AN AUTOMATIC WATERING SYSTEM WITH RECORDER FOR USE IN GROWING PLANTS[1]

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INTRODUCTION

It is often highly desirable to use automatic balances in studies of water relations in plants. There have appeared at different times various kinds of apparatus designed to keep the soil-moisture content constant and to record the amount of moisture lost by plants. The types of apparatus described,[2] as a rule, have not possessed both these features, or have been inaccurate apparently due to the effects of wind or temperature.

The apparatus described in this paper was designed for use in connection with studies now being carried on in the Office of Tobacco and Plant Nutrition on the response to length of day of plants at constant temperature and humidity; in these studies close control and accurate records of soil moisture are necessary. The system is mechanically somewhat similar to the apparatus used by Blackman and Paine [3] and Hamorak [4] and is adapted both to the control of soil moisture and to the recording of moisture used; it should prove as serviceable in the field as it has in the control room. It has been in operation for about two years and even in its original form has proved reliable and required but a few minutes' attention every day or two.

The essential component of the apparatus is a swinging or rocking funnel through which a stream of water flows at a constant rate. This stream of water is diverted into a plant container for almost exactly one minute whenever the loss in weight of the container causes the beam of the balance on which it rests to close an electrical contact. The same current that operates the funnel also moves a magnetically operated pen over a moving time chart, thus producing a permanent record. The quantity of water added is then easily computed, since it is equal to the flow of water per minute multiplied by the number of times the funnel has been actuated as indicated by the chart.

APPARATUS

The system may be said to comprise the following units, each of which will be discussed in turn: (1) A minute-contact master clock,

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[1] Received for publication July 1, 1929; issued February, 1930.

[2] Burgerstein, A. Die Transpiration der Pflanzen. Einige physiologische Monographie. 3 t., illus. Jena. 1904–25.

Briggs, L. J., and Shantz, H. L. An automatic transpiration scale of large capacity for use with freely exposed plants. Jour. Agr. Research 5: 117–132, illus. 1915.

Livingston, B. E., and Hawkins, L. A. The water-relation between plant and soil. 48 p., illus. Washington, D. C. 1915. (Carnegie Inst. Wash. Pub. 204.)

[3] Blackman, V. H., and Paine, S. G. A recording transpirometer. Ann. Bot. [London] 28: [109]–113, illus. 1914.

[4] Hamorak, N. Ein neuer Transpirograph. Ber. Deut. Bot. Gesell. 46: 2–7, illus. 1928.

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(2) a 30-volt storage battery with combined charging and timing panel, (3) a rocking funnel, (4) a balance, (5) a recorder, and (6) a soil-moisture distributor.

The minute-contact master clock employed has an accuracy, under normal room conditions, of ±20 seconds per month and closes an electrical contact, each minute on the minute, for about two seconds. However, as a clock error of even 14.4 minutes per month would correspond to an error of only 1 per cent in the quantity of water added, almost any fairly accurate clock having a minute contact can be used. If necessary, a clock having three hands can be converted into a suitable timing device by causing the second hand to dip into a mercury

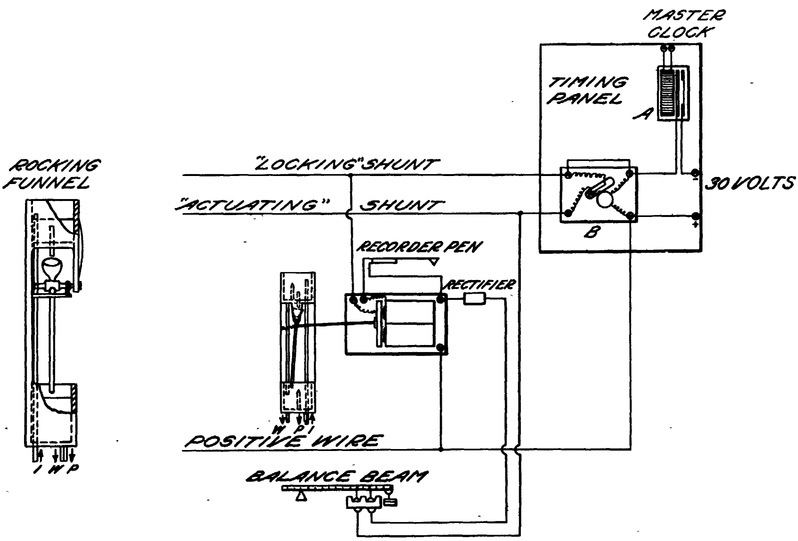

FIGURE 1.—Electrical circuits of a timing panel with one rocking funnel and balance. To the left is a side view of a rocking funnel and mounting comprising a water level with drip tube on top, support for pivoted shaft underneath, and double catch cup at the bottom. *a*, An intermittent relay operated by the minute-contact clock; *b*, mercury-vacuum relay; *i*, water inlet; *p*, outlet into plant container; *w*, waste

well once during each revolution, or by placing a cam on the second-hand shaft, which in turn opens and closes an electrical contact.

The combined charging and timing panel is shown in Figures 1 and 2. The former, with a 30-volt storage battery on trickle charge, is provided with a safety relay that opens when the line current fails. A specific description of its details is unnecessary, as they are standard and can be found in many good electrical textbooks. The use of storage batteries is considered advisable only in order to prevent interruptions due to line failure.

The timing panel consists of relays *A* and *B*, the former controlling both the "actuating" and the "locking" shunt wires to the "funnel" relays, and the latter the actuating shunt wire only. Relay *A* is an intermittent relay operated by the minute-contact clock. It alternately opens and closes each minute on the minute; that is, its contact is open for one minute, then shut one minute, then open one minute, and so on. Relay *B* is a mercury-vacuum switch having a somewhat greater time lag than relay *A*. It is operated by relay *A*, the closing of relay *A* resulting in the opening of relay *B*. The circuit through the actuating shunt is, therefore, closed only each alternate minute for a length of time corresponding to the difference in lag of the relays, since the actuating shunt circuit must be completed through the contacts of both relays.

It will be noticed that the positive wire from the battery goes to the lower coil post of each telegraph relay rocking the funnels. The current passing through the coils of these funnel relays can flow back to the battery through either the actuating or the locking shunt. Since the beam contact is in the actuating-shunt line, the closing of the funnel relays can occur only during the instant at the beginning of each alternate minute when relay *A* contact is closing and relay *B*

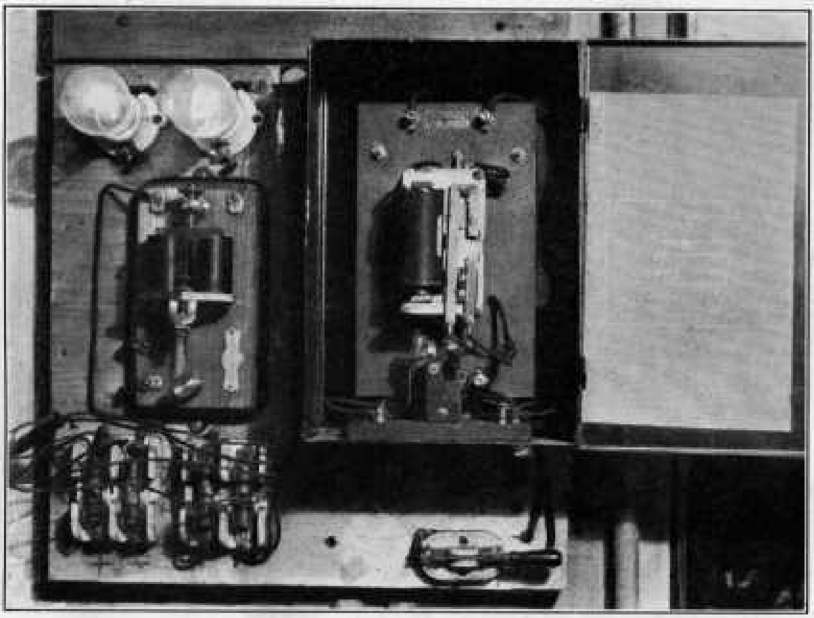

FIGURE 2.—Combined battery trickle charger with safety relay and timing relays

contact has not yet opened. Once the funnel relay is closed, however, the current passes through the funnel-relay contact and the locking shunt and locks or keeps the funnel relay closed until relay *A* contact opens at the end of the minute.

In order to prevent the feeding back of current to other watering units on these shunts, a kuprox or other dry rectifier unit, such as is used in battery charging on alternating current, is placed in series with each balance-beam contact. The use of spring contacts opened by the funnels, the method originally employed, was abandoned in favor of these units, which require less attention; that is to say, there is one contact less per automatic balance to require attention.

The rocking-funnel mounting (figs. 1 and 3) consists of a single brass casting, the top of which serves as a constant water level (1 inch deep) from which water flows at a fixed rate through a vertical vent or drip tube into the funnel suspended underneath. The inlet to the drip tube should be at least a quarter of an inch above the bottom of the constant water level. The funnel passes through a hole in a pivoted shaft and is biased by means of a spring. With the rocking funnel in the position shown in Figures 1 and 2, the water flows into the left-hand compartment of the catch cup and the waste runs out through tube *w*. In the event, however, that the container with its soil and plants loses weight, the beam contact of the balance on which it rests is closed, thus permitting the funnel relay to be closed during the instant the actuating-shunt circuit is completed through relay *a* and relay *b* contacts. The funnel relay at the same time closes its contact to the locking-shunt line and is thus prevented from reopening until relay *a* opens at the end of the minute. Closure of the funnel relay causes the funnel outlet to swing to the right and

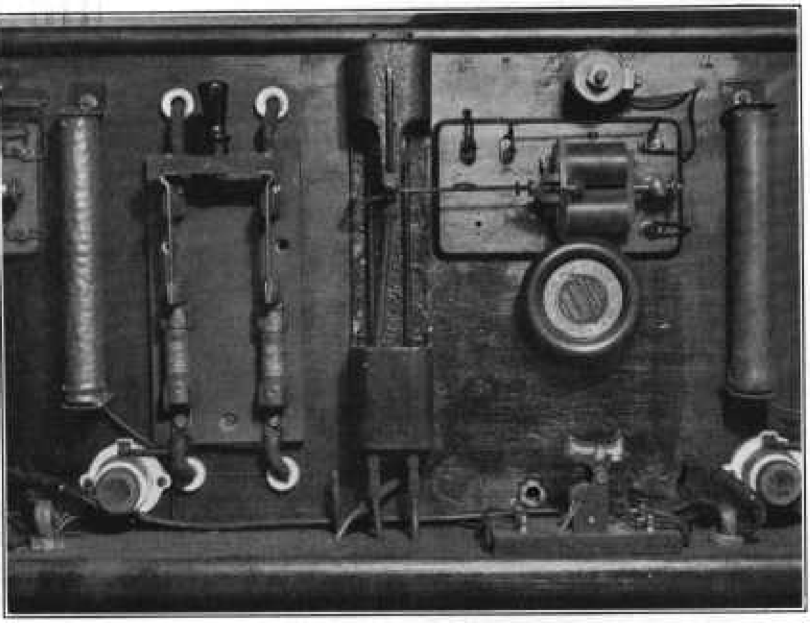

FIGURE 3.—Rocking funnel and relay as they appear on switchboard above light case. The rectifier unit, here functioning as a check valve, is just above the relay

empty into the right-hand compartment of the catch cup, whence the water flows through tube *p* into the plant container. Tube *i* is the water inlet to the water level at the top.

The balance contact consists of a nichrome wire U whose bend is twisted about another wire passing around the beam and firmly fastened to it. It is insulated from the beam, however. This U, or double contact, dips into two iron cups filled with mercury and supported in a fiber block that is bolted to the frame of the balance.

As designed, this system of automatic watering can readily be used with a recorder. The recorder should preferably be what is known as a time recorder[5] and is used only to record the times at which the funnels are rocked. Since, however, the water presumably is

[5] Since this paper was written, small, inexpensive ratchet counters have been found satisfactory when readings at regular intervals are practicable. These counters are actuated mechanically by the swing of the rocking funnel.

flowing at a constant rate and flows into the plant container for exactly one minute each time the funnel is rocked, the quantity of water added is equivalent to the number of times the funnel has been rocked multiplied by the water flow per minute.

Suitable recorders are being produced commercially or can be assembled with a moving chart and magnet pens. A recorder having pen coils of 30 ohms for use on 3 volts should prove satisfactory for use in series with 250-ohm funnel relays on 30-volt battery. Three typical 24-hour records at varying rates of water flow are shown in Figure 4.

In the event that a recorder is not required, the system can be greatly simplified, since in this case only the rocking funnels with their relays and the balances will be necessary.

METHOD USED TO DISTRIBUTE THE WATER THROUGH SOIL IN THE PLANT CONTAINER

If 80 pounds of wet soil per container are used, the theoretical degree of soil-moisture control with a balance sensitive to 1 ounce is ±0.04 per cent soil moisture on the wet basis. Ignoring the effect of increasing mass of the plant, this means that about 1.7 cubic inches of water, or 1 ounce, must be distributed through a volume of about 2,000 cubic inches; or, if only horizontal uniformity is considered, the 1.7 cubic inches of water must be spread over a soil area of 231 square inches (container about 16 by 16 inches at base) to a thickness of 0.0008 inch. Even if feasible, an absolutely uniform distribution of water throughout the soil mass would probably require costly and complicated apparatus. Therefore, like previous investigators, the writer decided to attempt only horizontal uniformity. This is, after all, the natural distribution of moisture in the soil of the field, although the objection might be raised that the roots of the plants will tend to grow into the soil level having the most favorable moisture content instead of scattering uniformly through the soil; that is, the roots are not entirely free from any influence caused by variation in soil moisture. Within certain limits the plants are not growing in soil of average moisture content represented by the whole vertical soil column.

Uniform horizontal distribution of the soil moisture was accomplished by adding the water through a copper tube of ¼-inch outside diameter perforated at 2-inch intervals. The tube was bent into an 8-inch square with two vertical risers used as inlet tubes. These risers, which were not perforated, projected above the soil. The tubes were cleated to the bottom of the plant container, covered with a half inch of sand saturated with water, and the soil added to within about 1 inch of the top. Moisture determinations made at different times in vertical soil columns were within ±1 per cent throughout the containers.

Evaporation from the plant containers is minimized as follows: The plant containers used in the present case are ¾-inch cypress (outside 17 by 17 inches by 10½ inches high), covered on the inside with asphalt applied hot and with two coats of white enamel on the outside. The lids, which are of galvanized iron, are coated on the inside with asphalt applied hot and on the outside with two coats of white enamel. There are altogether fifteen 2-inch holes and two 5/16-inch holes in each lid. The latter are made air-tight

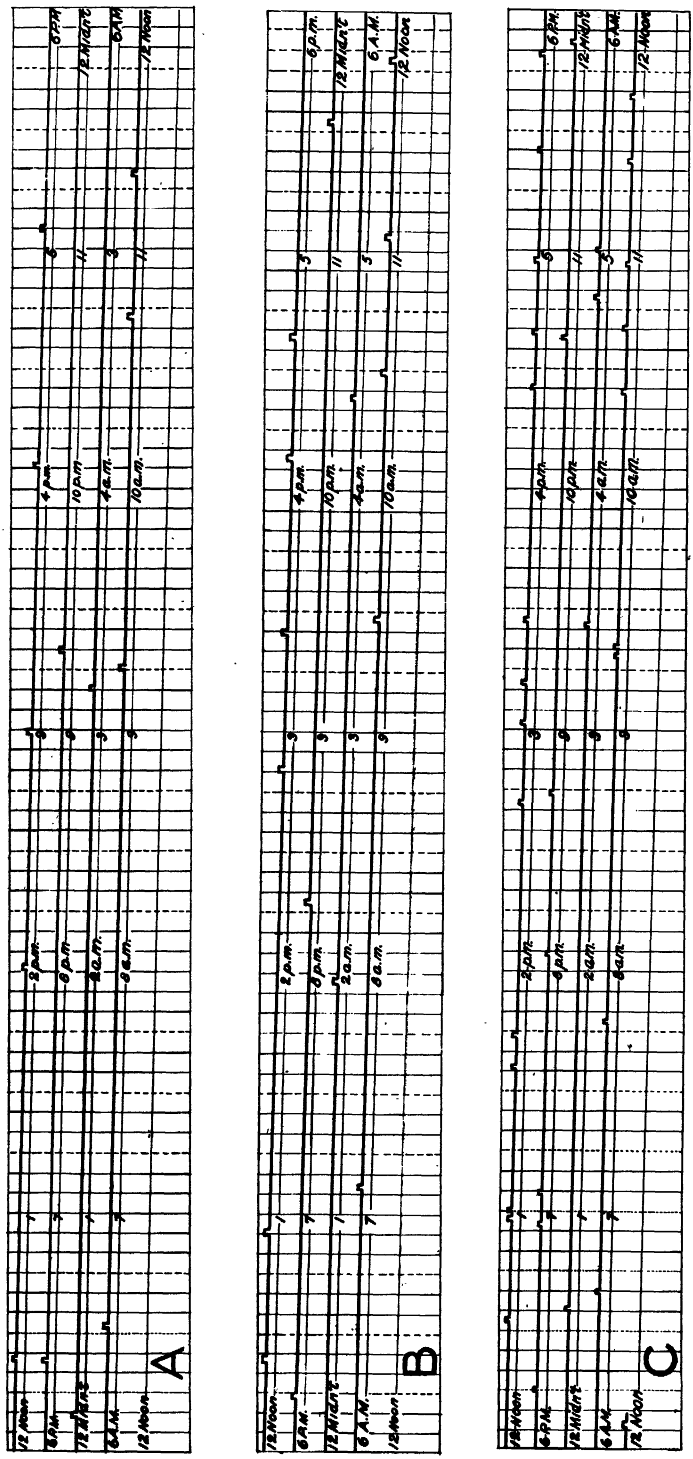

FIGURE 4.—Twenty-four-hour charts with transpiration records. Each tooth or notch corresponds to 50 gm. of water in A, 30 gm. in B, and 20 gm. in C

with rubber tubing around the risers from the watering tubes. The former are provided with perforated split paraffined corks. The corks are placed around the stems of the plants and can be packed with cotton to prevent loss of moisture. Evaporation from a container covered with a lid and unparaffined solid corks was 6,050 gm. when kept in a greenhouse from March 2, 1927, to January 11, 1928 (315 days), or less than 1 ounce a day.

Evaporation from a container at 77.0° ± 0.5° F. and 54.2 ± 0.75 per cent relative humidity under continuous artificial illumination of about 4,500 foot-candles with a Mazda lamp screened by 3 inches of water and with an air velocity of about 90 feet per minute amounted to 126 gm. per day or 5.26 gm. per light hour. A similar determination in the dark gave 3.98 gm. per unlighted hour. The holes in the split corks were left open in both cases.

DISCUSSION

The expectation of accuracy in results depends largely upon balance sensitivity for average soil moisture and upon the rate of water flow for transpiration or evaporation requirements. As has been noted, the balance sensitivity with the weights of soil used would theoretically provide for maintaining average soil moisture constant within a variation of ± 0.04 per cent with water flow of 1 ounce per minute. This is easily checked by observation of the balance beam. Its position should at all times indicate an exact tare of the plant container, so that the removal of an ounce of material from the container will throw in the balance contact.

Accuracy of transpiration records is largely dependent upon the accuracy with which each record on the chart represents a definite amount of water. The physical factors governing flow in small tubes and nozzles are known,[6] as is also the fact that deposition of sediment gradually reduces the rate of flow. Head is maintained constant by use of a water level with a large capacity overflow, and temperature by thermostatic control of the water temperature to ± 1.5° C. While sedimentation could be minimized or eliminated by the use of distilled water or of one of the well-known methods of water softening, these methods are costly and require considerable attention. It therefore seemed more practicable to determine, if possible, the conditions under which clogging is least and to clean the drip nozzles as necessary.

When the tap water in Washington, D. C., is used, clogging is believed to be due to the deposition upon the walls of the drip tube of colloidal material from the previously clear water. At least it was found that a strainer having holes one-fourth the bore of the drip tube would not retain the sediment. Briefly summarized, it appeared that the apparent self-cleaning action of the drip tube was greatest when the type of flow was intermediate between drops and streamline or even flow. Constancy between duplicate tests of the rate of flow is satisfactory, and although not so good as with streamline flow it is much better than when the flow is in drops. Maximum variations between duplicates at the rates studied in grams per minute were: (1)

[6] MARKS, L. S. MECHANICAL ENGINEERS HANDBOOK. PREPARED BY A STAFF OF SPECIALISTS. Ed 2, p. 281. New York and London. 1924.

16.15 ± 0.81 per cent for drops; (2) 20.20 ± 0.50 per cent for flow intermediate between drops and streamline flow; (3) 29.91 ± 0.57 per cent for flow as in 2; and (4) 49.80 ± 0.14 per cent for streamline flow. Decrease in rate of flow with time was found to be, respectively, as follows: (1) Inconsistent; (2) 0.93 per cent in 7 days (0.99 per cent variation between maximum and minimum during this interval); (3) 0.38 per cent in 15 days (1.09 per cent variation between maximum and minimum during this time); and (4) 1.08 per cent in 2 days. It is probable that it is entirely practicable to obtain a water flow and therefore transpiration records accurate to ± 0.5 per cent or better by an inexpensive method requiring very little attention. It is necessary to control the temperature of the water and to adjust for head of water and length, bore, and taper of the drip nozzle to obtain the proper type of flow. The drip nozzles should be cleaned when necessary by means of a soft copper wire slightly smaller than the bore of the drip.

The data below are given to permit duplication, and to give an idea of the relations between the dimensions of the drip nozzle and the rate of water flow. The drip tubes were made of 3/16-inch brass rod threaded for 1 inch and slotted at the top to permit adjustment for head of water. They were 1¼ inches long with untapered nozzles. The inside diameters of the tubes, in the same order as the flows given in the preceding paragraph, were 0.042, 0.0465, 0.052, and one-sixteenth inch at heads measured from top of tube of thirteen-sixteenths, seven-eighths, one-half, and seven-sixteenths inch.

Time accuracy in addition of water and in its recording is dependent upon the elimination of beam vibration or oscillation and upon variations in sensitivity of the balance.

There is nothing to prevent the outdoor use of this system of automatic balancing for soil-moisture control and record. The most important variables thus introduced are wind and rain. The first necessitates the use of an oil dashpot mounted on the balance beam, as used by Briggs and Shantz,[7] to prevent oscillation, and the latter a shelter. This system has, indeed, two distinct advantages over former systems in that the actuating contact is very short, occurs at intervals of two minutes, and minimizes though it does not eliminate the effect of beam oscillation. If necessary, all the control apparatus can be centralized in a shelter and the balances scattered in a surrounding field. Also, with the type of balance described herein, that is, beam below pan, the protection of the balance against rain is very simply accomplished by inverting a shallow square tray on the platform of the scale with the lip of the tray just short enough to avoid touching the ground. A still more effective method would be to place the scale on a platform a few inches high and extend the lip of the pan to below the bottom of the scale.

The system herein described, while subject to refinements, has given very satisfactory results, even in its original form, for over two years, eight units being in operation simultaneously for periods of six weeks or more at a time. It requires a minimum of attention every day or two to insure accurate control of average soil moisture to ± 0.2 per cent and transpiration records accurate to ± 1 per cent

[7] Briggs, L. J., and Shantz, H. L. Op. cit., fig. 13.

or better. The balance beams should be looked at every few days to make sure that the containers are tared; the water temperature should be kept constant to 1° or 2° F., and a wire should be passed through the drip outlets emptying into the funnels at least once every second day. If records of less accuracy are sufficient, the temperature control can be less accurate, while the drip outlets may be inspected only two or three times a week, depending on the accuracy desired.

SUMMARY

A fully automatic watering system that can be used with a recorder has been described for use in studies of plant transpiration and growth when soil moisture must be kept constant and a record must be made of the water used. Average soil moisture can be controlled as accurately as necessary by the use of a balance of sufficient sensitivity and horizontal uniformity of soil moisture to ± 1 per cent, while transpiration records accurate to ± 1 per cent can easily be obtained. The system requires, barring accidents, not over five minutes' attention per unit every second day. It is suitable for use indoors or outdoors. It is flexible enough to be used in single or multiple units, with or without a recorder, and its component parts are comparatively inexpensive and easily available.