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An evaluation of some drought indices in the monitoring and prediction of agricultural drought impact in central Italy

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Abstract. A comparative analysis of the performances of some drought indices in monitoring and predicting sunflower and sorghum crop yield in Central Italy is carried out. Considered drought indices include: Palmer drought indices (PDSI, Z, CMI), Standardized Precipitation Index (SPI) and a severity index (RS) derived from a Run theory applied to the soil water content time series. The indices were computed weekly using climatic data recorded from 1978 to 2003 in four sites for which also pedo-hydrological and crop data are available. An intra-seasonal correlation analysis enabled to identify the week during which each index shows the best correlation with the seasonal yield. Weekly indices cumulated in each growth stage were used for the implementation of the best crop yield-drought index models by a stepwise regression technique. Model's performances were evaluated using different goodness-of-fit measures. RS proved to be more suitable than other indices for the prediction of agricultural drought conditions. SPI, despite of the limited data requirement and the simple algorithm, leads to appreciable results similar to those obtained by using Z and CMI that. Finally PDSI models were sometimes not significantly related with crop yield and in general exhibit a lower reliability for crop yield prediction.

Keywords. Drought indices – Crop yield – Sunflower – Sorghum.

Evaluation de quelques indices de sécheresse pour le monitorage et la prévision de l'impact de la sécheresse agricole en Italie Centrale

Résumé. *Une analyse comparative a été conduite sur quelques indices de sécheresse afin d'étudier leur performance dans le monitorage et la prévision des rendements du tournesol et du sorgho en Italie Centrale. Les indicateurs de sécheresse considérés sont : les* indices de Palmer *(PDSI, Z, CMI), l'indice de précipitation standard (SPI), et un indice de sévérité (RS) calculé suivant une théorie de simulation appliquée à la série temporelle du contenu hydrique du sol. Les indices ont été calculés à échelle hebdomadaire en utilisant les données climatiques enregistrées de 1978 à 2003 pour quatre localités pour lesquelles les données pédo-hydrologiques et culturelles sont aussi disponibles. Une analyse de corrélation intra-saisonnière a permis d'identifier la semaine pendant laquelle chaque indice montre la meilleure corrélation avec le rendement saisonnier. Les valeurs hebdomadaires des indices, cumulées pour les différents stades de croissance, ont été utilisées dans une* régression *multiple progressive pour l'identification des modèles rendement-indice de sécheresse. Différents tests d'adéquation ont été utilisés pour évaluer la performance des modèles. L'indice RS s'est démontré le plus convenable pour la prévision des conditions de sécheresse agricole. Cet indice est plus robuste vue sa capacité de considérer les caractéristiques spécifiques des cultures même si cela demande un excés de données d'entrée. SPI, malgré le nombre limité des données d'entrée et son simple algorithme, a permis d'obtenir des résultats appréciables similaires à ceux de Z et CMI, qui dérivent d'algorithmes plus complexes. Les modèles PDSI ont présenté parfois des résultats qui ne sont pas significativement corrélés au rendement agricole, et, en général, leurs prévisions ont montré une moindre fiabilité.*

Mots-clés*. Indices de sécheresse – Rendement agricole – Tournesol - Sorgho.*

I – Introduction

As emphasized by Palmer (1965), drought is not an easily definable phenomenon because the term 'drought' assumes different meanings according to the context in which impacts are analyzed. Wilhite and Glantz (1985) distinguish four types of drought: meteorological, hydrological, agricultural and socio-economical. In the present paper the attention is focused on agricultural drought that occurs when the soil water availability for a specific crop is reduced to such a level that it adversely affects the cultivation production and therefore the corresponding profit (Panu and Sharma, 2002). Typically the drought indices enable to identify and to quantify the drought phenomena. Some indices are also valid tools for the drought event real time monitoring, useful to improve a proactive approach to drought management. With reference to agricultural drought the indices should be specific, since able to estimate the impacts on different crops of analogous climatic conditions. According to a generally accepted definition, the impact of the drought in agriculture can be quantified by the consequent yield reduction. Hence the goodness of an agricultural drought index can be evaluated by means of its ability to predict (and to monitor) the crop yield. In the paper this ability is tested with reference to two rainfed crops: sunflower (Helianthus annuus L.) and sorghum (Sorghum bicolor L.) grown in Central Italy. The considered drought indices are: three Palmer (1965; 1968) drought indices (PDSI, Z, CMI), the standardized precipitation index (SPI; McKee, 1993), and a severity index (RS; Mannocchi *et al.*, 1987). The Z and PDSI indices are considered able to characterize the conditions of short term water stress, which usually occur in the context of the agricultural drought. The CMI index, is considered a specific agricultural drought index. SPI, since the temporal scale can be varied, is suitable for the quantification of the various types of drought: for agricultural one, a temporal scale shorter than 3-4 months is suggested. Since RS is based on better description of the soil-crop-atmosphere interactions (Allen *et al.*, 1998), it has the potentiality to be a good agricultural index, also if more input data are required. In the next section a more detailed description of the selected indices is given underlining the differences in terms of required data input. Indices performances in crop yield prediction and monitoring will be evaluated by means of two different techniques: the former is based on an intra-seasonal correlation analysis between weekly values of the indices (during the crops growing seasons) and the seasonal experimental crop yield; the latter is based on the specification, for each index, of the best crop yield model by means of a stepwise regression technique.

II – Selected indices for the comparative performance analysis

In Table 1 are listed the indices selected for the performance analysis, to determine the most appropriate index for monitoring and for predicting the Sunflower and Sorghum crop yield in Central Italy. The indices have been selected among the most commonly used measures of agricultural drought. The main differences among them is the computational effort and the amount of input data required to quantify them (Table 1).

Table 1. Input data required by the indices. Rain: simple precipitation; ET0: reference evapotranspiration; ETm: crop maximum evapotranspiration; ETa: crop actual evapotranspiration.

	Index	DATA				
		Rain	ET0	ETm	ETa	Soil
Palmer Indices	Z (Anomaly Index)	√	√			
	PDSI (Palmer Drought Severity Index)	√	√			
	CMI (Crop Moisture Index)	√	√			
	SPI (Standardized Precipitation Index)	√				
	RS (Relative Severity)	√	√	√	√	√

1. Palmer Indices

Incorporated antecedent precipitation, moisture supply, and moisture demand into a hydrologic accounting system (Palmer, 1965). A two-layered model for soil moisture computations is used and certain assumptions concerning field capacity and transfer of moisture to and from the layers are made. Palmer applied Climatologically Appropriate for Existing Conditions (CAFEC) quantities to normalize his computations so he could compare the dimensionless index across space and time. This procedure enables the indices to measure abnormal wetness (positive values) as well as dryness (negative values), with persistently normal precipitation and temperature theoretically resulting in an index of zero in all seasons in all climates.

Anomaly Index (Z) The Palmer Z Index reflects the departure of the weather of a particular month from the average moisture climate for that month regardless of what has occurred in prior or subsequent months. The index can be quantified also at weekly time scale.

Palmer Drought Severity Index (PDSI) The Palmer PDSI Index determines the beginning, ending and severity of the drought periods. In PDSI computation, the drought severity for a month depends on the moisture anomaly for that month and on the drought severity for the previous and subsequent months. The index can be quantified also at weekly time scale.

Crop Moisture Index (CMI) The CMI (Palmer, 1968) index is designed as an agricultural drought index and depends on the drought severity at the beginning of the week and the evapotranspiration deficit or soil moisture recharge during the week. It measures both evapotranspiration deficits (drought) and excessive wetness (precipitation is more than enough to meet evapotranspiration demand and recharge the soil).

2. Standardized Precipitation Index (SPI)

In SPI computation (McKee, 1993) historical data are used to compute the probability distribution of the monthly and seasonal (the past 2 months, 3 months, etc., up to 48 months) observed precipitation totals, and then the probabilities are normalized using the inverse normal (Gaussian) function. The SPI methodology allows expression of droughts (and wet spells) in terms of precipitation deficit, percent of normal, and probability of non excedance as well as the SPI. The index can be quantified also at weekly time scale.

3. Relative Severity (RS)

The RS (Mannocchi *et al.*, 1987) is an index derived from a Run theory applied to the simulated (or measured) soil water volume dynamics (SWt) in the root zone with a truncation level SW0 (the soil water volume corresponding to the crop critical point). The drought runs occurs when both the following conditions occur: $dSWt/dt<0$ and $SWt<SW0$. The severity of the soil water deficit is quantified by the RS as the integral of the drought runs normalized with respect to the Total Available Water volume per unit surface in the root zone (TAW). RS can be quantified at any time scale.

III – Available data

For the selected crops (Sunflower and Sorghum) and for the soil-atmosphere units considered (Papiano, S.Apollinare, Osimo, Rieti) the following data were available (Monotti M. *et al.*, 1978-2003; Desiderio E. *et al.*, 1984-2003): a) agrometeorological data at daily time scale (precipitation, temperature) and at monthly time scale (wind speed, air humidity, solar radiation) from 1978 to 2003. In figure 1 mean weekly precipitation depths in the four sites during the growing season of sunflower and sorghum is shown. In table 2 mean seasonal precipitation depths and the corresponding standard deviation are given; b) hydrological soil data; c) phenological periods dates and growing seasons; d) experimental crop yield for sunflower and sorghum from 1978 to 2003. Some descriptive statistics are given in table 3.

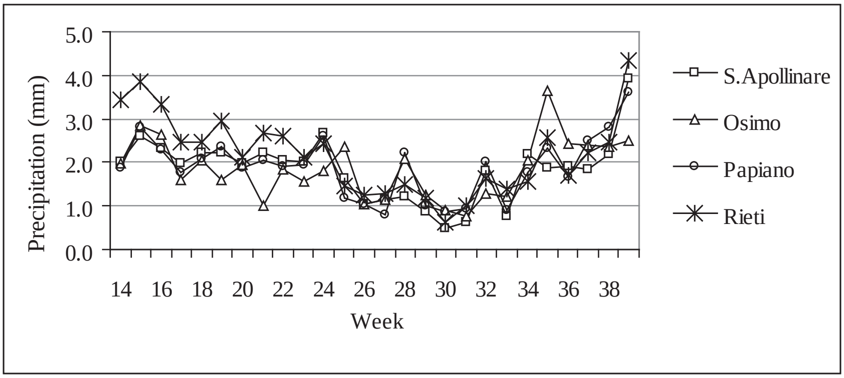

Figure 1. Mean precipitation depths of weeks from 14th to 39th for the selected sites (reference period: 1978-2003).

Table 2. Mean precipitation depths (*mean* $P_{apr\text{-}aug}$) for the period april-august and corresponding standard deviation $\sigma_{apr\text{-}aug}$ computed for the period 1978-2003 for the sites of the case study.

	Papiano	S.Apollinare	Osimo	Rieti
mean $P_{apr\text{-}aug}$ (mm)	266.6	263.2	265.7	320.2
$\sigma_{apr\text{-}aug}$ (mm)	81.6	90.0	109.2	76.5

Table 3. Yield experimental data number (*n*), mean seeding (*mean SD*) and flowering date (*mean FD*) and corresponding standard deviations σ_{SD} and σ_{FD}. Mean crop yield (*mean Y*)-(1978-2003).

	Sunflower			Sorghum		
	Papiano	S.Apollinare	Osimo	Papiano	S.Apollinare	Rieti
n	25	16	23	18	13	20
mean SD (day)	95	93	94	127	128	134
σ_{SD} (day)	5.8	4.1	7.6	3.6	3.3	8.3
mean FD (day)	180	181	177	202	203	211
σ_{FD} (day)	6.5	4.7	6.1	6.5	5.8	7.8
mean Y (t/ha)	3.52	3.59	3.03	6.55	6.93	8.31

IV – Intra-seasonal correlation analysis at weekly time scale

1. Correlation analysis

The indices have been quantified at weekly scale within however the crop growing season. For each week, the time series of the drought index value has been used within an analysis of correlation with the correspondent series of crop experimental yield. The same analysis has been performed for every index and for every unit. The values of the coefficient of correlation r for the different weeks, are given in the diagrams of the Fig. 2a for Sunflower and Fig. 2b for Sorghum.

In the figures growing season weeks were grouped in four growth stages according to FAO scheme (Allen *et al.*, 1998): 1st (initial), 2nd (development), 3rd (mid-season), 4th (late season). In the same diagrams have been also drawn the continuous lines that identify the extremes values of significance for r (α=0.05). In other words $|r| > |\text{extreme value}|$ the correlation is statistically significant. In particular r values are expected to be positive for PDSI, Z, CMI, SPI and negative for RS, as on the contrary of the other indices, it increases with the water deficit (i.e. when the yield decreases).

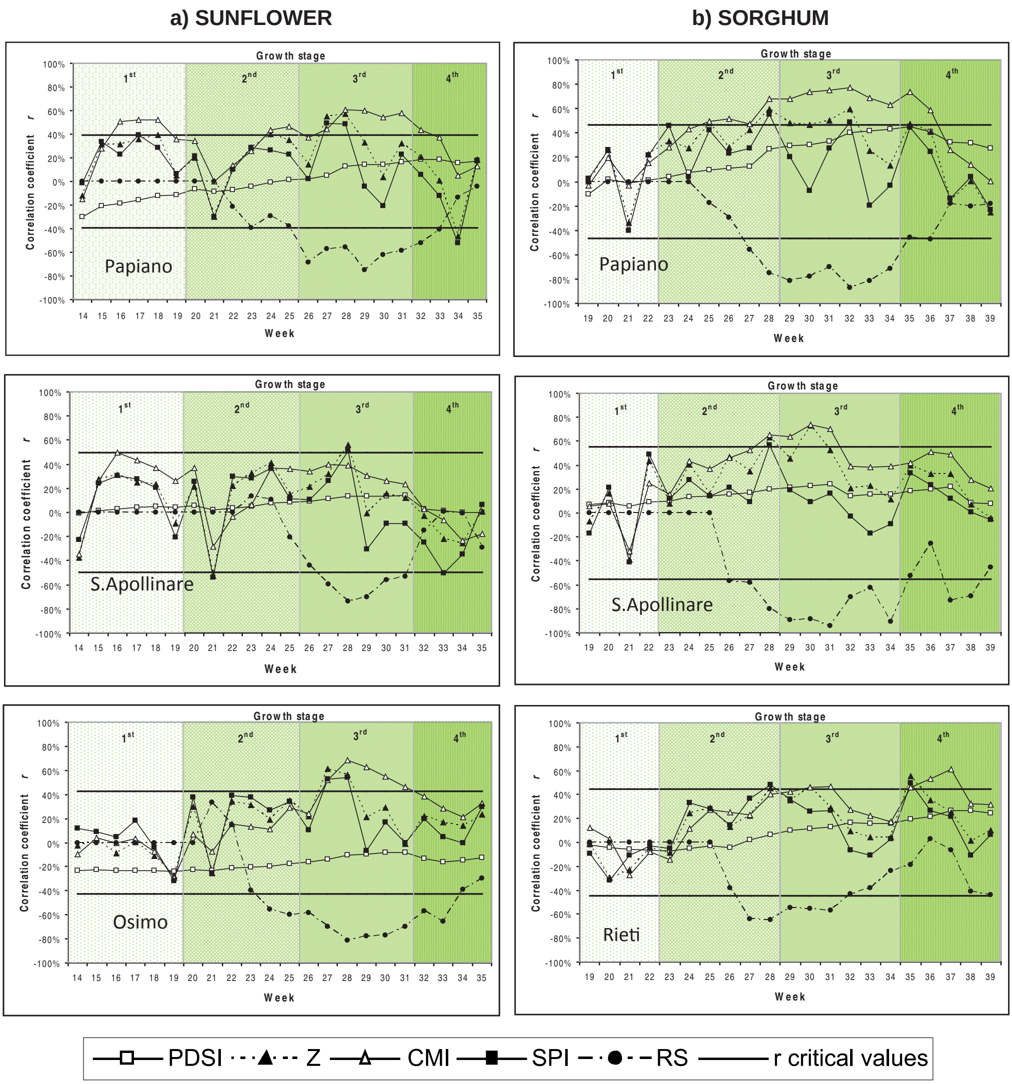

Figure 2. Correlation coefficients between weekly drought indices values and corresponding seasonal crop yield for sunflower and sorghum at different experimental sites.

2. Discussion of the results

For all the selected indices the correlation coefficient *r* increases until the 3rd growth stage, afterwards (4th and last stage) the correlation decreases. The increase is monotonic only for the PDSI, in the other cases the *r* value presents some off-hand oscillations particularly for the SPI, CMI and Z, anyway the increasing tendency is evident (Fig. 2a and Fig. 2b)

The sign of the correlation coefficient *r* is always negative for RS as this index quantify the stress of the crop that is inversely related to the crop yield.

The correlation typically becomes significant for few weeks in correspondence or in proximity of the 3rd stage, with the exception of the PDSI for which the correlation never becomes significant. The most correlated weeks are the 28th-29th for Sunflower and around the 30th for Sorghum. The index RS has the more evident correlation with the final yield both for the higher absolute value of the *r* and for the greater number of weeks when the correlation is significant. It is also possible to pinpoint weeks when correlation becomes different from zero (20th-21st for the sunflower and 24th-25th for sorghum) pointing out the period of the season when statistically water deficit begins to having repercussions on the yield. The weekly values of the PDSI index are weakly or non correlated with the final yield: the *r* is always included between the minimum values of significance, being next to zero in many cases (with the exception of the case Sorghum-Papiano where it catches up the significance limit during the 3rd stage). The CMI for some units shows high correlation values especially in correspondence of 2nd stage. Z and SPI, at last, show similar courses, even if the correlation value for SPI shows off-hand oscillations that can induce errors in the severity evaluation in real time. For the sunflower however it is possible to identify, both for Z and SPI, some weeks when the correlation values are high (27th and 28th).

V – Models based on the drought indices for the predictive assessment of the grain yield

1. Regression analysis

Regression type models based on a single index for predicting grain yield for Sunflower and Sorghum crops in central Italy are developed for each drought index and for each soil-crop-climate unit. For every growth stage i, one variable X_i obtained by the sum of the weekly values of the index, has been determined. The four values (X_1, X_2, X_3, X_4) can be considered to be the significant variables in the prediction/estimation of the grain yield by opportune models of linear multiple regression of the type:

$$\mathrm{Ya} = \lambda_1 \cdot \mathrm{X}_1 + \lambda_2 \cdot \mathrm{X}_2 + \lambda_3 \cdot \mathrm{X}_3 + \lambda_4 \cdot \mathrm{X}_4 + \mathrm{c} \tag{1}$$

where the coefficients λ_i (i=1…, 4), are like factors of sensibility of the crop to water stress in a given stage i and Ya is the estimated actual crop yield.

The technique of stepwise multiple regression, allows to exclude from the model the variables that do not contribute to meaningful increments of the explained variance. The exclusion of a variable X_i is obtained by setting at zero the corresponding λ_i value. After the application of such technique the characterized model will be able to introduce a reduced number of variables (till to become, eventually, a simple linear regression). For the final models the verification of the hypotheses on the residuals was performed using statistical tests (Shapiro-Wilk for residuals normality, Breusch-Pagan for heteroscedasticity and Ljiung-Box for autocorrelation). The coefficient of determination (R^2) and the Mean Absolute Error (MAE) have been finally used to test the reliability and the performances of the models. The indices adopted in this analysis are: the same of the correlation analysis at weekly time scale and two more indices (anyhow cumulated for every growth stage) that are the simple rain, R, and the deficit ratio ETa/ETm. In this last case the Jensen (1968) model has been adopted:

$$\frac{Ya}{Ym} = \prod_{i=1}^{N} \left(\frac{ETa}{ETm} \right)_i^{\lambda_i} \tag{2}$$

where Ya and Ym are respectively the actual and the maximum yield, ETa and ETm are respectively the actual and maximum evapotranspiration.

Considering four growth stages eq. (2) can be transformed in the following model:

$$\ln(Ya) = \lambda_1 \cdot \ln\left(\frac{ETa}{ETm}\right)_1 + \lambda_2 \cdot \ln\left(\frac{ETa}{ETm}\right)_2 + \lambda_3 \cdot \ln\left(\frac{ETa}{ETm}\right)_3 + \lambda_4 \cdot \ln\left(\frac{ETa}{ETm}\right)_4 + c \qquad (3)$$

being c=ln(Ym)

Therefore the intercept value, c, represents the crop yield under normal condition for the standardized indices (PDSI, Z, CMI, SPI) derived models, under null water supply for R and under optimal water supply for RS and ETa/ETm.

The λ_i coefficients, the intercept value c, the R^2 and the MAE, are given in the Table 4a for Sunflower and Table 4b for Sorghum.

Table 4. The λi coefficients of the regression models for the different soil-climate units, the intercept value c, the R^2 and the MAE. Highlighted models are not statistically significant (α=0.05). *The regression model adopted for this index is the Jensen equation, eq. (2)

a) Sunflower

	Site	Model					R^2	MAE (t/ha)
		λ_1	λ_2	λ_3	λ_4	c		
PDSI	Papiano	-0.1		0.1		3.5	0.41	0.43
PDSI	S.Apoll.		-0.1	0.1		3.6	0.22	0.32
PDSI	Osimo	0.1	-0.5	0.4		3.2	0.53	0.39
PDSI						**Mean**	**0.39**	**0.38**
Z index	Papiano	0.1		0.1		3.6	0.41	0.44
Z index	S.Apoll.			0.1	-0.1	3.6	0.36	0.31
Z index	Osimo			0.1		3.1	0.39	0.45
Z index						**Mean**	**0.39**	**0.40**
CMI	Papiano	0.1		0.1		3.2	0.48	0.39
CMI	S.Apoll.			0.1	-0.1	3.6	0.40	0.28
CMI	Osimo		-0.1	0.1			0.50	0.41
CMI						**Mean**	**0.46**	**0.36**
Rain	Papiano	0.0	0.0	0.0		2.1	0.48	0.39
Rain	S.Apoll.		0.0	0.0	0.0	3.3	0.41	0.29
Rain	Osimo		0.0	0.0		2.2	0.51	0.42
Rain						**Mean**	**0.47**	**0.37**
SPI	Papiano	0.1	0.1	0.2	-0.1	3.1	0.54	0.40
SPI	S.Apoll.		0.1	0.1	-0.2	3.7	0.59	0.23
SPI	Osimo		0.1	0.2		2.6	0.50	0.43
SPI						**Mean**	**0.54**	**0.35**
RS	Papiano			-0.2	-0.1	5.0	0.69	0.32
RS	S.Apoll.			-0.1		4.4	0.58	0.23
RS	Osimo			-0.1	-0.1	4.6	0.78	0.24
RS						**Mean**	**0.68**	**0.26**
ETa/ETm *	Papiano			0.8		1.5	0.61	0.34
ETa/ETm *	S.Apoll.			0.7		1.5	0.60	0.24
ETa/ETm *	Osimo			0.6	0.2	1.5	0.74	0.25
ETa/ETm *						**Mean**	**0.65**	**0.28**

b) Sorghum

	Site	Model					R^2	MAE (t/ha)
		λ_1	λ_2	λ_3	λ_4	c		
PDSI	Papiano	-0.3		0.2		6.8	0.57	0.87
PDSI	S.Apoll.	-0.5		0.5	-0.3	6.5	0.37	1.11
PDSI	Rieti		-0.1		0.1	8.2	0.23	1.06
PDSI						**Mean**	**0.39**	**1.02**
Z index	Papiano		0.1	0.2		6.6	0.62	0.76
Z index	S.Apoll.			0.2	0.2	7.2	0.38	1.34
Z index	Rieti	-0.2	0.1		0.2	8.2	0.42	0.95
Z index						**Mean**	**0.47**	**1.02**
CMI	Papiano			0.2		7.0	0.64	0.76
CMI	S.Apoll.			0.2		7.4	0.35	1.14
CMI	Rieti	-0.4			0.3	9.2	0.48	0.93
CMI						**Mean**	**0.49**	**0.95**
Rain	Papiano		0.0	0.0		4.4	0.62	0.73
Rain	S.Apoll.		0.0			6.0	0.19	1.32
Rain	Rieti		0.0		0.0	5.5	0.45	0.94
Rain						**Mean**	**0.42**	**1.00**
SPI	Papiano		0.5	0.4		5.4	0.57	0.81
SPI	S.Apoll.	0.6	0.7		0.3	5.7	0.54	0.89
SPI	Rieti		0.3		0.3	7.7	0.40	0.85
SPI						**Mean**	**0.51**	**0.85**
RS	Papiano			-0.4		8.9	0.90	0.42
RS	S.Apoll.		-0.9	-0.4		9.2	0.92	0.43
RS	Rieti			-0.3	-0.2	10.5	0.76	0.63
RS						**Mean**	**0.86**	**0.50**
ETa/ETm *	Papiano		1.8	0.5		2.1	0.75	0.58
ETa/ETm *	S.Apoll.		4.1	0.9		2.2	0.93	0.44
ETa/ETm *	Rieti			0.4	0.3	2.3	0.70	0.76
ETa/ETm *						**Mean**	**0.80**	**0.59**

2. Discussion of the results

An examination of the λ_i gives some information about the relative sensitivity of the crop yield to the stress during each of the four growth periods. As the indices PDSI, Z, CMI, R, SPI and ETa/ETm increase with the water supply, a significant positive λ_i suggests that yield may be sensitive to stress during that specific growing period. Conversely, a λ_i with a significant negative value suggests that yield may be enhanced by stress during that specific growth period. For RS an analogous but inverse observation can be made. The best predictive models have been obtained for the RS index that gives results very similar to the reference one ETa/ETm. The performance of the other indices is low and very similar to that obtained adopting the simple precipitation, R, with the exception of the SPI that gives better results. PDSI based models are often not significant and exhibit the lowest performances. In any case the results of this further analysis are in accordance to that obtained with the correlation analysis performed at weekly time scale. For **Sunflower** (Tab. 4a) all the models have the X_3 as significant independent variable (λ_i are positive for PDSI, Z, CMI, R, SPI, ETa/ETm and negative for RS). The X_2 is present always in the models obtained with the indices derived from precipitation (R and SPI), and the X_1 is present only in few cases. For Z, CMI, R, SPI the variable X_4, when significant, presents negative sensitivity coefficients. The results obtained are in accordance with the Sunflower characteristics that is very sensitive to the water stress during the 3rd stage (when flowering takes place) and sometimes penalized from water supply during the 4th one.

For **Sorghum** (Tab. 4b) the models reflect the characteristics of the crop to have an ability to recover rapidly after a period of water stress. Further, the sorghum is able to recover to a certain extent from water deficit in certain period in subsequent periods when the water supply is higher. For this reason a growth stage whose independent variable is always present in the models, is not distinctly present. Anyway the models for RS and ETa/ETm always have the X_3 as significant independent variable.

VI – Conclusions

A comparative analysis of the performances of some drought indices in monitoring and predicting sunflower and sorghum crop yield in Central Italy has been performed. The performances of the various indices have been tested both by an intra-seasonal correlation analysis between the weekly value of the indices and the crop yield and by an evaluation of the ability to predict agricultural drought impact. This ability has been tested by the goodness of crop yield estimation by regression models based on elaboration of the drought indices. In the quantification of such prediction models, several standardized indices (PDSI, Z, CMI, SPI) and not standardized indices (R, RS, ETa/ETm) were considered. The main difference between the selected indices is the effort required in quantifying them in terms of both computational procedure and amount of input data. The analysis shows clearly that for accurate estimate of the crop yield and for the real time monitoring the best predictive indices are those based on the actual evapotranspiration computation (RS, ETa/ETm). The performance of the other indices (PDSI, Z, CMI) has been found to be marginal compared to the effort required in quantifying them, infact the results came out to be similar to that obtained by the simple rain, R. The SPI, can be considered a good compromise between the computational effort and the performance in predicting the crop yield. In the paper the regression models based on the RS index are finally recommended for predicting and monitoring agricultural drought severity for Sunflower and Sorghum in Central Italy. In the case of low availability of data, SPI based model is recommended for prediction even if the correlation presents off-hand oscillations. The weeks when indices are more correlated with the final crop yield in Central Italy come out to be the 28th-29th for Sunflower and around the 30th for Sorghum.

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