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Plant Growth-Evapotranspiration Relations for Several Crops in the Central Great Plains[1]

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ABSTRACT

Lysimeters, which eliminated runoff and percolation below 90 cm, caused about 10 cm of additional water to be available for growth of grain sorghum in 1967. This additional water doubled yields, with an increase in evapotranspiration of only 50%. Evaporation from soil in the lysimeter was only 32% of the evapotranspiration, compared with 50% for the soil surrounding the lysimeter. Evaporation from the soil within a winter wheat crop during the acuively growing period in the spring, was estimated to be 15 and 37% of evapotranspiration for 1966 and 1967 respectively. Evaporation from the soil within the actively growing crop was estimated to be 34 and 20% of the evapotranspiration for oats and millet, respectively. Estimates of the amount of water evaporated from the soil within a crop allowed for estimation of transpiration from measurements of evapotranspiration. This data indicate that production and transpiration are directly related in this dryland area as de Wit (3) suggests.

Additional index words: **lysimeters, evaporation, transpiration.**

CROP growth in the Central Great Plains is inevitably connected with the supply of available water. Where other factors, such as fertility, disease, etc., do not limit growth, transpiration is strongly related to crop growth. Where water is not limiting, transpiration and plant growth are strongly related to weather factors. However, where water is limiting, transpiration and plant growth are related more to water availability than to weather factors. The review articles of Taylor (9), de Wit (3), and Penman et al., (7) discuss this subject in detail.

Much of the early work on the relation of plant growth to water use was conducted by growing plants in containers. The classical works of Briggs, Shantz, and Piemiesel at Akron, Colo. (28), Kiesselbach at Lincoln, Nebr. (6), and Dillman at Mandan, N. Dak. (4) are examples of such work. In these studies plants were grown in containers, which were sealed to eliminate evaporation of water from the soil, and water was added periodically so that water did not limit growth. Other factors such as fertility, etc., that may also limit growth were maintained at adequate levels. Until recently these studies were considered to have little relation to plant growth and water use under field conditions with limited water. The "water requirements," the ratio of weight of water used to weight of dry matter produced, was found to vary according to season in a manner not satisfactorily explained by the original authors. De Wit (3), however, maintains that the authors did not adequately analyze their data. He gives convincing evidence that plant growth (P) is directly related to the ratio of the cumulative transpiration (T) divided by the seasonal free water evaporation rate (E_0) according to equation [1] where the

$$P = m\frac{T_T}{E_0} \qquad [1]$$

proportionality constant, m, may have dimensions of (g dry matter m) (kg water day^{-1}) or kg dry matter $ha^{-1}day^{-1}$ depending on the dimensions of P, T, and E_0. The data of de Wit (3) show that the "m" value for any particular crop did not vary significantly at different locations in the Great Plains. Values of 207, 115, and 55 kg dry matter $ha^{-1}day^{-1}$ for 'Red Amber' sorghum, 'Kubanka' wheat and 'ADI-3' alfalfa, respectively, were found for several locations. The constant "m" according to de Wit is, to the first approximation, independent of weather, provided the nutrient level is not "too low," the availability of water not "too high," and the leaf mass is not "too dense." As pointed out by de Wit (3) these extreme conditions do not occur if growth in the field is limited by the supply of water. He concludes:

> "Consequently, the relation between transpiration and total dry matter production in the field under conditions of limited water supply, must be quantatively the same as in containers."

Arkley (1) examined much of the same data as de Wit using an expression involving relative humidity (1–relative humidity expressed as a fraction), in place of free water evaporation. His analysis indicates that the use of relative humidity gives results equally as good as free water evaporation. Further Arkley (1) maintains that the relative humidity correction is valid in humid regions where the free water evaporation correction does not apply.

Many investigators, as reported by Taylor (9) have measured plant growth as related to water used in water-limiting areas. However, few of these investigators attempted to evaluate transpiration from the crop, because it was difficult to separate from evaporation from the soil. Moreover, most of these investigations involved gravimetric sampling over fairly long periods of time, which introduced large errors in the data because of runoff or deep percolation.

It was the purpose of this investigation to evaluate evapotranspiration on a detailed time scale for various crops as related to plant growth under field conditions. A secondary purpose was to make reasonable estimates of transpiration and evaporation from the soil for the various crops.

PROCEDURE

To meet the objectives to the experiment, it was necessary to measure crop growth and evapotranspiration from the crop, and to estimate evaporation directly from the soil within the crop.

Evapotranspiration was measured by the use of simple hydraulic lysimeters described by Hanks and Shawcroft (5). Plant

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growth was measured by taking plant samples and determining the total dry matter. In some instances dry matter production was evaluated throughout the season by periodic sampling in a large plot. Since by this method dry matter production was measured on plots outside the lysimeter and ET was evaluated inside the lysimeter, the dry matter production in the lysimeter at time "t" during the season, P_{1t}, was infered by $P_{1t}=P_{1e}$ (P_{0t}/P_{0e}) where P_{1e} is the production of the lysimeter at the end of the season and at time t, respectively.

In some instances ET was measured by periodic soil sampling using gravimetric or neutron scattering techniques.

Measuring evaporation of water from a cropped soil is difficult because plant shading and decreased air flow influence evaporation. Consequently, evaporation from the soil for a crop was estimated by assuming that the evaporation from the soil within the crop was equal to fallow from planting until dry matter amounted to abou 200 kg ha^{-1}. Thereafter the evaporation from the soil within the crop was assumed to be some fraction of that from fallow for the same period, as explained later.

Pan evaporation was measured with a "BPI sunken pan." A correction factor of 0.92 $E_p=E_0$ was used to convert to free water evaporation from a large body. This correction factor may not be too meaningful, because placement of the pan greatly influences evaporation, but it is used to correspond with de Wit's (3) study.

The studies were conducted at the USDA Central Great Plains Field Station at Akron, Colo. The elevation is 1,396 m (4,580 ft) and the annual average precipitation is 42.3 cm (16.7 inches). Measurements were made for grain sorghum (*Sorghum vulgare*, var. RS-610), oats (*Avena sativa*, var. 'Fulton'), winter wheat (*Triticum vulgare*, var. 'Wichita'), and millet (*Panicum miliaceum*, local selection). The lysimeters, which were 1 m square, were placed in the center of 53- × 53-m plots replicated twice for each crop except for the 1967 sorghum and oats plots. In 1967 oats were grown on two plots early in the year and harvested in mid-June, after which sorghum was planted. These two plots, one dryland and one irrigated, were 137 × 152 m and 137 × 92 m, respectively. There were five lysimeters in each plot placed on a north-south line in the middle of the plot parallel to the 137-m dimension. The lysimeters were installed at 6.8, 34.2, 67.5, 102.8, and 130.2 m from the southern end of the plot.

RESULTS

That dry matter production of winter wheat is highly correlated with evapotranspiration, ET, is shown in Fig. 1. The data show that a nearly linear relation existed between evapotranspiration and yield from the beginning of the measurements until maturity was reached in 1967. The wheat did not mature in 1966 because of severe hail damage. If the data are extrapolated to zero yield, the evapotranspiration was about 8 or 10 cm. Winter wheat was planted in September of the previous year shown, but no yields were collected until after growth had begun the following spring. From planting until final harvest evaporation from fallow, E_f, was 12.5 and 26.0 compared with ET of 30.7 and 40.1 cm for 1966 and 1967, respectively.

The relation of yield to ET is shown for millet and oats for 1967. These data also show a strong linear relation between ET and yield. A linear regression equation extrapolated to zero yield gives a value of about 2 cm ET. Oats were grown until about the middle of June, at which time they were harvested and grain sorghum planted. From planting of millet until harvest time E_f was 9.7 cm compared with 26.2 cm ET. For oats, E_f from planting until harvest was 8.1 cm compared with 12.5 cm ET.

Figure 3 shows the yield-ET comparison for grain sorghum. These results are from one lysimeter experiment in 1966 and an experiment in 1967 with four variables. The lysimeter data for 1967 showed a much

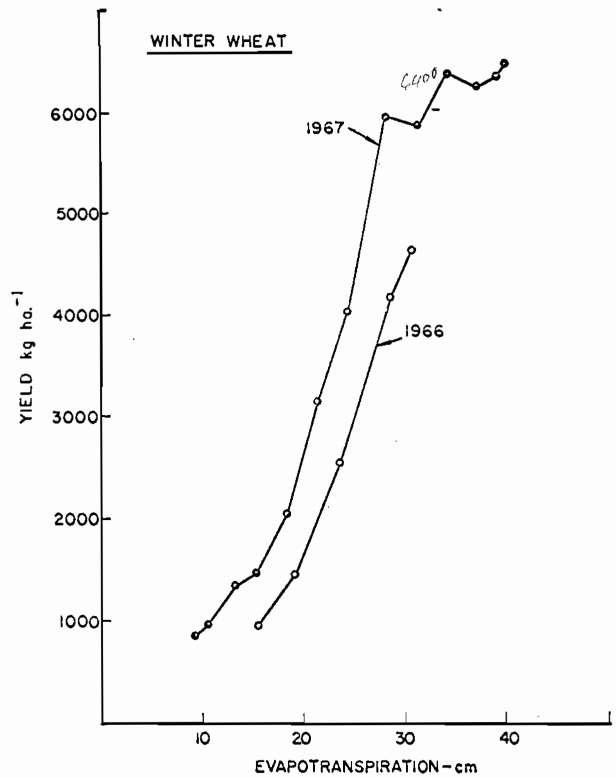

Fig. 1. Cumulative Evapotranspiration-cumulative yield relation for winter wheat.

greater soil water storage in the lysimeters than outside which resulted in much larger ET and dry matter production as shown in Table 1. Although there were large differences in ET and yield among the treatments, the relation between yield and ET appears to be quite similar for all the treatments. The high correlation coefficient is indicative of the very strong linear relation between ET and yield. The regression equation extrapolates to an ET of about 8 cm for zero yield.

The ratio of E_f/ET from planting until harvest was 0.52, 0.44, 0.33, 0.65, and 0.50 for treatments 1 through 5 (Table 1), respectively. The lysimeters eliminated runoff and water flow below 90 cm, which resulted in a higher soil water content in the lysimeters (Fig. 5). Apparently because of this higher water content, yields in 1967 were increased in the lysimeter by 2.2 and 2.1 times those outside the lysimeter in the dry and irrigated plots, respectively. In 1966 a similar result was measured because yields in the lysimeter were 4,510 kg ha^{-1} compared with 2,040 kg ha^{-1} in the surrounding outside plots. Although yields in 1967 were more than doubled inside the lysimeter, compared with the outside plot, ET was only 1.5 times more. Unfortunately, no comparison of ET outside the lysimeter is possible for 1966 because soil sampling was not done.

In 1967 yields of millet inside the lysimeter were 6,120 kg ha^{-1} compared with 4,900 kg ha^{-1} in the surrounding outside plot. However, the dry matter yield of winter wheat inside the lysimeter was 6,400 kg ha^{-1} compared with 9,550 kg ha^{-1} in the surrounding plot. Winter wheat was planted in September 1966. Precipitation was very low from planting time

Table 1. Evapotranspiration, yield, estimated evaporation from the soil, and calculated values of "m" for grain sorghum. The notation (y) refers to the data for the entire year (6/22 to 9/30, 1966, and 6/20 to 10/3, 1967), and (a) refers to data for the portion of the year when plants were actively growing (7/28 to 9/30, 1966 and 7/25 to 10/3, 1967).

	TREATMENT				
	(1) Lys. 1966	(2) Lys. dry 1967	(3) Lys. irr. 1967	(4) Samp. dry 1967	(5) Samp. irr. 1967
Yield (year) kg ha^{-1}	4510	5960	8450	2690	4090
Yield (active) kg ha^{-1}	3560	5690	8159	2568	3951
ET (y) cm	31.4	32.9	42.9	21.8	28.1
ET (a) cm	19.1	24.2	31.7	14.0	19.1
E_f (y) cm	17.8	14.2	14.2	14.2	14.2
E_f (a) cm	9.3	7.2	7.2	7.2	7.2
E_o (a) cm day^{-1}	0.48	0.47	0.47	0.47	0.47
m (a) for $E_s = E_f$	175	158	157	177	156
m (a) for $E_s = 0.75\ E_f$	142	143	146	140	136
m (a) $E_s = 0.50$	119	130	137	116	120

until late May 1967. With the relatively long period of time in which root growth could occur, it is probable that water was extracted below 90 cm by the wheat plants outside the lysimeter. This could account for the higher yields outside the lysimeter.

DISCUSSION

The data presented herein could be used to evaluate a value of "m" for equation [1] if the transpiration could be estimated. Estimation of transpiration requires an estimate of the evaporation from the soil within the crop during the season. At best any estimate of evaporation from the soil within a crop will be a guess without more information than is currently available. However, any estimate based on some fraction of E_f during periods of relatively little rainfall should not be in error, in an absolute sense, too greatly

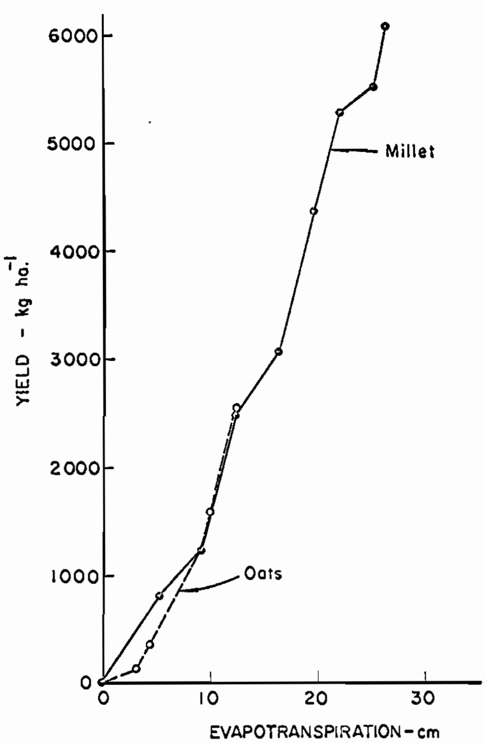

Fig. 2. Cumulative Evapotranspiration-cumulative yield relation for millet and oats in 1967.

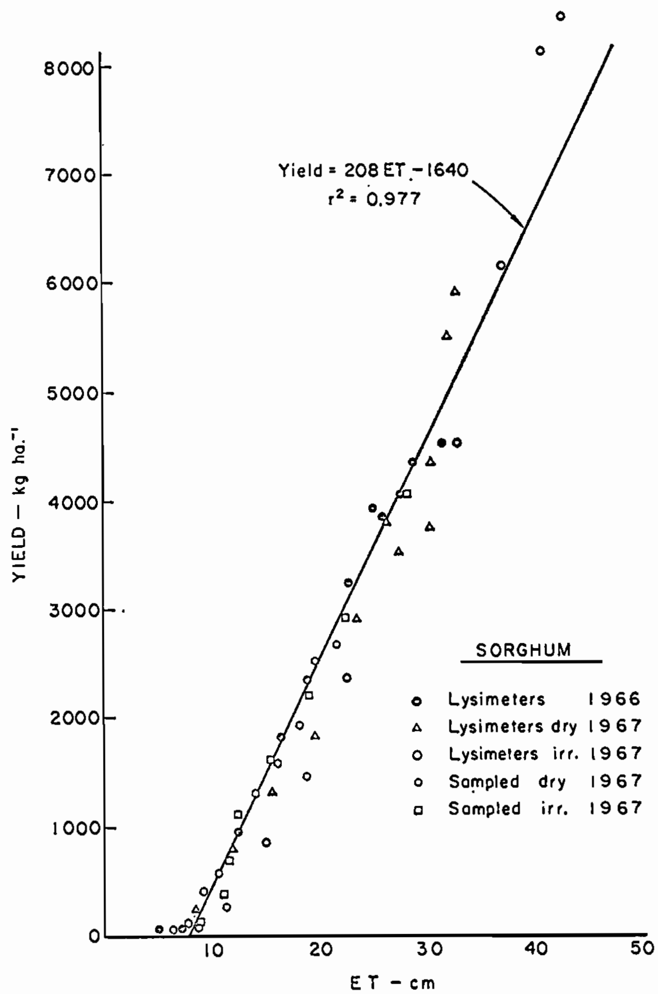

Fig. 3. Cumulative Evapotranspiration-cumulative yields relations of grain sorghum both in lysimeters and in surrounding plot.

because the absolute amount of E_f is small. The effect of shading, if data from stubble plots can be considered as a measure, is minimized if the periods between rains is long. In 1966, rainfall was considerably below average. For the period of April 6 to May 31, 1966, the ET from the wheat was 15.1 cm compared to E_f of 3.7 cm. If the ratio of E_s/E_f is assumed to vary from 1.0, to 0.25, the value of m varies from 140 to 113 kg dry matter ha^{-1} day^{-1}. If equation [1] is valid, a value of m of 125 would be accurate within about 10%. This compares with a value of 124 computed from the data of Briggs and Shantz for the two winter wheat varieties tested. In contrast to 1966, 1967 was a year of above-average rainfall during the growing season for winter wheat. From the date of first dry matter sampling until maturity, April 20 to June 20, E_f was 10.0 cm and ET was 19.3 cm. The estimate of E_s has a much larger influence on the value of m computed from the 1967 data than from the 1966 data. If the ratio of E_s/E_f is taken to vary from 1.0 to 0.25 for 1967, the value of m varies from 162 to 90 kg dry matter ha^{-1} day^{-1}. A value of 125±5, for m, would give a E_s/E_f ratio of 0.62±0.13 and 0.72±0.05 for 1966 and 1967, respectively. These values for E_s are reason-

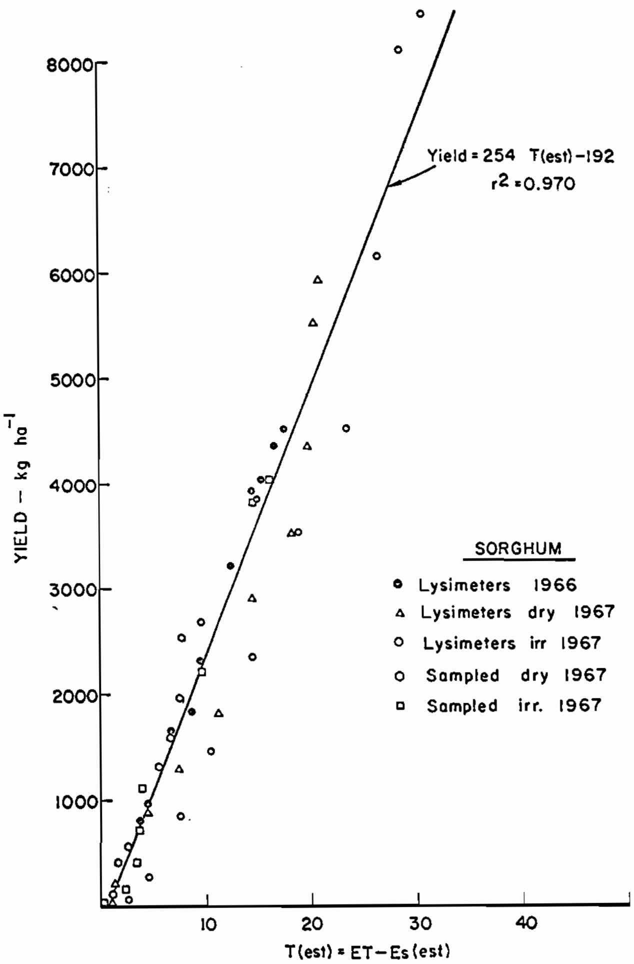

Fig. 4. Cumulative Estimated transpiration-cumulative yield relations for grain sorghum both in lysimeters and in the surrounding plot.

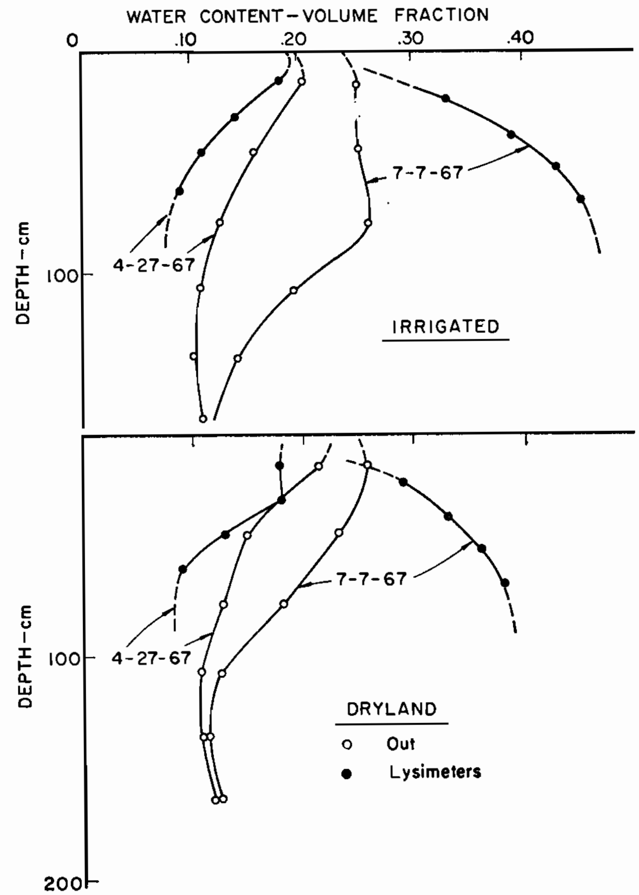

Fig. 5. Water content profiles inside lysimeters and in the surrounding plot for grain sorghum on 4/27/67 and 7/7/67.

able. These data would support the validity of equation [1].

The data for oats, for which appreciable growth occurred, cover the period from May 23 to June 13, 1967. ET during the period was 8.3 and E_f was 5.4 cm. For ratios of E_s/E_f varying from 1.0 to 0.25, the value for m varies from 223 to 94 kg dry matter ha^{-1} day^{-1}. Since this period was one of high precipitation, the estimates of E_s greatly influence the value of M. The data of Briggs and Shantz (2) for two varieties of oats yield a value for m of 118 kg dry matter ha^{-1} day^{-1}.

The data for millet for which appreciable growth was measured cover the period from August 1 to September 26, 1967. This was a fairly rainless period and E_f was only 5.5 cm compared with ET of 21.0 cm. For ratios of E_s/E_f varying from 1.0, to 0.25, the value of m varies from 167 to 132 kg dry matter $ha^{-1}day^{-1}$. The data of Briggs and Shantz (2) for four millets and prosos gave much higher values of m, ranging from 296 to 223 kg dry matter ha^{-1} day^{-1}. Varietal differences may explain the differences in results.

The data for grain sorghum are more extensive than for the other crops because of more treatments in 1967. The data are summarized in Table 1. For the active growing period with $E_s/E_f = 0.75$ the value of m for all the treatments is within 4% of the mean value of 141 kg ha^{-1} day^{-1}. If equation [1] holds, the value of m would be the value for which the variation among treatments for different ratios of E_s/E_f was least. Variation among these treatments was smallest for E_s/E_f of 0.75. This is a reasonable value for this crop with 102-cm (40-inch) rows with ground coverage of only about 40% by the end of the season. The ratio of E_s/E_f would undoubtedly be greater for the full season than for the actively growing period. If equation [1] holds and a value of m of 141 kg ha^{-1} day^{-1} is used, the ratio of E_s/E_f for the full season would average about 93%. The data of Briggs and Shantz (2) are not for any sorghum similar to that used. Figure 4 shows the yield versus the estimated transpiration for grain sorghum. The ratio of E_s/E_f of 0.75 during the actively growing period was used for this computation. The data show a high linear correlation of yield and T (est.) of r =0.97. This is strong evidence that for grain sorghum, dry matter production is directly proportional to transpiration. This same relation seemed to hold equally well for plants grown in lysimeters where ET was greater than the energy available as net radiation, as well as field plots where ET was much less than net radiation.

One finding of this study that has added significanse to water use-plant growth relations was that by eliminating runoff and deep percolation, dry matter yields of sorghum were doubled with only a 50% increase in ET.

Figure 5 shows the water content profiles for all four treatments on April 27 and July 7. The water balance of the four treatments is shown in Table 2. The data show an increase in storage in the lysimeter on the dry plot, of 16.3 cm compared with 6.0 cm on the outside plot. For the irrigated plot there was an increase in storage of 22.1 cm for the lysimeter and 12.5 cm for the outside plot. If the ET from the plots outside the lysimeter is assumed to be the same as inside the lysimeter during the period, then runoff and deep percolation was 9.6 and 10.3 cm for the irrigated and dry plots, respectively. Runoff from the watershed in which the experiment was run was about 5 cm. If this figure is used, deep percolation would be about 5 cm also. This seems high. It may be that runoff was more than 5 cm or the data are in error.

The data presented here do not prove the validity of de Wit's equation and conclusions, but they certainly support it. Further tests are needed at several locations using present-day varieties to determine if measurements of dry matter production and transpiration performed in the manner of Briggs and Shantz (2) can be applied directly to the field.

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