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Agron. Sustain. Dev. 27 (2007) 255–260

DOI: 10.1051/agro:2007019

Available online at:
www.agronomy-journal.org

Original article

A simple method to improve the estimation of the relationship between rainfall and crop yield

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(Accepted 13 March 2007)

Abstract – The time-course of rainfall is commonly presented as bar, line or scatter plots, which may sometimes be chaotic, while leading to subjective and vague assertions. More objective criteria quantifying rainfall distribution may therefore be helpful, e.g. when different years are examined concurrently. Here, some practical indices are presented based on the distance between cumulative rainfall curves and the respective theoretical evenness rainfall lines, the line joining the lowest and highest cumulative rainfall values within the considered period. After an introduction to the theory and calculation of the indices, the relationships between the indices and two major crops, maize and sugar beet, are evaluated for a period of 33 years. The results show good correlations between the indices and crop yields, up to r = 0.81, especially when the evenness index was weighted on the mean daily rainfall, i.e. the slope of the evenness line. Significant correlations were also found by recalculating the indices over strategic short-term periods for maize, which indicates how the effectiveness of these indices may be increased by choosing appropriate periods for different crops. Finally, the different indices showed no correlation, indicating little redundancy and thus suggesting a profitable conjoint use of them.

water / maize / sugar beet / indices

1. INTRODUCTION

A number of studies report that not only the amount of rainfall but also its distribution can drastically affect yield: see Condon et al. (2004); Keating and McCown (2001); Cavazza et al. (1983); and Passioura (1977). Rainfall distribution could be more important than rainfall amount, due to a number of reasons, such as inadequate water availability during critical growth stages (Kar et al., 2007; Asseng et al., 2003; Rhoads and Bennett, 1990) and the ineffective storage capacity of soils during copious and infrequent rainfall events (Barzegar et al., 2003, Stephens and Lyons, 1998).

Typically, researchers present rainfall data by a visual approach, e.g. scatter or bar plots, which sometimes makes quantitative data analysis difficult, leading to subjective assertions. For example, the rainfall distribution over time may be analysed as a dichotomic subjective variable, which may appear more or less uniform to different readers. Furthermore, the uniformity of the rainfall distribution is typically not quantified. Time-integrated numerical indices to characterise the rainfall distribution over an arbitrary period may be helpful in many instances, e.g. when comparing rainfall effects in critical periods, or for ranking periods of different years, or even in the same year. The literature includes a large number of studies on rainfall distribution and its effects on crop yield (Asseng et al., 2003; Turner, 1997). Nonetheless, it is rather surprising that rainfall distribution has not been generally quantified in terms of evenness or shape, which means, respectively, how regularly rainfall events are distributed in time, and how early or late events affect the rainfall distribution. The meaning of rainfall distribution over time is also not very clear. Some authors simply quantified it by the number of rainfall days exceeding a certain threshold (Wilgosz et al., 2005); however, this simple approach does not take into account the evenness and intensity of rainfall events. In other work, rainfall distribution is simply calculated as the amount of rainfall occurring early or late in the growing season (Kumar et al., 2005). Again, this seems too vague as no quantitative estimate of early or late rainfall distribution is given.

The aim of this work is to introduce some indices to quantify the evenness and the distribution of rainfall, later on indicated as "evenness" or "shape indices". The calculations are based on a comparison of the actual rainfall course with the theoretically most regular one, over the whole growing season or an arbitrary short period. The method generates continuous variables, and thus objective indices, accounting for the evenness and shape of rainfall distribution within such a period.

The theory and calculations of the indices are discussed in the first part. Thereafter, an example is presented showing the relationships between the rainfall indices and sugar beet or maize yields. Of course, these indices cannot give mechanistic explanations of crop responses to water availability, which instead requires a multivariable approach taking into account a number of complex interactions, involving plant genetics, farm management and environmental effects.

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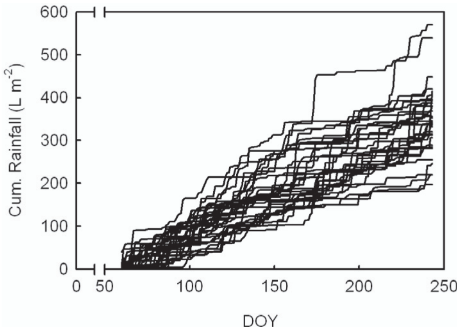

Figure 1. Time-course of cumulative rainfall over 33 years (1972–2004). DOY indicate days of the year.

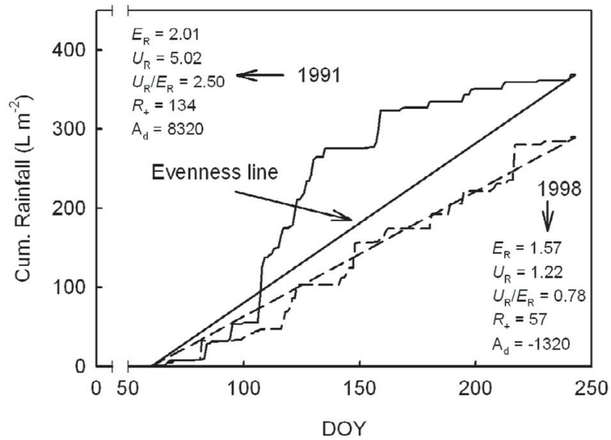

Figure 2. Example of index calculation. Scatter lines represent cumulative daily rainfall of two arbitrary years (1991 and 1998); sloping lines, named evenness lines, represent the theoretical highest evenness on a daily basis within the considered period of 60–240 days of the year (DOY). E_R is the daily rainfall, i.e. the slope of the evenness line, U_R, the index of uneven rainfall distribution (i.e. the sum of square of the distances of the actual cumulated rainfall points from the respective evenness lines); R_+ and A_d, rainfall shape indices, i.e. the number of data points above the evenness line, and the difference between the areas below the cumulative and evenness lines, respectively.

2. MATERIALS AND METHODS

This example refers to rainfall data collected from the meteorological station near the experimental farm of the University of Bologna (44° 33' N, 11° 21' E, 33 m a.s.l.), in the period March-August, i.e. approximately corresponding to the growing cycle of the two considered crops, maize and sugar beet, in the years 1972–2004. The dataset is conventionally shown by a line plot of cumulative rainfall vs. time (Fig. 1). It clearly appears that the seasonal variation of rainfall among years was considerable (from about 150 to over 550 L m^{-2}); however, the rainfall course in the different years appears extremely confused, and comparisons among years might be biased, unless objective indices are available.

To illustrate the calculations, two different years in terms of rainfall amount and distribution (1991 and 1998) were taken as examples (Fig. 2). The same calculations were then repeated for the rest of the years in order to analyse the correlations between the estimators and crop yields. First, the cumulative rainfall values within the considered period have to be calculated; then, the line joining the first and last cumulative rainfall values is drawn. Later on, this line will be named the evenness line. It should be underlined that the evenness line does not represent the best fitting of cumulative rainfall data, but the most uniform rainfall course within the considered period. The slope of the evenness line, E_R (i.e., the cumulative rainfall divided by the number of days), represents the mean daily rainfall of the period (60–240 DOY, in this example). The index of the unevenness of rainfall distribution (U_R) is an estimate of the scattering of actual rainfall around the evenness line, i.e. how the actual rainfall course deviates from the respective evenness line. More simply, U_R is obtained by the sum of squares of the distances of each cumulative rainfall data point from the correspondent point lying on the evenness line:

$$U_R = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y_e)^2}{n}}$$

where y_e is the cumulative rainfall value corresponding to that lying on the evenness line (y_i), and n is the number of days within the considered period. Therefore, the higher U_R is, the lower the evenness. It turns out that U_R should be negatively related to the yield, water being expected to be used more effectively under a more regular rainfall course. U_R was also weighted on E_R (i.e. U_R/E_R), to obtain a new estimator taking into account both the unevenness and amount of rainfall.

Like U_R, the shape of rainfall distribution may be expected to significantly affect the crop productivity, and in some cases this effect can be even more significant than U_R. In fact, the highest U_R does not necessarily lead to the best crop response. For example, it is widely known that, in maize, water availability during blooming and seed ripening is a major determinant of the yield, while late rainfall events weakly affect the yield (Armstrong, 1999; Rhoads and Bennett, 1990). Therefore, in this case, copious rainfall events during blooming may benefit the crop more than moderate regular rainfall over the whole growing season.

We propose here two shape indices for rainfall course, which can be obtained either by counting the data points (x_i) below (R_-) or above (R_+) the evenness line, or subtracting the area below the evenness line from the area below the cumulative line (A_d). These areas were calculated using the trapezium rule, i.e. by approximating the region under the curve by a trapezium and calculating definite integrals within the considered periods. Early rainfall events will lead to a much higher A_d (or R_+) than the late ones, as illustrated in Figure 2. In 1991, the rainy days occurring from DOY 110 to 130 caused R_+ to be more than twice that in 1998; equally, A_d was 8320 and –1320 in 1991 and 1998, respectively.

The yields of maize (grain) and sugar beet (tap root) were taken as an example to test the relationships between the indices (E_R, U_R, R_+ and A_d) and crop yield. These two crops

Table I. Descriptive statistics of the indices.

Statistics	E_R	U_R	R_+	R_-	A_d	U_R/E_R
Mean	1.89	2.60	88.6	94.5	10533	1.40
SE	0.08	0.19	9.5	9.5	868	0.10
Median	1.88	2.35	80	103	9330	1.28
Kurtosis	1.23	–0.34	–1.30	–1.30	–0.79	0.31
Skewness	0.59	0.82	0.27	–0.27	0.27	0.94
Range	2.03	3.80	169	169	18532	2.17
Minimum	1.07	1.22	10	4	1068	0.71
Maximum	3.09	5.02	179	173	19600	2.88
CV	0.23	0.42	0.61	0.57	0.68	0.40

were chosen as they represent the most conventional ones in this area. Nearly all treatments for these two crops have been maintained fairly constant over the years and the yield data can be easily found, whilst being reliable even for a such a long period. For both crops, the yield data were collected from the Annual Agricultural Report of the National Institute of Statistics (ISTAT, 1972–2004) and refer to the province of Bologna (Po valley, 44° 33', 33 m a.s.l.), over a period of 33 years. Both crops were grown according to the most conventional agricultural practice: maize was sown from mid- to late April. On average, a dose of 150 $kg\,ha^{-1}$ of nitrogen (N) was distributed at sowing time, while one or two irrigations were performed at blooming time. Sugar beet was generally sown in early March, never irrigated and with an average fertilisation dose (N) of 120 $kg\,ha^{-1}$. The statistical significance of the indices was tested according to Pearson's correlation test for $P \leqslant 0.05$.

3. RESULTS AND DISCUSSION

3.1. Comparing years

The indices enabled us to attain a quicker and more objective comparison of rainfall distribution among years than a visual approach (Fig. 1). The diverse indices resulted in a very different variation over the 33 years, with R_+ changing slightly more than A_d and much more than U_R (Tab. I). The three indices (U_R, A_d and R_+) also showed a higher variation than E_R, thus revealing that the rainfall distribution was much more variable than the amount of rainfall, and that many years were similar in the amount of rainfall, but very different in rainfall distribution. For example, the years 1979 and 1996 showed equal E_R values (2.3 mm), while U_R was 1.9 and 4.7 mm, respectively. Similarly, E_R was 2.1 mm in both 2002 and 2004, while R_+ differed considerably (162 and 4 d, respectively).

Figure 3 shows that the indices are generally uncorrelated, with the exception of A_d and R_+ ($r = 0.87^{**}$), thus indicating that only one of those should be reasonably used. In contrast, the other indices were not statistically related or redundant (backward stepwise procedures, $P \leqslant 0.05$), so their conjoint use may be suggested for a more exhaustive analysis of relationships between crop responses and rainfall events. For example, U_R denotes the magnitude of the uneven rainfall distribution, but it does not reveal how the rainfall distribution changed in the two years. It could be the case, for example, of two years having equal E_R and U_R values in spite of a mirror rainfall distribution, e.g. one year with rainfall events occurring early, and another in which they occur late (Fig. 4). To sum up, a low U_R denotes a very even rainfall distribution, while a low A_d indicates a regular shape, which does not necessarily entail a uniform rainfall distribution. Of course, when U_R is zero, A_d will be zero too. However, it is not true the other way round; that is, when A_d is zero, U_R and E_R may assume unlimited values. Therefore, an integrated use of E_R, U_R and A_d may significantly improve the strength of analysis.

3.2. Correlating indices and annual yields

The annual yields of maize and sugar beet were closely related (r = 0.73**), thus suggesting a significant effect of the year on yields. However, both crops were not related to E_R, while they were significantly related to U_R, and these correlations were even closer when U_R was weighted on E_R (Fig. 5).

R_+ was not significantly related to the annual yield of maize, while it was weakly related to sugar beet yield (r = 0.47*). A_d showed a distinct quadratic relationship with maize yield, and a negative correlation with sugar beet yield (Fig. 5). This seems to indicate that maize is more susceptible than sugar beet to an irregular course of rainfall events, whether they occur early or late. Thus, the higher yields of maize were achieved with A_d approaching zero, i.e. when the rainfall distribution was most regular, which is confirmed by the negative linear relationship between maize yield and U_R (Fig. 5). Conversely, sugar beet seemed to take advantage of early rainfall events and even rainfall distribution (i.e. low U_R values).

The main objective of this study was to present a possible methodology and some examples to improve the use of rainfall data, while the best period in which to calculate the indices for each crop was not investigated. However, to show how the effectiveness of indices may increase by referring them to critical crop-specific periods, we recalculated the indices, restricting the window from March-September to July, i.e. the likely most critical period for maize production (Fig. 6). From this analysis, it was shown that sugar beet yield was unaffected by the U_R/E_R ratio, while maize showed higher correlation coefficients than those referring to a longer period.

The strong influence of the rainfall distribution on crop yield, as shown in this study, is consistent with several related studies (Condon et al., 2004; Turner, 1997; Cavazza et al., 1983). The explanation of this involves a number of physical, physiological and biochemical processes, as well as complex interactions between the environment and intrinsic plant characteristics which will not be discussed here, since they do not represent the objective of this study. Regardless of all possible mechanistic relationships between water availability and crop yield, it is rather surprising, however, that the literature lacks unbiased empirical indices to quantify rainfall distribution, despite the fact that this is often considered a major determinant of crop yield (Asseng et al., 2003; Richards et al., 2002; Stephens and Lyons, 1998; Turner, 1997).

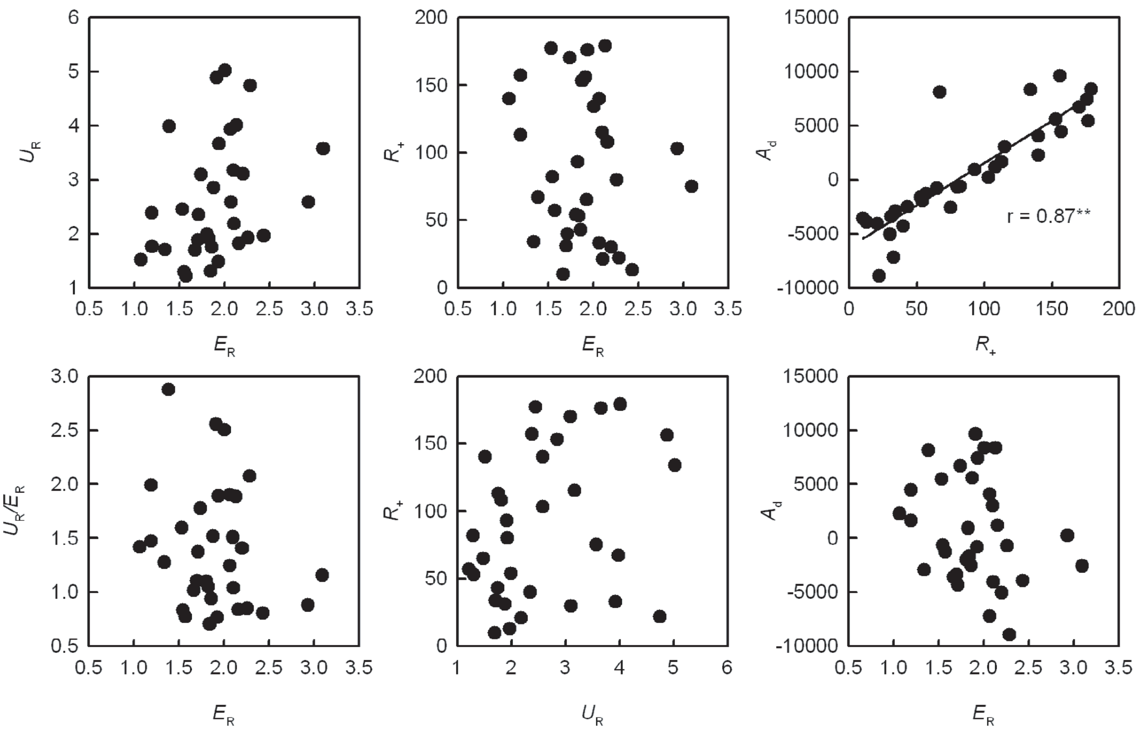

Figure 3. Relationships among different indices.

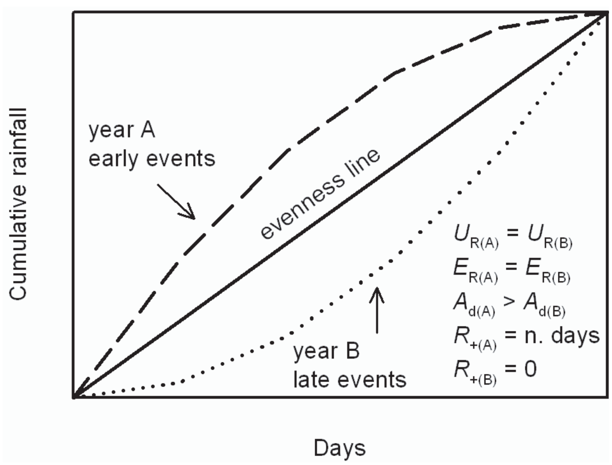

Figure 4. An example of two hypothetical years with a completely different shape of rainfall distribution, despite a similar U_R and E_R.

The preliminary results obtained by relating maize yields to the indices recalculated over a short strategic period for this crop (July) revealed very interesting perspectives to enhance the potential effectiveness of these indices, but a more profound investigation of this is not the aim of this paper. However, even when the indices were calculated over a fixed period, that is, regardless of crop water requirements, the correlations between indices and crop yield appeared generally noteworthy, with more than half of the annual yield variation being explained by U_R, or even better, by the index U_R/E_R. This was somewhat unexpected, as the yield is likely to be influenced by several factors other than rainfall course (e.g. genotype selection, improvement of agricultural practices, etc.), which are not included in the rainfall estimators. Nonetheless, given these significant correlations, some preliminary considerations concerning the relationships between indices and crop yield may be proposed later on.

Analysing rainfall data over a period of 6 months, maize appeared less affected by rainfall distribution than sugar beet. This was even clearer when the unevenness index was weighted on the mean daily rainfall (U_R/E_R). A possible explanation could be that the tap root of sugar beet exhibits a regular growth, whereas maize yield is drastically affected by drought conditions at blooming and during the initial ripening time, which takes about one month (Armstrong, 1999; Hay, 1995; Rhoads and Bennett, 1990). The fact that maize yield showed much higher correlations with indices limited to only July seems to corroborate this statement. Therefore, integrated short-term indices seem more adequate for maize than those calculated for the whole summer season.

Maize and sugar beet also differed in response to the shape of rainfall distribution, as expressed by the A_d index. Specifically, maize showed a curvilinear relationship, approximating the highest yields just next to A_d equal to zero, i.e. when the shape was the most regular, which does not necessarily mean the most uniform, too. In contrast, sugar beet exhibited a negative linear relationship with A_d, thus revealing that early rainfall events benefit the root yield much more than late ones. This is in agreement with other findings on this crop: see Pidgeon et al. (2001) and Hsiao (1973) for an extended review.

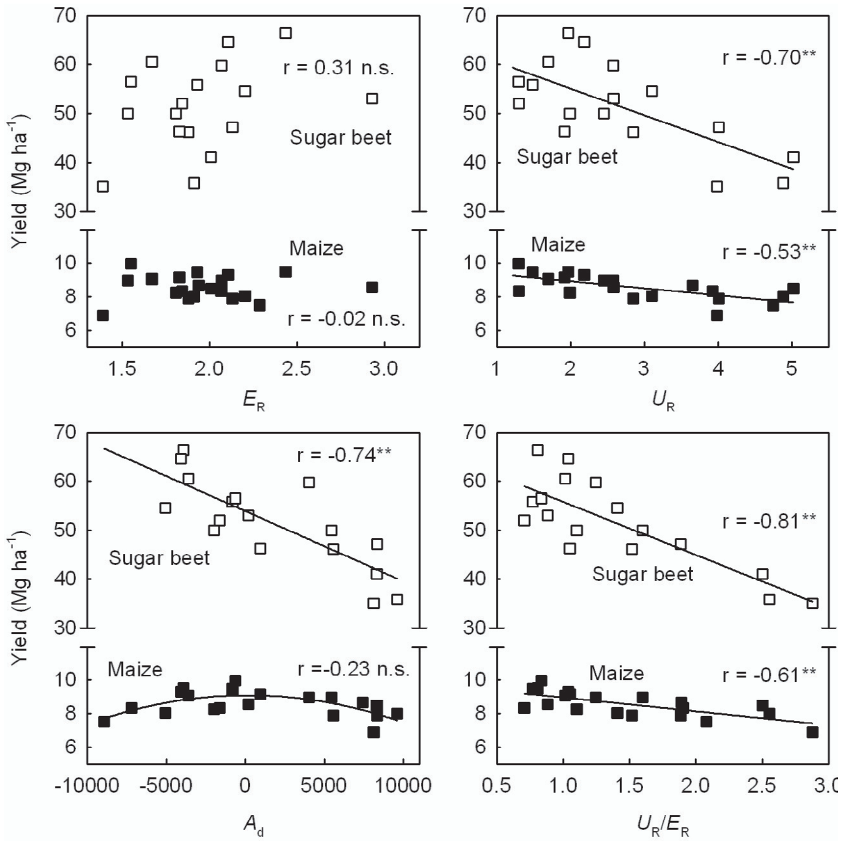

Figure 5. Relationships between rainfall indices and maize (blank symbols) or sugar beet (filled symbols) yields. E_R, U_R, R_+ and A_d are the indices of mean daily rainfall, unevenness and shape of rainfall distribution (the last two), respectively. r_m and r_s, correlation coefficients of maize and sugar beet, respectively; **, statistically significant for $P \leqslant 0.01$ (Pearson's test).

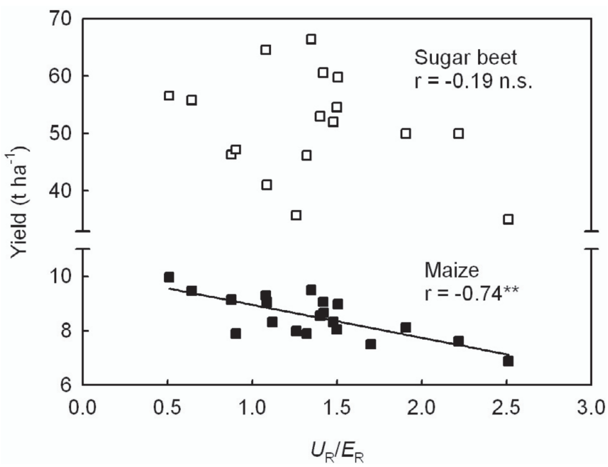

Figure 6. Relationships between maize and sugar beet yields (grain and roots, respectively) and the unevenness index weighted on daily amount of rainfall (U_R/E_R), calculated over the most critical period for maize (i.e. July).

4. CONCLUSION

Rainfall distribution is a major determinant of the yield, especially in rainfed crops. The literature lacks methods to calculate practical numerical indices to quantify and summarise the rainfall course over long or short strategic periods for different crops. The absence of objective estimators can sometimes lead to fuzzy and questionable assertions, particularly when a visual approach is used. This study presents a novel methodology to determine some indices of rainfall distribution, yielding a numerical value for the evenness and shape of rainfall. We showed that these indices are closely related to the annual yield variation, especially when they are calculated over a strategic period. Particularly, the index of the uneven rainfall distribution (U_R) when weighted on mean daily rainfall, was very effective at describing the yield variation. Furthermore, the indices appeared generally not redundant and this allows us to suggest their conjoint use.

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