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Crop growing periods and irrigation needs of corn crop at some stations in Northeast Brazil

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Abstract—Results of a climatological study of soil moisture under corn crop at six stations in the semiarid region of Northeast Brazil are reported in this paper. Daily values of available soil moisture during the wet season are evaluated using a six-zone versatile soil moisture budget (VSMB) model. A first order Markov chain model is applied to the daily soil moisture data. Soil moisture averages and probabilities are used to identify the optimum growing periods for corn crop at the stations, and the irrigation needs during these periods are evaluated. The effect of soil hydro physical properties in the VSMB model is discussed. The use of mean daily precipitation values in the model in place of actual precipitation data is briefly discussed.

Key-words: versatile soil moisture budget, available soil moisture, crop growing periods, irrigation needs, Markov chain probabilities

1. Introduction

Soil moisture is an important parameter in agriculture, forestry, and hydrology. It plays a significant role in determining crop yields and in the hydrological balance of a region. Since it is impractical to measure soil moisture on the time and space scales required for agro-climatological studies, several models have been developed in the past for its estimation (*Thornthwaite* and *Mather*, 1955; *Holmes* and *Robertson*, 1959; *Baier* and *Robertson*, 1966; *De Jong* and *Shaykewich*, 1981; *Robertson*, 1985). The versatile soil moisture budget (VSMB) originally developed by *Baier* and *Robertson* (1966) takes into

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consideration the rooting depth of the crop, root concentration in different soil zones, and water holding and water release characteristics of each zone. In addition, allowance can be made for the changes in root concentration, as the crop develops towards maturity.

De Jong (1988) compared the soil moisture estimates from the VSMB and SPAW (soil-, plant-, air-water) models with measured data in the semiarid region of Saskatchewan. He found that both models gave equally good results, and that the VSMB model required less crop and soil information as input than the SPAW model. *Boisvert et al*. (1992) used the VSMB model to predict the water table depth. It has also been used to study the soil moisture conditions in the Canadian prairies (*De Jong et al*., 1992). The VSMB model has been used to estimate soil moisture under palm plantations in Malaysia (*Robertson* and *Foong*, 1977), to calculate soil moisture in arid soils in India (*Robertson*, 1977), and to predict summer drought conditions under grass land in South Africa (*Dyer* and *De Jager*, 1986). Recent developments in soil water modeling including the VSMB model were reviewed by *De Jong* and *Bootsma* (1996) and *Baier* and *Bootsma* (1999).

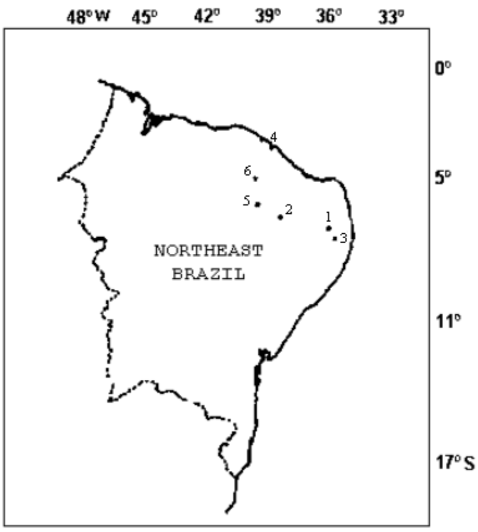


Fig. 1. Location of stations. 1. Campina Grande; 2. São Gonçalo; 3. Umbuzeiro; 4. Fortaleza; 5. Iguatu; 6. Quixeiramobim.

The present paper is based on a study of soil moisture conditions under corn crop at six stations in the semiarid zone of Northeast Brazil (*Fig. 1*). Northeast Brazil comprises an area of about 1.5 million km^2 and consists about 30% of the country's population. In the coastal areas rainfall can be up to 2000 mm per year. About 35% of the region lies in the zone of equatorial climate and 65% in the zone of subtropical climate. The highest and lowest recorded temperatures are 41.5 °C and 11.6 °C, respectively. About 10% of the region receives less than 250 mm of annual rainfall and about 60% receives more than

600 mm. Apart from the generally low amount of rainfall, the highly irregular nature of rainfall during the year is responsible for the frequent occurrence of droughts in this region. In most years about 90% of annual rainfall occurs from December to April or May. The duration of the rainy season is fairly constant, but its starting point, which generally coincides with the sowing time, may vary between 60 to 90 days.

The semiarid zone occupies 60% of Northeast Brazil and contains 40% of its population. The main climatic characteristics are: annual rainfall of 400–800 mm with a high coefficient of variability, high air temperatures, and high potential evapotranspiration rates (averaging 2000 mm). The crops grown in the semiarid zone are cotton, corn, and beans.

In the semiarid zone the main constraint to crop production is rainfall and its extreme variability. Studies of soil moisture conditions under agricultural crops are thus a matter of much importance in this region.

2. Methodology

In the present study, long term mean decadal (ten day periods) potential evapotranspiration (*PE*) values derived from Thornthwaite's procedure (*Thornthwaite*, 1948, *Thornthwaite* and *Mather*, 1957) are used to obtain daily *PE* values, and these together with daily precipitation data are used to evaluate daily soil moisture values. A versatile soil moisture budget model is used for this purpose, and the computations are carried out for a minimum period of 25 years. Values of 75, 100, 150, and 200 mm are assigned to the available moisture capacity (*AWC*) of the root zone of the soil. The *AWC* is defined as the difference between the field capacity and the permanent wilting point. The soil root depth is divided into six zones and approximately 5, 7.5, 12.5, 25, 25, and 25% of the total *AWC* are attributed to zones one to six respectively.

The contribution of each zone to the total actual evapotranspiration (*AE*) is evaluated from following expression:

$$PAE_{j,x} = K_{i,j}\left(WS_{j,x-1}/WC_j\right)Z_{j,x}PE_x, \tag{1}$$

where $PAE_{j,x}$ = partial evapotranspiration from the *j*th zone on day *x*;
$K_{i,j}$ = crop coefficient for the *j*th zone in growth stage *i*;
$WS_{j,x-1}$ = available moisture content of the *j*th zone at the end of day *x*–1;
WC_j = available moisture capacity of *j*th zone;
PE_x = potential evapotranspiration on day *x*;
Z = factor depending on soil dryness characteristics.

A set of 100 values between 0.0 and 1.0 are assigned to Z corresponding to 100 values between 0.0 and 1.0 of WS/WC on the assumption, that the ratio AE/PE remains equal to unity until relative available moisture content WS/WC decreases to 0.7 and then decreases linearly with WS/WC. Such an assumption is a reasonable first approximation for most medium textured soils.

The K coefficients reflect the root activity at different depths during different growth stages of the crop. The corn crop-growing period is divided into three principal stages, and in each stage different K values are assigned to the six zones. When the upper zones of the soil are dry, relatively more moisture is removed from the lower zones than in the case of uniformly wet soil. To take this aspect into consideration, the K coefficients for each zone below the first are increased as a function of the moisture content of the respective upper zones.

$$K'_j = K_j + K_j \left[\sum_{m=1}^{j-1} K_m \left(1 - \frac{WS_m}{WC_m} \right) \right], \tag{2}$$

where K'_j = adjusted K coefficient for the jth zone;
WS_m = available moisture content in the mth zone;
WC_m = available moisture capacity of the mth zone;

The available moisture content and the moisture loss from each zone are obtained from the following expressions:

$$\begin{aligned} WS_{j,x} &= WS_{j,x-1} - PAE_{j,x}, \\ WS_{j,x} &= 0 \ \text{ if } \ PAE_{j,x} > WS_{j,x-1}, \end{aligned} \tag{3}$$

where $WS_{j,x}$ is the available moisture in the jth zone at the end of day x.

$$\begin{aligned} AE_{j,x} &= PAE_{j,x} \ \text{ if } \ PAE_{j,x} \le WS_{j,x-1}, \\ AE_{j,x} &= WS_{j,x-1} \ \text{ if } \ PAE_{j,x} > WS_{j,x-1}. \end{aligned} \tag{4}$$

The sum of $AE_{j,x}$ for the six zones gives the actual evapotranspiration (AE) on day x. The sum of $WS_{j,x}$ for the six zones represents the available moisture content of the root zone of the soil on day x, if no precipitation occurs on that day. If precipitation occurs the values of $WS_{j,x}$ for some or all the six zones will increase.

On days with precipitation it is assumed, that moisture loss due to evapotranspiration occurs before precipitation. Precipitation enters the first zone and if this zone reaches its moisture holding capacity, the excess water enters the second zone, and so on. Excess water leaving the sixth zone is considered the water surplus on that day.

In each year the computations are carried out for different four-month corn growing periods for the four *AWC* values assumed.

Each month is divided into three decades, the last decade having 8, 9, 10, or 11 days depending on the month. Based on the daily soil moisture data for the study periods, mean decadal available moisture contents are obtained. A first order Markov chain model is applied to the daily soil moisture data, and the initial and conditional probabilities of dry and wet days are computed. The critical moisture content separating a wet day from a dry day is taken to be half of the assumed *AWC* value. For each decade during the growing period, the probability of occurrence of five consecutive wet days, *P*(5W) is evaluated using the above probabilities. Soil moisture averages and probabilities are used to determine the optimum growing periods for corn at the stations.

The soil moisture model described above is also used to evaluate the irrigation needs for corn crop at the stations. The computations for *AWC* values of 100, 150, and 200 mm are repeated with the modification, that each time the available moisture content decreases to a predetermined value, the moisture content on that day is replaced with that corresponding to 95% of the *AWC*. In practical terms this means, that each time the soil moisture is depleted to a preselected value, irrigation is applied to bring it back to a safe level. This part of the study is carried out assuming three limiting soil moisture levels (50%, 70%, and 90% of the *AWC*). The number of irrigation applications during the four-month (optimum) growing period and the mean interval between irrigations are obtained for each year, and from these numbers the mean values for the study period are derived.

3. Results and discussion

Mean decadal values of available moisture content at Campina Grande are evaluated for different growing periods during the wet season for the four *AWC* values considered and results for AWC_{200} are shown in *Fig. 2*. It is found that in general, the available moisture content as a fraction of *AWC* decreases with the increase in *AWC* value from 75 to 200 mm. During the period May–August, available moisture content was almost always more than 50% of the *AWC* even though the climatic water balance based on Thornthwaite's procedure (*Thornthwaite*, 1948; *Thornthwaite* and *Mather*, 1957) shows large water deficiency during the months August-September. Based on mean decadal values of available moisture content, the period May–August is found to be the optimum growing period for corn at Campina Grande. Values of probability of occurrence of five consecutive wet days, *P*(5W) are evaluated for each of the twelve decades in successive four-month periods. The results once again indicate that the period May–August is the best of the three growing periods considered. The same conclusion is drawn on the basis of *Table 1,* which shows the available moisture content, exceeded at different probability levels. However, even during the period May–August, supplementary irrigation is found necessary for corn growth.

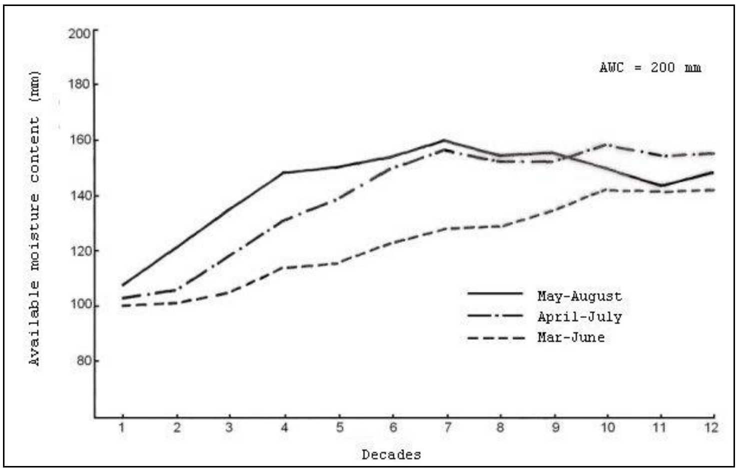


Fig. 2. Available soil moisture at Campina Grande in different growing periods.

Mean decadal values of *AE* for the months February–May for the 25-year study period at Teresina are compared with the corresponding *PE* values. During February, March, and May, *AE* is much smaller than *PE*. In April the moisture content in the root zone is quite high, and the sum of the *K* coefficients for the six soil layers is more than unity. Hence, *AE* during the three decades in April exceeds the *PE*. Under well watered conditions, *AE* estimates from the VSMB model exceed *PE* during a part of the growing cycle (*Dyer* and *Mack*, 1984). This in turn implies values of crop coefficient K_c, which relates evapotranspiration to reference crop evapotranspiration (*Doorenbos* and *Pruitt*, 1977) higher than 1. Values of K_c for corn between 1.0 and 1.2 during certain growth stages have been reported by *Allen et al*. (1998) and *Doorenbos* and *Kassam* (1979).

One of the parameters of the VSMB model is the *Z* factor, which is the ratio between *AE/PE* and *WS/AWC*. Much controversy surrounds the relationship between these two ratios, and the use of incorrect relationship in the model may lead to erroneous soil moisture estimates. To study this aspect, daily values of available moisture at Campina Grande are computed for 25 years using *Z* tables corresponding to the different curves of *Fig. 3*. The results are shown in *Fig. 4a* and *b*.

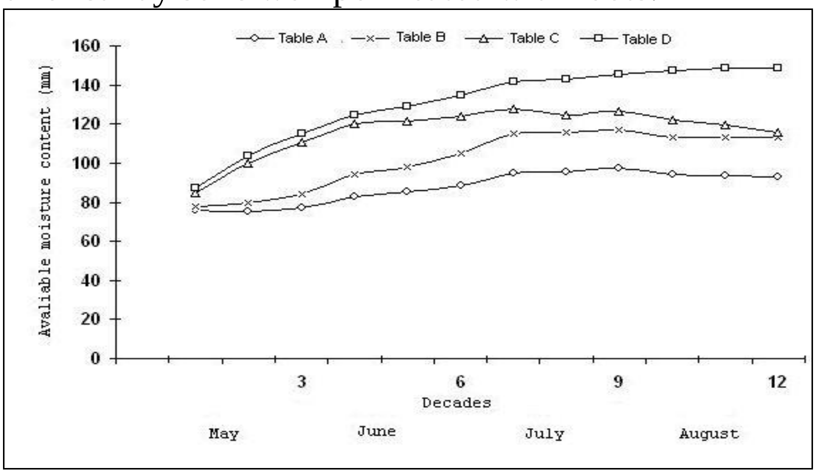
Table 1. Estimated soil water content (mm) exceeded at given probabilities

Probability	**March–June**			**April–July**			**May–August**		
Decade	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
1	98	94	89	110	98	93	112	101	96
2	122	85	79	125	106	85	147	110	94
3	131	89	74	138	114	91	177	129	96
4	149	96	80	172	132	99	190	151	111
5	149	109	73	179	144	105	191	165	109
6	169	105	84	187	162	118	196	176	111
7	168	120	87	192	164	141	196	174	124
8	164	132	94	188	172	126	189	171	123
9	169	138	102	189	169	132	186	168	132
10	176	145	126	196	178	138	175	158	142
11	182	148	115	190	174	129	174	151	125
12	187	144	104	187	166	146	175	142	121

Station: Campina Grande Available water capacity: 200 mm

Fig. 3. Relationship between *AE/PE* and available soil moisture content (*Baier* and *Robertson*, 1966).

The lowest values of moisture content are observed when curve A is used in the model. This curve is based on the assumption, that moisture is equally available to plants for evapotranspiration over the range from field capacity to the permanent wilting point. According to *Baier et al*. (1979), this assumption is probably valid for sandy soils well permeated with roots.



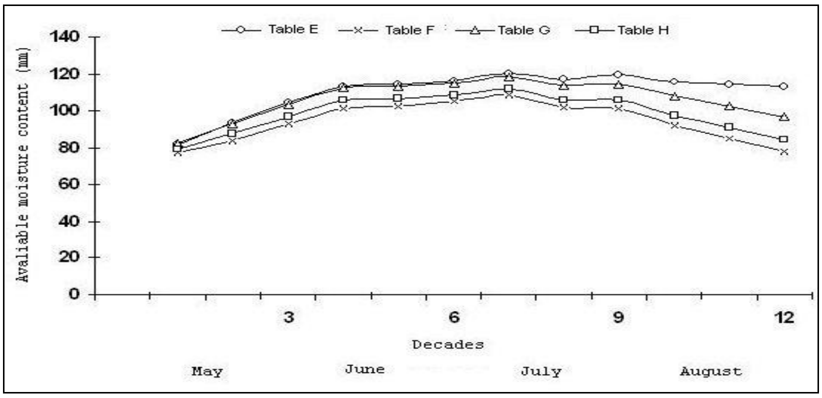


Fig. 4. Available soil moisture at Campina Grande based on different *Z* tables.

According to curve B, no significant decrease in evapotranspiration occurs except in very dry soil. This concept was suggested by *Pierce* (1958) and was used by *Gardner* (1960) for a sandy soil. Curve C assumes a linear relationship between the *AE/PE* ratio and the soil moisture percentage. Such a relation was supported by various authors (*Denmead* and *Shaw*, 1962; *Gardner* and *Ehlig*, 1963; *Smith*, 1959). Curves D, E, and F assume no reduction in the *AE/PE* ratio over the range of available moisture from 100 to 70% (curve D), to 50% (curve E), and to 30% (curve F). Beyond these limits the *AE/PE* ratio decreases rapidly with the drying of the soil. Curve G assumes no reduction in *AE/PE* over the range from 100 to 70% of available moisture and a linear decrease below 70%. This curve is recommended for most medium textured non-irrigated soils. Curve H is similar to curve G, except that no reduction in *AE/PE* ratio is assumed over the range from 100 to 50% of available soil moisture.

Soil moisture estimates based on curves B and E are quite similar, while the highest values of soil moisture are obtained with the use of curve D. Soil moisture values based on curves E, F, G, and H are very close to each other over a large part of the four-month growing period. The results based on curve C are quite close to those obtained from all other curves except curve A. This is in agreement with *Baier*'s (1969) suggestion, that if soil moisture observations are not available for comparison, curve C provides a reasonable approximation.

If daily precipitation data over a long time period is not available, mean daily precipitation values derived from climatic monthly mean values can perhaps be used in the VSMB model to obtain an estimate of actual evapotranspiration. This aspect is studied using data for Campina Grande. *Brook*'s (1943) sine curve interpolation technique is used to derive daily precipitation values from climatic monthly means, and the resulting daily values are used together with the daily *PE* values to obtain daily values of *AE* during the growing season. From the 122 daily values, mean values for each decade are derived. These values are compared with mean decadal *AE* values obtained from the use of actual daily precipitation data for 25 years in the model (*Fig. 5*). Actual evapotranspiration obtained using mean daily precipitation data is always higher than that based on daily precipitation data. Use of mean precipitation data also shows the surface soil layers wetter and water surplus lower than in the case of using daily precipitation data. Actual evapotranspiration during the crop-growing season is an important parameter, and the close agreement between the two curves is quite encouraging.

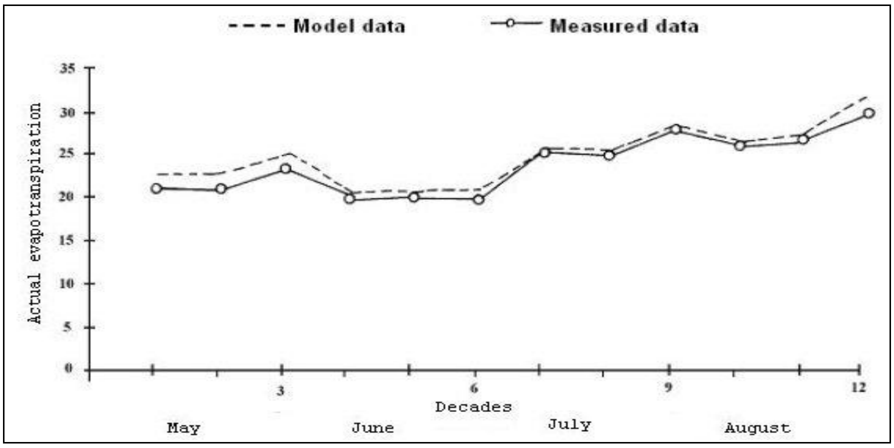


Fig. 5. Actual evapotranspiration (mm/decade) at Campina Grande obtained from the VSMB model using (1) mean daily precipitation data and (2) actual precipitation data.

Results of irrigation computations for Fortaleza for a limiting moisture value (*VC*) of 105 mm are given in *Table 2*. A summary of the results for all the stations is presented in *Table 3*.

As it is expected, the number of irrigations increases and the mean interval between irrigations decreases as the limiting moisture level increases. However, the change in the total water need is not very pronounced, since at higher *VC* values less water is applied in each irrigation. Comparison of water surplus data under irrigated and unirrigated conditions shows that, in general, the fraction of irrigation water that is lost as water surplus increases as the limiting moisture level increases.

Table 2. Irrigation requirements at Fortaleza.
AWC=150 mm, *VC*=105 mm. Period: April–July

Year	Number of irrigations	Mean interval between irrigations (days)	Number of days with available moisture content (mm) between		
			105–120	120–135	135–150

25	6	22	29	40	53
26	5	28	26	36	60
27	5	29	25	38	59
28	7	19	32	40	50
29	5	28	21	31	70
30	4	37	33	35	54
31	6	22	28	43	51
32	8	17	39	51	32
33	6	23	30	35	57
34	6	24	21	19	82
35	4	38	16	26	80
36	7	19	38	35	49
37	4	40	19	28	75
38	4	40	20	41	61
39	5	26	26	37	59
40	4	37	13	29	80
41	7	19	35	50	37
42	7	20	44	39	39
43	7	19	37	34	51
44	6	22	24	30	68
45	3	58	8	24	90
46	5	28	23	37	62
47	5	29	26	28	68
48	3	59	24	36	62
49	5	30	17	21	84
50	6	23	27	24	71
51	5	30	37	37	48
52	6	23	28	34	60
53	6	23	21	39	62
54	6	24	29	29	64
55	6	23	26	33	63
56	7	19	31	50	41
57	7	19	35	35	52

Table 3. Irrigation needs at the stations. *AWC* = 150 mm

Station	**Crop growing period**	**Limiting soil moisture level (mm)**	**Number of irrigations**	**Mean interval between irrigations (days)**	**Irrigation amount (mm)**
Iguatu	Mar – Jun	75	2	90	135
		105	4	37	150
		135	25	5	190
Fortaleza	Apr – Jul	75	3	74	200
		105	5	28	190
		135	29	5	220
Quixeramobim	Apr – Jul	75	3	55	200
		105	7	20	260
		135	37	3	280

São Gonçalo	Feb – May	75 105 135	2 4 27	94 41 5	135 150 200
Umbuzeiro	Jun – Sep	75 105 135	2 3 16	106 72 9	135 110 120
Campina Grande	May – Aug	75 105 135	1 2 13	116 78 10	70 75 100

The climatic water balance table for Sao Gonçalo based on Thornthwaite's procedure (*Thornthwaite* and *Mather*, 1957) for AWC value of 250 mm indicates the following values for the period February–May: PE = 507 mm, AE = 499 mm, P = 678 mm. It may be mentioned here, that this procedure is based on the relationship between *AE/PE* and *WS/AWC* given by curve C of *Fig. 3*.

Table 4. Potential evapotranspiration (*PE*), actual evapotranspiration (*AE*), and precipitation (*P*) during the growing periods based on Thornthwaite's procedure

Station	**Campina Grande**	**Umbuzeiro**	**Iguatu**	**Fortaleza**	**Quixeramobim**	**São Gonçalo**
Period	**May – Aug**	**Jun – Sep**	**Mar – Jun**	**Apr – Jul**	**Apr – Jul**	**Feb – May**
PE	304	284	492	511	543	507
AE	294	261	403	492	344	499
P	367	317	465	668	331	679

Results of the present study show, however, that even to maintain the moisture content above 50% of *AWC* irrigation is needed in each year of the 36-year study period. Comparison of data presented in *Table 4* with irrigation needs at the stations (*Table 3*) indicates, that climatic water balance data may not be of much use in evaluating the agricultural potential of a region. Irrigation needs are evaluated at Campina Grande for *AWC* values of 100 and 200 mm and a *VC* level of 85%. The results show that to maintain similar moisture levels in the soil, more irrigation is necessary in the case of AWC_{100} than for AWC_{200}. Similar result was reported by *De Jong* (1985).

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