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Development of a Direct Reading Evaporation Pan for Scheduling Pasture Irrigation

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Contents

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Development of a Direct Reading Evaporation Pan For Scheduling Pasture Irrigation

John W. Wolfe and D. D. Evans

One of the oldest and most perplexing problems of irrigators is determining when it is time to irrigate and how much water to apply. Many methods have been developed with varying degrees of success. Experienced growers can tell when the plant is visibly showing signs of moisture stress, but when this occurs, the optimum time for irrigation has usually passed. The use of sensitive indicator plants has been able, in some cases, to give a warning a little sooner.

In general, soil-moisture measurement has been the most reliable method of scheduling irrigations. The best of these methods, however, involves the use of fairly expensive instruments and the labor of making measurements. In some areas of Oregon and California, growers have partially solved these two objections by purchasing instruments cooperatively and hiring a man to make the readings.

A bookkeeping method of keeping track of soil moisture from pan-evaporation measurements at a central station has been initiated in Washington. In various other parts of the world, estimates based on other climatological measurements have been used with some success.

None of the methods devised to date completely satisfies the grower. One grower summed up his needs by expressing a desire for a magic wand he could carry in his pocket, which, when inserted into the soil any place in the field, would tell him immediately whether or not an irrigation was needed and how much water was required. The objective of the work reported in this bulletin was to develop an evaporative device which would come one step closer to the concept of the magic wand.

Methods of Estimating and Comparing Evaporation and Consumptive Use

Numerous attempts have been made to determine a relationship between evaporation from a free water surface and consumptive use of crops. No attempt will be made here to review all of the work conducted outside of Oregon. In two neighboring states, however, an empirical approach has been used with considerable success. In Washington, consumptive use has been estimated by multiplying the evaporation from a Class A Weather Bureau pan by a coefficient characteristic of the crop. The crop coefficient has been found to be nearly constant for a given crop "during its optimum cover" (Middleton, 1962). In California, Pruitt (1962) found a nearly constant ratio of consumptive use of ryegrass to evaporation from a Class A Weather Bureau pan of about 0.75 when windy days were not included. On days with a hot, dry north wind blowing, he measured as much as *twice* the consumptive use and *four times* the pan evaporation when compared with an otherwise similar day without wind. A buried Class A pan had a factor very nearly 1.0 on calm days.

Several equations have been developed for estimating free water surface evaporation and consumptive use. The energy equation has been used with considerable success. Pruitt (1962) has found a very close correlation between measured and estimated consumptive use of ryegrass using Penman's equation. His best correlations were obtained, however, when he used measured rather than estimated values of net radiation, and when he discounted the days with high advected energy. The soil was kept very moist during these measurements, so that soil moisture tension would not be a limiting factor.

The second and one of the oldest equations expresses evaporation as a function of vapor-pressure deficit of the air with reference to the water surface or leaf surface. Vapor-pressure deficit is a function of temperature at the surface. Pruitt (1962) found that evaporation from a Class A pan lags behind consumptive use of ryegrass. The lag is no doubt due to the lag in the temperature of the water surface as compared to the temperature of a leaf surface. More time is required for the water because of its greater heat capacity. A linear wind factor is usually included in this equation.

The effect of wind on evaporation and consumptive use is one of the most difficult to describe mathematically. The meteorological equation for estimating consumptive use, as expressed by Lemon (1956), based on turbulent transport theory, may have improved our ability to estimate wind effect, but it still does not explain the disproportionate increase in pan evaporation as compared to consumptive use of ryegrass as measured by Pruitt (1962). Stammers (1963) has observed water literally being blown out of a shallow pan at Hermiston, Oregon. Olivier (1961) presents data indicating that the height of the rim of a pan above the water surface can control the effect of wind velocity on evaporation. He has summarized other data which probably indicate a tendency for evaporation to increase with increased depth of pan, although the results reported are somewhat conflicting.

Gardner (1962) has expressed transpiration as a function of diffusion pressure depression (DPD) in the leaf, soil-moisture tension, plant impedance, and soil impedance. The two impedance terms represent the resistance to flow of water through the soil and plant, respectively, whereas the difference between DPD and soil-moisture tension represents the net force available to move the water up to the leaf. He has found, however, that this relationship holds true only after the DPD has reached and exceeded a certain critical value which is characteristic of a plant. For lower values, transpiration is a function of net radiation. He states that this transition occurs when the stomata close, and that for the plants studied this DPD value is about 10 or 15 bars. In this same series of experiments, the soil impedance was found to be relatively small when the soil-moisture tension was less than one bar.

Martin (1943) found that when a plant is brought suddenly from darkness into light, the increase in transpiration is greater than the increase in energy from the light. Since the stomata were open before the light was introduced and remained open, he concluded that the increase in radiation caused a decrease in impedance in the plant. If this is true, even to a small degree, it suggests that consumptive use might be related to radiation raised to a power greater than one during part of the day, or that radiation might have some effect on consumptive use even after DPD reaches the critical value. No other support was found for this hypothesis.

In addition to these four somewhat theoretical equations (Gardner's combines the first and second), there are a number of empirical relationships derived primarily from statistical analyses. Some of these work very well in certain areas. They are not reviewed here.

Pruitt (1962), using a lysimeter, showed that on August 6, 1961, an abrupt change in net radiation caused by cloud cover in the middle of the day was followed very closely by a corresponding change in consumptive use. On March 21, 1961, he found that net radiation was closely in phase with consumptive use, leading it by perhaps 30 minutes. In contrast, the peak of the ambient-temperature curve and the vapor-pressure deficit curve, measured one meter above the ground, lagged the consumptive-use curve by nearly three hours. Evaporation from a Class A pan would likely have been somewhat in phase with the vapor-pressure deficit curve. Crabb (1952), on the other hand, found that evaporation from a very shallow black pan was a reasonably good index of solar radiation. The close association between radiation and consumptive use has been observed by numerous other investigators with Briggs and Shantz (1917) among the earliest. On a seasonal basis, both net radiation and pan evaporation, where plotted against consumptive use, seem to show a hysteresis loop in the curve. The loops go in opposite directions, however, because net radiation *leads* and evaporation *lags* consumptive use.

If one desires to estimate consumptive use by making one simple single measurement, it appears from this review that this measurement should be evaporation. Evaporation appears to be affected by all of the weather factors which affect consumptive use, including vapor-pressure deficit in the air, wind, and radiation. Admittedly it ignores the impedance in the plant and in the soil, but these appear to be nearly constant until certain critical values are reached. Among the three weather factors, evaporation from a Class A pan appears to be less sensitive to radiation than it should be to obtain a close correlation with consumptive use. It would seem reasonable, therefore, that an evaporative device which was designed to intercept more solar energy would be ideal if it could be designed to balance out the leading effect of the solar radiation with the lagging effect of vapor-pressure deficit. It should then have a high correlation with consumptive use on calm days. To take care of the days with high advective energy, this device must apparently be provided with some kind of shield to reduce the effect of wind on evaporation.

Experimental Procedure

A field test was established in an irrigated pasture in 1957. The principal variable imposed was degree of intensity of solar radiation. The variation was obtained by placing plastic shade cloths over seven plots. The cloth ranged from a very loose weave to a rather tight weave, and one plot had no shading whatsoever. The manufacturer rated the fabrics as providing 92, 72, 63, 55, 47, and 30% shade, respectively. The dark green color of the cloth permitted absorption and subsequent dissipation of a portion of the solar energy at its location six feet above the ground surface. The plots were laid adjacent to each other in a single north-south line, with the line being oriented across the direction of the prevailing westerly wind. The shade cloths extended three feet down the east and west sides of the plots, leaving the lower three feet exposed for restricted wind movement. They are shown in Figure 1.

The seven plots, each 25 feet by 25 feet, were irrigated to field capacity on three-week intervals. At the time of the irrigation the plots were clipped, the shades rotated among them at random, and nitrogen fertilizer applied at the rate of 30 pounds per acre. During the first two seasons the plots were irrigated individually with experimental plot irrigators. During the third season all plots were irrigated equally with conventional rotating sprinklers. Consumptive use was measured by means of 10 tapered gypsum stakes installed in each plot. Each stake had an electrical resistance unit at 6-, 12-, 18-, and 24-inch

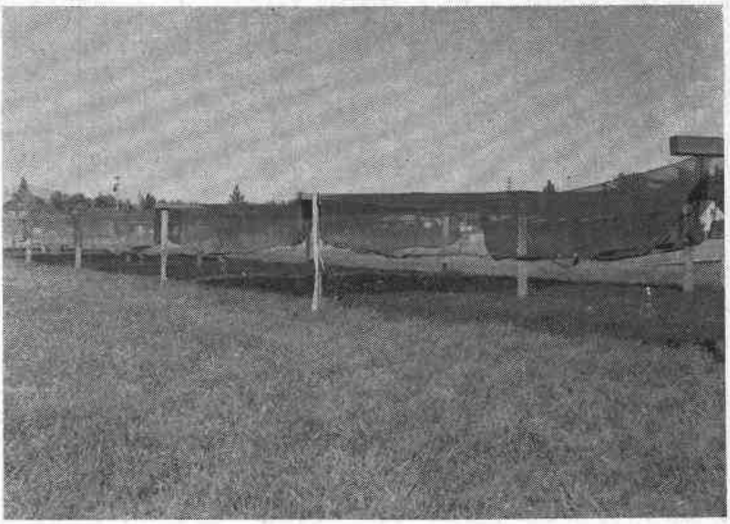

Figure 1. Shaded plots in 1959.

depths. These units were calibrated to the soil and were able to give a reasonably accurate estimate of the volume of water in the soil, except in the very moist range. An accurate measurement of consumptive use could not be obtained for about the first 10 days after irrigation, probably in part because the gypsum is not as sensitive in the wet range. All data reported from the plots were recorded during the last 10 days of each 3-week period; readings were taken at 2-day intervals.

Evaporative devices included Livingston black and white atmometer bulbs as used by Veihmeyer and Hendrickson (1957) in California, and a shallow black pan as used by Crabb (1952) in Michigan. A new device called the oven pan (see Figure 2) was designed and tested. This pan increased the effect of insolation on evaporation by increasing the area of black surface exposed to sunlight by about 18%. The extra surface area was a closed air chamber at the end of the pan, painted black inside, and covered with glass. The air chamber, actually a solar heated oven, extended back under the pan to increase the heat exchange surface. Variations of both the oven pan and the plain black pan were employed. Daily evaporation readings were taken. Figure 3 shows these devices. All but the tall cylinder in the left foreground, a patented evaporimeter manufactured in England, were replicated in each plot.

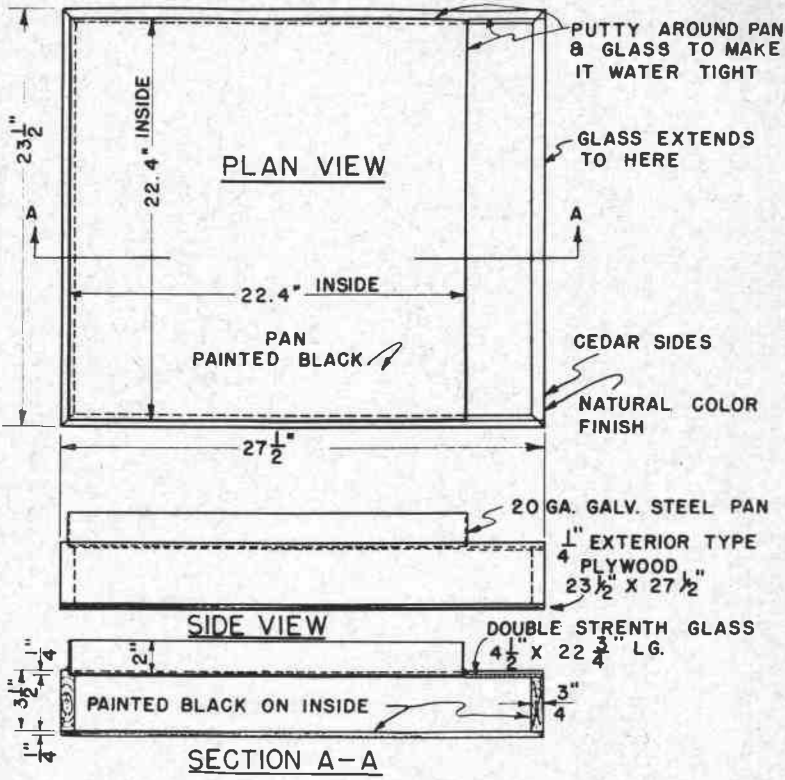

Figure 2. A scaled drawing of the 22.4-inch oven pan tested in the shaded plots.

Data were obtained from the plots in 1957, 1958, and 1959. In 1960 a few scattered stations were established at random in pastures with sprinkler irrigation to check the hypothesis that the data obtained from the plots would be applicable generally, and to see if a pan could be used as a direct indicator of when and how much to irrigate. By 1961 it was clear that the oven pan could be modified to make it a direct scheduling device for pasture irrigation. The depth of the pan was increased to eight inches to represent the approximate amount of available water in a three-foot root zone of Willamette, Carlton, Dayton, and Amity soil series encountered in the OSU pastures. A one-inch wire mesh screen was placed over the top of the pan to keep out animals and reduce the effect of high-velocity wind. The size of the oven was increased to compensate for the reduction

Figure 3. Evaporation devices in one plot in 1959.

in evaporation rate caused by the screen. All modifications were designed to preserve the evaporation rate of the oven pan successfully tested in the shaded plots. In 1962 the pan was again modified by adding a flare or funnel on top just large enough to compensate for the drops of water from rotating sprinklers that hit the screen and splashed off. These pans are shown in Figures 4, 5, and 6.

In the spring of 1961 and 1962, the pans were filled to a level corresponding to the inches of available moisture deficit in the soil. Whenever possible they were placed while the soil was still at field capacity from the winter rains, so that the pans could be completely filled. No additional water was added by hand. The pans were filled with water only from the irrigation sprinklers and from rainfall. It was hypothesized that if they should go dry, evaporation would cease, but so would transpiration, nearly, because the soil moisture would be at the wilting point. When too much irrigation was applied the pans overflowed, but the soil-moisture reservoir did likewise. When the pans were about half full, it was considered time to irrigate with just enough water to fill the pans. In 1961 and 1962 the pans were placed in groups of three, 25 feet apart in a line making a 45° angle with the irrigation lateral, for systems with a 40 foot by 60 foot rectangular sprinkler spacing. Even though the amount of water applied can be assumed to

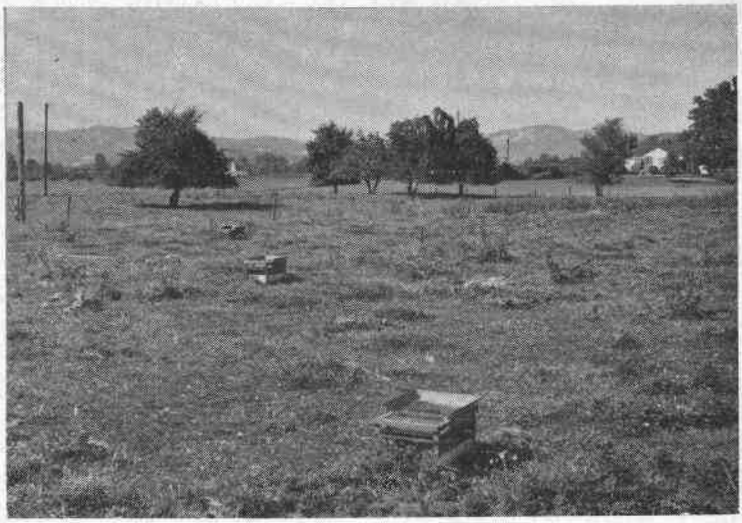

Figure 4. Three pans in the Taylor pasture, 1962. Funnels have been added to the 1961 model pans.

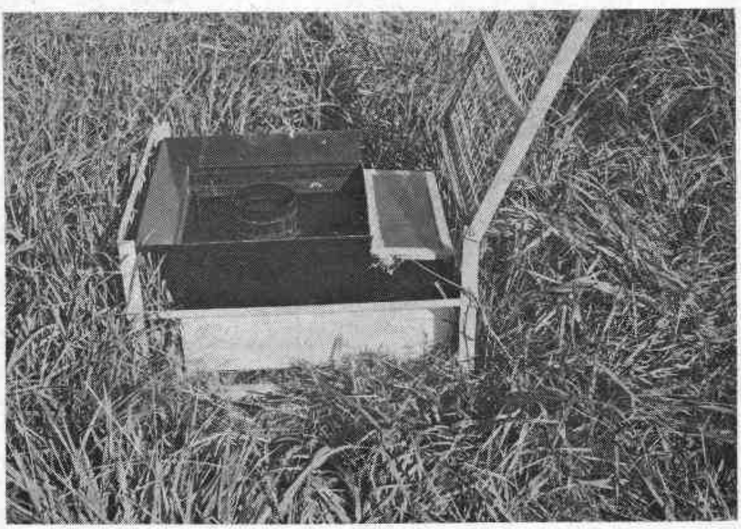

Figure 5. A 1962 model pan with a funnel as a part of the pan. Wire screen and a steel frame furnish protection. The screen has just been lifted for inspection.

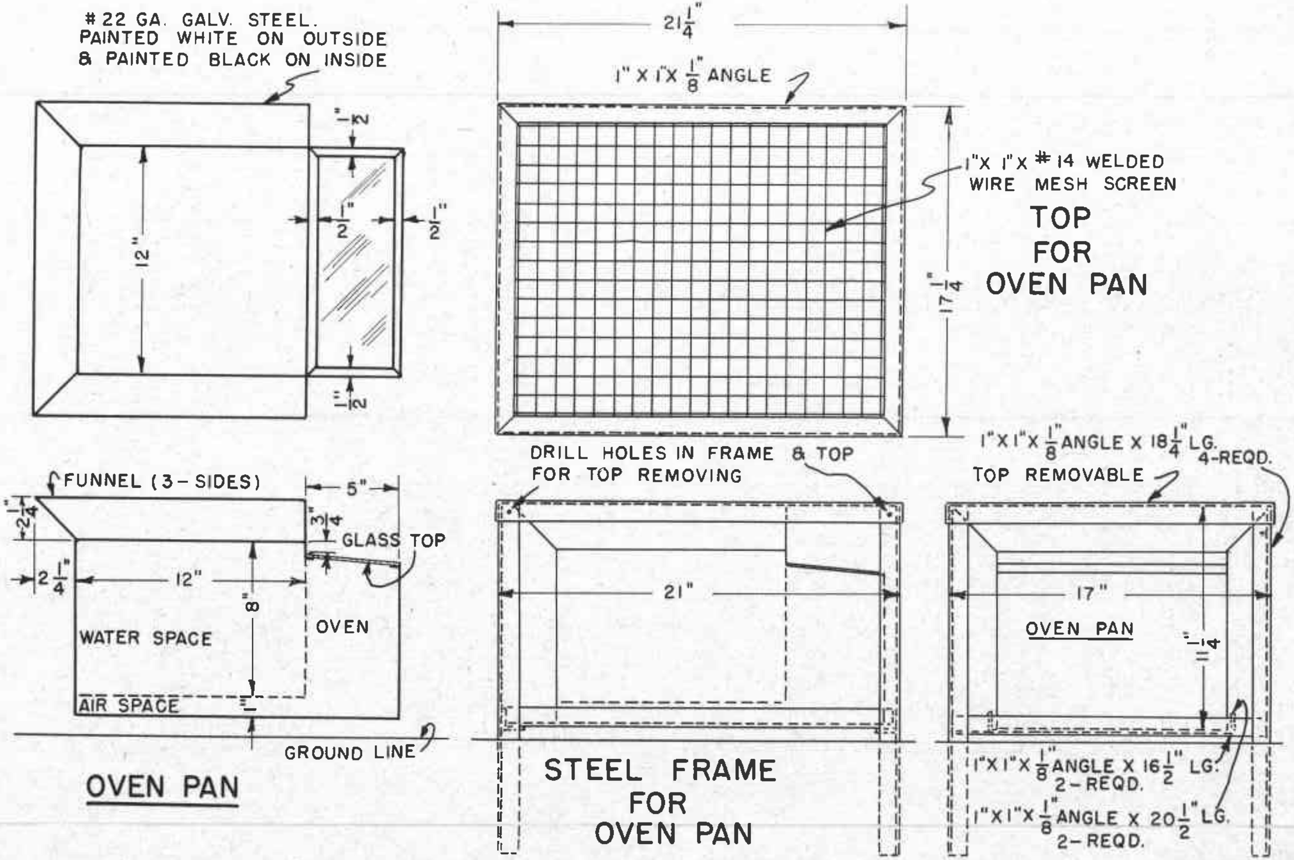

Figure 6. Drawing of oven pan, 1962 model.

vary over the area, the average of the increase of water caught in the three pans during an irrigation is assumed to represent the average water applied to the field. Measurements of the deficit of water in the pans and the deficit in the soil were plotted twice weekly. Water level in the pasture pans was measured with a hook guage. Late in the summer of 1962, some additional pans were placed in annual crops. In this group of pans the water level was measured by observing a scale mounted on the side of the pan. Soil-moisture measurements were obtained from five gypsum stakes per site. A running plot was made of the deficit of water in all pans and another of the corresponding deficit in the soil. The two were superposed and compared visually. Supporting data recorded included height of the crop, height of the pans if raised to match the crop, and depth to water table. There were four 10-day measurement periods each year.

Shading Experiment Results

Three-year summary

The wide range of variation of shading among the plots made it very convenient to plot consumptive use directly against evaporation. Such a plotting is shown in Figure 7. The points are well distributed along the line, since the data from plots with the most shade supplied the points closest to the origin and those from plots with less shade fell progressively farther from the origin.

Coefficients were calculated for the regression of consumptive use on evaporation for each of the three years of data. A test for homogeneity of the regression coefficients for the three years failed to show any difference among them. Data for all three years were then pooled. Final computations from the pooled data are shown in Table 1, arranged in order of decreasing correlation coefficients. Note that the 22.4-inch oven pans have the highest correlation at 0.911.

Table 1. Evaporation vs. Consumptive Use of Pasture (Three-Year Summary)

Evaporative device	Regression coefficient	Correlation coefficient	C. U. intercept inches
22.4-inch oven pan	0.994	0.911	0.131
2 B-W atmometers*	0.003583	0.904	–0.498
3 B-W atmometers*	0.002072	0.903	–0.634
Black bulb atmometer	0.004672	0.885	–0.665
22.4-inch pan	1.076	0.829	0.138
B-W atmometer[a]	0.00791	0.701	0.917

* 2B-W stands for twice the black-bulb evaporation minus the white-bulb evaporation, etc.

Table 2. CONSUMPTIVE USE INTERCEPT VALUES IN INCHES

Evaporation device	1957	1958	1959	Mean	Pooled values
Oven pan	–0.401	+0.573	–0.124	0.016	0.131
Black pan	–0.485	+0.664	–0.030	0.050	0.138
2 B-W atmometers	–0.970	–0.106	–0.563	–0.546	–0.498
Mean	–0.619	+0.377	–0.239	–0.160	

The atmometers were close behind when evaporation was calculated by multiplying each black-bulb evaporation measurement by either two or three and then subtracting the corresponding white-bulb evaporation from it. The black bulb atmometer alone did fairly well with a correlation of 0.885, followed by the shallow black pan, without oven, at 0.829. A technique used successfully in California for subtracting the white-bulb evaporation directly from the black-bulb evaporation failed to produce a high correlation with consumptive use.

Further statistical analysis showed that there was a difference among the consumptive-use intercept values for the three years. This was true for the atmometers as well as the evaporation pans. Table 2 shows these values computed for each of the three years. For each of the three devices listed, the 1957 year intercept was about one-half inch less than the three-year mean, and the 1958 value was a similar amount greater than the mean. The consistency among the three devices suggests that the variation from year to year is because of variation in the consumptive-use measurements against which evaporation from all three devices was plotted. These differences probably were the result of changed electrical resistance characteristics of the gypsum in the stakes from year to year. Some change could have occurred when the gypsum was recast on the stakes and some when the stakes were used for an extended period without recasting. In spite of these observed differences, the best estimates of consumptive-use intercepts are probably the pooled values shown in the last column of Table 1. These differences can be visually observed in Figure 7 from the fact that most of the points from 1957 appear on one side of the regression line, and those measured in 1958 appear mostly on the other side. It appears that if these differences could be removed by improved techniques for measuring consumptive use, all correlation coefficients for pooled data would be much higher.

Comparison between 6-day and 10-day intervals

All results reported so far have been based on measurements of evaporation and consumptive use extending over a 10-day period. The 10-day period was selected because it was the longest period of ac-

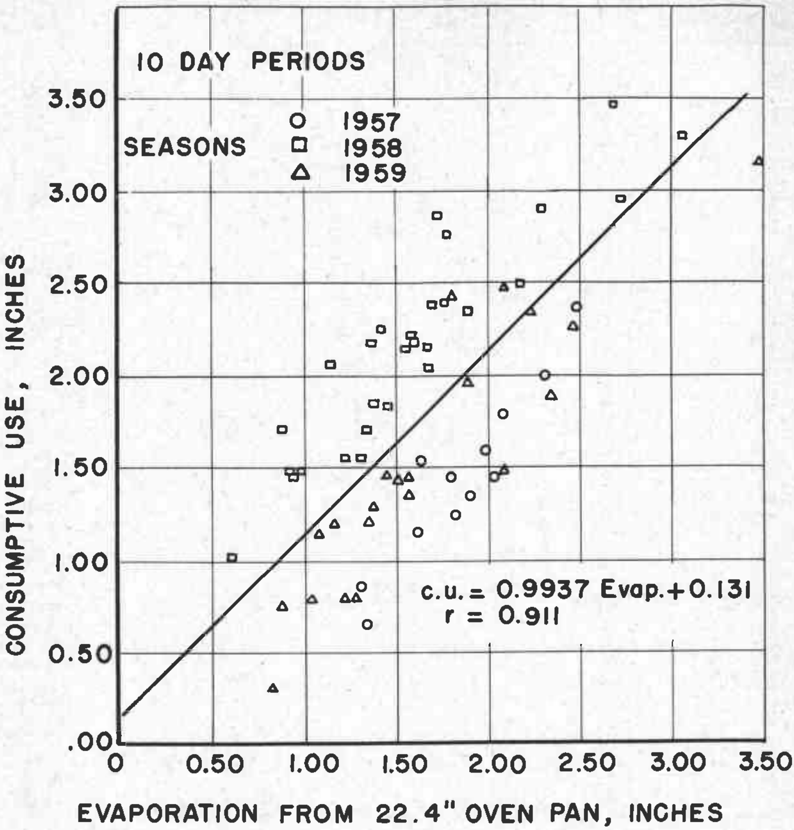

Figure 7. Evaporation from a 22.4-inch oven pan vs. consumptive use of pasture for 10-day intervals.

curate measurements available between irrigations, and because it gave consistently higher correlations than the measurements for shorter periods. A 2-day interval could have been used since that was the frequency of measurement. Typical results are shown by the comparison in Figures 8 and 9 between 6-day and 10-day intervals. Three overlapping 6-day intervals exist within each 10-day interval, so there are three times as many points on the 6-day plot. In this case, a correlation coefficient of 0.917 is to be compared with 0.881 for the shorter interval. Continued analysis of this type led to the selection of the 10-day interval for all subsequent computations.

Atmometers

Evaporation from atmometer bulbs also had a high correlation with consumptive use during the 3-year period. Table 1 shows that the highest correlations for atmometers were obtained by multiplying the evaporation from the black bulb by either two or three before subtracting the white-bulb evaporation from it. Correlation coefficients are 0.904 and 0.903, respectively, for these two computations. The black bulb atmometers alone were not far behind with a correlation of 0.885, but the correlation coefficient for black minus white dropped to 0.701. Subtracting the white-bulb evaporation from that of the black bulb is supposed to correct for the night-time evaporation that occurs while

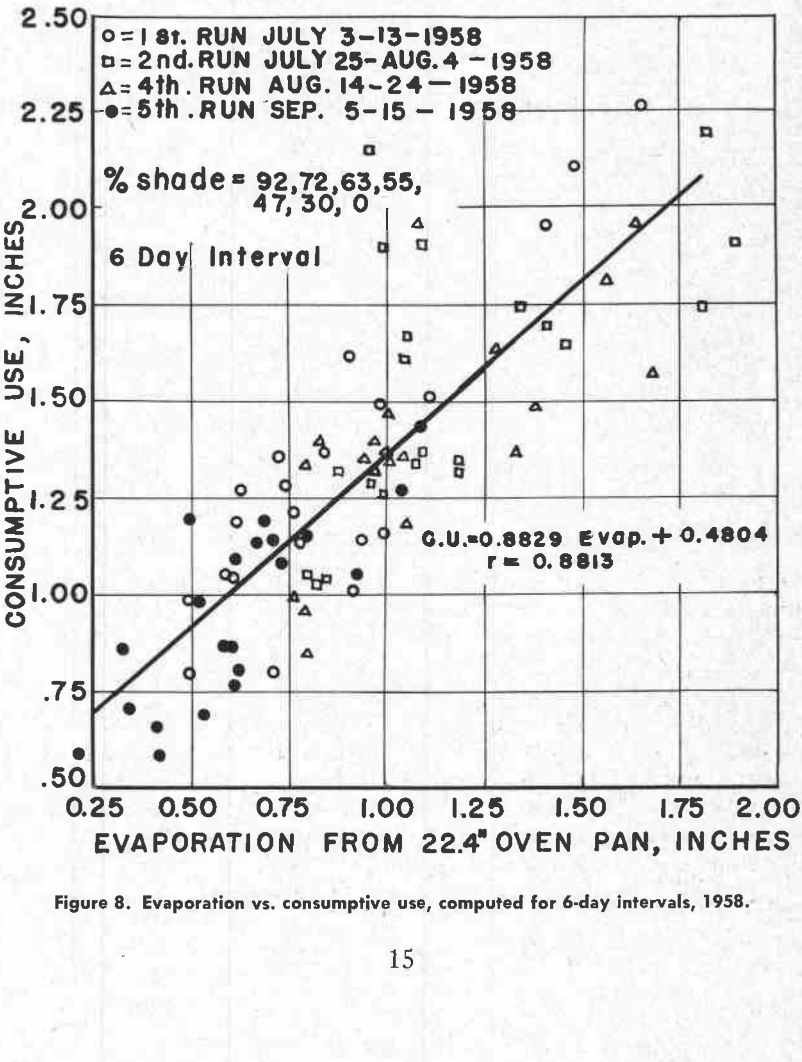

Figure 8. Evaporation vs. consumptive use, computed for 6-day intervals, 1958.

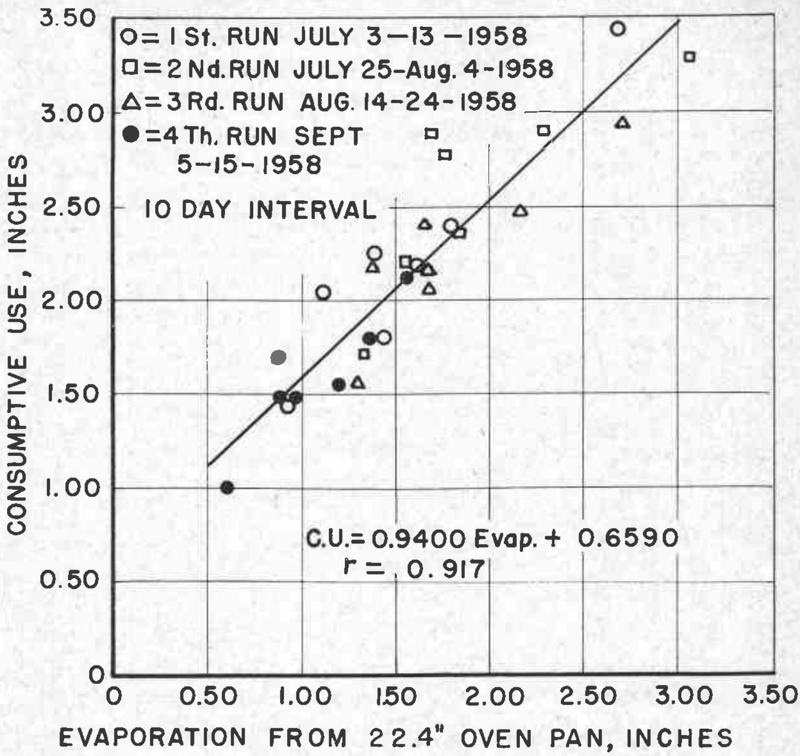

Figure 9. Evaporation vs. consumptive use, computed for 10-day intervals, 1958.

consumptive use is zero because of closed stomata. In Oregon, because of cool nights and a corresponding rise in relative humidity, the night-time evaporation is very small. Even if the evaporation from the white bulb were the same day and night, it would seem logical that only about half the evaporation from the white bulb should be subtracted from the black-bulb evaporation because certainly no more than half of it would occur during the night. So far as correlation is concerned, this is equivalent to taking twice the black, minus the white (2B-W in the table). This alternative computation procedure might have made the consumptive-use intercept closer to zero.

The 1958 atmometer data are shown in Figures 10 and 11. These four plottings serve to show the type of scatter obtained. Note that the white bulb atmometer alone appears to have very little, if any, correlation with consumptive use. The black bulb alone is much better but the scatter of points is still visibly greater than for twice the black, minus the white.

It appears from these data that atmometer evaporation could yield data nearly as good as the oven pan data if the devices were carefully maintained and protected from breakage. The labor and hazard of breakage make them entirely unsuited for open field use, although they could conceivably be a part of a protected weather station.

Another inherent disadvantage of the atmometer is that the evaporation rate reduces with time. A random sample of the atmometers employed was recalibrated at the end of the study. The results indicated that the evaporation rate had gone down about 9%. About half the bulbs recalibrated had been in use for two years, and the remainder for three years. This reduced evaporation rate would have the effect of increasing the regression coefficient. Actual regression coefficients calculated were 0.003351, 0.003374, and 0.003858 for 1957, 1958, and 1959, respectively. Statistically speaking, these regression coefficients were not significantly different, but it is interesting to observe that the coefficients do appear to increase with time at a rate that could be accounted for by the change in evaporation coefficients of the atmometers.

It is also interesting to note that if the evaporation rate from two black atmometer spheres minus one white one in cubic centimeters per-unit time were converted to inches of evaporation over the total surface of one sphere (approximately $2\frac{1}{4}$-inch diameter) per-unit time, the result would be found to have roughly a one to one ratio with consumptive-use rate.

The oven pan

From Table 1 it is apparent that the 22.4-inch oven pan has a higher correlation with consumptive use than the other devices tested. In addition, the table also points out its other superior characteristics. The pooled consumptive-use intercept is only 0.131 inches which is less than for any of the other devices. Ideally, the absolute value of the intercept should be zero. The other superior characteristic is the unity regression coefficient (0.994 in the table). This means that one inch of evaporation from the pan corresponds to one inch of consumptive use. Thus, the device with the one to one evaporation ratio also has the highest correlation coefficient and the least consumptive-use intercept.

During the 1958 season only, a comparison was made to determine the effect of the size of the oven on correlation. A new set of pans was constructed with a glassed-in oven area three times the size of the original ovens. Correlation coefficients obtained for the plain black pan without oven, the regular oven pan, and the pan with the very

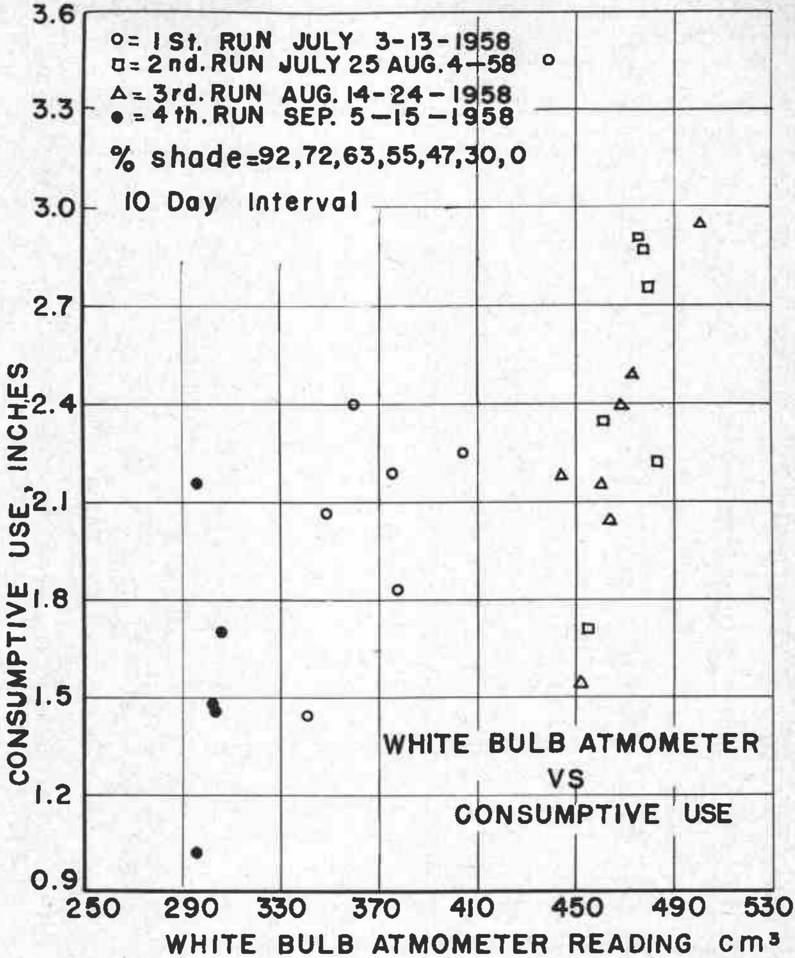

Figure 10A. Evaporation from a white bulb atmometer vs. consumptive use of pasture.

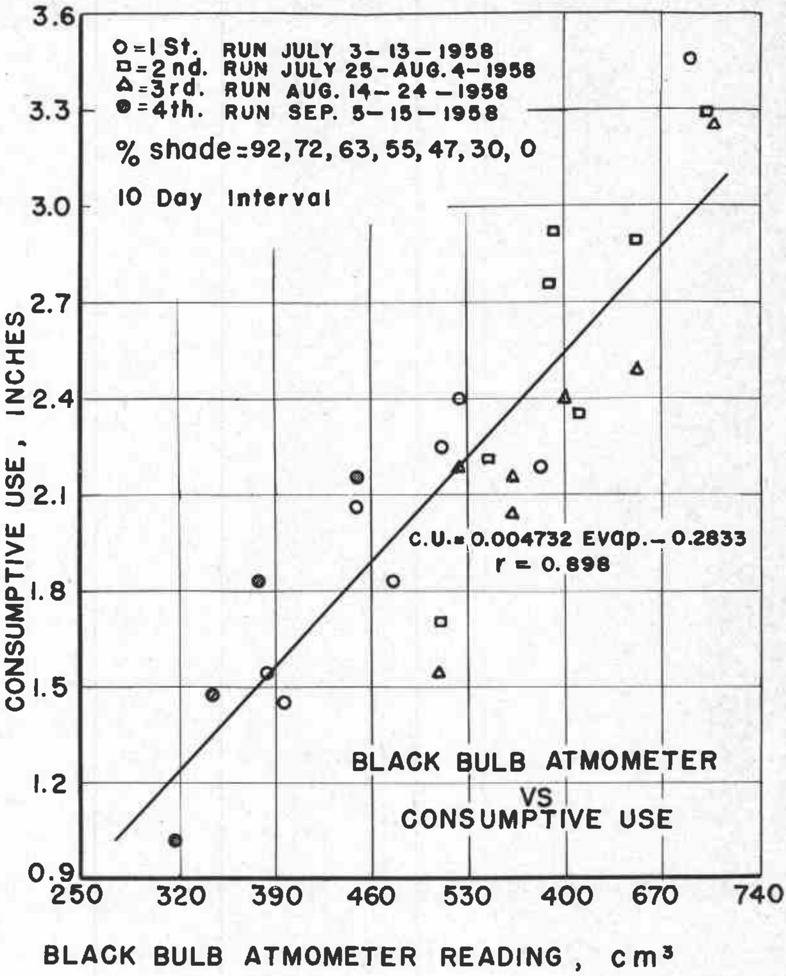

Figure 10B. Evaporation from a black bulb atmometer vs. consumptive use of pasture.

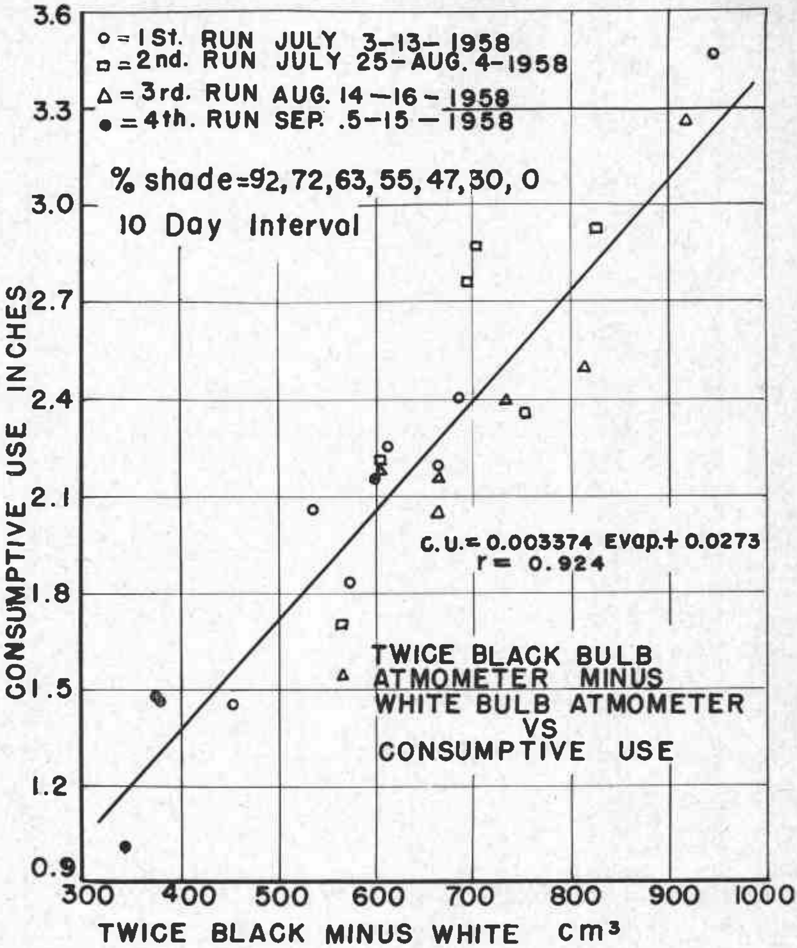

Figure 11A. Differences in evaporation from twice the black bulb atmometer minus the white bulb atmometer vs. consumptive use.

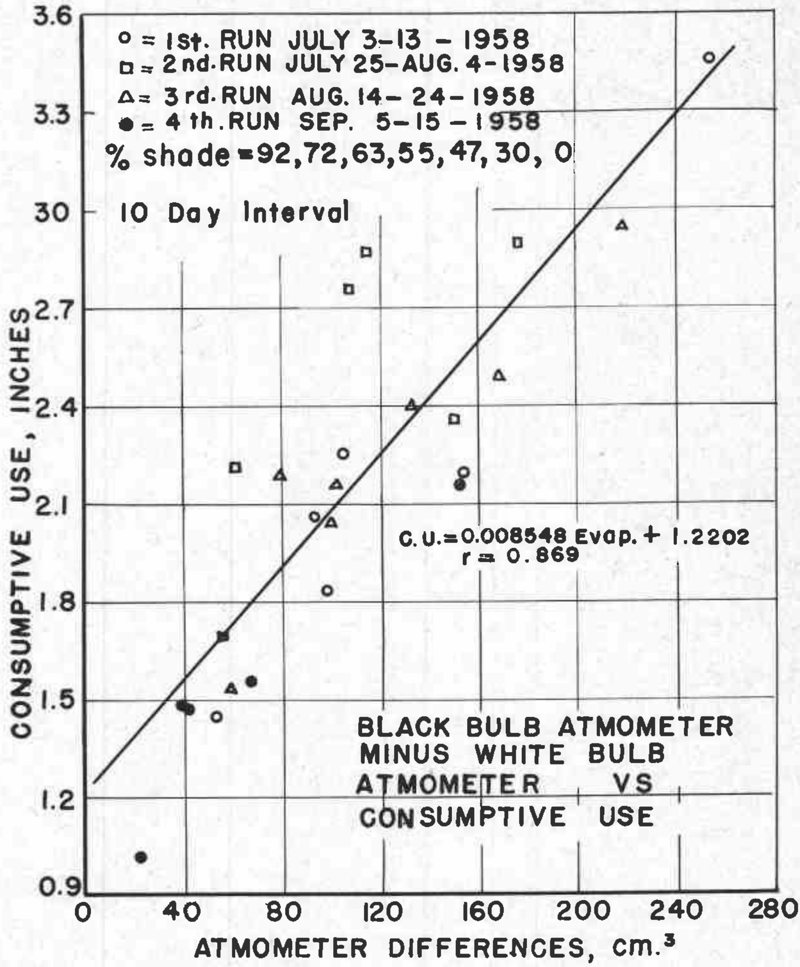

Figure 11B. Differences in evaporation from black bulb atmometer minus white bulb atmometer vs. consumptive use.

large oven were 0.89, 0.92, and 0.91, respectively. From this it was concluded that increasing the size of the oven did not increase the correlation. The regression coefficient for the large oven pan was lower than for the smaller oven, and the consumptive-use intercept was slightly greater. This performance led to discontinuing the use of the larger oven.

During the 1959 season, an effort was made to determine if a smaller pan could be used without reducing the reliability of the results. Six-inch and twelve-inch square pans were tested both with and without ovens. The size of the oven was scaled down proportionately. Lightweight screens were fabricated from chicken wire and placed over each pan. The screens were added in anticipation of placing pans in the field. Parts of the results of this study are shown in Table 3. It is interesting to note that the 12-inch oven pan appears to have a slightly higher correlation with consumptive use than the regular 22.4-inch oven pan. Even the 12-inch plain pan, without oven, performed exceptionally well. Whether or not this trend would continue is not known, but at least it suggests that the size of the pan can be reduced to 12 inches for field use. The regression coefficients for the 12-inch pans were higher than for the 22.4-inch pans because the wire screens reduced evaporation. The screens could also have been responsible for the higher correlation.

Table 3 also includes data from a 22.4-inch oven pan which was constructed entirely from sheet metal. On the regular pans, the oven enclosure was made from wood. Apparently the metal frame conducted the heat from the oven to the water more rapidly because the regression coefficient is slightly lower. The use of this style of pan was discontinued after one year.

Further analysis of the small pans was made by comparing their evaporation with that from the 22.4-inch oven pans. Results of this

Table 3. Comparison of Variations in Pan Design (1959 Data)

Pan description	Regression coefficient	Correlation coefficient	C. U. intercept inches
22.4-inch oven pan, sheet metal frame	0.880	0.907	0.157
12-inch pan, plain, with screen	1.312	0.913	−0.282
12-inch oven pan, with screen	1.266	0.924	−0.362
22.4-inch oven pan (for comparison)	1.011	0.906	−0.153

comparison are shown in Table 4. These regression calculations were all based on evaporation from the 22.4-inch oven pans as the abscissa. Hence, the effect of the screen was to make the regression coefficient less than one.

The 12-inch oven pan appears to have a higher correlation with the 22.4-inch oven pan than do any of the other smaller pans. It does not, however, appear to be any better than the 22.4-inch plain pan without a screen. It is clear from these two analyses that the 12-inch oven pan is the best selection among the small pans for field use. It is also apparent that the size of the oven must be increased to allow for the effect of the screen on evaporation.

Table 4. Evaporation From Various Pans vs. Evaporation From 22.4-inch Oven Pan (1959 Data)

Pan description	Regression coefficient	Correlation coefficient	Intercept inches
22.4-inch pan, plain	0.885	0.988	-0.001
12-inch oven pan	0.934	0.981	-0.01
12-inch pan, plain	0.794	0.970	-0.005
6-inch oven pan	1.032	0.961	-0.01
6-inch pan, plain	0.856	0.932	-0.01

Yield from grass plots

In general, there was no difference in dry-matter yield found to be associated with degree of shading on the plots. There appeared to be a definite trend, however, for the plot with the most shade (92%) to have a slightly lower yield, and in 1958 it was significantly lower. Beyond this, no trends could be observed. In other words, the plot with 72% shade appeared to have yields as high as one with no shade in spite of the fact that its consumptive use was usually less than half that of the open plot.

Table 5. Forage Yields From Shading Experiment (Dry Weight)

Degree of shading	1958	1959
Percent	*Gms. per plot*	*Gms. per plot*
0	2,393	1,943
30	2,505	1,876
47	2,706	2,067
55	2,749	1,960
63	3,183	1,801
72	2,549	1,811
92	1,911	1,630

Data From Unshaded Pasture Sites

Exploratory work in 1960-61

In 1960 the first pan with a depth to correspond with the total available moisture-holding capacity of the soil was constructed—in this case eight inches. Several shallower pans were also tested at various locations in the pasture. All pans were fitted with a protective screen.

In 1960 results served only to point out needed changes in the design and placement of the pans. Whenever the grass was permitted to grow up above the height of the top of the pan, evaporation was reduced to a value much less than consumptive use. The pans must therefore be set high enough to avoid shading by the crop. It was learned also that a pan should not be set close to a fence, because the fence deflects part of the water from the sprinklers and probably influences evaporation as well. The 8-inch deep pan did appear promising, and sufficient data were obtained to select the size of oven required for an evaporation rate equal to consumptive use of pasture.

During 1961, five stations were selected and three evaporation pans were placed at each station. Several operational problems were again encountered, including a high water table and the discontinued use of two pastures in the middle of the season. Results indicated that one more modification was needed in the design of the pans: a method to catch more water from the irrigation sprinklers. Apparently some of the drops of water were bouncing off when they hit the wire screen. A funnel was added to the pan for use the following year. The 1961 results on the Willamette station in Figure 12 look much better than for the other four stations (not shown) with respect to filling during an irrigation. In spite of these problems, the 1961 results were very gratifying, including a lack of damage to the pans from livestock.

Results from pasture stations in 1962

Results for 1962 are shown in Figures 12, 13, and 14. Three of these stations, the Willamette, Dayton, and Carlton silty clay loam sites, were located on the OSU pasture where a water table persisted at depths ranging from three to six feet below the surface. The other two sites were located on private land, on well-drained Chehalis soil. The well-drained sites were selected because it was feared that a fluctuating water table would cause errors in measurement of moisture in the upper two feet of soil. It was also considered possible that the plants were drawing some moisture directly from the zone near the water table.

Each chart represents a running record of the deficit of water below the level of the top of the pan and the deficit of soil moisture below field capacity. When these two lines approach the zero at the top

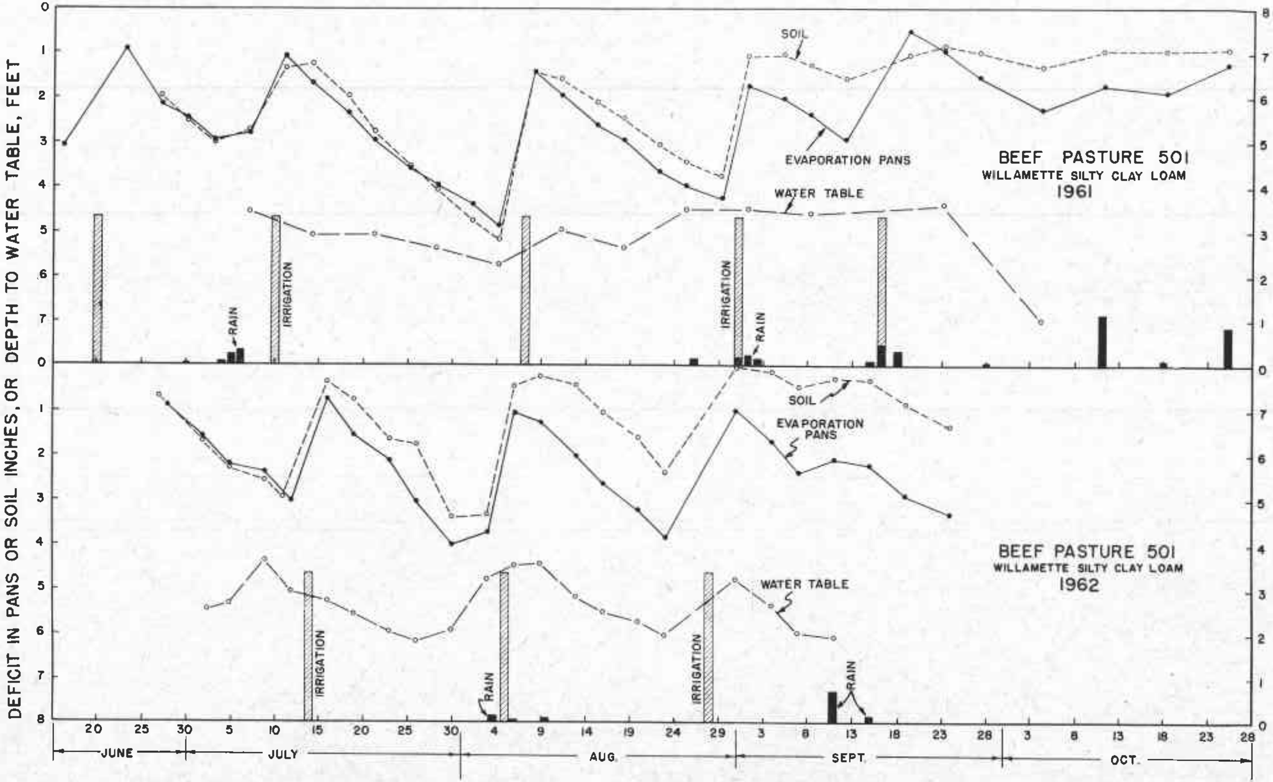

Figure 12. Deficit in evaporation pans compared with soil-moisture deficit for Willamette silty clay loam, 1961 and 1962.

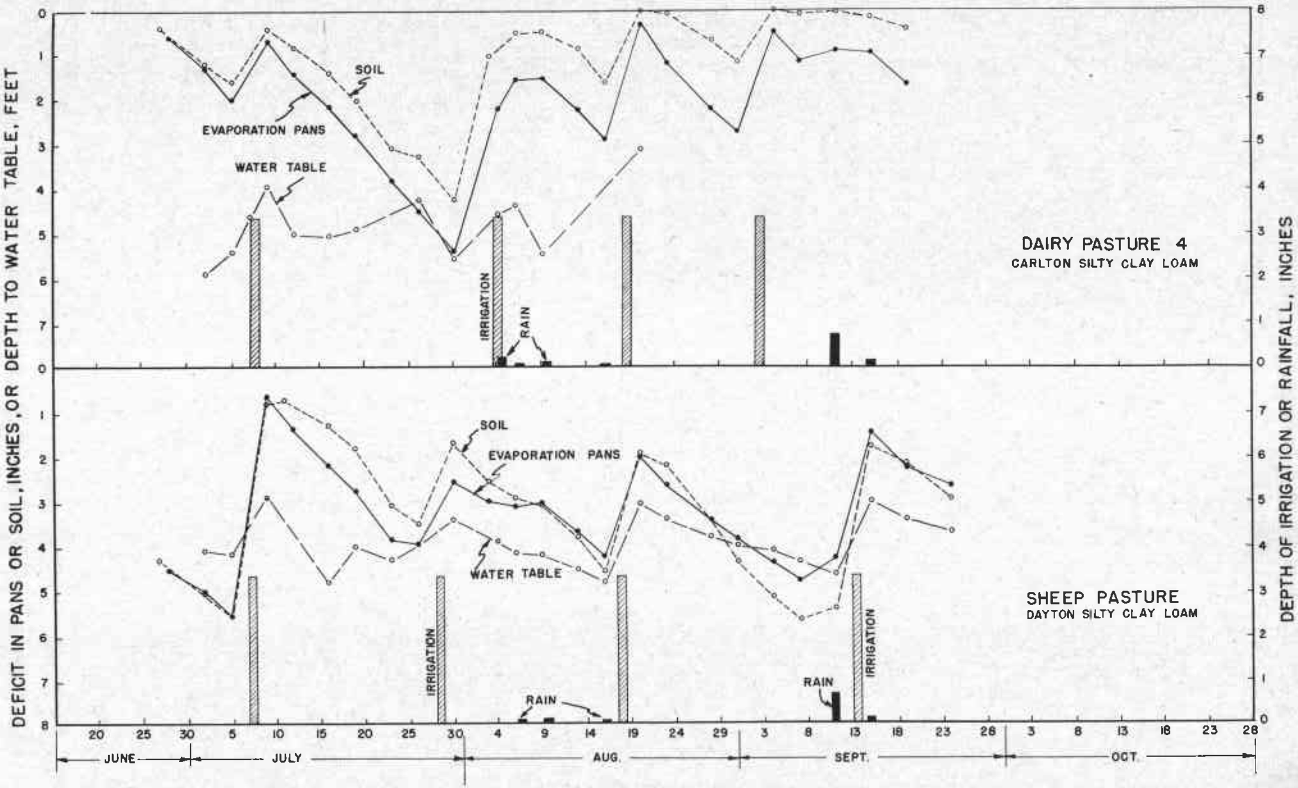

Figure 13. Deficit in evaporation pans compared with soil-moisture deficit on poorly drained sites, 1962.

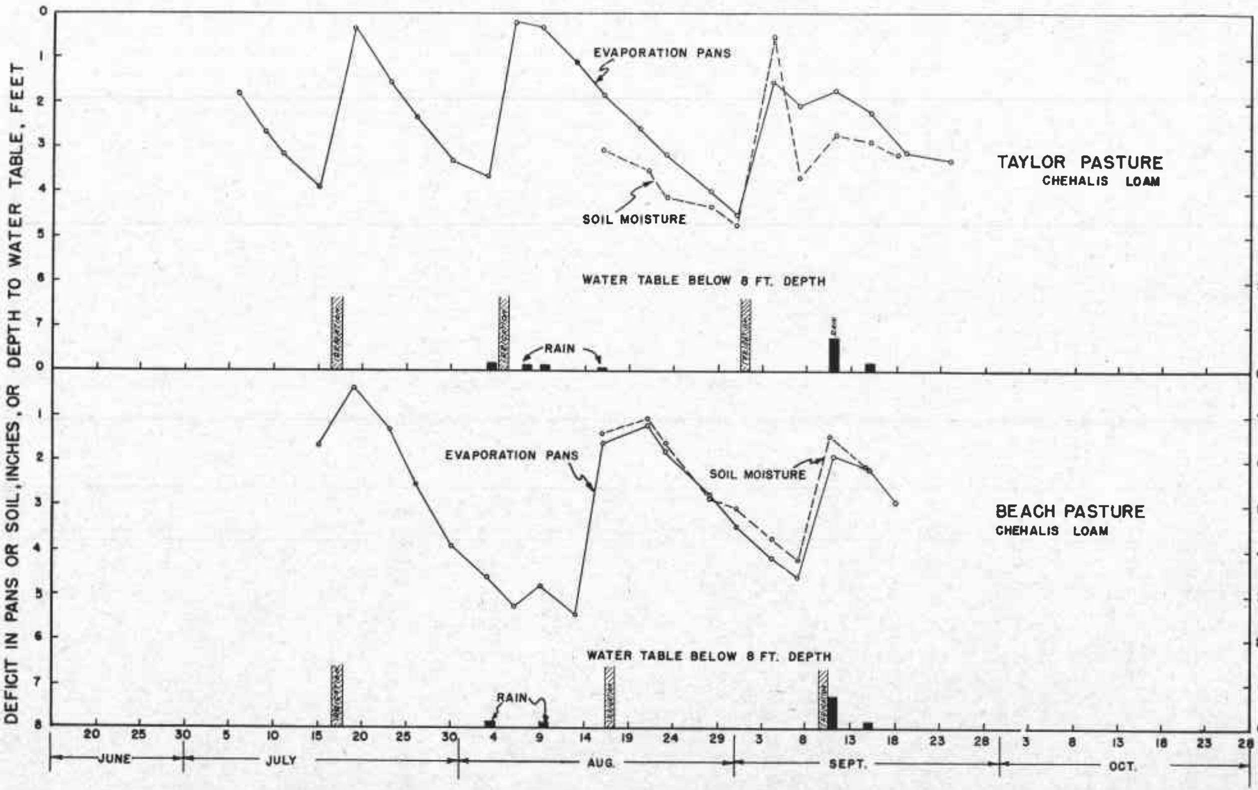

Figure 14. Deficit in evaporation pans compared with soil-moisture deficit on well drained sites, 1962.

of the chart, it means that the pans are full and the soil is approximately at field capacity. The 8-inch depth at the bottom of the chart represents an empty pan and soil near the wilting point in the upper $2\frac{1}{2}$ to 3 feet. The pan would be an ideal estimator of available soil moisture if the two lines would coincide throughout the season.

Rainfall was measured, but irrigation was not. All irrigations were shown as $3\frac{1}{2}$ inches, the normal amount in an $11\frac{1}{2}$-hour set, but often the night sets were considerably longer than the day sets, and no record was kept. This probably accounts for most of the apparent discrepancies between the indicated application and the amount of water caught.

The shallowest water table occurred on the Dayton site, ranging from about 3 to 5 feet. Note that it comes up at each irrigation and falls between irrigations. Soil-moisture curves are steeper than evaporation curves, probably because of continued drainage as the water table falls. A restrictive layer in this soil keeps most of the roots in the upper $1\frac{1}{2}$ to 2 feet. Grass height during the season ranged from 10 to 15 inches and did not cause shading of the inside of the pan. In spite of the water-table problem, the pan served as a very good indicator of soil-moisture deficit, with the deviation never exceeding one inch.

On the Carlton site, the water table seemed to have little effect except when it rose in late August and during a short period about July 25. The rise on July 25 was probably the result of an irrigation from a lateral close by, because it did not show in the evaporation pans but did show in the soil moisture. The rise on August 22 was because of an irrigation that continued after the soil reached field capacity. As a result, the soil-moisture curve was slower to start down after the irrigation. Another excessive irrigation occurred about September 3. These two irrigations served to bring the two lines close together at the top of the charts, even though they separated somewhat between irrigations. In general, results at this site were very good with a maximum discrepancy between the two lines of just a little more than one inch.

On the Willamette site in 1962, the soil-moisture deficit and the deficit in the pan followed fairly closely together at the beginning of the season but gradually spread farther apart. Most of the discrepancies seemed to occur at the time of the irrigation and for the first few days thereafter. For some reason, the pans did not catch as much water during an irrigation as the soil did. This discrepancy is believed to be caused by a slight malfunction of the funnels when they were not set squarely over the pans. In fact, on this site the pans performed as well in 1961 without the funnels. The cause of most of the remaining discrepancies seems to be associated with the rise of the water table after irrigations on August 5 and 28. Grass roots on this soil normally extend to a 3- or 4-foot depth, so some water could easily have been supplied directly to the plants from the water table while it was above normal. It is interesting to note that the soil-moisture curve does not start down until the water table has started down.

Grass height exceeded 20 inches for a short period during July on the Willamette station, but apparently this was not sufficient to cause undesirable shading of the pan. The two moisture-deficit lines remain nearly parallel during the period from September 7 to 24. Rainfall during the period totaled less than an inch, but it resulted in an increase in both pans and soil. The increase appears to be less than the rainfall because it is diminished by evaporation and transpiration between measurements.

The water table on the two Chehalis stations was about 20 feet below ground surface. The record of soil moisture is shorter than that of evaporation from pans because the electrical resistance method of measuring was found unsatisfactory in this soil. By mid-August a neutron meter for measuring soil moisture was available. The values shown were those obtained by the neutron meter. On the Taylor pasture there is considerable fluctuation of the soil-moisture curve that is not easily accounted for. Measurements on September 4 and 8 indicate a consumptive use of about 3 inches in 4 days. Actual consumptive use in September rarely exceeds one-fourth of an inch per day. One or both of these values, therefore, must be in error. Possibly the discrepancies can be contributed to inexperience in the use of the neutron meter.

Results from the Beach pasture appear to give an excellent correlation, even though it had been more than a month since the pans were installed with a deficit equal to the soil-moisture deficit. The two deficits were still nearly equal on August 15 and remained very close together until the end of the season. The grass was kept to a height of about 2 inches, but its consumptive-use rate appears to be as great as from the taller grasses in the other fields. The soil moisture must have been very close to the wilting point before the irrigation on August 14.

Summary and Conclusions

A number of evaporative devices were correlated with consumptive use of pasture during a three-year study on shaded plots. The highest correlation was obtained from an oven pan, that is, a pan with a glassed-in air space on one edge to trap more solar radiation. This pan also happened to have an evaporation rate equal to consumptive use.

Next highest correlation was obtained from Livingston black and white atmometer spheres. However, the set of values with the high correlation was computed by multiplying the black-bulb evaporation by two and then subtracting the evaporation from the adjacent white bulb from it.

The oven pan was redesigned for use as a direct-scheduling device for pasture irrigation. It was reduced from a 22.4-inch square to a 12-inch square, and its depth increased from 2 to 8 inches. The 8-inch depth corresponds to the approximate available moisture-holding capacity of the soil within the root zone. A protective cage was placed around it with a screen over the top. It was designed to catch one inch of water for each inch of irrigation applied, and to evaporate one inch for each inch of consumptive use of pasture. It is initially filled and placed in the field when the soil is at field capacity. Thus, each inch deficit in the pan represents an inch deficit in soil moisture. For many crops, irrigation should commence before the pan is half empty and cease just before the pan overflows.

Results indicated that the redesigned oven pan can be used successfully for scheduling pasture irrigation. It should also be adaptable to other perennial crops by selecting the size of the oven and the depth of pan to fit the crop and soil, respectively. When used with annual crops, it might result in over-irrigation in the spring if it is designed for the period of peak use, but if water is available, slight over-irrigation at this time might not be objectionable. If applied to orchards, it would have to be placed with full exposure to the sun, not under a tree.

The principal advantage of the oven pan as a scheduling device is freedom from labor during the season. It is sufficiently accurate unless the crop is receiving a significant portion of its water from a water table. It tells at a glance when it is time to irrigate, how much to apply, and when to stop the irrigation. It would lend itself to automatic scheduling of solid coverage systems. Investigation will be continued for further verification of these claims.

Literature Cited

Briggs, L. J., and H. L. Shantz. Daily transpiration as a factor in crop production and its correlation with weather. Jour. of Agr. Res., *9*:277. 1917.

Crabb, G. A., Jr. Insolation: A primary factor in evaporation from a free water surface in Michigan. Mich. Agri. Expt. Sta. Quarterly Bulletin, *35*(2):186-192. 1952.

Gardner, W. R., and C. F. Ehlig. The influence of soil suction and water content on transpiration. Presented to the Western Society of Soil Science. Corvallis, Oregon. 1962.

Lemon, E. R. Evapotranspiration. Irrigation department report. University of California, Davis, California. 1956.

Martin, E. V. Studies of evaporation and transpiration under controlled conditions. Carnegie Inst. of Washington Pub. 550. 1943.

Middleton, J. E. Use of evaporimeters in Washington. Presented at ARS-SCS workshop on consumptive use. Tempe, Arizona. 1962.

Olivier, Henry. *Irrigation and Climate*. Edward Arnold Limited, London. 1961.

Pruitt, W. O. Evapotranspiration of perennial ryegrass in the Sacramento Valley as measured by lysimeters. Presented at the ARS-SCS workshop on consumptive use. Tempe, Arizona. 1962.

Stammers, W. N. Investigations on the improvement of irrigation practices in the Umatilla Irrigation Project. Ore. Agri. Expt. Sta. Spec. Rept. 166. 1963.

Veihmeyer, F. J., and A. H. Hendrickson. Use of black and white atmometers for measuring the use of water by crops, evaporation, and solar radiation. Intern. Comm. on Irrigation and Drainage, Third Congress, Question 8, p. 523. San Francisco. 1957.