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Agricultural drought: indices, definition and analysis

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Abstract An agricultural drought is considered to have set in when the soil moisture availability to plants has dropped to such a level that it adversely affects the crop yield and hence agricultural profitability. In brief, the definition of agricultural drought is concerned with the soil moisture deficiency in relation to meteorological droughts and climatic factors and their impacts on agricultural production and economic profitability. A soil water time series provides the framework for evaluating agricultural drought parameters. Soil moisture measurements are generally not available as time series. Hence drought could be better studied by means of a regional analysis involving a set of variables associated with the crop water consumption process, but the interactions are very complex. Consequently, an effort must be made toward an objective definition of agricultural drought and its related indices. In the present paper an attempt is made to give a simple interpretation of some traditional agricultural drought indices and to define the functional relationship between crop yield and soil moisture deficit. This relationship can be used to identify the critical soil moisture deficit (related to the critical crop yield level) which leads to an unsatisfactory agricultural profitability. So conditions of real agricultural drought or aridity are present.

Key words agricultural drought characteristics; crop yield

INTRODUCTION

There has been considerable debate about the problem of accurately defining the term drought (Yevjevich, 1967; Dracup, 1980; da Cunha *et al.*, 1983; Wilhite & Gantz, 1987; Pereira, 1990; Rodriguez-Iturbe, 2000).

The term drought is used widely in agriculture too; it has traditionally been accepted that a given area is affected by agricultural drought when the soil moisture availability to plants has dropped to such a level (threshold level) that it is insufficient for normal crop growth and maturation and adversely affects the crop yield. In brief, the definition of agricultural drought hovers around the soil moisture deficiency in relation to meteorological droughts and climatic factors and their impacts on agricultural production (Panu & Shama, 2002).

This concept has been developed by many authors on a very large spatial scale and as such they have based their work on either an analysis of soil moisture alone (Bell *et al.*, 1980; Smart, 1983), or on a definition of the relevant indices (Palmer, 1965; Karl, 1983; Ramachandra-Rao & Padmanabhan, 1984; Petrasovitz, 1990; Palfai, 1990). When the problem is analysed on a smaller scale (Mannocchi & Mecarelli, 1987, 1989; Rodriguez-Iturbe *et al.*, 2000) the phenomenon of agricultural drought must be studied by first analysing the individual hydrological processes associated with crop water consumption and the conditions of their interaction, and then by establishing the selective information about the processes to be considered. Finally, an objective definition of agricultural drought must be performed so that the related characteristics (or indices) can be estimated (for example by means of run theory).

However, in some cases the use of the term drought in agriculture seems controversial because:

(a) A human factor is always associated with agriculture (land use, choice of crop, production technology, etc.) and introduces a deterministic component into the process of plant water consumption (no longer a nature-produced phenomenon).
(b) The time series involved in agricultural drought analysis consists of observed or estimated punctual data (precipitation, evapotranspiration, soil water content) so that the investigation should be valid only for a single point (no spatial extent is considered).
(c) Water shortages in agriculture above a given threshold level can occur for quite long periods and have cyclic characteristics associated with typical climatic seasonal conditions and with the specific crop growing season (no hazard condition).
(d) The critical level of the significant imbalance between demand and supply that determines the occurrence of an agricultural drought has not been defined in a quantitative manner (uncertain drought condition).

On the other hand:

(a) The deterministic component introduced into the process of plant water consumption, has more influence on overall water consumption than on the appropriate methods of implementation which remain essentially those of a natural process and therefore of a stochastic type.
(b) The time series analysis is therefore still an essential investigation method of the phenomenon, even though in agriculture, demand data is related to each particular soil-crop unit.
(c) The analysis must be preliminarily performed for single different points (soil-crop-unit analysis) and then regionalized (Rossi *et al.*, 1992) to determine the drought areal extent.
(d) The run theory applied to soil water time series is able to estimate the characteristics of an agricultural water deficiency during each growing cycle (i.e. potential period of seasonal agricultural drought: soil moisture below a threshold level).
(e) The achievement of a critical imbalance value determines harvest loss which in turn makes the cultivation of a given crop economically not productive for a given growing season.
(f) An interseasonal analysis is able to verify if the above critical conditions correspond, for the given crop, to an agricultural drought (unpredictable extreme event among the seasonal negative runs) or to an agricultural aridity (steady values exceeding the critical value among the seasonal negative runs).

Hence it is clear the importance of precisely quantifying the adjective "significant" in order to define the critical level of imbalance which has a strong influence on the definition of agricultural drought.

For this purpose an attempt was made to define a functional relationship between the crop yield and the agricultural potential drought characteristics (duration, relative severity, relative severity index) as defined in Mannocchi & Mecarelli (1987, 1989) and to quantify the water stress conditions to which the crop yield index reaches the zero economical value.

The study pertains to an area in Central Italy (Papiano, district of Umbria region) where the Department of Agronomy of Perugia University experimented growing sunflowers in some plots where all the agronomic conditions were at an optimal level and water scarsity was the only factor limiting the final yield. So, time series of sunflower yields are available for 15 years (from 1978 to 1980, from 1982 to 1992, 1994). The related climatic data (daily precipitation and temperature), soil and crop data (crop coefficients, root depth, yield response factors, crop critical point) are also available. The basic characteristics of the climate in the region are low rainfall during the sunflower growing season with a high coefficient of variation and high temperature. The soil is characterized by a low organic content with a moisture storage capacity $U = 150$ mm in one metre of soil profile (Monotti *et al.*, 1994).

COMPUTATION PROCEDURE

According to Mannocchi & Mecarelli (1987, 1989) the characteristics of potential periods of seasonal agricultural drought have been estimated, according to run theory, for the different sunflower growing seasons during the period of the time series.

If $SW(t)$ is the function describing the soil water volume dynamics, the occurrence of a potential period of seasonal agricultural drought is tested by the two following constraints:

$$\frac{\mathrm{d}SW(t)}{\mathrm{d}t} < 0 \qquad (1)$$

$$SW(t) < SW_0 \qquad (2)$$

(where SW_0 is the threshold level defined as the crop critical point multiplied by U).

The characteristics of the potential drought can be estimated on the basis of (1) and (2). In particular:

(a) Duration D (days), defined as the sum of the days of the growing season where (1) and (2) are verified;
(b) relative severity RS (days) defined as the ratio between severity (area of negative run in mm·day) and U in mm;
(c) relative severity index RSI (days) defined as:

$$RIS_c = \frac{1}{U_c} \cdot \sum_{j=1}^{m} S_{j,c} \cdot Ky_{j,c}$$

where j represents the generic growing stage, m is the number of growing stages, S_j is the relative severity for the j-th stage, Ky_j is the yield response coefficient for the j-th stage.

Table 1 Annual estimated relative severity (*RS*), relative severity index (*RSI*), duration (*D*), crop yield (*Y*); crop: sunflower; climatic station: Papiano; $U = 150$ mm.

Year	*D* (days)	*RS* (mm days mm^{-1})	*RSI* (mm days mm^{-1})	*Y* (q ha^{-1})
1978	36	3.1	1.4	45.0
1979	57	11.2	6.2	26.3
1980	54	14.0	8.1	24.3
1982	30	7.3	5.8	30.7
1983	53	12.3	7.4	25.5
1984	49	9.2	5.6	27.7
1985	59	14.5	9.0	23.1
1986	21	1.5	0.6	49.4
1987	47	8.8	5.1	31.9
1988	41	8.8	4.3	35.9
1989	26	3.3	2.2	44.3
1990	53	10.2	6.5	28.7
1991	45	4.3	2.6	40.8
1992	39	5.6	2.8	40.0
1994	47	8.9	4.5	35.3

Furthermore the actual crop yields Y (q ha^{-1}) have been estimated according to Mannocchi & Mecarelli, (1994) and Rao *et al.* (1988) by considering a maximum crop yield $Y_m = 57$ (q ha^{-1}). The results of the analysis are shown in Table 1.

The 15 years time series in Table 1 were used for a preliminary investigation on the nature of the functional relationship between crop yield and agricultural potential drought characteristics. Five regression type models were developed:

$$Y = -0.612\,D + 60.744 \qquad R^2 = 0.707 \qquad \text{standard error: SE} = 4.70 \tag{3}$$

$$Y = -2.0088\,RS + 50.398 \qquad R^2 = 0.919 \qquad \text{standard error: SE} = 2.472 \tag{4}$$

$$Y = -3.285\,RSI + 49.715 \qquad R^2 = 0.958 \qquad \text{standard error: SE} = 1.77 \tag{5}$$

$$Y = -0.02\,D - 1.96\,RS + 50.86 \qquad R^2 = 0.919 \qquad \text{standard error: SE} = 257 \tag{6}$$

$$Y = -0.108\,D - 2.88\,RSI + 52.52 \qquad R^2 = 0.966 \qquad \text{standard error: SE} = 1.66 \tag{7}$$

It becomes obvious that the most correlated independent variable is the relative severity index as this variable not only takes into account the crop water stress, but also the influence of the period in which it occurs (yield response coefficients, *Ky*). So, equation (5) is used to validate the regression model.

Therefore it is necessary that the hypothesis of zero mean, constant variance, normal distribution and independence of residuals be verified. The model, equation (5), was first validated conducting the residual analysis. The observed as well as the estimated grain yield data and the corresponding residuals are given in Table 2. It is apparent from the table that the residuals have the mean of zero. The assumption of constant variance was verified with a plot of residuals against time (Fig. 1). The absence of a trend in this figure is indicative of the presence of constant variance in residuals. The normality of residuals was verified using a normal probability plot.

Table 2 Analysis of regression residuals of observed and estimated grain yield of sunflower.

Year	Observed yield (q ha^{-1})	Estimated yield (q ha^{-1})	Residuals (q ha^{-1})
1978	45.0	45.1	–0.1
1979	26.3	29.3	–3.0
1980	24.3	23.1	1.2
1982	30.7	30.7	0.1
1983	25.5	25.4	0.1
1984	27.7	31.3	–3.6
1985	23.1	20.2	3.0
1986	49.4	47.7	1.7
1987	31.9	33.0	–1.1
1988	35.9	35.6	0.3
1989	44.3	42.5	1.8
1990	28.7	28.4	0.4
1991	40.8	41.2	–0.4
1992	40.0	40.5	–0.6
1994	35.3	34.9	0.3
mean	33.9	33.9	0

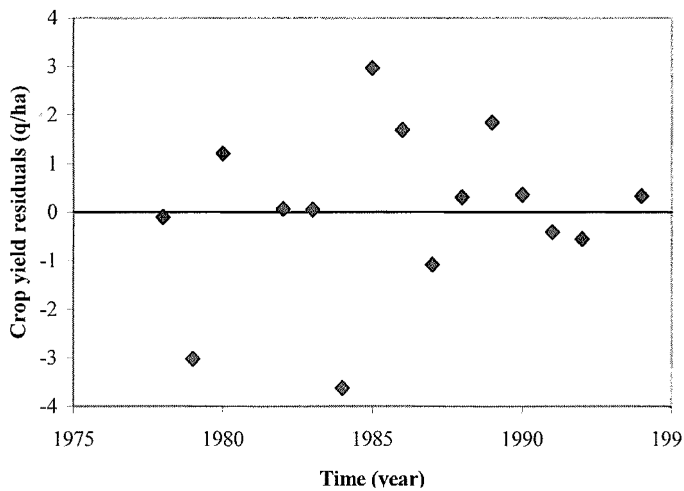

Fig. 1 Variation in crop yield residuals.

Once the underlying assumptions were validated the model (equation (5)) was verified using the experimental data set (Table 3). The data estimated by the model are compared with the experimental data (Table 3) and a good relationship is obtained between the observed and estimated values (Fig. 2). In order to quantify the deviation between estimated ($\hat{Y}$) and experimental (Y_R) data, the mean percentage error

$$e = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{Y_R - \hat{Y}}{Y_R}\right|$$

has been quantified in $e \approx 6\% < 10\%$. The difference between observed and estimated data is graphically shown in Fig. 2.

Table 3 Summary of experimental and estimated grain yield of sunflower.

Year	Observed yield (q ha^{-1})	Estimated yield (q ha^{-1})	Residuals (q ha^{-1})
1978	45.1	47.0	1.9
1979	29.3	28.0	–1.3
1980	23.1	22.6	–0.5
1982	30.7	28.0	–2.7
1983	25.4	25.5	0.1
1984	31.3	27.1	–4.2
1985	20.2	22.8	2.6
1986	47.7	45.9	–1.8
1987	33.0	35.1	2.1
1988	35.6	33.1	–2.5
1989	42.5	42.1	–0.4
1990	28.4	32.9	4.5
1991	41.2	44.9	3.7
1992	40.5	39.5	–1.0
1994	34.9	35.7	0.8

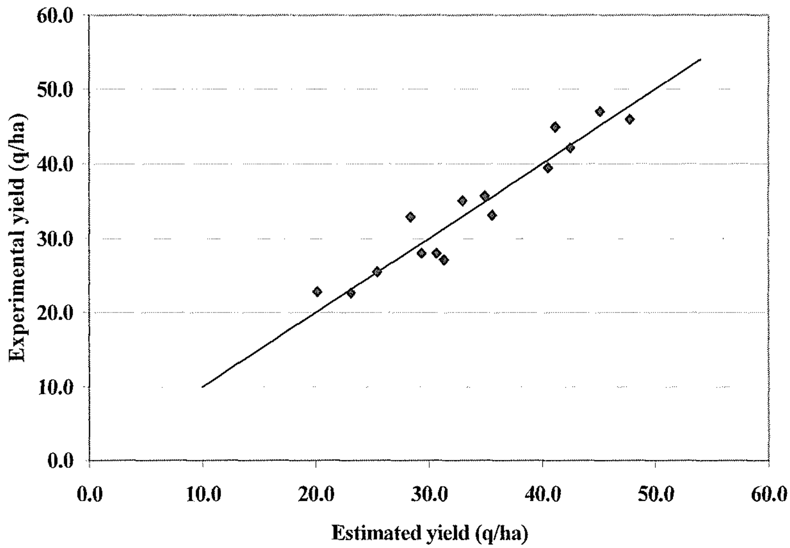

Fig. 2 Crop yield prediction.

Furthermore the *RSI* is implementable at an intraseasonal time scale (growing season). Therefore the model can be used, year after year, in the study area for estimating the grain yield of sunflower in its intraseasonal temporal dynamics. In other words, under the hypothesis of steady crop response factors (*Ky*) within each growth stage and under the further hypothesis that the model (Equation (5)) can also be used for the intraseasonal value of the *RSI*, the sunflower grain yield reduction dynamics can be easily estimated and continuously monitored during the growing season (Fig. 3). Figure 3 shows the *RSI* dynamic also along a growing season.

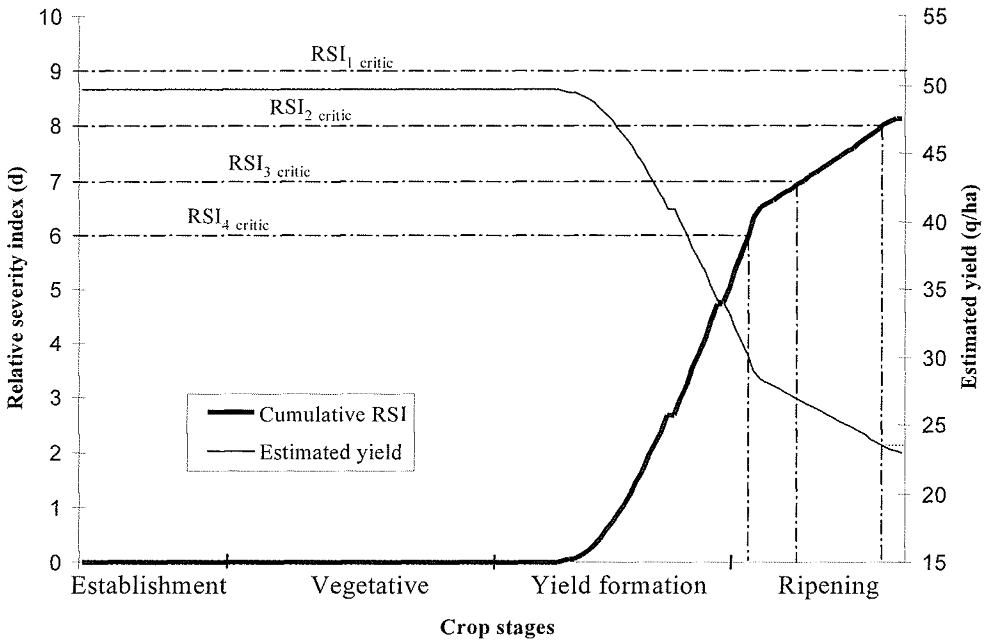

Fig. 3 Crop yield reduction dynamic (sunflower, Papiano, 1980).

ECONOMIC ANALYSIS TO ASSESS AGRICULTURAL DROUGHT RISK

It has already been stated that harvest losses is a consequence of a water imbalance between crop demand and the natural supply (potential period of seasonal agricultural drought) and that this **imbalance** becomes **significant** when the soil moisture availability to plants has dropped to such a level (threshold) for long enough that the harvest losses make the cultivation of a given crop economically not productive. In other words it is necessary to quantify the critical crop yield (Y_{critic}) that annuls the agricultural net benefit (*NB*) according to the following equation (8):

$$NB = P_s Y_a + PAC - C \tag{8}$$

where *NB*, net benefit per unit area (€ ha^{-1}); P_s, sale price of yield (€ q^{-1}); *PAC*, European Community contribution (€ ha^{-1}); Y_a, actual crop yield per unit area (q ha^{-1}); *C*, fixed costs of production per unit area (€ ha^{-1}).

In Equation (8) the agricultural net benefit is defined (Mannocchi & Mecarelli, 1994) as the difference between revenue and costs of production. The revenue is estimated as being proportional to productivity whilst the cost consists of a fixed component. Furthermore, the Y_{critic} corresponds to the critical relative severity index RSI_{critic} in the regression model adopted (Fig. 4).

In the study area the RSI_{critic} has been quantified by using the prices of the year 2002, $P_s = 21$ (€ q^{-1}); $PAC = 237.51$ (€ ha^{-1}); and four different levels of fixed cost of production: very low with $C_1 < 660$ (€ ha^{-1}), in this case there is not a drought condition because the corresponding value $RSI_{1,critic} > 9$ days, has a sample frequency equal to 0; mild with $660 < C_2 < 725$ (€ ha^{-1}), in this case there is a drought condition because the corresponding value $RSI_{2,critic} \geq 8$ days, has a sample frequency equal to 0.13; high with $725 < C_3 < 775$ (∊ ha^{-1}), this case too suggests a drought condition because the corresponding value $RSI_{3,critic} \geq 7$ days has a sample frequency equal to 0.20; and very high with $C_4 > 900$ (∊ ha^{-1}) where an aridity condition is suggested by the corresponding value $RSI_{4,critic} \geq 6$ days which has a sample frequency equal to 0.33. The high costs can be justified by the experimental nature of the crop yield data considered.

The utility of the proposed procedure is obvious when considering that by monitoring the *RSI* as the growing season advances, one can pin point the moment when the *RSI* value approaches its critical value RSI_{critic} and a seasonal agricultural drought is in action. Hence making intervention with remedial measures possible.

CONCLUSIONS AND DISCUSSIONS

Several functional relationships between the sunflower crop yield and the agricultural potential drought characteristics (relative severity, relative severity index, duration) have been developed for a particular area in central Italy (Papiano district of Umbria Region). In the development of these relationships, the contribution of the relative severity and duration have been found to be marginal compared to the strong contribution of the relative severity index. A simple model (Equation (5)) based only on the relative severity index provides reasonably good estimates of the experimental grain yield (Fig. 2 and Table 3). Furthermore the RSI can be easily quantified during the growing season by monitoring the climate (Fig. 3). Therefore the model could be used in the study area for the real time estimation of the harvest losses during the growing season. An economic analysis has been performed in order to assess the agricultural drought risk for different levels of production costs. In future the analysis will be extended to other areas of central Italy.

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