A MODULATED SOIL MOISTURE BUDGET

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ABSTRACT

Most meteorological soil moisture budgets do not account for soil moisture stress changes in the drying cycle or for changes in ground cover or expanding root system. A simple modulated technique is described which considers these factors. Soil moisture stress determined by this technique has a significantly higher correlation with wheat yield than does moisture stress determined by a common method.

1. INTRODUCTION

An important phase of research in agricultural meteorology and soil physics is concerned with soil moisture and the process of evaporation. The soil, plant, and atmosphere each play important roles in this process but are only parts of a continuous system of transport of water from the earth to the atmosphere. While much emphasis has been placed on the individual components of this continuum, there has been less attention devoted to the system as a whole than it would appear to merit.

It is recognized that moisture use by crops cannot pass a maximum which is determined by the amount of energy available, from the sun and the horizontal transfer of heat, to convert liquid water to water vapor. As long as water is freely available for evaporation at the earth-atmosphere interface, the rate of evaporation is mostly dependent upon meteorological parameters. The amount of evapotranspiration required to satisfy the atmospheric demand has been called potential evapotranspiration (PE) [20]. However, as the soil dries, the available moisture decreases, hydraulic tension increases, and transport of water to the interface is insufficient to meet the atmospheric demand and actual evapotranspiration (AE) falls short of PE [6, 7].

The commonest soil moisture budget consists of subtracting daily PE from daily rainfall. This amount is then subtracted (or added when rain exceeds PE) from the moisture present in the soil to give the new soil moisture storage, until available stores have been exhausted. For budgeting irrigation water, this process is continued on a daily basis until a certain permissible soil moisture deficit occurs. At this time an amount of water equal to the deficit is applied to return soil moisture storage to field capacity. This is a simplified description of moisture use by crops under irrigation. "Dryland" soils present many problems with meteorological moisture budgets because they are rarely at field capacity and plant roots explore deep moisture stores.

Most methods of determining PE are semi-empirical [2, 6, 10, 14, 15, 20, 21]. Evaporation pans or atmometers have also been used [3, 5, 8, 12, 24]. As stated previously, when the soil dries out AE becomes less than PE. Thornthwaite suggests that AE is in ratio to the soil moisture in storage (SM). That is, when SM is ½ the total storage possible, AE is ½ PE. He proposes that evapotranspiration continues to near oven dryness. Thornthwaite's data supporting his soil moisture depletion curve were obtained from vapor pressure and temperature profile measurements taken at O'Neil, Nebr. [21]. Curves C and D, figure 1, represent Thornthwaite's concept; curve D continues to the wilting point and C to oven dryness.

Blaney and Criddle [2] correlated actual measurements of consumptive use (evapotranspiration) with monthly mean temperature and daylength in an attempt to obtain a soil-plant coefficient that, when incorporated into their empirical relationship, would give it a wide application. The plant coefficients varied from 0.85 for alfalfa to 1.2 for rice, and applied to semiarid and arid conditions.

Pierce [16] used Thornthwaite's method of calculating PE and compared these data to total water use by 2d year meadow as measured by weighing lysimeters. Thornthwaite's PE was adjusted upward to correct for crop density, age, and rooting depth. Pierce's "dryness" correction curve is represented in curve B figure 1, while his seasonal correction for 2d year meadow (state of growth and time of year) is represented in figure 2. This curve is thought to apply to many soils, provided drainage is not restricted.

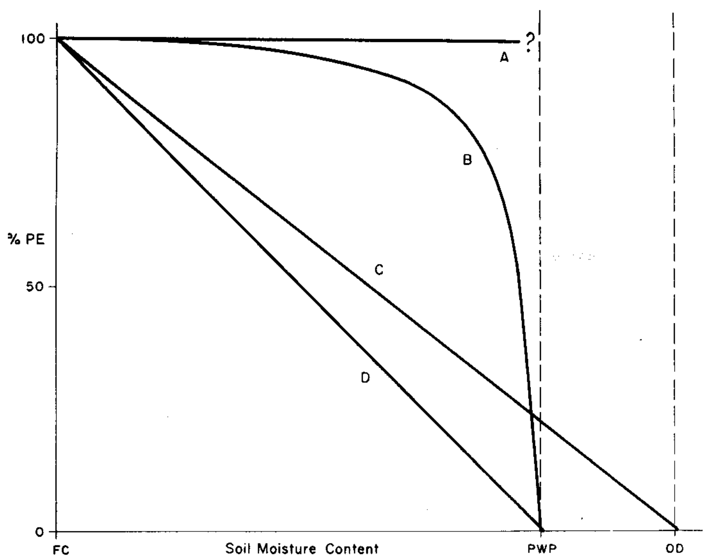

FIGURE 1.—Various proposals for adjustment of PE as soil moisture decreases. A, Veihmeyer; B, Pierce; C and D, Thornthwaite.

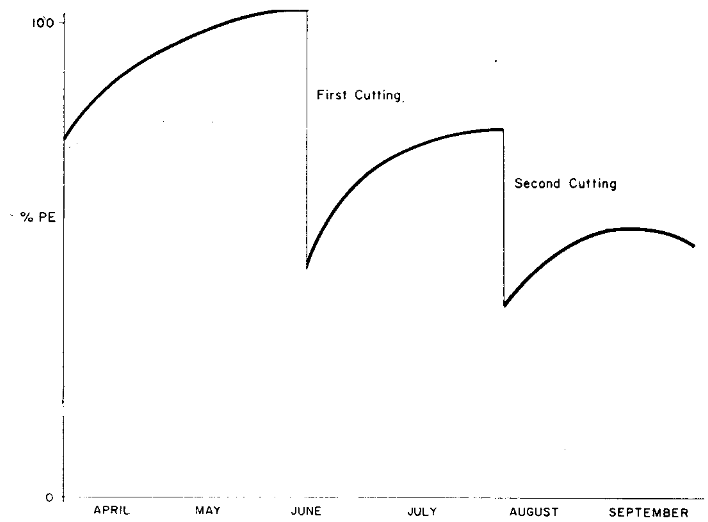

FIGURE 2.—Adjustment of PE for stage of growth of meadow. (Pierce)

Van Bavel's [22] method of determining PE is a simplification of Penman's equation. Nomograms have been drawn to simplify the estimation of daily PE. No allowance is made for soil dryness and crop density (ground coverage) and only moisture within the root zone is considered. (This amount would increase as the crop develops with increasing depth of root zone.) Curve A figure 1 represents Van Bavel's relationship between soil dryness and PE. This curve is similar to that proposed by Veihmeyer [24].

In a recent review of Russian literature, Lemon [11] presents several soil moisture evaporation curves. They are divided into three portions; (a) evaporation proceeds in accordance with the atmospheric demand, (b) evaporation rate declines rapidly as moisture films to the surface become discontinuous and transfer of moisture to the interface decreases, (c) extremely slow moisture movement is dominated by adsorptive forces at liquid-solid interfaces within the soil. Curves in figure 3 suggest this concept. Except for the initial plateau, this is characteristic of many "tension-moisture content" curves.

Marlatt [13] investigated the change in AE as the soil in lysimeters and field plots dried out. By regular soil sampling at 3-inch intervals to 48 inches under a corn crop throughout the season, curves similar to those of Lemon [11] were obtained. He found that AE proceeded at the potential rate up to a point depending chiefly on rooting depth, then AE fell off sharply. These data are represented by the curves in figure 3. The deflection points correspond to the various crop rooting depths at different periods during the season. Philip [17] obtained the same type of curves by analysis of the mathematical and physical aspects of soil moisture evaporation. The horizontal portion of the curves may roughly correspond to the zone of "complete depletion," described by Hagan [4]. This zone may be defined as the volume or, in the case of closely spaced plants, the depth from which soil moisture is withdrawn at or near the potential rate until most of the available water has been removed. The soil in this zone would be thoroughly permeated with fine roots. The second and third portions of the curves may correspond to the "transitional zone" of Hagan [4]. This area contains a varying concentration of roots, decreasing with distance from the plant and extending to a considerable depth.

Marlatt [13] compared the measured and computed soil moisture content of lysimeters and field plots. Measurement was accomplished by sampling, and computation was achieved by adjusting Thornthwaite's PE to soil dryness and rooting depth (according to curves in fig. 3). His correlation was 0.997. Using Van Bavel's [22] nomograms he found departures of the computed and measured SM, particularly when the soil was dry.

2. MOISTURE BUDGETS

To be useful, a scheme for the budgeting or control of soil moisture by the meteorological method should have several characteristics. First, the method of characterizing the drying ability of the atmosphere should (a) be convenient and simple to use, (b) integrate into one measurement all the various meteorological factors affecting the evaporating ability of the atmosphere, (c) (instruments) be free of structural components that distort evaporation measurements.

Second, the manipulation of evaporation data should (a) be realistic in its description of natural processes, (b) have accuracy compatible with the use to which it is put, (c) be simple and practical.

Many of the methods presently used to measure evaporation do not fill the above requirements as they are not simple or convenient. Those that are, do not accurately integrate meteorological factors affecting evaporation into one measurement. Many instruments are cumbersome and are not free of structural disadvantages. A case in point

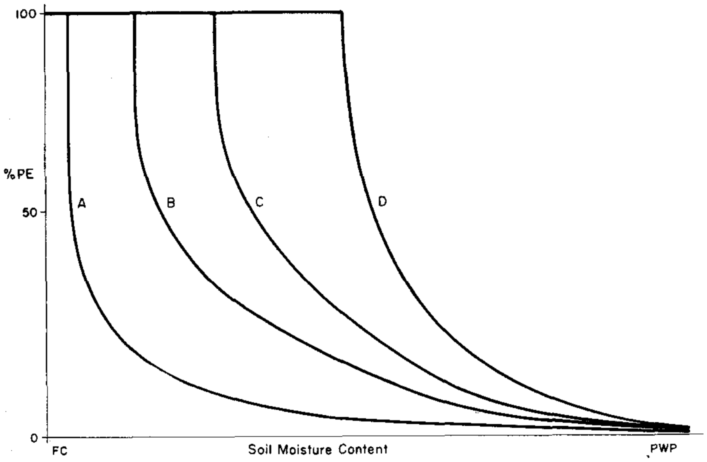

FIGURE 3.—Adjustment of PE for soil dryness and rooting depth of crop (Lemon, Marlatt). Curves A to D correspond to increases in rooting depth of crop.

is that of evaporation pans. Many authors have claimed that atmometers fill most of the above requirements [5, 12, 24], and two recent papers compare an evaporation pan and several atmometers [8, 18]. The black Bellani plate atmometer was described as an accurate and simple instrument that adequately characterizes the evaporation demand of the atmosphere for water.

Similarly, few of our present moisture budget methods (as opposed to evaporation measuring techniques) fulfill all of the above requirements. The accuracy of many present techniques is doubtful; most of them are not realistic in that they do not account for the drying of the soil as moisture loss continues.

It is clear that any accurate description of the moisture status of a soil will not be simple. The plant is the only true indicator of this factor and at the present time it is not possible to measure plant moisture stress, per se. It is necessary then in any budget scheme to make *some* simplifying assumptions, which will be based on crop growth stage, rooting characteristics, and other soil and plant factors. In making these assumptions it is desirable, at the same time, to fulfill the requirements set forth concerning evaporation data manipulation.

A soil moisture budget has been developed which, in the opinion of the authors, fulfills the requirements of the "model" budget described above. Soil dryness is compensated for in a manner similar to that described by Lemon [11], Marlatt [13] and Philip [17]. Crop rooting depth and soil storage may be adjusted periodically during the growing cycle, and rainfall is evapotranspired at the potential rate on the day of the rain and on subsequent days depending on the amount of rain. Percolation, runoff, and soil dryness by zones are also estimated.

The assumptions made in the technique are: (a) all moisture from the zone of "complete depletion," described earlier, is evapotranspired at the potential rate, (b) PE is modulated so that moisture in the "transitional zone" is withdrawn at a decreasing rate depending on the percentage of available moisture remaining, (c) available moisture is withdrawn from the topmost layer of soil, before extraction occurs from lower layers, (d) rainfall occurring after a dry spell is evapotranspired at the potential rate until it has been depleted, unless rainfall percolates into the "transitional zone"; then PE is modulated and withdrawal is at a slower rate, (e) percolation is regarded as complete; if the soil is saturated, rainfall is regarded as runoff. Soil moisture between saturation and field capacity is assumed to percolate.

The weakest assumption is (c) since a plant withdraws water from any zone occupied by roots so long as soil moisture in that zone is available. However, the essentials of the problem are retained since the plant withdraws water from soil zones of varying moisture contents at varying rates, depending on the moisture content of each

TABLE 1.—*Daily PE and soil moisture*

Month—April			Soil moisture storage—Percent of PE											
			100		50		20		10		5			
			Soil zone capacity (inches)											
			0.25		0.25		0.25		0.25		0.25			
Date	PE	Rain	AE	SM	AE	SM	AE	SM	AE	SM	AE	SM	Deficit	Surplus
Last page				0.25		0.25		0.25		0.25		0.25		
1	0.15		0.15	.10										
2	.10		.10	.00										
3	.05	0.06	.05	.01										
4	.08	.05	.06	.00	0.01	.24								
5	.22				.11	.13								
6	.26				.13	.00								
7	.20						0.05	.20						
8	.24						.06	.14						
9	.28						.07	.07						
10	.16						.04	.03						
11	.16						.03	.00	0.00	.25				
12	.10								.01	.24				
13	.05	.35	.05	.25		.05								
14	.03	.33	.03	.25		.25		.10						
Total	2.08	.79	.44	.25	.25	.25	.25	.10	.01	.24	0.00	.25	0.00	0.00
Total AE	.95													

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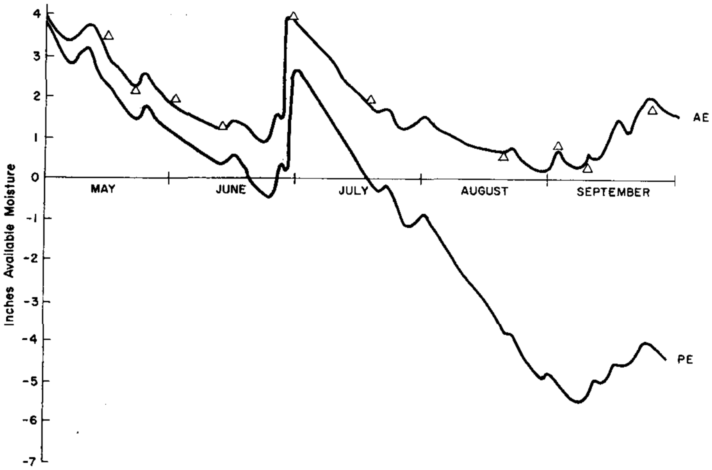

FIGURE 4.—Soil moisture loss calculated by modulated budget (AE) and by simple budget (PE). (Δ indicates spot Coleman moisture block readings.

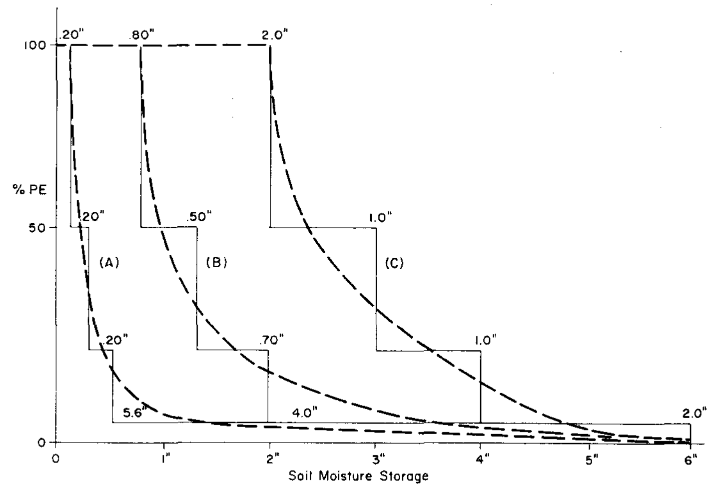

FIGURE 5.—IBM 650 program for adjustment of PE as soil dries and plant roots expand. (Curve A for Aug. 1 to May 31; curve B June 1 to June 30; curve C for July 1 to July 31.)

zone. Recent work by Vasquez and Taylor [24] substantiates this view. There may be some criticism of assumption (e) since local conditions and individual soils may seriously retard percolation.

The individual operations of this technique are set forth in table 1. For purposes of demonstration, the soil zone of complete depletion was assumed to contain 0.25 inch of available water and the transitional zones, 1.0 inch of water, making a total soil storage of 1.25 inches of available moisture. The uppermost 0.25 inch of moisture was evapotranspired at 100 percent of PE; the remaining 1.0 inch was withdrawn in a stepwise fashion with 0.25 inch per step, in such manner that the steps were the best fit to the type of curves in figure 3. In other words, the first 0.25-inch portion of the 1.0 inch in the transitional zone was withdrawn at 50 percent, the second at 20 percent, the third at 10 percent, and the fourth at 5 percent of PE.

Figure 4 compares soil moisture loss by a grass-legume sward calculated by two techniques: (a) the modulated budget described above, and (b) the common type discussed briefly at the beginning of this paper. PE was estimated with a black Bellani plate atmometer [8]. The differences are clearly discernible particularly as the soil begins to dry out. Spot moisture block readings verified the accuracy of the modulated technique.

3. COMPARISON OF TWO BUDGET TECHNIQUES

The two moisture budget techniques partially described above were programmed for an IBM 650 and soil moisture calculations were made for Lethbridge, Alberta, for 36 years (1921–56 inclusive). In both techniques, PE was estimated by Thornthwaite's method [19].

Common Budget (A): The method employed in the simple budget technique has been outlined by Robertson and Holmes [18] and others [20, 22].

Modulated Budget (*B*): The basic characteristics of this technique are outlined in section 2 of this paper. The apportionment of the soil zones and the amount of moisture in each zone is shown in figure 5. The soil drying curve at Lethbridge for stubble or trash covered plowed ground is approximated in the dashed curve A. The stepwise best fit curve used in programming the IBM 650 is drawn over the ideal curve. The length of each step indicates the amount of moisture leaving the soil at the rate of PE shown on the ordinate. This curve was used to calculate soil moisture loss from August 1 (approximate harvest date) to May 31 (seeding date, approximately May 1). The June soil moisture loss curve is represented in curve B, and conditions during July are shown graphically in curve C. These curves were established by laboratory and field observations. Yield data from a 36-year old "continuous spring wheat" rotation at Lethbridge were available for correlation comparisons.

Using the common and modulated budgets, PE, AE, and soil moisture deficits (monthly average below field capacity) during the growth months (May, June, and July) were calculated and compared, through multiple and simple linear correlation, with yields of wheat. The results are shown in table 2.

The data indicate that wheat yields at Lethbridge were not significantly correlated with the evaporating ability of the atmosphere (PE). Soil moisture deficit was more significantly correlated with wheat yields than was actual moisture use (AE). Plant response has been shown to be more closely related to the energy required to take up water (e.g. deficit), than to moisture use per se [4, 13, 17]. The correlation between yield and average monthly moisture deficit below field capacity improves as the season progresses. This indicates that as the crop ages and the roots are more fully ramified throughout the soil, such factors as rooting habit, soil moisture stress, etc., may cause a more pronounced effect on the yield than atmospheric conditions. Allowance is made for these factors in the modified budget (B). Army and Ostle [1] noted an inverse relationship between the evaporating ability of the atmosphere (e.g., PE) and evapotranspiration from

Table 2.—*Simple and multiple correlations between soil moisture factors AE, PE, and deficit (calculated by common (A) and modulated (B) methods) and yield of wheat at Lethbridge, Alberta*

Soil moisture	Correlation coefficient and method							
	May r_{y1}		June r_{y2}		July r_{y3}		$r_{y\,123}$	
	A	B	A	B	A	B	A	B
PE[1]	−0.27	−0.27	−0.04	−0.04	−0.14	−0.14	0.28	0.28
AE[2]	------	.20	-------	.29	-------	**.48	------	**.58
Deficit	−.37	*−.38	.32	**−.46	*−.44	**−.63	.46	**.68

[1] PE is calculated the same way in both A and B methods.
[2] AE is not calculated in method A.
$r_{y1,2,3}$ etc., indicates correlation between yield and May, June, and July soil moisture factors, respectively.
* **indicate significance at the 1 and 5 percent levels respectively.

wheat (e.g., AE). An explanation of this anomaly was found in the complex interrelationship of plant growth, available soil moisture, and climate under semi-arid conditions. Results reported here indicate a similar trend. The correlation between August PE and AE is $r=-0.57$ (significant at the 5 percent level).

Even though the results with the modulated budget indicate considerable versatility and improvement over the simpler meteorological methods of estimating soil moisture status, one may wonder why correlations with yield of wheat are not higher. Hopkins [9] pointed out that inhibitory factors such as wind, disease, weeds, insects, etc., are important in many seasons, and that statistical methods may lead to some underestimation of the actual association of yield of wheat and meteorological factors.

4. SUMMARY

The results presented show that a realistic, yet simple meteorological soil moisture budget is possible. Such a budget readily accounts for soil moisture stress and plant rooting characteristics, etc., and yet has accuracy compatible with other methods of determining moisture use by crops. When soil moisture drying curves (such as those in fig. 5), and accurate estimates of the drying ability of the atmosphere such as those obtained with a black Bellani plate atmometer are available, a daily record of soil moisture is possible. By changing the soil drying curves and coefficients, the scheme can be programmed to fit a wide variety of soils, crops, and crop sequences.

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