The authors have no suggestions to offer for the improvement of the auto-irrigator units used in these experiments. The mechanical and physical properties and shape of the porous water-supplying surface seemed fairly ideal. No trouble was experienced with leaks or breakage. Since the soil moisture tension and moisture content ranges over which auto-irrigators can be successfully used appear to be limited primarily by the moisture absorbing and transmitting properties of the soil, it seems appropriate to review briefly some of these properties.

The rate at which an air dry soil absorbed moisture when placed in a six-inch irrigator pot and protected from evaporation is shown in figure 4. The irrigator initially was supplied with moisture at a tension of 22 cm. of mercury, and even after 30 days the soil moisture percentage had not fully reached equilibrium. The abrupt rise in the weight curve occurred when all tension was removed from the water supply. In this condition rapid wetting takes place and equilibrium soil moisture content was reached in 48 hours or less. When the tension of the supply water was again raised to 22 cm. of mercury, by lowering the water supply container, water was rapidly extracted from the soil and again no further pot weight change occurred after the second day. Numerous such curves have been obtained (**9**) and give a basis for the generalization that under comparable conditions soil wetting by capillary processes takes place much less rapidly than soil drying. The decrease in the readiness with which soils absorb and transmit water as the moisture content of the soil is decreased, limits the use of auto-irrigators to the wet end of the plant growth moisture range. WILSON and RICHARDS (**13**) have summarized the experimental data on this subject. A decrease of a few per cent. in the moisture content of soils may cause a hundredfold decrease in the moisture conductivity, or permeability to unsaturated flow.

While it may be said that low conductivity makes impossible the proper functioning of auto-irrigators with drier soils, it must not be assumed that moisture movement becomes insignificant as far as plant use is concerned at any moisture content above the permanent wilting percentage. It has been found for instance with pressure-membrane apparatus (**10**) that layers of soil one centimeter thick can be dried from saturation to below the wilting percentage in 24 hours or less, thus indicating that while moisture movement at or near the wilting point may be slow it is not absent.

We have emphasized conditions under which auto-irrigators have failed to operate successfully because the limitations of auto-irrigators do not appear to have been adequately presented in the literature. Auto-irrigators may be expected, however, to give satisfactory moisture control whenever the rate at which moisture can be transported from the irrigator wall through the soil is greater at all times than the maximum rate at which moisture is extracted from the soil. In some kinds of work where constant moisture conditions are not required the desired moisture control may be obtained by alternately raising and lowering the tension of the supply water of the irrigator. The water-supply arrangement shown in figure 1 is more elaborate than is ordinarily required and can be replaced by a simple water connection to a reservoir at a lower level (fig. 5). A pointer, equivalent to a hook gage, can be used for accurate refilling of the reservoir when water use measurements are desired. An especially valuable feature of this assembly

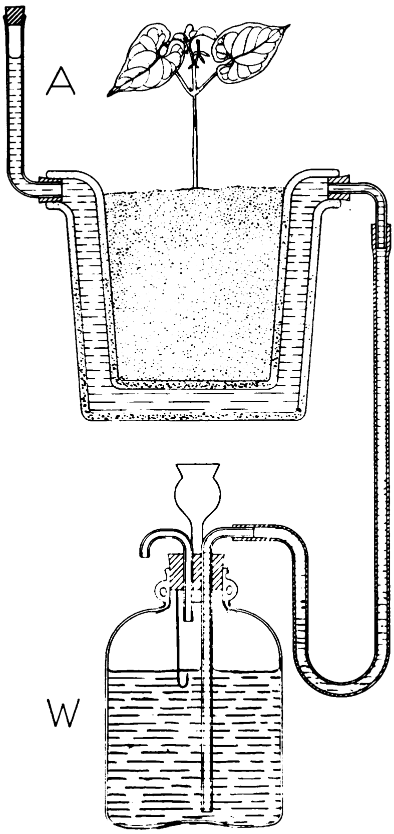

FIG. 5. A convenient assembly for growing plants in auto-irrigators. Water tension is varied by raising or lowering the reservoir W.

is its rapid drainage to equilibrium (compare fig. 4), so that surface watering may be used at will without appreciably affecting the experimental conditions.

It is not possible at present to enumerate the conditions under which auto-irrigators will work satisfactorily because in addition to the irrigator, the soil, the plant, and the entire physical environment are involved. The following, however, appear to be types of experimental work for which auto-irrigators may be successfully used for varying or controlling soil moisture:

seed germination; early seedling growth; rooting of cuttings or work with plants that transpire slowly and do not rapidly develop root mats and become potbound; and the study of the development and control of soil-borne insects and pathogens when cultured in the absence of rapidly transpiring plants. Also the study of soil bacterial processes, nitrogen transformations, organic matter decomposition and carbon dioxide evolution may be greatly facilitated by the use of auto-irrigators. The porous wall of the irrigator acts as a bacterial filter, and this property may be of use in certain experiments where sterile irrigation is necessary.

Summary and conclusions

A detailed study has been made of the precision of moisture control attainable with six-inch and ten-inch double-walled irrigator pots. Maize, soybeans, wheat, and oats were grown in various soils. Records were kept on gross pot weight, water input to the pot, and tension in the soil water, as well as air temperature, humidity, and atmometer evaporation rate. It was found with low barostat tensions that good moisture control was attained while the plants were small, and there was no change in the average pot weight from day to day. With larger plants, however, when the daily transpiration loss was greater than about 100 ml. per day (350 ml. per day for the 10-inch pots), it was not possible to maintain the soil moisture content, even with the supply water for the reservoir at tensions as low as 2 to 4 cm. of mercury.

The range of usefulness of auto-irrigators for controlling soil moisture in plant experiments appears to be definitely overrated in the literature. Satisfactory growth can be obtained and the rate at which the plants absorb water varied, but soil moisture under crop plants having high transpiration rates and rapidly developing root systems cannot be maintained at any reasonably constant value except near saturation. The moisture tensions of 40 to 60 cm. of mercury that have been mentioned in the literature are far beyond the successful moisture control range of auto-irrigators containing rapidly transpiring plants.

The limitation in the range of successful operation of irrigators may be ascribed primarily to the slow rate at which drying soils absorb and transmit water, particularly when the soil moisture is under appreciable tension. The hysteresis effect in the relation between the soil moisture tension and the moisture content accounts in part for the fact that it is difficult for an auto-irrigator to rewet soil from which the moisture has been depleted by roots. Also, a decrease of a few per cent. in the moisture content may cause a hundredfold decrease in the moisture conductivity or permeability of soils for unsaturated flow, and local decreases are probably characteristic of the soil immediately surrounding all roots that are absorbing moisture rapidly.

The design and construction of the irrigator pots used are fairly ideal.

No trouble was experienced with leaks or cracks. These units appear to have definite usefulness in soil moisture control problems that do not require the rapid movement of moisture through soil.

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