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Drought impacts on yield potential in rainfed agriculture

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Abstract. In this paper a simplified methodology for the estimation of drought impacts on crop yield in rainfed agriculture is proposed. The methodology is based on empirical models for the estimation of actual to potential evapotranspiration ratio (ET/PET). This ratio is related to the Reconnaissance Drought Index (RDI), an expression of cumulative precipitation to cumulative potential evapotranspiration. The actual to potential evapotranspiration ratio is the basic variable in the simple linear regression functions used for estimating the relative crop yield (actual/potential yield). A case study from Thessaly (Greece) is presented in which a large number of years were analysed to assess production losses.

Keywords. Drought – Crop yield – RDI – Evapotranspiration.

I – Introduction

Mediterranean water resources are limited, fragile and threatened. Water shortage, caused mainly by drought and human activities and processes, is placing an increased pressure on an already stressed situation. Water shortage conditions may cause significant social, environmental and economic impacts. Nowadays, the water shortage problem is considered as a major problem in many parts of the world attracting the attention of the international communities of scientists and policy makers.

The most important consumer of water in Greece is irrigated agriculture accounting for about 85% of the total water consumed. The steadily increasing irrigated areas along with the need for more competitive products magnify the problem. In areas as the region of Thessaly in central Greece, where the economy is mainly based in agricultural production, an urgent solution is needed. Replacing crops with crops consuming less and focusing to rainfed agriculture may be such a solution (Pereira, 2007). Since human activities cannot influence the rainfed agricultural system significantly, drought is a key factor regarding the crop yield. Drought impacts can be assessed taking into account the severity of drought and the vulnerability of the agricultural system (Tsakiris and Tigkas, 2007).
In this paper the direct impact of droughts on rainfed agriculture is studied, through a simplified methodology with the aim to reach practical results. The methodology is based on empirical models for the estimation of actual to potential evapotranspiration ratio (ET/PET). Drought severity is represented by the Reconnaissance Drought Index (RDI), which is an expression of cumulative precipitation to cumulative potential evapotranspiration. Finally, the reduction of yield potential in rainfed agriculture in the Thessaly plain is estimated for the historical sample 1995-2002.

II – Methodology

1. Reconnaissance Drought Index (RDI)

The Reconnaissance Drought Index (RDI) can be characterised as a general meteorological index for drought assessment (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007). In this paper we will focus on two forms of RDI, the initial $\alpha_k$ and the standardised RDI $\alpha_{st}$.

The initial value ($\alpha_k$) is presented in an aggregated form using a monthly time step and may be calculated on a monthly, seasonal or annual basis. The $\alpha_k$ for the year $i$ and a reference period of $k$ (months) is calculated as:

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, \quad i = 1 \ (1) \ N$$

where $P_{ij}$ and $PET_{ij}$ are the precipitation and potential evapotranspiration of month $j$ of year $i$, starting from October which is the onset of the hydrological year for most Mediterranean countries and $N$ is the total number of years of the available data. The mean annual $\bar{\alpha}_{i_2}$ is equal to the well-known Aridity Index of the area (UNEP, 1992).

The calculation of RDI $\alpha_{st}$ can be performed by fitting the gamma probability density function (pdf) to the given frequency distribution of $\alpha_k$ (Tigkas, 2008; Tsakiris et al., 2008). Positive values of $\alpha_{st}$ indicate wet periods, while negative values indicate dry periods compared with the normal condition of the area. The severity of drought events increases when $\alpha_{st}$ values are lower. Drought severity can be categorised in mild, moderate, severe and extreme levels, with corresponding thresholds of $\alpha_{st}$ (-0.5), (-1.0), (-1.5) and (-2.0), respectively.

2. Assessing yield loss caused by droughts

Although RDI is a general index designed mainly to represent meteorological drought, it can be used to assess variables related to agricultural production, especially for rainfed crops. This is due to the fact that a number of empirical crop production functions include the ratio of actual (ET) to potential evapotranspiration (PET) as an independent variable. Many models and methods can be used to estimate the ratio ET/PET using RDI. One of them is described by the following simple equation referring to a certain period (Zhang et al., 2004):

$$\frac{ET}{PET} = 1 + \frac{P}{PET} \left[1 + \left(\frac{P}{PET}\right)^w\right]^{-1/w}$$  \hspace{1cm} \text{(2)}$$

where $P$ is the precipitation for the given period. According to Zhang et al. (2004) the coefficient $w$ depends on the land cover of the region and may vary from 2.84 for areas covered by trees to 2.55 for areas with low vegetation.
Using equation (1) for a period of one hydrological year, equation (2) becomes:

\[
\frac{ET}{PET} = 1 + a_{12} - \left[1 + \left(a_{12}\right)^w\right]^{1/w}
\]  

(3)

Crop yield from a unit of land may be roughly estimated by a simple linear production function:

\[
\frac{y}{y_0} = k_y \cdot \frac{ET}{PET} + (1 - k_y)
\]  

(4)

where \(\frac{y}{y_0}\) is the ratio of actual to maximum yield and \(k_y\) is a coefficient which depends on the type of crop (e.g. Doorenbos and Kassam, 1979).

Equation (4) is a lumped model for estimating yield loss due to suppression of the ratio of \(ET/PET\). For more analytical approaches the dated production functions should be used. In these functions each growth stage is modelled separately from the other growth stages. Then a simplified multiplicative or additive function is used accounting for the entire growth period resulting in the final loss in crop yield.

Using equation (3), equation (4) is then transformed into the following equation:

\[
\frac{y}{y_0} = k_y \left(a_{12} - \left[1 + \left(a_{12}\right)^w\right]^{1/w}\right) + 1
\]  

(5)

Equation (5) can be used firstly to estimate the rainfed yield potential of a certain crop in an agricultural area by inserting the average \(a_{12}\) for the area based on a significant number of years. Further, by using the \(\alpha_{12}\) value of each year of drought we have the estimation of the yield potential of this crop for this specific year. By comparing the above two we can estimate the shrinkage of yield potential for each drought year.

### III – Case study

#### 1. Study area

The above methodology was applied to one of the most water deficient agricultural areas of central Greece, the Thessaly plain (Fig. 1). This area suffers from low annual precipitation depths and from frequent and persistent droughts. The high water demands of agriculture makes Thessaly plain one of the most vulnerable areas of Greece in terms of waters scarcity.

![Fig. 1. Location of the study area (region of Thessaly).](image-url)
2. Drought assessment

For the identification of drought years, data from the Greek Meteorological Service were used. Monthly precipitation and temperature (average, minimum and maximum) data were analysed for a period of 47 hydrological years (1955-2002). The potential evapotranspiration (PET) was calculated using Hargreaves methods. Based on these data, the RDI (α values and RDI\textsubscript{st}) were calculated.

In Fig. 2 the annual values of RDI (α\textsubscript{12}) are presented. The average of α\textsubscript{12} which is equal to the Aridity Index of the area is indicated by the dotted line. The RDI\textsubscript{st} values are shown in Fig. 3, in which it is easier to identify the drought years and the drought severity. As can be seen from Figs 2 and 3, the significant drought events in the area occurred during the hydrological years 1958-59, 1969-70, 1970-74, 1992-94, 1997-98 and 1999-2000.

![Fig. 2. Annual RDI (α\textsubscript{12}) for the period 1955-2002 (dotted line indicates average conditions corresponding to the Aridity Index).](image)

![Fig. 3. Annual standardised RDI\textsubscript{st} values for the period 1955-2002.](image)
3. Relative yield loss

For the assessment of the relative yield loss in the study area, equation (5) was used for three crops: winter wheat ($k_y = 1.0$), sorghum ($k_y = 0.9$) and maize ($k_y = 1.2$) (Doorenbos and Kassam, 1979). The relative yield loss ($\Delta y_i$) is considered only for the years of drought in which RDIst < 0:

$$\Delta y_i = \frac{\overline{y} - y_i}{\overline{y}} \quad (6)$$

where $y_i$ is the annual crop yield of the specific year and $\overline{y}$ is the annual yield potential of the specific crop in the area ($a_{12}$ equal to the aridity index $a_{12}$).

As presented in Figs 4, 5 and 6, very significant yield losses occurred in the year 1965-66 and 1984-85, while there are 6 more years with crop losses over 40% compared with the yield potential of the area under study.

![Fig. 4. Relative yield loss for wheat in the area of Larissa in drought years (period 1995-2002).](image)

![Fig. 5. Relative yield loss for sorghum in the area of Larissa in drought years (period 1995-2002).](image)
From Figs 4, 5 and 6, it may be also noticed that higher losses occurred for maize and then for wheat, whereas sorghum seems to be more resistant to droughts. The maximum yield loss encountered reached 100% for maize, nearly 50% for wheat and 35% for sorghum.

The above results were compared with the real information on yield losses from Cooperative Agricultural Organisations of the area. Although no crisp figures but qualitative information was available from these organisations, it seems that their records on the years of high losses on the above crops coincide with the years with high losses estimated by the proposed simplified procedure. Needless to say that due to the gross assumptions adopted in this approach, rounded figures should be finally produced.

**IV – Concluding remarks**

In this paper a simplified procedure for estimating drought impacts on rainfed agriculture was proposed. It was shown that drought indices such as the Reconnaissance Drought Index can be used for estimating the level of crop yield losses for rainfed crops for the drought years. The proposed procedure is based on the crop yield potential of the area under study. Using simplified lumped crop yield functions the negative deviation from the yield potential for the crop and the area is calculated and expressed in relative values.

The importance of the proposed procedure lies in the fact that it is simple and easy to understand and therefore it may be accepted by all interested parties in a preparedness plan for facing drought in rainfed agriculture.

The proposed methodology after customisation and refinement could be also used for devising insurance policies and compensation strategies related to drought episodes.

**References**


