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Assessing drought Vulnerability of Bulgarian Agriculture through Model Simulations

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***Abstract*—**This study assesses the vulnerability of Bulgarian agriculture to drought using the WINISAREG model and seasonal standard precipitation index SPI(2) for the period 1951-2004. This model was previously validated for maize on soils of different water holding capacity (TAW) in various locations. Simulations are performed for Plovdiv, Stara Zagora and Sofia. Results relative to Plovdiv show that in soils of large TAW (180 mm m^{-1}) net irrigation requirements (NIRs) range 0-40 mm in wet years and 350-380 mm in dry years. In soils of small TAW (116 mm m^{-1}), NIRs reach 440 mm in the very dry year. NIRs in Sofia are about 80 mm smaller. Rainfed maize is associated with great yield variability (29%<Cv<69%). Considering an economical relative yield decrease (RYD) threshold, 32 % of years are risky when TAW=180 mm m^{-1} in Plovdiv, that is double than in Sofia. In Plovdiv region reliable relationships (R^2 >91%) were found for seasonal agricultural drought relating the SPI (2) for "July-Aug" with the simulated RYD of rainfed maize while in Stara Zagora and Sofia the relationships are less accurate (R^2>71%). When rainfed maize is grown on soils of large TAW economical losses are produced when high peak season SPI (2) < -0.50 in Plovdiv/Stara Zagora and SPI (2) < -0.90 in Sofia. The corresponding NIR thresholds were identified.

***Keywords*—**Drought vulnerability, ISAREG simulation model, South Bulgaria, SPI-index

I. Introduction

DROUGHT is a protracted period of precipitation deficit that results in damages to a variety of ecosystems including agriculture and water supply [1], [2], [3]. In the lowlands of South East Europe (SEE), including Bulgaria, drought is a recurrent phenomenon as proved by numerous local studies [4], [5], [6], [7]. The climate in the most part of Bulgaria is continental with semi-arid features. Plovdiv (La 42o09' N, Lg 24o45' E, Alt 160m) and Stara Zagora (La 42o25' N, Lg 25o39' E, Alt 169m) in the Thracian Lowland, which is an important agricultural area, experience the warmest and driest climate, while Sofia field (La 42o15' N, Lg25o45', Alt 555m) is one of the coolest and wettest agricultural region in this country. The soil in both regions has variable water holding capacity classified as small (total available water TAW=116 mm m^{-1}) for alluvial and luvisol soils, medium (TAW=136 mm m^{-1}) for cambisol, and large (TAW=173-180 mm m^{-1}) for vertisol soils. A variety of standard indices exist to support operational drought definition [2]. Among them, the Standard Precipitation Index SPI is the mostly recommended index by many researchers and meteorological services. However some limitations of SPI and other indices have been recognized [8], [9]. In general these indices do not take into account drought impacts on economy, mainly relative to losses of crop yield and increased irrigation requirements.Crop models, like WAVE [10], CERES [11], [12], [13] and ISAREG [14], [15], are increasingly being used for analyses of risk assessment of drought consequences under maize and wheat in this country [16], [17], [18], [19], [20], [21]. In previous studies the WinISAREG model [15], an irrigation scheduling simulation tool for simulating the soil water balance and evaluating the respective impacts on crop yields, was validated using independent data sets relative to long term experiment with early and late maize hybrids. The objective of this study is to assess the vulnerability of rainfed/irrigated maize to drought at Plovdiv, Stara Zagora and Sofia fields, South Bulgaria, using the validated WinISAREG model and seasonal standard precipitation index SPI(2) for the period 1951-2004.

II. Material and Methods

A. Climate

The standard precipitation index SPI is a wide-spread indicator of droughts. SPI computed on the basis of 6, 3 and 2 months, SPI (6), SPI (3) and SPI (2), for Plovdiv, Sofia and Gorna Oriahovitsa were initially used as climate characteristics in this country over the period 1931-2004 by [22].A version of seasonal standard precipitation index SPI [9], that is an average or sum of the index during periods of maize sensitivity to water stress, is used as crop specific drought indicator (Fig.1) in this study. The monthly values of SPI (6), SPI (3) and SPI (2) were computed using long-term (1951-2004) monthly precipitation data from Plovdiv and Sofia Central MTO stations - NIMH and Tsalapitsa field - ISSNP. Average SPI (2) for several periods referring to maize sensitivity to drought, such as the vegetation season "May-Aug", the Peak Season "June-August", and the High Peak Season "July-August" (Fig.1) were used to define categories of agricultural drought relative to summer crops in Sofia and Plovdiv region.

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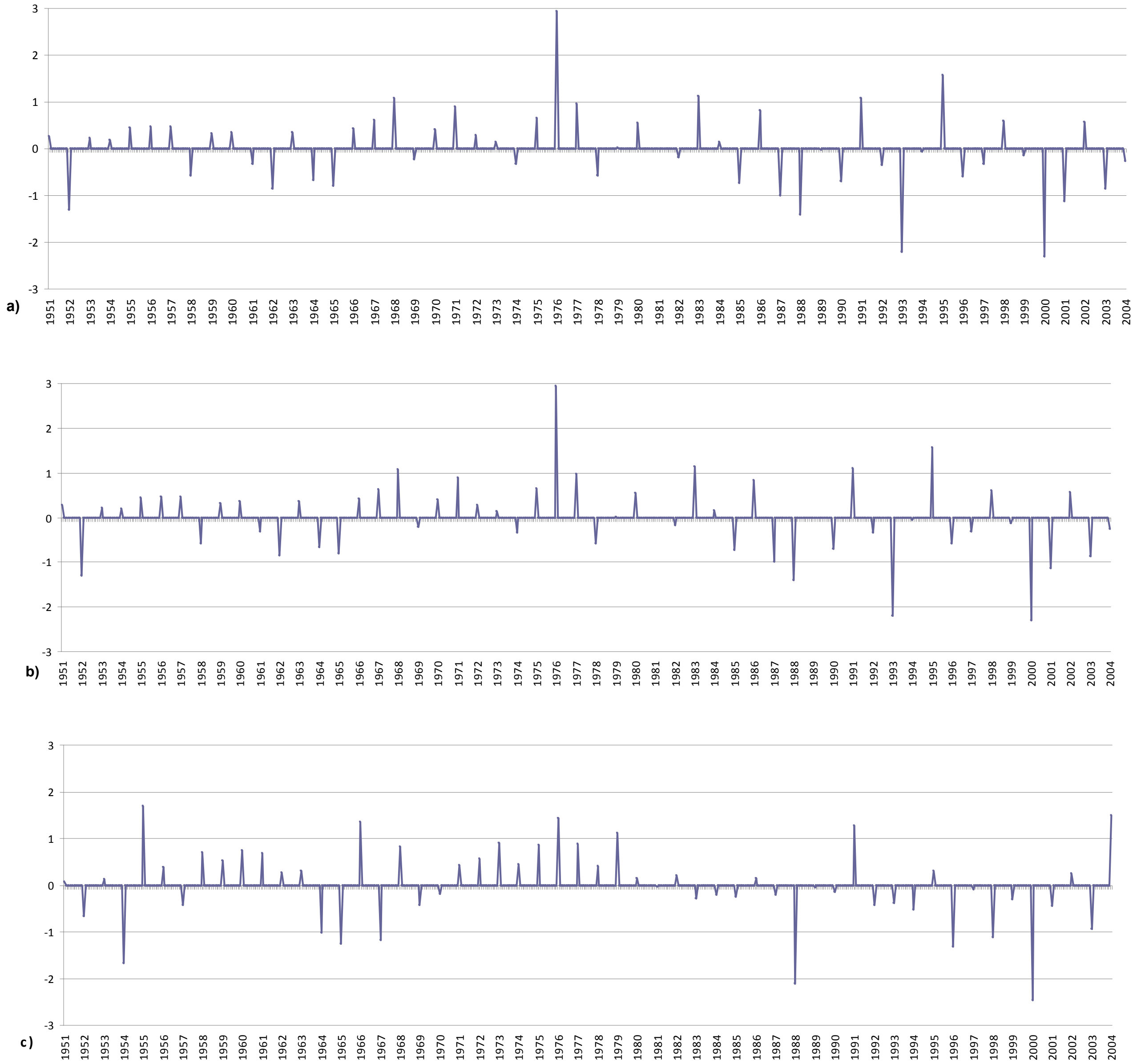
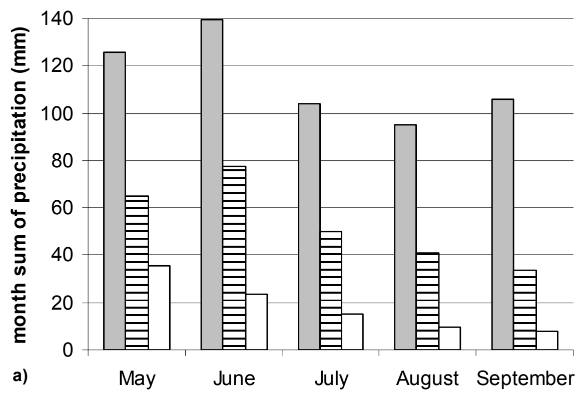


Fig.1 Evolution of High Peak Season (July-Aug) SPI (2) at: a) Sofia, b) Plovdiv, and c) Stara Zagora (Data from Central Climate Stations of NIMH), 1951-2004.

The seasonal SPI (2) relative to "July-Aug" in Sofia field plotted in Fig. 1a indicate that irrigation season in 1993 and 2000 were the driest over the last 54 years. The high peak seasonal SPI (2) "July-Aug" in Fig. 1b also show that in the region of Plovdiv summer is become dryer over the last 20 years when compared with the previous 34 years.

Monthly precipitation for the average, wet and dry seasons, heaving probability of exceedance of precipitation P=50%, P=10% and P=90% are compared for Sofia and Plovdiv in Figs.2a and 2b.



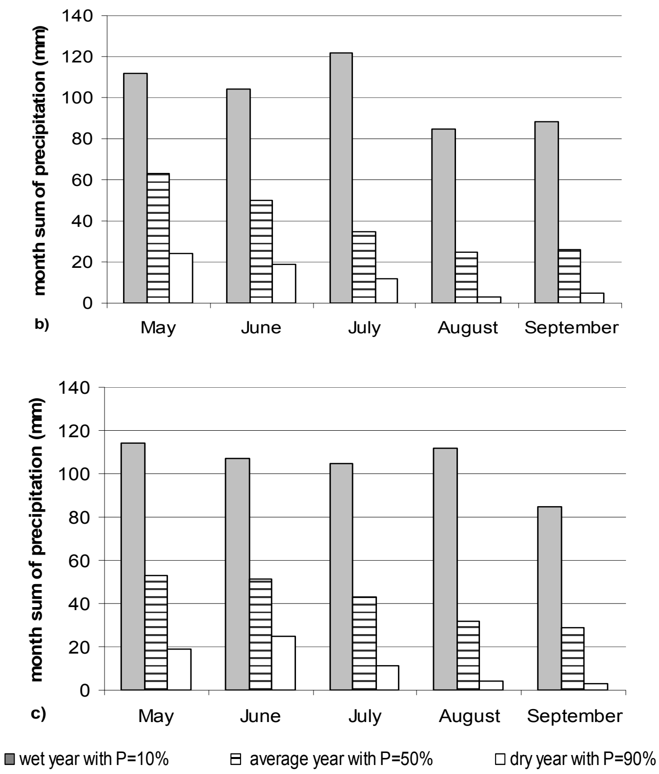


Fig. 2 Average monthly precipitation for the average (probability of exceedance of precipitation (P=50%), wet (P=10%) and dry (P=90%) seasons at: a) Sofia, b) Plovdiv and c) Stara Zagora, Central Stations of NIMH 1951-2004.

The results indicate that monthly precipitation in Sofia field for June, July and August is about double when compared with those in Plovdiv.

B. Soil Data

The study adopted formerly studied soil properties of Tsalapitsa, Zora, Pustren, and Bojurishte fields to determine the total available water in the root zone (TAW) for the alluvial and chromic luvisol, cambisol and vertisol soils of small, medium and large water holding capacity. Detailed data about soil texture, field capacity, wilting point and bulk density from several soil pits were used [23], [24], [25], [26], [21], [27]. The study is carried out for four typical soil profiles with total available water (TAW) of 116, 136, 173 and 180 mm m^{-1}.

C. Crop Data

Maize was selected as the typical summer crop for the country. Detailed and good quality crop data from long term field experiments carried out in the Thracian lowland and Sofia field are available (see [24], [25], [28], [29], [30], [31], [32], [33], [34]. In our previous studies, crop coefficients Kc and the yield response factor Ky [35] were calibrated and validated using independent datasets relative to long-term experiments with a late maize variety H708 carried out under different irrigation schedules in Tsalapitsa, Plovdiv region and Pustren, Stara Zagora [25], [26], [27], [36], [37]. In this study, additional data on rainfed maximum yields were used to adjust the yield response factor Ky to semi early maize hybrids for Sofia field [32], [33]. The simulated yield decrease RYD = 1-Ya/Ymax was transferred to actual yield values (Ya) by using data on maximum yield (Ymax) relative to late and early maize hybrids (late: H708, 2Л602 and BC622; early: SK-4, SK-4BA, Px-20 P 37-37) observed in Sofia and Plovdiv regions over the period 1973-1991 [38].

D.Simulation Model

The WinISAREG model [15] is an irrigation scheduling simulation tool for computing the soil water balance and evaluating the respective impacts on crop yields. The model adopts the water balance approach of [39] and the updated methodology to compute crop evapotranspiration and irrigation requirements proposed by [35]. Yield impacts of water stress are assessed with the Stewart one-phase model when the yield response factor Ky is known [40]. Crop coefficients Kc and yield response factors Ky for late maize hybrids were validated in previous studies [26], [37], [27], [36], [41]. The simulation options to compute net irrigation requirements NIRs and to execute the water balance without irrigation were used in this study. A specific ISAREG file was elaborated using previously validated soil and crop data. The soil data were representative for soils of small, medium and large water holding capacity (TAW) and crop data (mainly Ky) were additionally validated using independent data from local experiments with early and tardy maize hybrids.

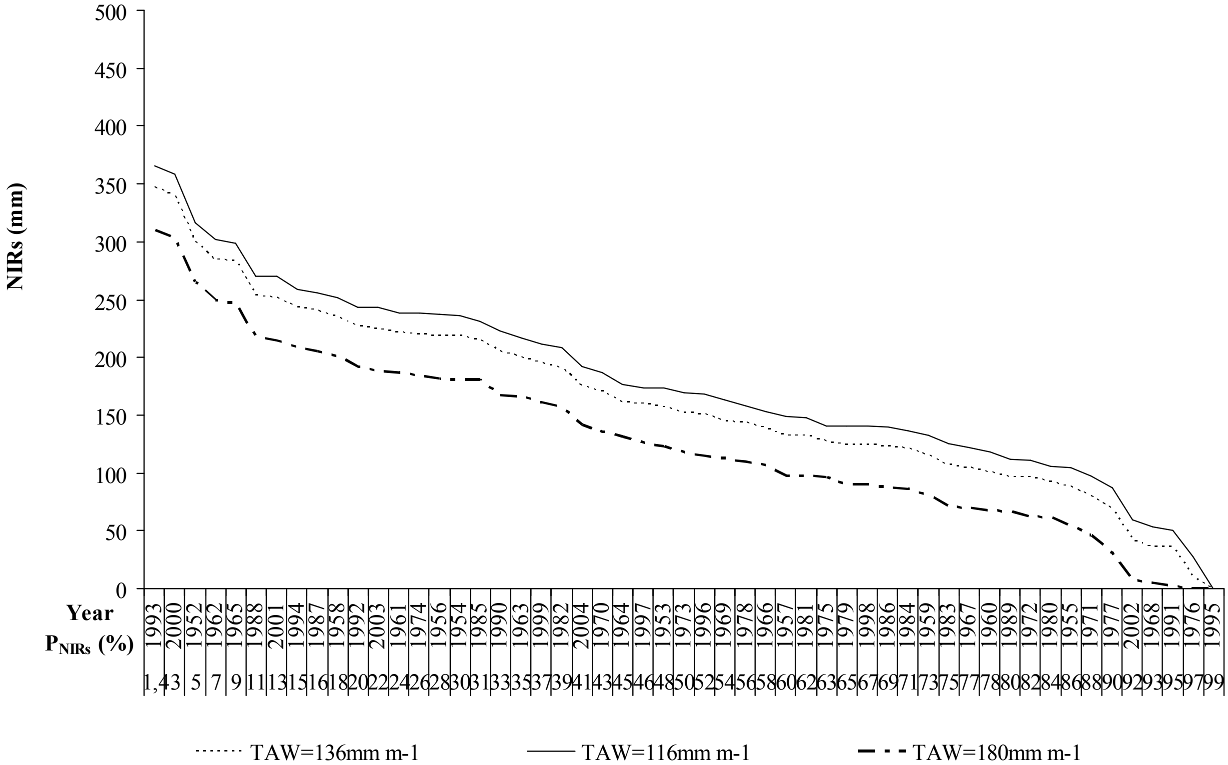
III. Findings and Discussions

A. Irrigation requirements, NIRs

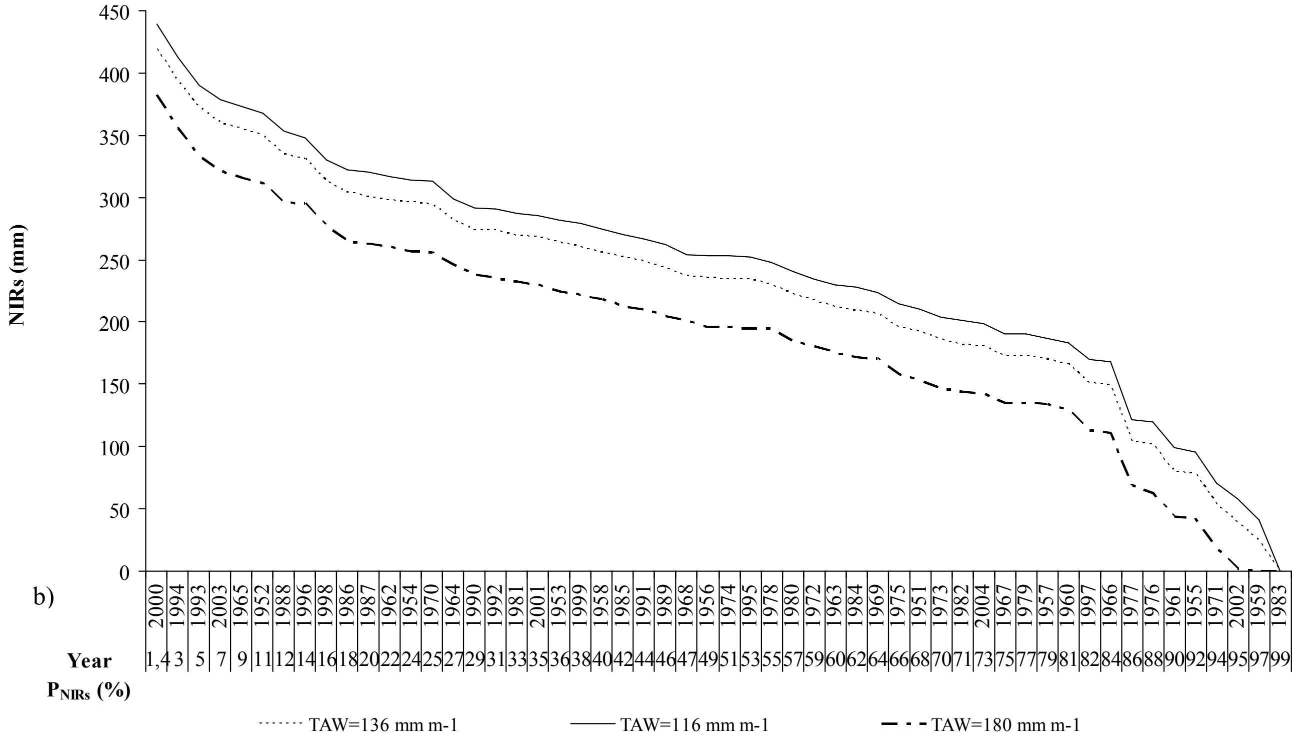
Probability curves of maize net irrigation requirement (NIRs, mm) and rainfed maize yield decrease (RYD, %) for Sofia, Plovdiv and Stara Zagora regions were built using ISAREG model simulations over the period 1951-2004.

Net irrigation requirements of maize (NIRs) computed for the soils of small, medium and large water holding capacity (TAW) are presented in Figs.3a, 3b and 3c.Results relative to Plovdiv show that in soils of large TAW (180 mm) net irrigation requirements (NIRs) range from 0-40 mm in wet years having probability of exceedance P_I>95% to 135-218 mm in average demand seasons (40%<P_I<75%) and reach 350-380 mm in very dry years (P_I<5%)(Fig.3b). In soils of small TAW (116 mm), NIRs reach 440 mm in the very dry year. NIRs in Sofia are about 80 mm smaller (Fig.3a).Considering the trend of NIRs for the period under study, an average increase by 1.5 mm $year^{-1}$ i.e. 80mm over the whole period is found for Plovdiv; contrarily to irrigation requirements grain production of non-irrigated (late maize hybrid, H708) decreases by RYD=0.35% $year^{-1}$ on the average that is 19% for the period 1951-2004 (Fig.4a). NIRs increase by only 0.5 mm year $^{-1}$ while grain production decrease by 0.23 % $year^{-1}$ that is 12 % for the whole period for the region of Stara Zagora (Fig.4b).

Trends towards NIRs increase and yields decrease on drylands maize have not been found for Sofia field.


NIRs (mm)
500
450
400
350
300
250
200
150
100
50
0
Year
P_NIRs (%)
1993 2000 1952 1962 1965 1988 2001 1994 1987 1958 1992 2003 1961 1974 1956 1954 1985 1990 1963 1999 1982 2004 1970 1964 1997 1953 1973 1996 1969 1978 1966 1957 1981 1975 1979 1998 1986 1984 1959 1983 1967 1960 1989 1972 1980 1955 1971 1977 2002 1968 1991 1976 1995
TAW=136mm m-1
TAW=116mm m-1
TAW=180mm m-1

a)


NIRs (mm)
450
400
350
300
250
200
150
100
50
0
2000 1994 1993 2003 1965 1952 1988 1996 1998 1986 1987 1962 1954 1970 1964 1990 1992 1981 2001 1953 1999 1958 1985 1991 1989 1968 1956 1974 1995 1978 1980 1972 1963 1984 1969 1975 1951 1973 1982 2004 1967 1979 1957 1960 1997 1966 1977 1976 1961 1955 1971 2002 1959 1983
Year
P_NIRs (%)
TAW=136 mm m-1
TAW=116 mm m-1
TAW=180 mm m-1

b)

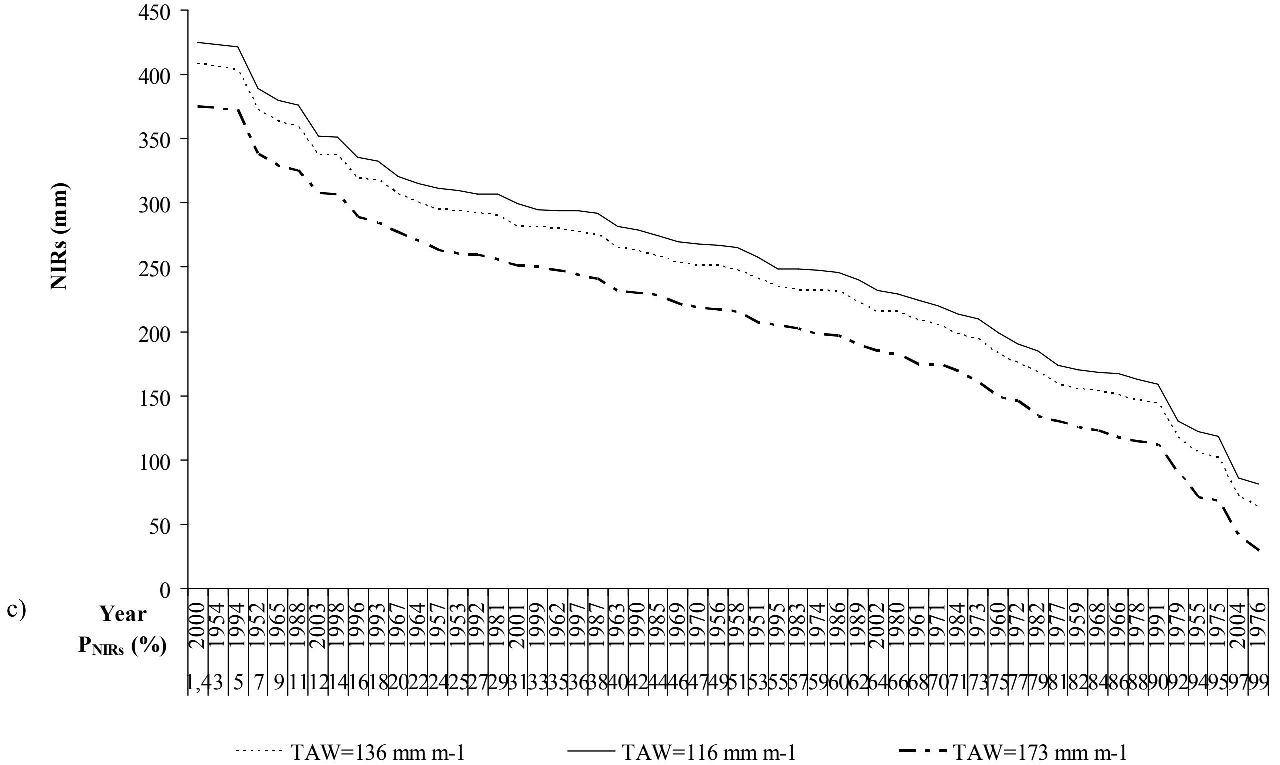
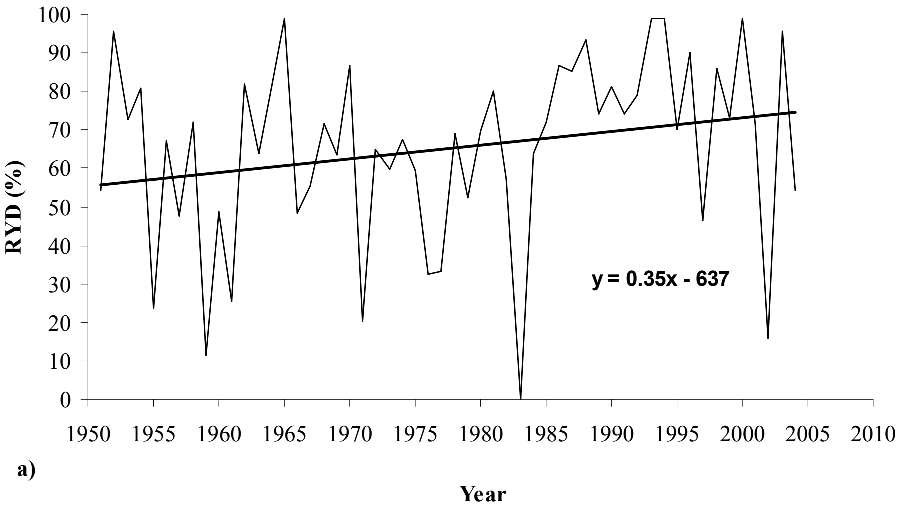
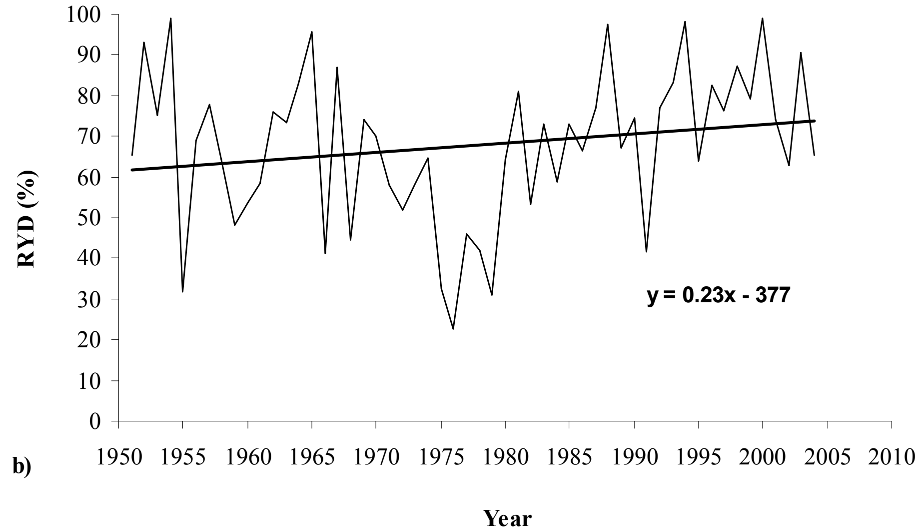


Fig. 3 Net irrigation requirements (NIRs) probability of exceedance curves relative to soil of small, average and large water holding capacity (TAW) at: a) Sofia field; b) Plovdiv and c) Stara Zagora, Thracian lowland 1951-2004





b)

Fig. 4 Relative yield decrease RYD for a rainfed late maize hybrid (H708), Ky=1.6, soil of TAW=116 mm m^{-1}, a) Plovdiv region and b) Stara Zagora, 1951-2004

B. Rainfed Maize Yield and Risky Years

Simulated relative yield decrease (RYD, %) with the yield response factor Ky = 1.6 and the option 'maize without irrigation' for soil of small water holding capacity (TAW=116 mm m^{-1}) at Sofia are sorted in a descending order in Fig.5. Additional RYD data from long-term experiments with semi-early maize hybrids conducted in Chelopechene field are plotted as well [32], [33]. Comparing both RYD data series show that adopted Ky value in the model simulations take into account the sensitivity of semi-early maize variety to water stress under rainfed conditions in Sofia.

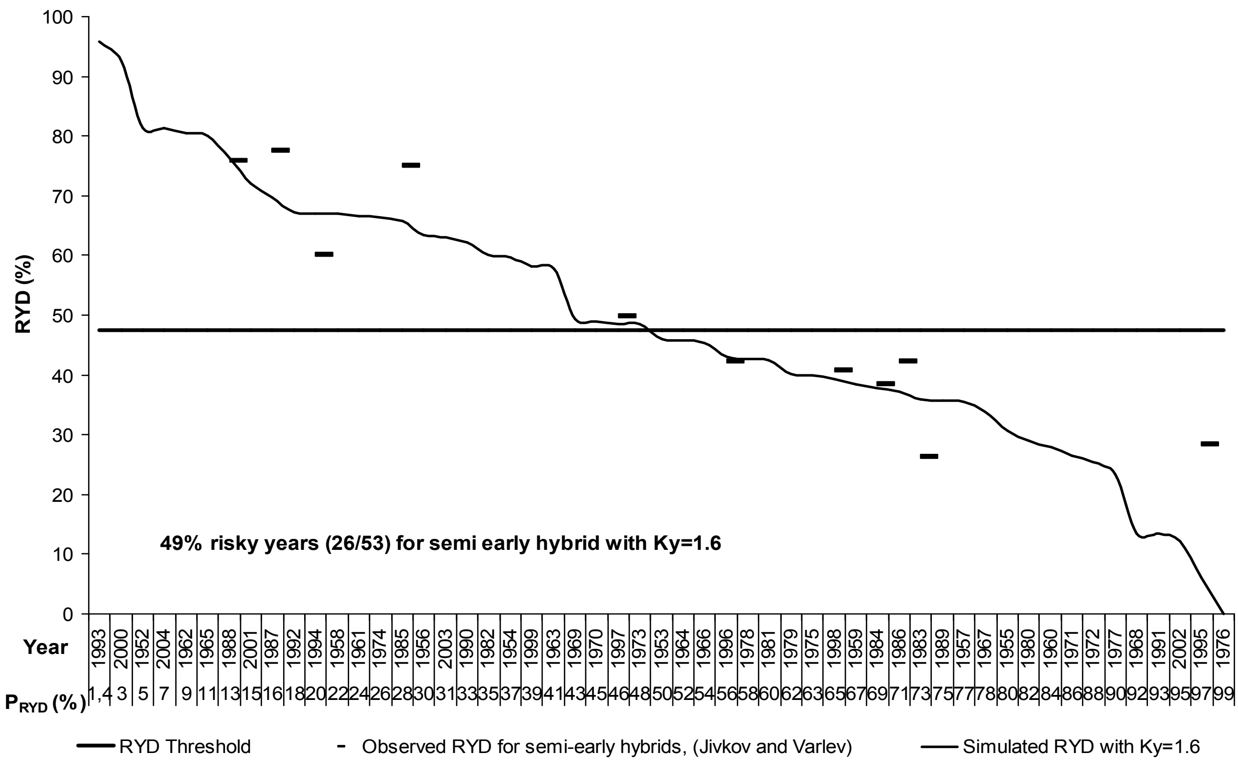


Fig. 5 Probability of exceedance curve of relative yield decrease RYD under rainfed maize computed with Ky=1.6 for soils of small (TAW=116 mm m^{-1}) water holding capacity, Sofia field, 1951-2004

Similar analyses used to be performed for Tsalapitsa field, Plovdiv region, and the soil of small TAW [37] and Pustren field, Stara Zagora but using data relative to the late maize hybrid H708 [31], [24], [25]. Results show that a factor Ky=1.6 could reflect well the yield of rainfed maize there too. Figs. 6a, 6b and 6c illustrate the derived “one to one” regressions between observed and simulated relative yield decrease RYD (%) with Ky=1.6 for the experimental sites in Tsalapitsa, Chelopechene and Pustren. Derived regression coefficients (b=0.99, b=0.95 and b=1.00) and coefficients of determination (R^2=0.61, R^2=0.82 and R^2=0.66) indicate that yield response factor Ky=1.6 is statistically reliable to be used in the study.

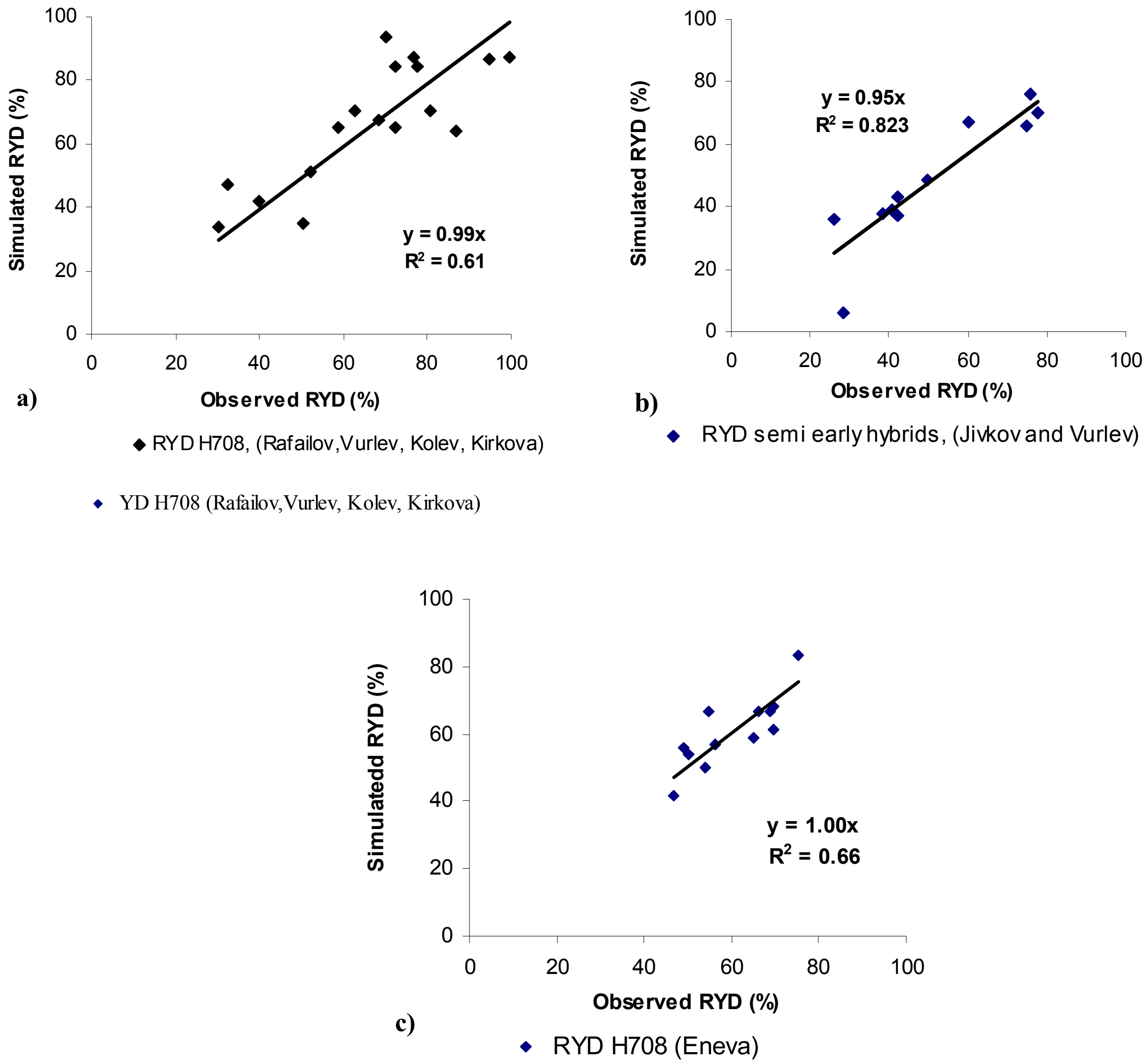
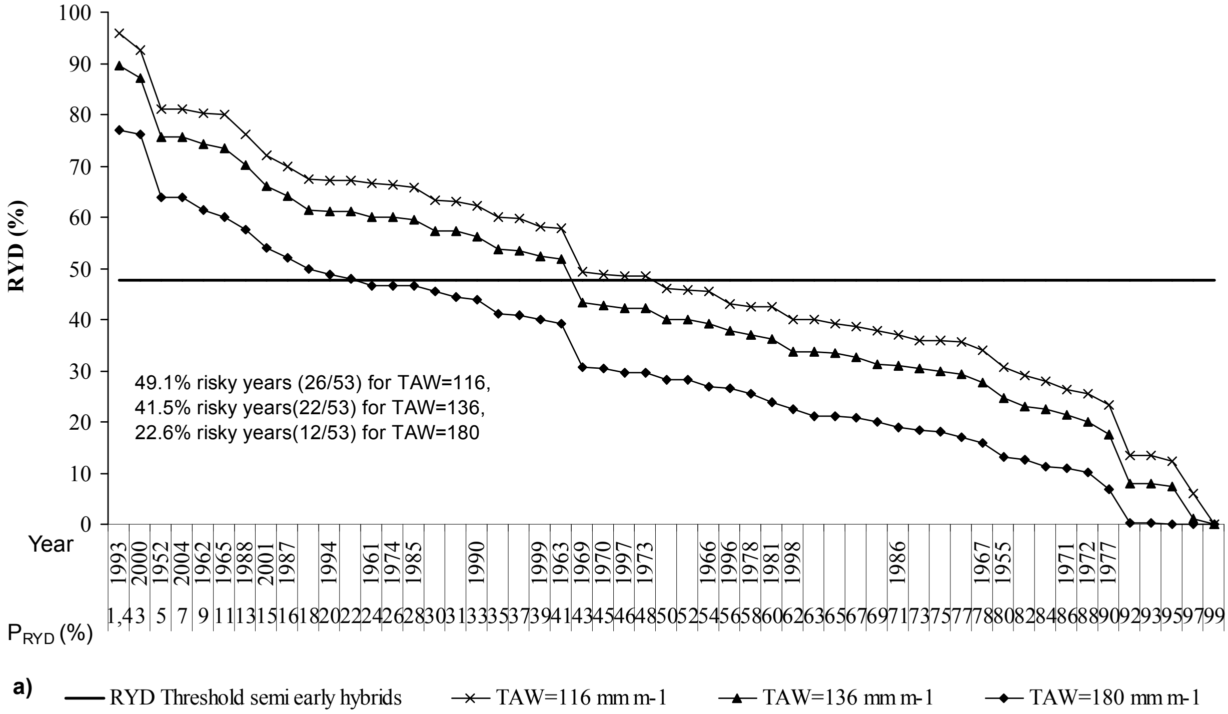
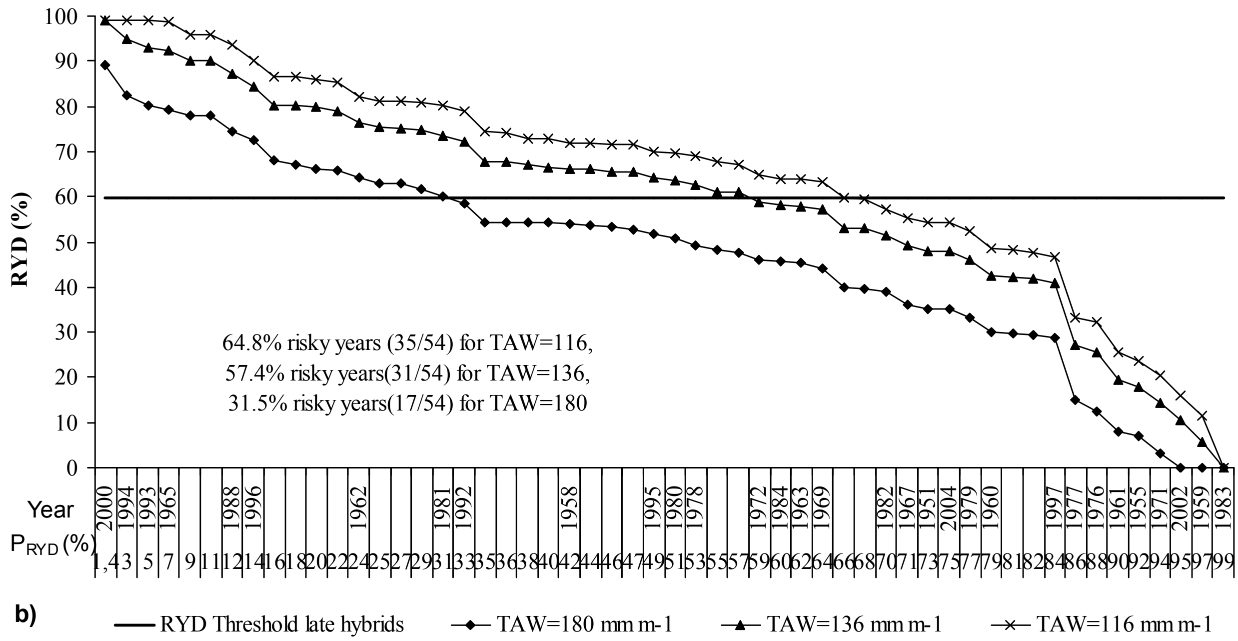


Fig. 6 One to one regression between observed and simulated relative yield decrease RYD (%) with Ky=1.6 for soil of TAW=116 mm m^{-1} at: (a) Tsalapitsa, Plovdiv and (b) Chelopechene, Sofia; and (c) Pustren (TAW=173 mm m^{-1}), Stara Zagora

The risky years relative to the soils of small, medium and large water holding capacity were identified using the probability of exceedance curves of computed relative yield decrease under rainfed maize with Ky=1.6 and the economical thresholds of RYD=48% for Sofia field (Fig. 7a) and RYD=60% for Plovdiv and Stara Zagora region (Figs. 7b and 7c).


RYD (%)
Year
P_{RYD} (%)
49.1% risky years (26/53) for TAW=116,
41.5% risky years(22/53) for TAW=136,
22.6% risky years(12/53) for TAW=180
RYD Threshold semi early hybrids
TAW=116 mm m-1
TAW=136 mm m-1
TAW=180 mm m-1

a)


RYD (%)
Year
P_{RYD} (%)
64.8% risky years (35/54) for TAW=116,
57.4% risky years(31/54) for TAW=136,
31.5% risky years(17/54) for TAW=180
RYD Threshold late hybrids
TAW=180 mm m-1
TAW=136 mm m-1
TAW=116 mm m-1

b)

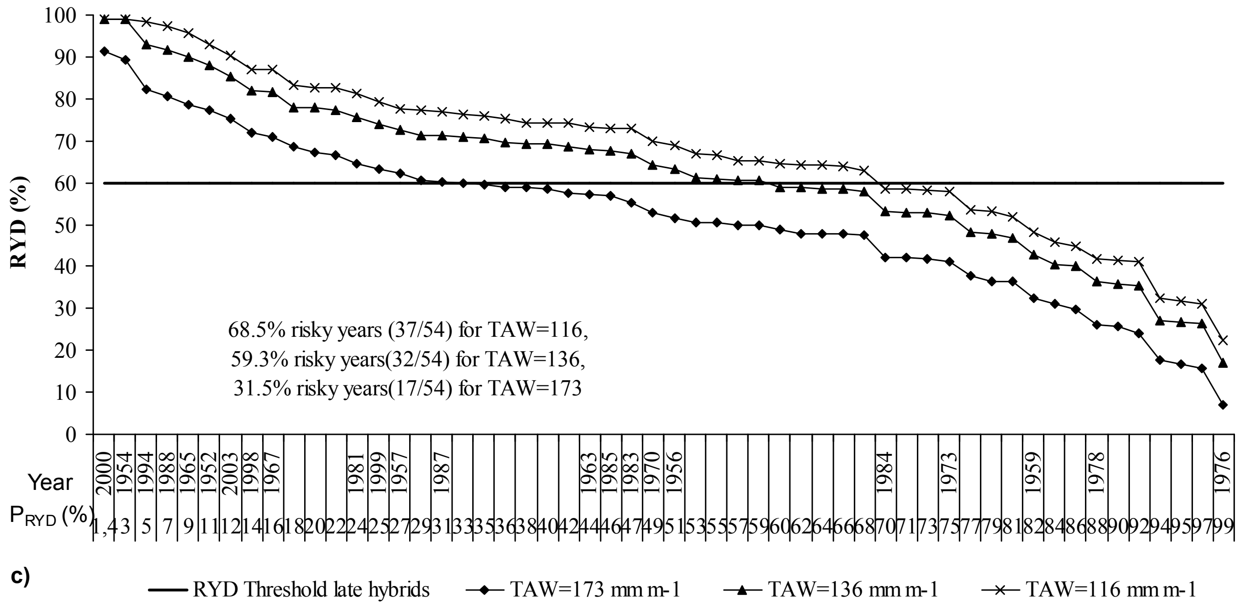


Fig. 7 Probability exceedance curves of relative yield decrease under rainfed maize RYD on the soil of small, medium and large water holding capacity TAW (116, 136, 173 and 180 mm m^{-1}), Ky=1.6, at: (a) Sofia for a semi early maize hybrid; b) Plovdiv and c) Stara Zagora for a late maize hybrid (H708), 1951-2004

Both thresholds were found considering that maize cultivation is not profitable at a grain price 200 lv t^{-1} in Bulgaria when yields are below 4500 kg ha^{-1}. The economical threshold RYD=60% corresponds to the average potential yield under tardy maize hybrids (H708, 2Л-602 and BC622) with Ymax = 11 228 kg ha^{-1} in Tsalapitsa field, while the threshold RYD=48% refers to Ymax = 8460 kg ha^{-1} for semi-early maize hybrids (HD-225, SK-48A, Px-20, P37-37) in the field of Gorni Lozen, Sofia [38].

It is found that 2/3 (65%) of the years are associated with economical losses on rainfed fields in Plovdiv (Fig. 7b) when the soil water holding capacity is small (116 mm m^{-1}). Maize production suffers economical losses in half of the years when is considered the soil of TAW =136 mm m^{-1}. If soil water holding capacity is large (TAW=180 mm m^{-1}) economical risk refers to only 1/3 of the years. The risky years in Sofia field are 50, 42 and 23% respectively for soils of small, medium and large TAW (Fig.7a).

The specific thresholds of net irrigation requirements NIRs, 224 and 168 mm, were identified for conditions under which the soil moisture deficit leads to severe impacts on rainfed maize yield for soils of small TAW in both studied regions. The study shows that severe drought affect mostly the crop during the high sensitive periods of maize vegetation in 1993 and 2000, in Sofia field, These are linked to significant reduction of yields on rainfed maize with soils of small TAW (RYD>90%) (Fig.7a). Droughts in 2000, 1993, 1994 and 1965 led to a total loss of yield in Plovdiv (Fig.7b). In Stara Zagora the drought consequences to maize grain yield were the most severe in 2000, 1954, 1994 and 1988. Rainfed maize is associated with great yield variability in this country (table I).

In Sofia field, the coefficient of variation of yields, Cv, is within the range 29-43% for semi-early maize hybrids. The smaller Cv = 29% refers to the soils of largest water holding capacity while Cv = 43% is typical for the soils of small TAW. Late hybrids (H708) grown without irrigation on soils of small TAW<116 mm m^{-1} in the Thracian Lowland produce the most variable yields in Plovdiv region (Cv=69%) and Cv=58% in Stara Zagora.

TABLE I
VARIABILITY OF RAINFED MAIZE YIELD CHARACTERIZED BY THE AVERAGE VALUE, KG HA^{-1}, AND THE COEFFICIENTS OF VARIATION CV, %, DEPENDING ON THE SOIL WATER HOLDING CAPACITY AND REGION, 1951-2004.

Soil water holding capacity		Sofia field, semi early hybrids		Thracian Lowland, late hybrids			
				Plovdiv region		Stara Zagora region	
		Average grain Yield, kg ha^{-1}	Cv, %	Average grain Yield, kg ha^{-1}	Cv, %	Average grain Yield, kg ha^{-1}	Cv, %
small	TAW=116 mm m^{-1}	4317	43	3894	69	3634	58
medium	TAW=136 mm m^{-1}	4808	38	4550	59	4211	51
	TAW=180 mm m^{-1}	5769	29	5915	43		
large	TAW=173 mm m^{-1}					5397	40

C. Deriving of Drought Vulnerability Categories

Seasonal SPI (2) were computed for crop specific sensitive periods important for maize yield formation and the whole season "May-Aug", The Peak Season "June-August" and the High Peak Season "July-August" were related to respective simulated RYD of rainfed maize for soils of small, medium and large TAW in Plovdiv, Stara Zagora and Sofia (Figs.8, 9 and 10). The relationships in the figures were derived using climate data from NIMH-Central stations.

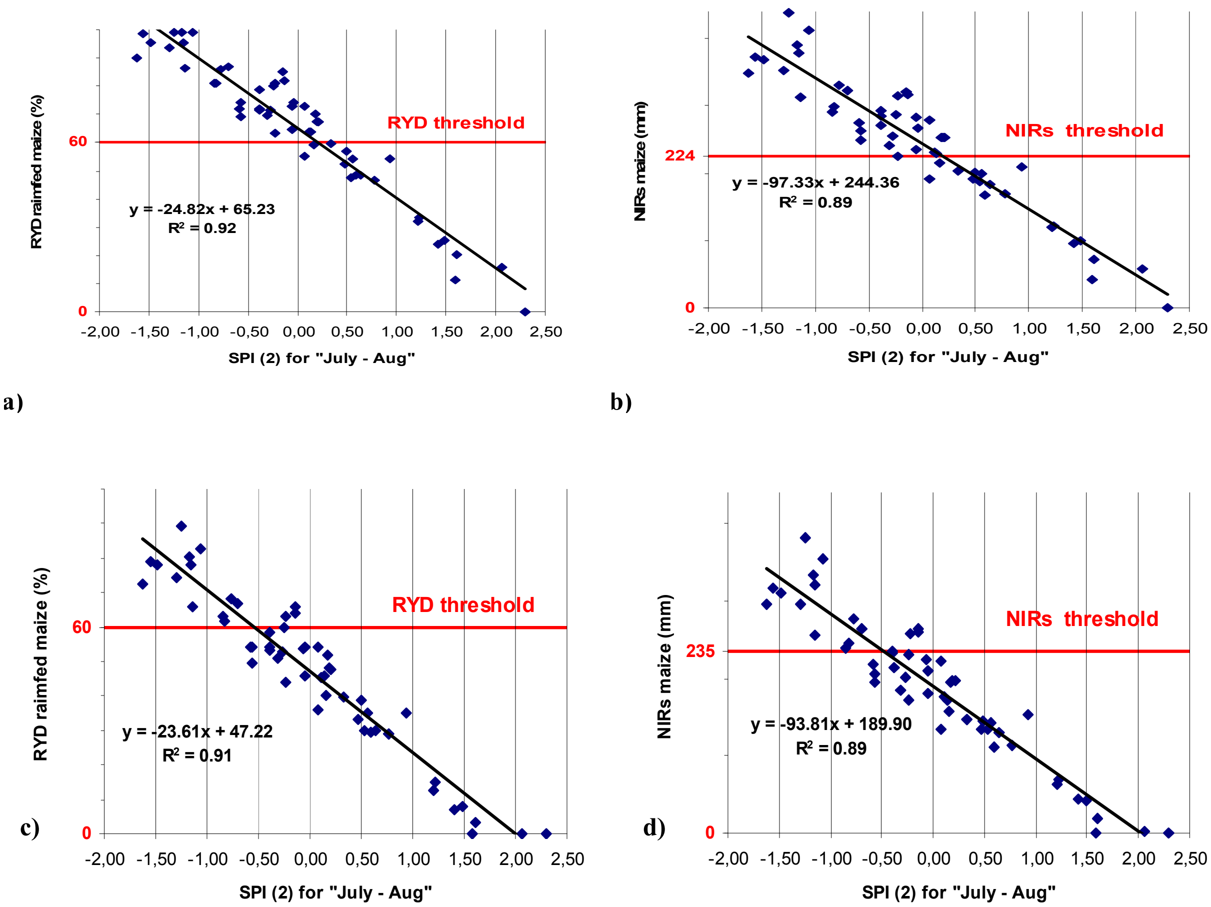


Fig. 8 Relationships between seasonal SPI (2) "July-Aug" (X-axis) and relative yield decrease RYD for late maize hybrids Ky=1.6 (Y-axis): (a) soil of small TAW=116 mm m^{-1} and (c) soil of large TAW=180 mm m^{-1}, or net irrigation requirements NIRs (Y-axis): (b) TAW=116 mm m^{-1} and (d) TAW=180 mm m^{-1}. Risky years of RYD>60%, Plovdiv

Soil specific threshold of seasonal SPI (2) “July-Aug” for soils of small, medium and large TAW were defined in Plovdiv and Stara Zagora regions, Thracian lowland, under which soil moisture deficit leads to severe impacts on rainfed maize productivity. Results indicate that farming maize without irrigation on soils of large TAW (173 and 180 mm m^{-1}) are less affected by seasonal water stress since unprofitable farming is produced when High Peak Season SPI (2)<-0.50 (Figs.8c and 9c). Corresponding NIR threshold of 235mm and 251 mm was identified (Figs. 8d and 9d).

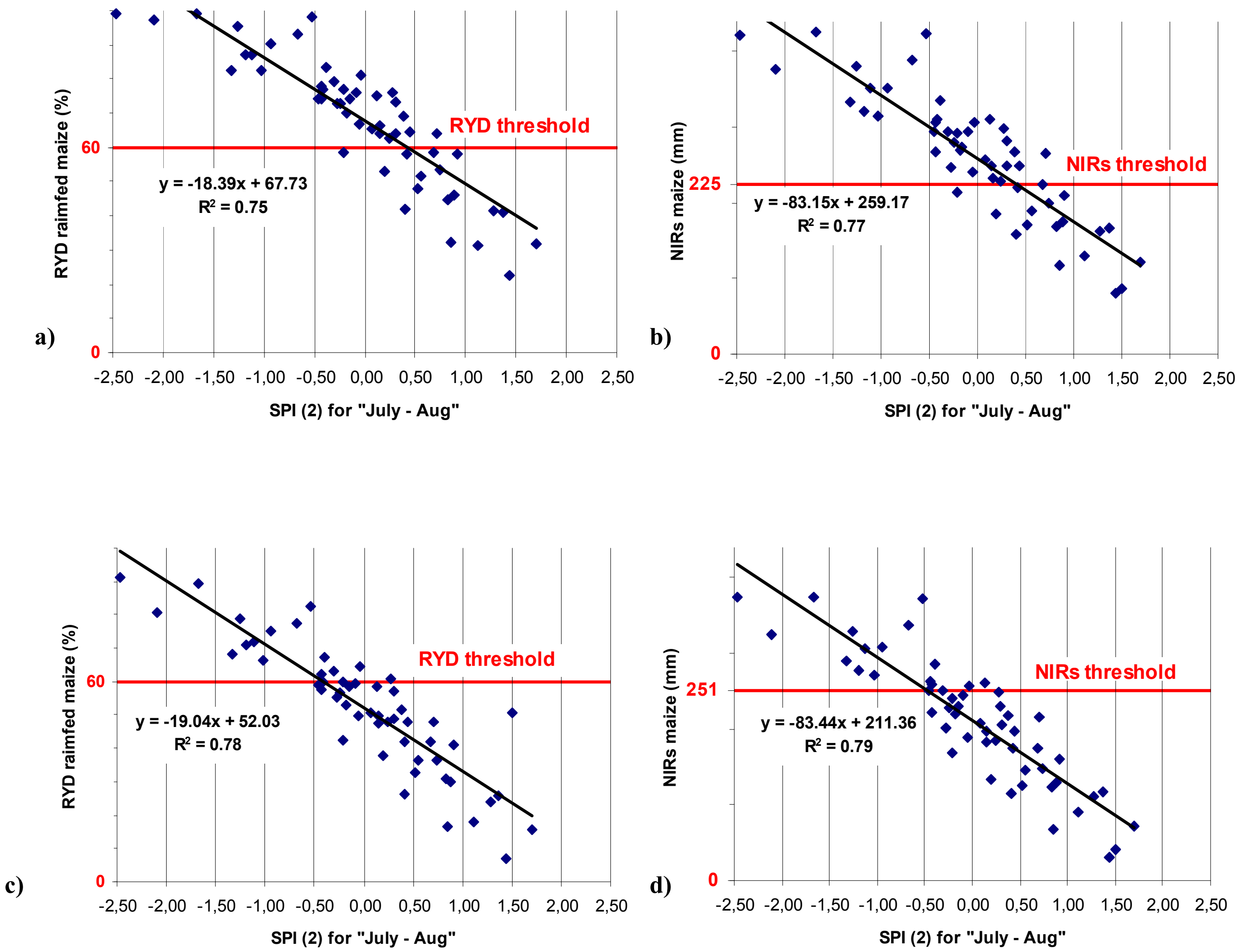


Fig.9 Relationships between seasonal SPI (2) “July-Aug” (X-axis) and relative yield decrease RYD for late maize hybrids Ky=1.6 (Y-axis): (a) soil of small TAW=116 mm m^{-1} and (c)soil of large TAW=173 mm m^{-1}, or net irrigation requirements NIRs (Y-axis): (b) TAW=116 mm m^{-1} and (d) TAW=173 mm m^{-1}, Risky years of RYD>60%, Stara Zagora

When relating seasonal agricultural drought to the SPI (2) for “July-Aug” with simulated RYD in Sofia field, the derived relationships are less accurate (R^2>71%) (Figs. 10a and 10c). It is found that when rainfed maize is grown on soils of large water holding capacity (TAW=180 mm m^{-1}) economical losses are produced when high peak season SPI (2) is smaller than -0.90 (Fig. 10c). The corresponding threshold of NIRs is 188 mm (Fig. 10d).

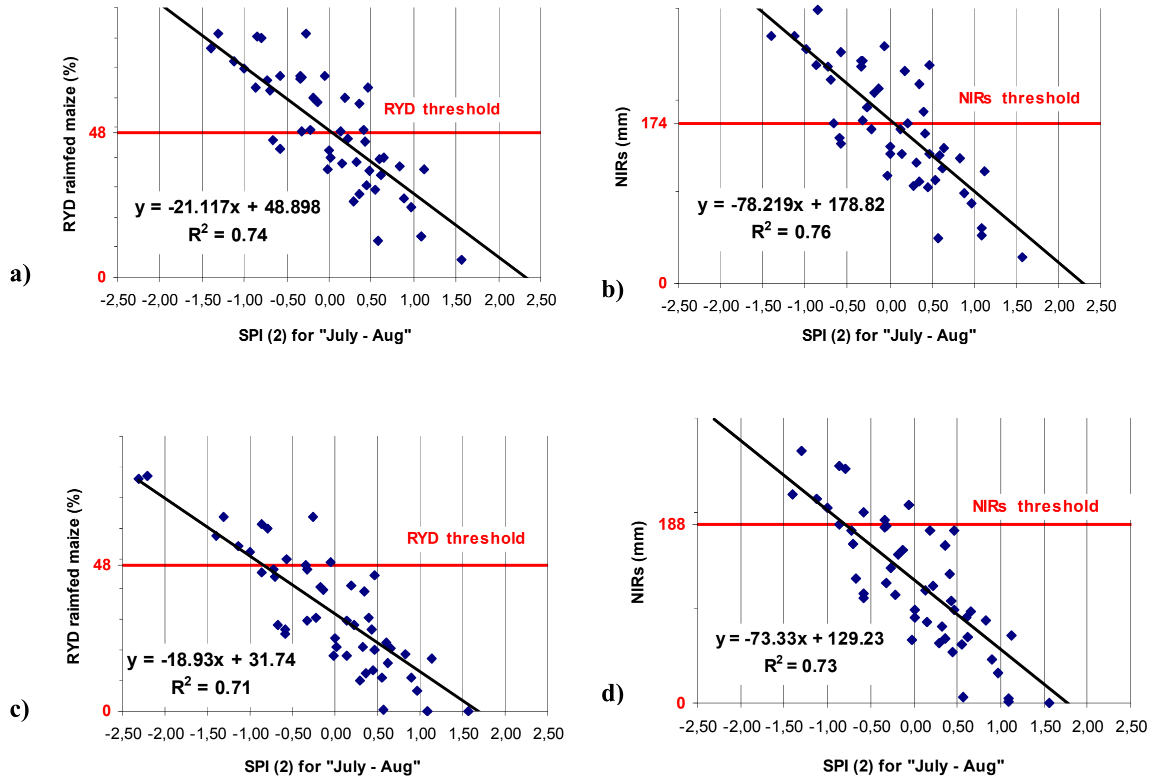


Fig.10 Relationships between seasonal SPI (2) "July-Aug" (X-axis) and relative yield decrease RYD for late maize hybrids Ky=1.6 (Y-axis): (a) soil of small TAW=116 mm m^{-1} and (c) soil of large TAW=180 mm m^{-1}, or net irrigation requirements NIRs (Y-axis): (b)TAW=116 mm m^{-1} and (d) TAW=180 mm m^{-1}. Risky years of RYD>48%, Sofia field.

IV. Conclusions

The study relative to the period 1951-2004 in South Bulgaria shows that:

- On the soils of large TAW (173-180 mm) in Stara Zagora and Plovdiv regions, the net irrigation requirements of maize (NIRs) range from 0-40 mm in wet years. The NIR increase to 350-380 mm in the very dry years, when demand is only exceeded in 5% of the time. NIRs vary from 140 to 220 mm in average demand seasons (40%<P_I<75%). In soils of small TAW (116 mm) in the same regions, the NIRs reach 420- 440 mm in the very dry year. NIRs in Sofia are about 80 mm smaller.
- According to the detected trend in Plovdiv, NIRs have increased by 80 mm for the last period, corresponding to 1.5 mm $year^{-1}$; contrarily but consequently, the yield of rainfed maize has decreased by 19%, i.e. 0.35% $year^{-1}$. NIRs increase for the period is 27mm i.e. 0.5 mm $year^{-1}$ in Stara Zagora where rainfed maize yield has decreased by 0.23% $year^{-1}$ or 12% for the whole period. However there are no similar trends towards NIRs increase and yield decrease on drylands identified in Sofia field.
- Rainfed maize is associated with great yield variability in this country. In Sofia field, the coefficient of variation of yields, Cv, is 29-43% for semi-early maize hybrids. The smaller Cv = 29% refers to the soils of largest water holding capacity while Cv = 43% is typical for the soils of small TAW. Late hybrids (H708) grown without irrigation on soils of small TAW<116 mm m^{-1} in the Thracian Lowland produce the most variable yields in Plovdiv region (Cv=69%) and Cv=58% in Stara Zagora.
- Considering an economical yield threshold of 4500 kg grain ha^{-1}, the relative yield decrease threshold under which maize cultivation is not profitable in Plovdiv and Stara Zagora is RYD=60%. In Sofia field the economical threshold is RYD=48%. It is found that 2/3 of the years are associated with economical losses on rainfed fields in the Thracian Lowland when the soil water holding capacity is small (116 mm m^{-1}). If soil water holding capacity is large (TAW=180 and TAW=173 mm m^{-1}) only 1/3 of the years relate to economical risk. Differently, the risky years in Sofia are 50% and 23% respectively for soils of small and large TAW.
- In Plovdiv region reliable relationships (R^2 >91%) were found for seasonal agricultural drought relating the SPI (2) for "July-Aug" with the simulated relative yield decrease of rainfed maize (RYD). However, In Stara Zagora and Sofia the derived relationships are less accurate (R^2>75% and R^2>71% respectively).
- The study allowed to define soil specific threshold related

with the seasonal SPI (2) "July-Aug" under which soil moisture deficit leads to severe impacts on maize yield. It is found that when rainfed maize is grown on soils of large water holding capacity (TAW=173-180 mm m^{-1}) economical losses are produced when high peak season SPI (2) < -0.50 in Plovdiv and Stara Zagora and SPI (2) < -0.90 in Sofia field. The corresponding NIR threshold was identified.

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