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Institute of Hydraulic and Rural Water Management

APPLICATION OF DROUGHT AND HEAT INDEXES FOR PANNONIC CONDITIONS

Master thesis

In partial fulfilment of the requirements

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submitted by:

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"Try not to become a man of success, but rather try to become a man of value."

A. Einstein

ABSTRACT:

Agriculture is highly affected by climate change introducing droughts and increasing temperatures. The presented study focuses on assessing effective drought and heat stress indices to monitor yield impacts of main crops (winter wheat, spring barley, maize and sugar beet) cultivated in Gross-Enzerdorf situated in Lower Austria (48.2° N, 16.55° E,148 m.a.s.l.). Following research questions were addressed: (1) Compilation of the weather characteristic of the area, through data collected by the weather station (precipitation and temperature from 1990 to 2013), by FDR- Sensor (water content in the soil between 2005 and 2012) and by a lysimeter (evapotranspiration from 1990 to 2013). (2) Computation of meteorological drought indices (PDSI, sc-PDSI and SPI, Z index and sc-Z index), hydrological drought index (HPDI) and agricultural drought index (CMI). (3) Computation of the HDH index. (4) Analysis of the relationship between drought and heat stress indices with yields data of winter wheat, spring barley, maize and sugar beet (from 2006 to 2010). Long and short-term drought indices show worst scenario during recent years (2012 and 2013). Short-term drought indices can be considered good indicators of soil water content during summer (r higher than 0.7; for a soil layer between 0 and 50 cm soil depth). The results show the different ability of the four crops considered to tolerate drought and heat stress. In particular, Winter wheat was more vulnerable to drought (r= 0.92 between yield and both SPI and sc-PDSI); then drought indexes should be taken into account for interpretation of cultivar development. Spring Barley is vulnerable to both drought and heat stress (r= 0.83 between yield data and Z-Index; r=0.72 between yield data and HDH index), and Sugar Beet only to heat stress (r=-0.787 between yield and HDH index). Finally, Maize is more vulnerable to drought than heat (r= 0.62 between yield and Z-Index; r=0.67 between yield and soil moisture). Soil moisture as well as short-term drought indices could be considered for crop development analyses.

In general, both drought indicators and heat indicator can assist and enhance understanding of crop performances, to maintain stable yields under stress conditions.

ABSTRAKT:

Die landwirtschaftliche Produktion ist stark von Klimaänderungen, durch Dürre- und Hitzeperioden, betroffen. Das Ziel der vorliegenden Arbeit ist die Bewertung von Trockenheits- und Hitzeindikatoren für vier Feldfrüchte (Winterweizen, Sommergerste, Mais und Zuckerrübe) die sehr verbreitet in Gross-Enzerdorf, Niederösterreich (48.2° N, 16.55° E, 148 m.ü.A) kultiviert werden. Die folgenden Forschungsfragen behandelten: (1) Zusammenfassung der Wetterdaten für das Gebiet, gegeben durch eine Wetterstation (Niederschlag und Temperatur von 1990 bis 2013), durch FDR- Sensoren (Wasseranteil im Boden von 2005 und 2012) und durch ein Lysimeter (Evapotranspiration von 1990 bis 2013). (2) Berechnung der meteorologischen Trockenheitsindizes (PDSI, sc-PDSI und SPI, Z Index und sc-Z Index), des hydrologischen Trockenheitsindexes (HPDI) und des Agrartrockenheitsindexes (CMI). (3) Berechnung eines Hitzeindexes. (4) Analyse der Beziehungen zwischen Trockenheit und Hitzestress mit dem Ertrag, von Winterweizen, Sommergerste, Mais und Zuckerrübe (von 2006 bis 2010). Langzeit- und Kurzzeitindizes zeigen den größten Stress in den vergangenen Jahren 2012 und 2013. Kurzzeitindizes stellen gute Indikatoren für den Bodenwassergehalt dar ($r > 0.7$; für eine Bodenschicht von 0 bis 50 cm). Die Ergebnisse zeigen die unterschiedliche Toleranz der vier untersuchten Feldfrüchte in Bezug auf Trockenheit und Hitzestress. Im Detail war Winterweizen sensitive auf Trockenheit ($r= 0.92$ zwischen Ertrag und SPI und sc-PDSI-Indizes), Sommergerste reagierte sowohl auf Trockenheit und Hitzestress empfindlich ($r= 0.83$ zwischen Ertrag und Z-Index; $r=0.72$ zwischen Ertrag und HDH Index), und Zuckerrübe zeigte eine Reaktion nur auf den Hitzestress ($r=-0.787$ zwischen Ertrag und HDH Index). Schlussendlich war Mais mehr von dem Hitzestress als von der Trockenheit beeinflusst ($r= 0.62$ zwischen Ertrag und Z-Index; $r=0.67$ zwischen Ertrag und Bodenfeuchte). Die Bodenfeuchte und der Kurzzeittrockenheitsindex können als gute Indikatoren für die Analyse der Pflanzenentwicklung angesehen werden.

Zusammenfassend kann gefolgert werden, dass sowohl Trockenheitsindikatoren als auch Hitzestressindikatoren zur Beschreibung der Pflanzenentwicklung, bzw. des Umweltstresses herangezogen werden können. Auch die Ertragssicherung kann dadurch verbessert werden.

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ABBREVIATIONS:

α	Coefficient of evapotranspiration
β	Coefficient of moisture recharge
γ	Coefficient of Runoff
δ	Coefficient of Loss
AWC	Available Water Content in Soil
CAFEC	Climatically Appropriate for Existing Conditions
CMI	Crop Moisture Index
d	Moisture departure for a particular month
ea	Actual vapour pressure
es	Saturation vapour pressure
es-ea	Saturation vapour pressure deficit
ET	Evapotranspiration
$\overline{ET}$	Mean Evapotranspiration
$\widehat{ET}$	CAFEC Evapotranspiration
ETo	Reference evapotranspiration
FC	Field Capacity
G	Soil Heat Flux Density
HDH	High Temperature Degree Hours
K	Climatic Characteristic (or weighting factor)
L	Net Loss of soil moisture

HDSI	Hydrological Drought Severity Index (or HPDI)
P	Precipitation
PE	Potential Evapotranspiration (ETo)
PDSI	Palmer Drought Severity Index
PL	Potential Loss of soil Moisture
PR	Potential Recharge (amount of soil moisture required to bring the soil to FC)
PRO	Potential Runoff
R	Recharge
RO	Runoff
Rn	Net Radiation at the Crop Surface
SMI	Soil Moisture Index
S	Soil Moisture
S‘	Available moisture available at the beginning of the month
T	Temperature
u2	Wind Speed at 2m height
WP	Wilting Point
z	Preliminary estimation of Z
Z	Moisture anomaly Index

1 INTRODUCTION:

1.1 BACKGROUND:

The “Drought monitoring system for Austrian agriculture” (AgroDroughtAustria) project is funded by the Austrian Climate and Energy Funds (5th Call) for the time period 2013-2016. It gathers the following five research partner institutes:

1) BOKU Institute of Metereology and of Hydraulics and Rural Water Management (IHLW);

2)Lehr- und Forschungszentrum für Landwirtschaft, Raumberg-Gumpenstein – LFZRG;

3) Bundesanstalt für Wasserwirtschaft – BAW, Petzenkirchen;,

4) Central Institute for Meteorology and Geodynamics – ZAMG;

5) Global Change Research Centre AS CR v.v.i - CzechGlobe, CZ;

6) National Drought Mitigation Center - NDMC, USA.

AgroDroughtAustria aims at developing and testing a crop specific drought monitoring and forecasting system for agriculture in Austria by reaching the following objectives:

1) Establish a data base and develop methods for crop drought stress detection;

2) Establish a now- and forecasting approach modelling drought occurrence;

3) Adapt and validate methods and test the crop specific drought monitoring system for operational use.

The Institute of Hydraulic and Rural Water Management at BOKU is carrying out within the project AgroDroughtAustria a comparison of various drought estimation methods to find out the relation with crop yield at selected agricultural regions in Austria. To achieve this goal, the major factors involved in the crop-yield reduction phenomenon within the atmosphere and the soil-water interaction system are presented in figure1.

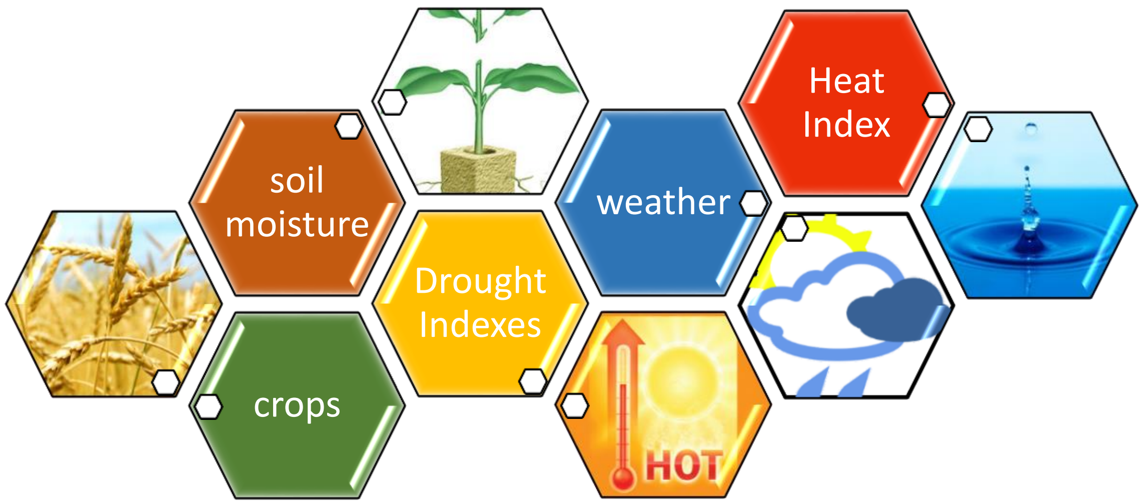


Figure 1: Representation of the major factors involved in the crop Yield reduction phenomenon within the soil-plant and weather interaction system. Weather data, soil moisture, drought and heat stress indices will be compared with the crop yields.

1.2 OBJECTIVE OF THESIS:

The Master thesis is part Work package 1 of the AgroDroughtAustria project aiming at developing a database on crop specific drought and heat vulnerability and impacts under Austrian and climate change conditions for major crops (winter wheat, spring barley, maize and sugar beet).

In particular, the study focuses on assessing effective drought and heat indexes to monitor yields impact under Pannonic conditions in Gross-Enzersdorf (48.2° North latitude, 16.55° East longitude and 148 meters elevation above the sea level), Austria, by using:

- ➔ 1. Weather and soil moisture time series;
- ➔ 2. Drought and heat stress indices modelling;
- ➔ 3. Crop yield data of winter wheat, spring barley, maize and sugar beet.

The steps followed to reach the objective of the project, are described in figure 2.

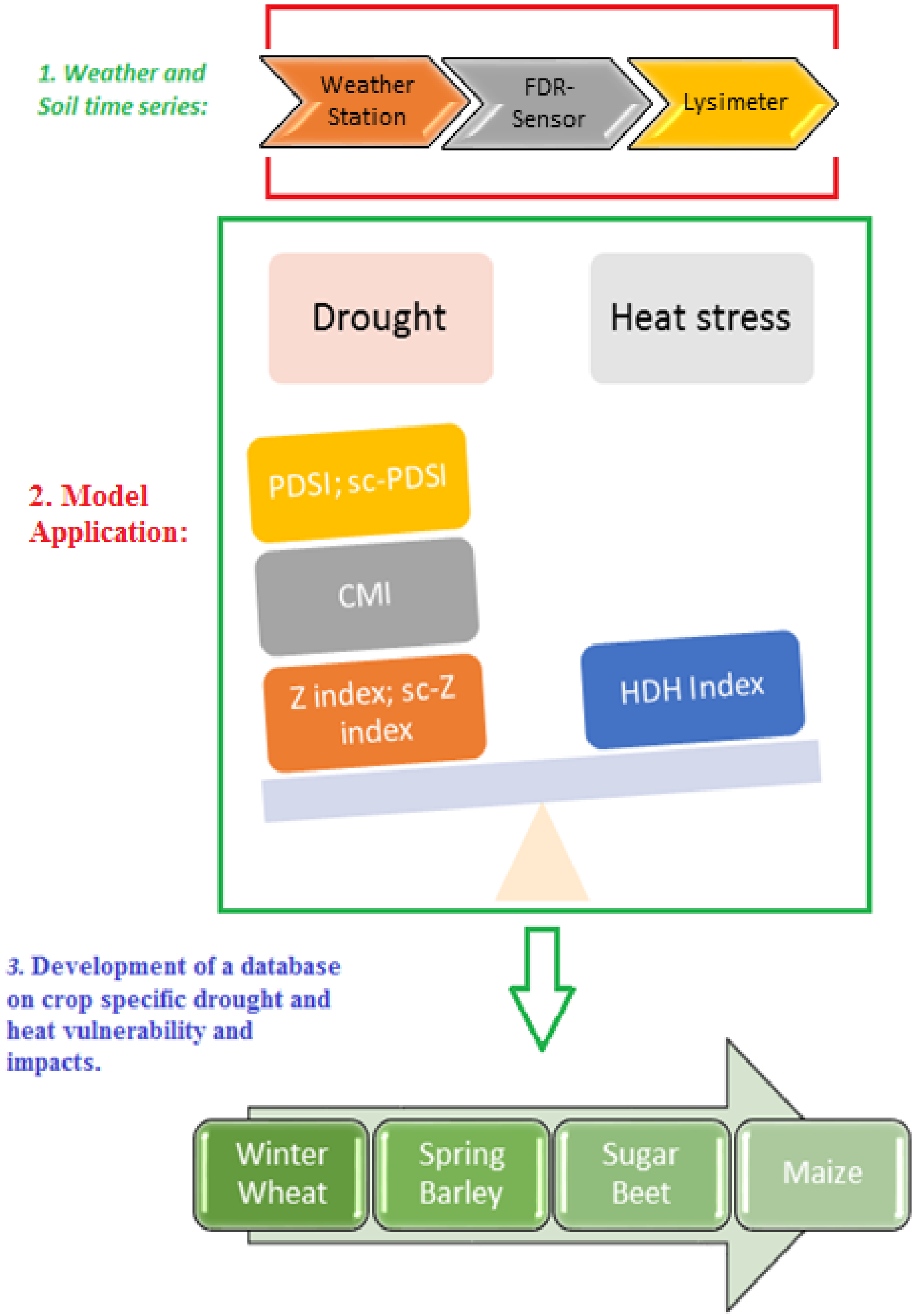


Figure 2: Steps developed to reach the object of the project: (1) Use of weather data and soil moisture time series ;(2) Drought and heat stress indices modelling; (3) Development of a database on crop specific drought and heat vulnerability and impacts.

1.3 THE IMPORTANCE OF THE TOPIC:

Increases in surface air temperature and increase of the occurrence of drought events during the 20th century have been recorded in most of Europe. Temperature increases amount up to 0.8 °C in annual mean temperature of the entire continent (Schär, 2004). The recent period shows a trend considerably higher than the mean trend: +0.4°C/decade for the period between 1977 and 2001 (Moberg, 2006). This trend is even stronger in Central, north-eastern Europe and in mountainous regions (Tank, Signals of anthropogenic influence on European warming as seen in the trend patterns of daily temperature variance, 2005). Not only an increase of temperature has been observed. There are indications of changes in the rainfall pattern as indicated by the frequency of drought events during spring and early summer; they indicates an increase of drought in Western and Eastern Europe (Tank, 2002). Furthermore, weather conditions have a direct impact on agriculture.

The agricultural sector is extremely vulnerable to weather events, such as drought and other extreme phenomena (European Commission, adaptation to climate change). It has been recognized as one of the factors contributing to recent stagnation in wheat yields in parts of Europe despite continued progress in crop breeding (Brisson, 2010). Agricultural drought periods occurred in the past decades in middle and south Europe, which also had a big impact on the economy (J. Eitzinger, 2003). The Final Report of StartClim2004 (Vienna,2005) reported that the average maximum temperature increases by 1 °C in June 2003 in Austria, which induces barley and wheat grain yield reductions by 0.1 to 0.15 t/ha. In contrast, the report also showed that the same temperature increase in August 2003 was associated to reductions of maize grain yield and grassland productivity by 0.2 to 0.45 t/ha, respectively.

Drought and heat stress are among the most important environmental factors influencing crop growth, development and yield processes.

Drought, heat stress and their impacts are defined in the introduction, then the main parameters used for the study are presented (precipitation, temperatures, evapotranspiration, soil moisture which characterized the studied area), considering their relation with drought and heat stress.

1.4 FUNDAMENTALS:

In the following section drought, heat stress and associated processes within the soil-plant-water system such as evapotranspiration and soil moisture will be defined. Figure 3 provides an overview of the main components and exchanges within the climate system.

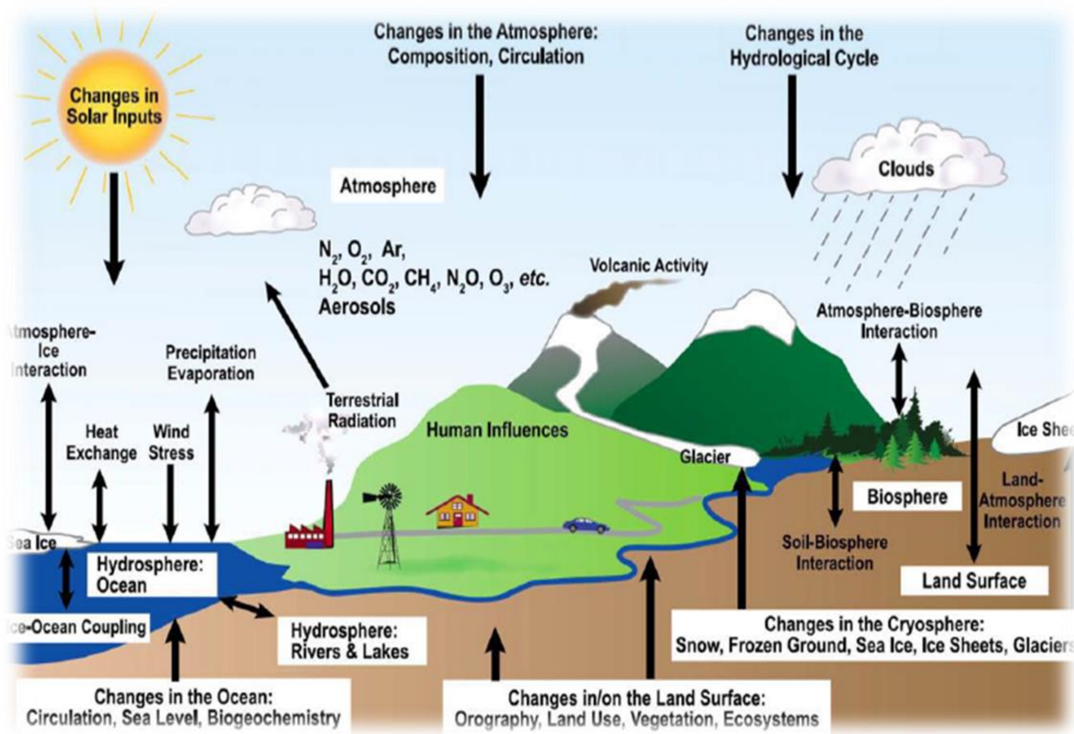


Figure 3: Main Components and exchanges within the climate system: Global Climate System, from IPCC, 2007. The atmosphere and the oceans are strongly coupled and exchange, among others, water vapour and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. Atmosphere and oceans also exchange, among other gases, carbon dioxide, maintaining a balance by dissolving it in cold polar water, which sinks into the deep ocean, and by outgassing in relatively warm upwelling water near the equator. The biosphere also affects the input of water in the atmosphere through evapotranspiration, and the atmosphere's radiative balance through the amount of sunlight reflected back to the sky.

The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the Sun.

The main climate system's components related to drought phenomenon are precipitation, evapotranspiration and soil moisture content.

Precipitation and evapotranspiration are the major components of continental water cycle; evapotranspiration returns 60% of the land precipitation back to the atmosphere (Seneviratne, 2010).

Vegetation and soils at the land surface control how energy received from the Sun is returned to the atmosphere. Soil moisture is a source of water for crops and for the atmosphere through processes bringing to evapotranspiration from land. It has a strong influence on the surface temperature, because the evaporation of soil moisture requires energy (Climate Change 2007,IPPC, 2007).

1.4.1 DROUGHT AND HEAT STRESS DEFINITION:

Drought (water stress) and heat stress (increases in above-optimum air temperatures) can occur simultaneously, but they can have very different effects on various physiological, growth, developmental, and yield processes.

Drought is a prolonged absence or marked deficiency of precipitation (UNESCO-OMM, 1992). Other definitions of drought have been developed, depending on the focus. It is usually defined both conceptually and operationally.

Conceptually, Drought is a dry spell relative to its local normal condition (Dai, 2011). It results in extensive damage to crops, impacts on surface and groundwater resources (in terms of quality and quantity), reduction of productivity, as the power generation, as shown in figure 4.

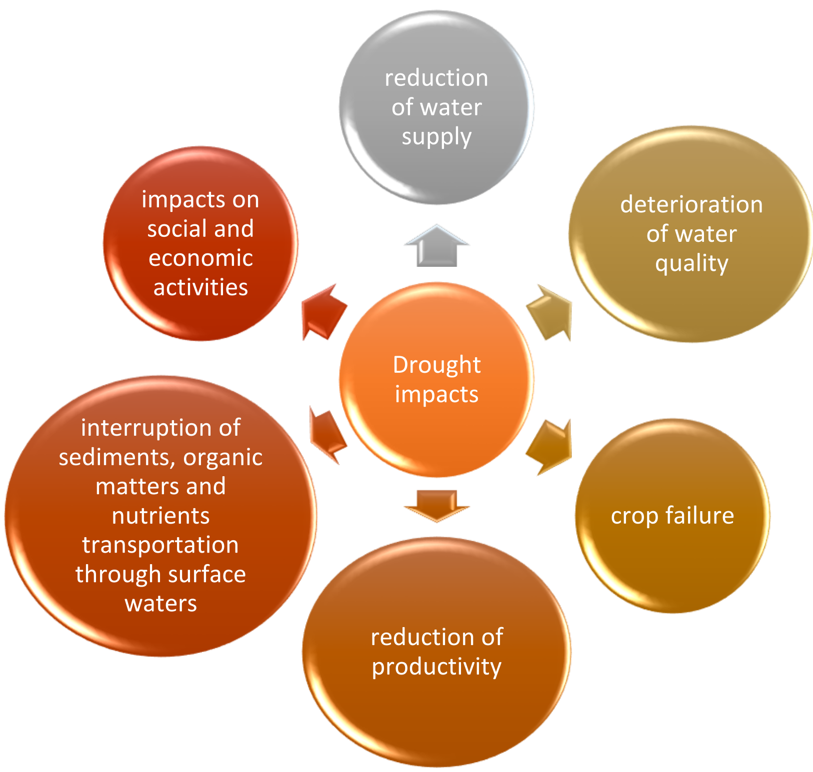


Figure 4: The main Impacts of drought are the reduction of water supply, the deterioration of water quality, the interruption of sediments and nutrients transportation through surface waters, the crops failure, as well as the reduction of productivity.

On the other hand, an operational definition is used to analyse drought frequency, severity, and duration for a given historical period. Such definition requires weather data on hourly, daily, monthly, or other time scales and, possibly, impact data (The National Drought Mitigation Centre).

Drought occurs over most parts of the world, even in wet and humid areas and the primary factor controlling this phenomenon is the lack of precipitation.

Drought can be difficult to understand because its impacts vary from region to region. In general, it originates from a deficiency of a precipitation over an extended period. The lack of rainfall leads to soil water depletion. It also impact the evapotranspiration (ET) phenomenon, since ET responds to variability in atmospheric conditions and decreases at lower values of available soil moisture that (Teuling, 2013).

The following specific drought definitions have been developed depending on the scope (Mishra, 2010) and the concept is presented in Figure 5:

1. Meteorological drought considers drought as a precipitation deficit with respect to average values (period below normal precipitation);
2. Hydrological drought is related to a period with surface water resources below long term mean levels, and one of the main factors influencing this kind of phenomena is the geology;
3. Agricultural Drought refers to a period with dry soils (declining of soil moisture) which lead to crop failure. A decline of soil moisture depends on factors, which affect also meteorological and hydrological droughts considering also the difference between actual evapotranspiration and potential evapotranspiration. Plant water demand depends on prevailing weather conditions but also biological characteristics of the specific crop (and stage of growth), and by properties of soil. Several drought indices, based on a combination of precipitation, temperature and soil moisture, have been derived to study agricultural droughts.

Sometimes the concept of Socio-economic drought also arises. Socio-economic drought is associated with the failure of water resources to meet water demands. Thus, it associates droughts with the supply of and the demand for an economic good (Mishra, 2010).

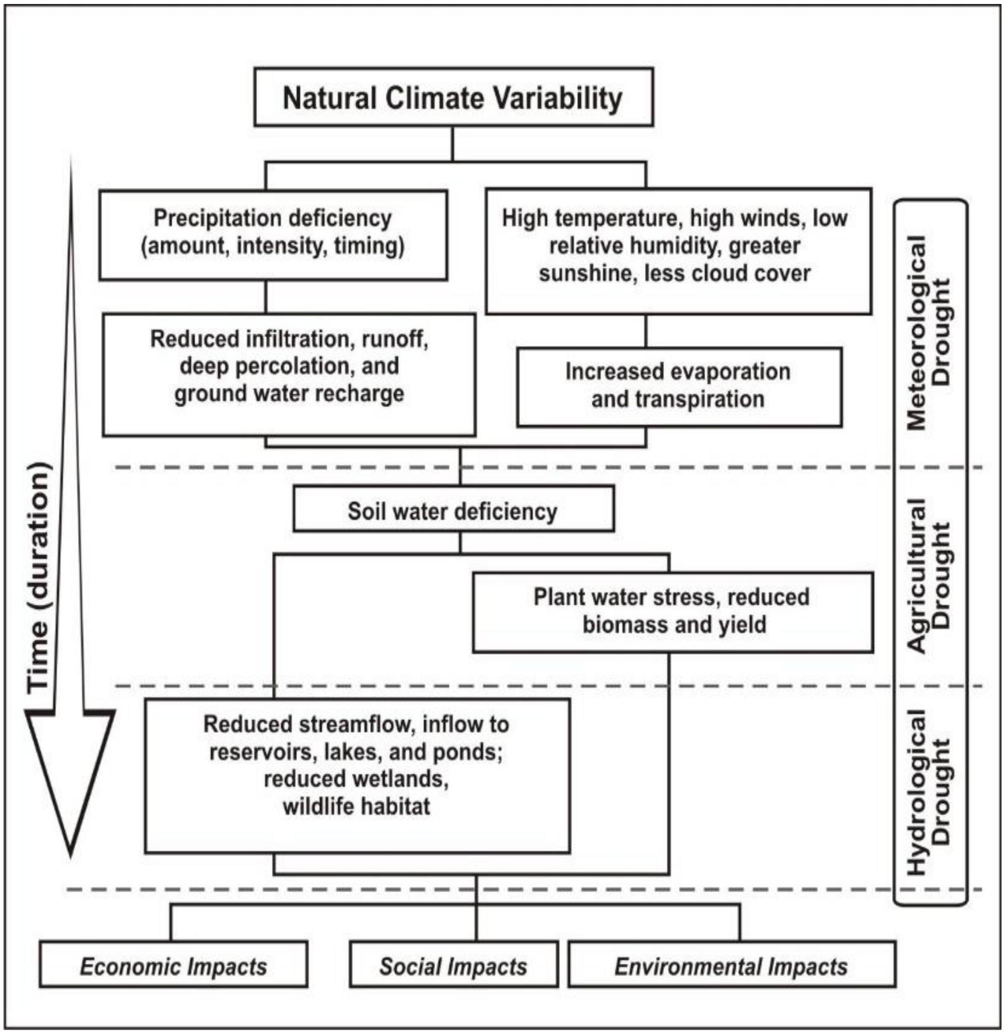


Figure 5: Sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of drought and impacts cascade from this deficiency. (National Drought Mitigation Center)

Drought definition has been developed in different ways, depending on the focus; there is also a lack of convergence in definitions regarding the term heat stress. The term is increasingly used to describe negative impacts of high temperature on plant growth (E.Rezaei, 2014). Heat stress is defined in a broad sense as the increases in above-optimum air temperatures (E.Rezaei, 2014); other authors have defined heat stress as the departure from the regular linear yield response to rising temperatures that occurs when a threshold is surpassed (Schlenker, 2009).

Crop development is mostly described as a function of temperatures: warmer temperature stimulates more rapid development of leaf canopy and causes the overall crop development rate to increase; in this way the crop growing season is shortened (P. V. V. Prasad, 2008). The higher the temperature the faster is the development and thus the shorter is the duration of the growth phase. Heat stress can influence water and soil relations of crops indirectly through faster depletion of water stored in the soil, by an increasing of evaporation and transpiration processes.

1.4.2 EVAPOTRANSPIRATION:

Apart from precipitation, evapotranspiration is the major component in the hydrologic budget (Hanson, 1991). The Evapotranspiration (ET) is the combination of two separates processes. Evaporation is the transfer of liquid water into water vapour from different surfaces, as lakes, rivers, soils; transpiration is the vaporization of liquid water contained in plant tissues (FAO). Figure 6 shows the contribution of evaporation and transpiration for over the growing season for a maize crop:

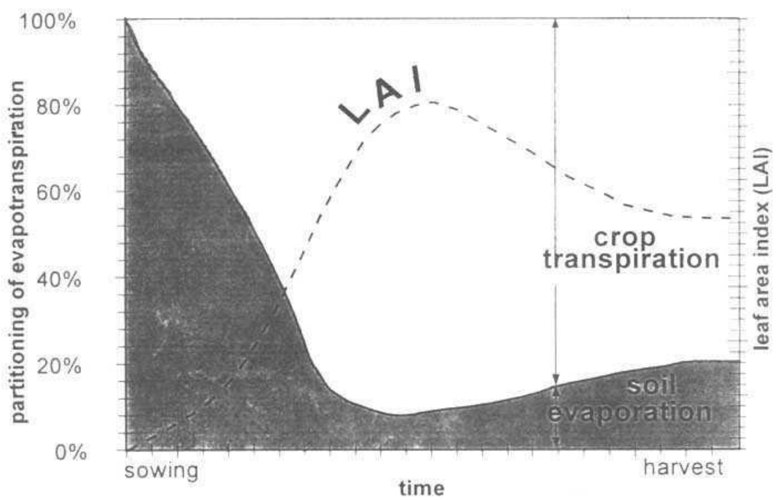


Figure 6: Contribution of evapotranspiration and transpiration over the growing period for a maize crop, from FAO.

The Leaf Area Index (LAI), a dimensionless quantity, is the leaf area (upper side only) per unit area of soil below it. It is expressed as m^2 leaf area per m^2 ground area. The active LAI is the index of the leaf area that actively contributes to the surface heat and vapour transfer. It is generally the upper, sunlit portion of a dense canopy. The LAI values for various crops differ widely but values of 3-5 are common for many mature crops. Leaf area expansion is often limited under drought stress; leaf expansion is among the most sensitive growth processes to drought. Loss of leaf area can help limit water loss (P. V. V. Prasad, 2008).

The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed (fig.7).

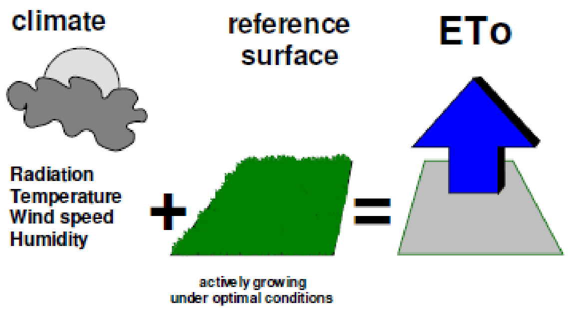


Figure 7: Parameters defining potential evapotranspiration, FAO

Several procedures have been developed to assess the evaporation rate from these parameters. The evaporation power of the atmosphere is expressed by the potential evapotranspiration (ET_o). Today ET is commonly computed from weather data. A large number of empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data. The FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ET_0. Evapotranspiration measurements can be obtained also with lysimeter, where the crop grows in isolated tanks filled with soil. Lysimeters are expensive to construct and operation and maintenance require special care.

1.4.3 SOIL MOISTURE:

Soil moisture is a major source of water for the crop. Therefore, it reflects the water stress of the plant. Figure 8 illustrates the soil moisture concept by distinguishing the saturated zone from the unsaturated one, where the root zone is also situated.

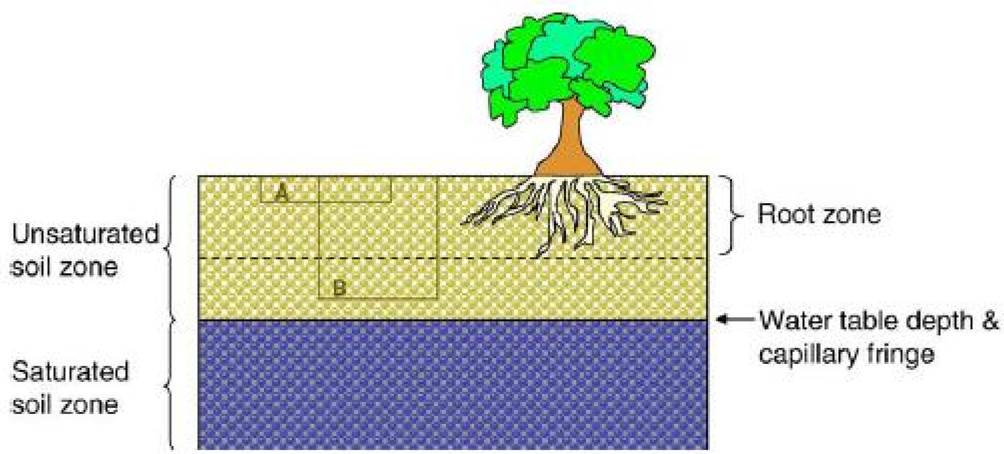


Figure 8: The saturated and unsaturated soil zones. A and B denote two distinct soil moisture volumes. (Seneviratne, 2010).

A water depletion in the unsaturated zone drives to plant water stress, since both precipitation and irrigation implies an increase of the soil water content.

The volumetric soil moisture is defined in equation 1 as:

$$\theta = \frac{volume\ of\ water\ in\ V}{V} \qquad (1)$$

Where the Volume V may be a function of space and time (as a function of the plants' rooting depth, or the water table depth).

Other important quantities to define are the actual maximum soil moisture content of the given soil volume, called saturation soil moisture content, θsat, and the maximum volume of water available to plant, defined as the difference between the field capacity, θfc, and the permanent wilting point θwilt, which is the soil water content at the stage where the plant dies. The quantities mentioned are represented in figure 9: on the right side is represented a soil sample of depth d; at saturation, all pores are filled with water. The water stored in the soil and with the time, it is taken up by the plant roots or evaporated from the topsoil into the atmosphere and if no additional water is supplied to the soil, it gradually dries out. The dryer the soil becomes, the more tightly the remaining water is retained and the more difficult it is for the plant roots to extract it. At a certain stage, the uptake of water is not sufficient to meet the plant's needs. The plant loses freshness and wilts; the leaves change colour from green to yellow. Finally the plant dies. When the soil water content reaches the permanent wilting point, the soil still contains some water, but it is too difficult for the roots to suck it from the soil. Both field capacity and wilting point depends on soil properties, such as soil texture and structure. In this way, the term "plant available water" (PAW) is defined in equation 2:

$$PAW = \frac{\theta - \theta_{wilt}}{\theta_{fc} - \theta_{wilt}} \qquad (2)$$

In general, the absolute moisture content is often expressed as SM, soil moisture [mm]:

$$SM = \theta * d \qquad (3)$$

Where d is the considered the soil depth.

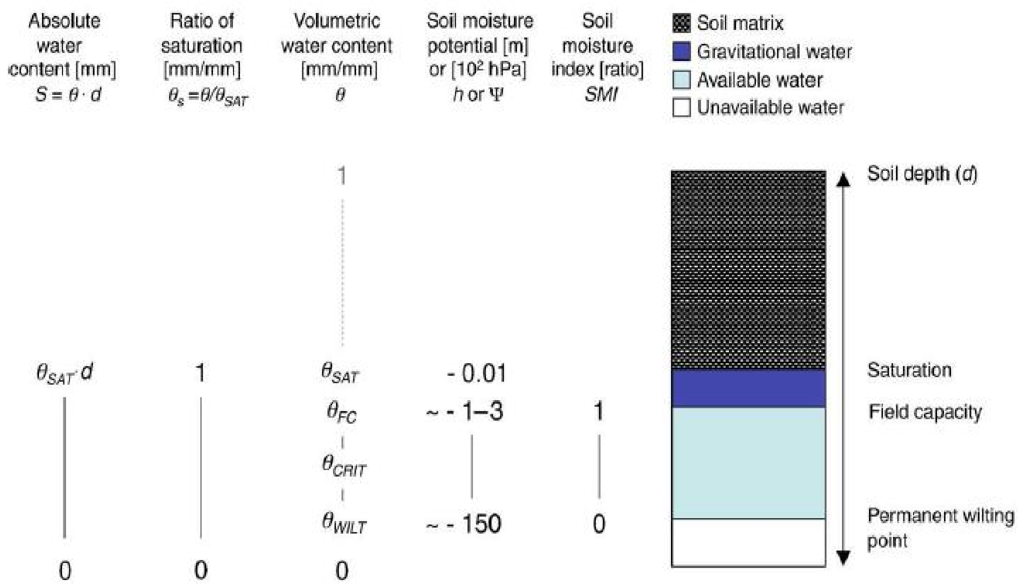


Figure 9: Characteristic soil moisture contents. On the right is represented a soil sample of depth d. At saturation, all pores are filled with water. At the wilting point only the water strongly bound to the soil matrix is remaining and it is inaccessible to the plant. (Seneviratne, 2010).

Recent studies have focused on the interaction between soil moisture and precipitation. The IPCC (Intergovernmental Panel on Climate Change), "Climate Change 2007", showed evidences from observations to validate the relationship between soil moisture and evapotranspiration; this relationship is high in zones between dry and wet climates. In dry regions the evapotranspiration (ET) is strongly controlled by soil moisture, but the absolute values and variations are too small to impact climate variability; on the other side, in wet regions, ET is large, but not controlled by soil moisture (or better, the impact of soil moisture is little). In figure 10 soil moisture content and corresponding evapotranspiration are defined: EF denotes the evaporative fraction, the ratio between latent heat flux and net radiation, and EFmax denotes its maximal value. In the figure, the two main evapotranspiration regimes e defined are the soil moisture-limited regime, in which soil moisture provides a first-order constraint on evaporation and the energy-limited evapotranspiration regime, where evaporative fraction is independent of the soil moisture content.

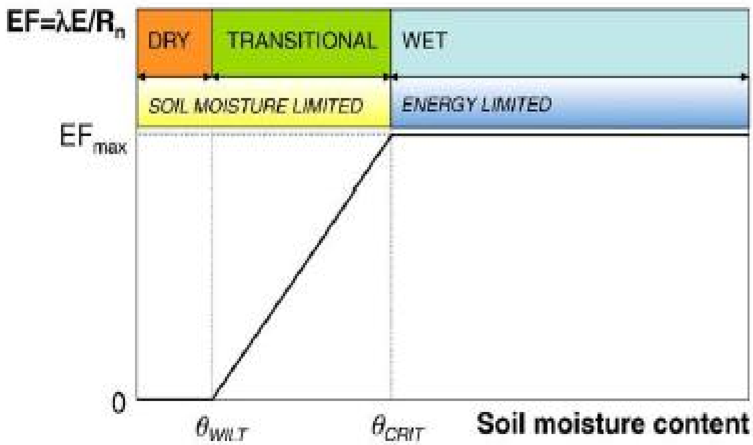


Figure 10: Definition of soil moisture content and corresponding evapotranspiration. EF denotes the evaporative fraction (ratio between latent heat flux and net radiation) and EFmax its maximal value. Two main evapotranspiration regimes are defined: the soil moisture-limited regime (soil moisture provides a first-order constraint on evaporation) and the energy-limited evapotranspiration regime (evaporative fraction is independent of the soil moisture content). (Seneviratne, 2010)

In Figure 11, the processes regarding soil moisture and temperature are presented: Orange arrows indicate processes supporting a drying/warming in response to a negative anomaly soil moisture. Decreased evapotranspiration leads to an increase in sensible heat flux and thus an increase in air temperature.

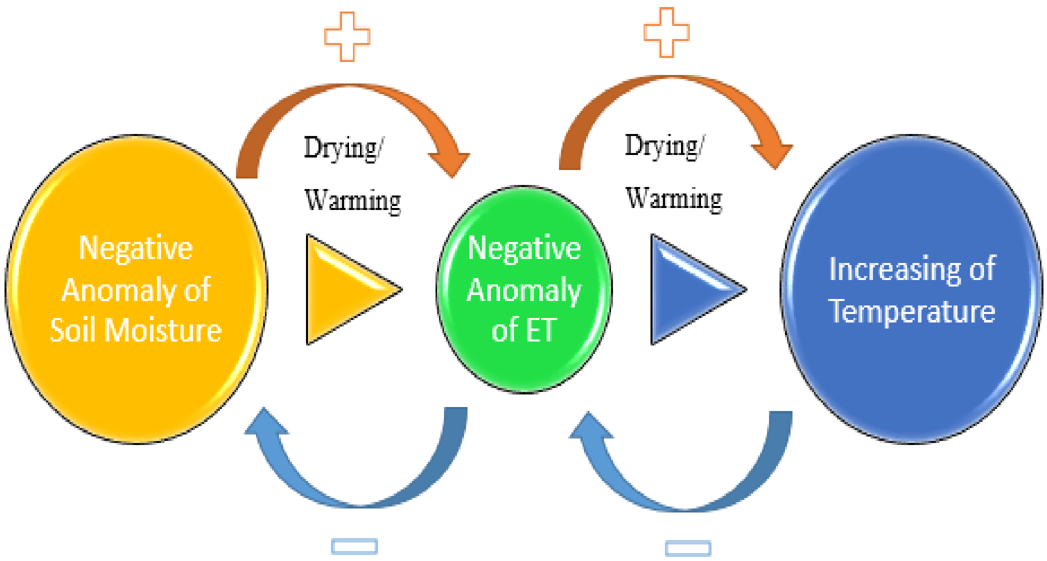


Figure 11: Processes regarding soil moisture and temperature interaction. Orange arrows indicate processes supporting a drying/warming in response to a negative anomaly soil moisture. Decreased evapotranspiration leads to an increase in sensible heat flux and thus an increase in air temperature (Seneviratne, 2010). The blue arrows indicate the opposite phenomena.

In figure 12, the relationship between soil moisture and precipitation is presented: the directly interaction between precipitation and soil moisture is the easiest to establish, but the one between evapotranspiration and precipitation requires more investigations. Increasing evapotranspiration decreases the available soil moisture (and vice versa), but it is not sufficient that enhanced soil moisture and evapotranspiration supporting an additional precipitation: the increasing in precipitation needs to be at least equivalent to the increasing in evapotranspiration in order to observe a reduction of original soil moisture anomaly.

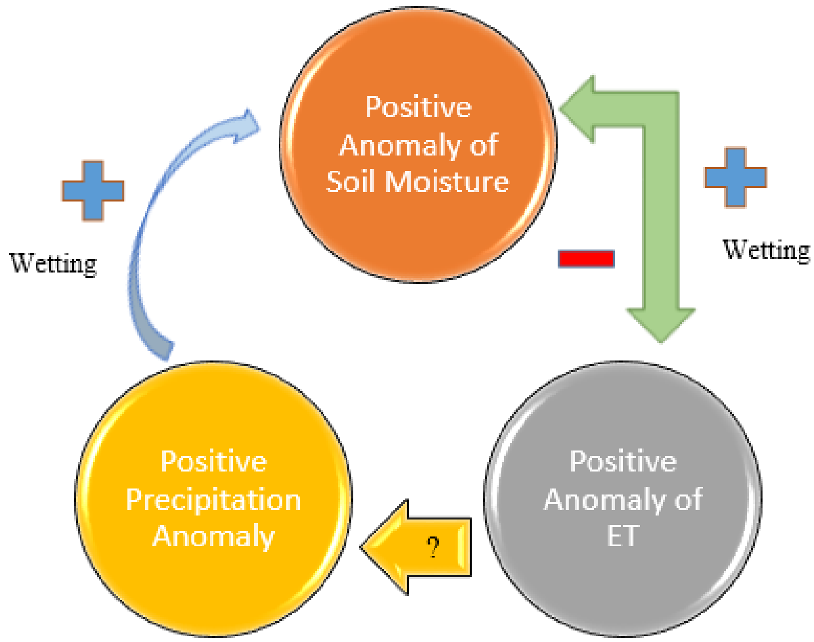


Figure 12: Processes regarding soil moisture and precipitation. The relationship between precipitation and soil moisture is the easiest to establish (Seneviratne, 2010), but the relationship between evapotranspiration and precipitation is the most subject to uncertainty (Koster et al., 2004). Increasing evapotranspiration decreases the available soil moisture (and vice versa), but it is not sufficient that enhanced soil moisture and evapotranspiration supporting an additional precipitation: the increasing in precipitation needs to be at least equivalent to the increasing in evapotranspiration in order to observe a reduction of original soil moisture anomaly (Seneviratne, 2010; Horton, 1933; Dune, 1978).

1.4.4 DROUGHT INDICES:

Drought is quantified through indices. A drought index is a computed value, which is related to some of the cumulative effects of a prolonged and abnormal moisture deficiency. An index of hydrological drought corresponding to levels below the mean in streams, lakes, reservoirs, and the like. However, an index of agricultural drought must relate to the cumulative effects of either an absolute or an abnormal transpiration deficit (UNESCO-OMM, 1992).

The most important characteristics of a drought index are reported in figure 13 (Tsakiris, 2009):

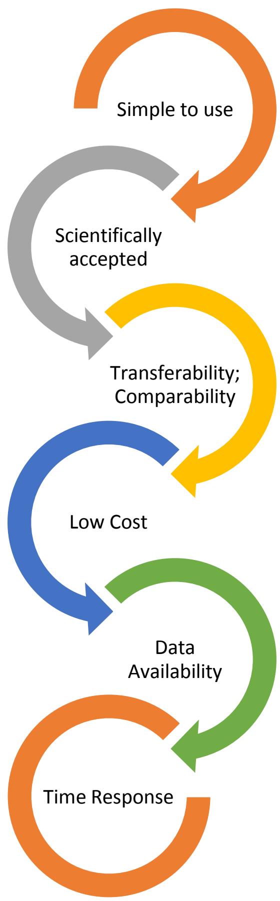


Figure 13: Most important characteristic of a drought index. Simplicity (ease of use and understanding); Correct definition (with scientifically accepted physical sense); Sensitivity (response to a large range of values); Timely response to climate fluctuations; Transferability (ability to use the index in different regions); Data availability (access to long time series and good data); Low cost to produce the index. Adapted from Karampourniotis, 2012.

According to Heim, 2002 due to the complexity of drought, no single index has been able to adequately represents the intensity and severity of drought and its potential impacts on such a diverse group of users. Therefore, many drought parameters have been developed.

On table 1, the most common drought indices are reported, presenting the researcher who has developed them, the year that were developed, the variables that are being analysed and their application.

Table 1: Most common drought indices reporting the researcher who has developed them, the year that were developed, the variables that are being analysed and then their application. Palmer Drought Severity Index (PDSI) is one of the most used meteorological drought index in US. The Standard Precipitation Index (SPI) is one of the most used in Europe.

Index	***Researcher, Year***	***Variables***	***Application***
PDSI	Palmer,1965	Rainfall and temperature on water balance model	Meteorological Drought
SPI	McKee et all,1993	Rainfall	Meteorological Drought
Rainfall Deciles	Gibbs and Maher,1967	Rainfall	Meteorological Drought
Crop Moisture Index	Palmer, 1968	Rainfall and temperature on water balance model	Agricultural Drought
Crop Specific Drought Index	Meyer, 1993	Evapotranspiration	Agricultural Drought
Palmer Hydrological Drought index	Palmer	Rainfall and temperature on water balance model	Hydrological Drought

In 1965, Wayne C. Palmer developed an index to measure the departure of the moisture supply (Palmer, 1965). Palmer based his index on the supply-and-demand concept of the water balance equation, represented in figure 14, taking into account more than just the precipitation deficit at specific locations.

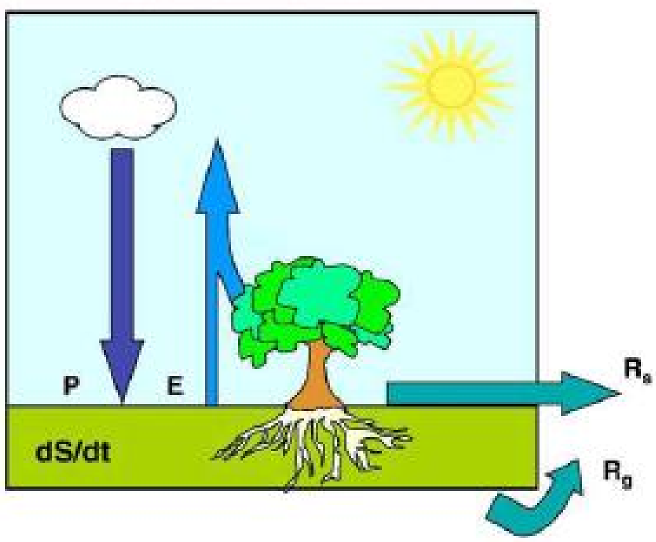


Figure 14: Land water balance scheme for a given surface soil layer. The methodology developed by Palmer to compute drought indexes is based on the supply and demand concept of the water balance; dS/dt refers to the change in water content (as surface moisture, surface water and snow). P is the precipitation, E the evapotranspiration. Rs is the surface runoff and Rg the drainage. The water balance, without considering lateral exchange between adjacent soil volumes is expressed as dS/dt=P-E-Rs-Rg. (Seneviratne, 2010).

The objective of the Palmer Drought Severity Index (PDSI) was to provide measurements of moisture conditions that were standardized. It is a meteorological drought index, and it responds to weather conditions that have been abnormally dry or abnormally wet. The PDSI is calculated based on precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer.

The Palmer Index varies roughly between -6.0 and +6.0; all the values regarding the magnitude of the drought classified by Palmer are reported in table 2.

Palmer arbitrarily selected the classification scale of moisture conditions based on his original study areas in central Iowa and western Kansas (Palmer, 1965). The Index has been calculated on a monthly basis.

Table 2: Values that PDSI uses for the quantification of the drought phenomenon and its qualitative attributes. (Palmer, 1965).

PDSI value	Classification
4.0 or more	Extremely wet
3.0	Very wet
2.0	Moderately wet
1.0	Slightly wet
0.5	Incipient wet spell
Between 0.45 and -0.45	Near normal
-0.5	Incipient dry spell
-1.0	Slightly dry
-2.0	Moderately dry
-3.0	Very dry
-4.0 or less	Extremely dry

The Palmer Index is popular and has been widely used for a variety of applications across the United States. The soil moisture is assumed stored in two soil layers, as shown in figure 15: Palmer defined the upper soil layer; on the other hand, each researcher depending on the study area defines the limit of the underlying soil layer.

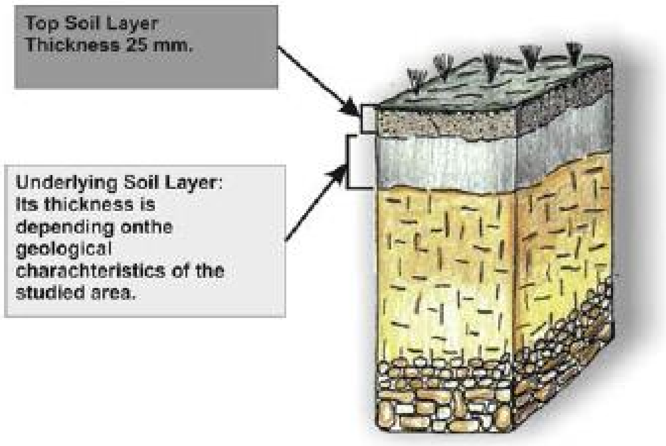


Figure 15: Definition of the upper and underlying layer used by Palmer. From (Karampourniotis, 2012).

One of the most important Palmer's assumption is that evapotranspiration losses takes place only if the potential evapotranspiration is higher than the precipitation.

The analytical steps implemented in Palmer's computational procedure are:

1. Definition of the study area and definition of the necessary assumptions.
2. Finding, processing and tabulation of the monthly rainfall (P) and potential evapotranspiration (PE) data.
3. Calculation of the difference between potential evapotranspiration and precipitation in a monthly step.
4. Definition the available water capacity of the soil (upper layer and the underlying layer) (AWC).
5. Calculation of moisture loss from the upper and underlying soil layer in a monthly step.
6. Calculation of the total losses.
7. Calculation of the stored moisture in the upper and underlying soil layer.
8. Calculation of the total stored moisture
9. Determination of the "calculated" evapotranspiration.
10. Estimation of the potential recharge (PR), potential loss (PL) and Potential Runoff (PRO): there are some items, which have been tabulated as part of the accounting procedure because they will be needed later, but they are not used directly in the water

balance computation: the potential values. Potential values express a measure of a maximum condition that could exist (Palmer, 1965). The potential recharge (PR) is defined as the soil moisture required to bring soil to the total soil moisture maximum. The potential recharge for each month is defined as:

$$PR = S_{max} - S' \qquad (4)$$

Where S' is the total soil moisture at the beginning of the month and S_{max} is the maximum soil moisture content, refered to all layers. The potential soil moisture loss is the amount of moisture that could be lost; it is defined as:

$$PL = min(PE, S') \qquad (5)$$

The potential run-off (PRO) is calculated as:

$$PRO = P_{max} - PR \qquad (6)$$

11. Calculate the average monthly values of all variables of the studied sample.
12. Calculate the constants values:

The coefficients α, β, γ and δ are means for each month averaged over the total period. The example reported by Palmer explanation (1965) to understand better the process, is the follow: the mean evapotranspiration in June is equal to 4.11 mm and the average potential evapotranspiration, for the same month, is equal to 6.11 mm. The average ET is about 67% of the average PE in June. 0.67 is called coefficient of evapotranspiration, and it is indicated with α. In this way, it is possible to estimate the amount of evapotranspiration that one can normally expected in the specific area, in term of PE for that climate. In other words, the coefficient α is used to estimate the amount of ET that would be normal for a particular place after having taken account of the moisture demand (PE) during a particular month (Palmer, 1965).

In the same way are calculated β, coefficient of soil moisture recharge, γ, coefficient of run off and δ, coefficient of loss.

$$\alpha = \frac{\overline{ET}}{\overline{PE}} \qquad (7)$$

$$\beta = \frac{\bar{R}}{\overline{PR}} \qquad (8)$$

$$\gamma = \frac{\overline{RO}}{\overline{PRO}} \qquad (9)$$

$$\delta = \frac{\bar{L}}{\overline{PL}} \qquad (10)$$

13. Calculating CAFEC values of Evapotranspiration (ET) Recharging (R), Runoff (RO) and loss (L): these coefficients are used to estimate the "Climatically Appropriate for Existing Conditions" (CAFEC) values. If in a particular June was much warmer than normal, for example PE=7.00 mm, then it is possible to obtain the evapotranspiration as 0.67*7.00, that is 4.69 mm, and this derived evapotranspiration is called "CAFEC"ET ($\widehat{ET}$). With the same procedure is possible to calculate the CAFEC values for all the factors, for each month:

$$\widehat{ET} = \alpha * PE \qquad (11)$$

$$\hat{R} = \beta * PR \qquad (12)$$

$$\widehat{RO} = \gamma * PRO \qquad (13)$$

$$\hat{L} = \delta * PL \qquad (14)$$

14. Calculation of the CAFEC Precipitation (Pcafec):

The CAFEC precipitation ($\hat{P}$) is defined as the amount of precipitation that would be have maintained the water resources of the area at an appropriate level (Palmer, 1965).

$$\hat{P} = \widehat{ET} + \hat{R} + \widehat{RO} - \hat{L} \qquad (15)$$

15. Calculation of the rainfall excess and deficits deficit (d): The difference between the actual precipitation (the mean precipitation of each month) and the CAFEC precipitation, the departure from the normal weather is calculated:

$$d = P - \hat{P} \qquad (16)$$

16. Calculation of the climate characteristic K : the average moisture supply for a month or a period is: $\bar{P} + \bar{L}$.

    On the other hand the average moisture demand is: $\overline{PE} + \bar{R}$.

    The ratio between the demand and the supply is the climatic characteristic, k that can be estimated for each of the 12 months:

$$k = \frac{\overline{PE} + \bar{R}}{\bar{P} + \bar{L}} \qquad (17)$$

17. Calculation of the index disorder moisture (z): the k-values are used as weighting factors for each of the monthly moisture departures, and the “moisture anomaly index”, z, is calculated:
18.

$$z = d * k \qquad (18)$$

19. Calculation of drought severity for the initial month of the studied sample:

Drought severity is approximated using equation 19:

$$Xi = \frac{\sum_{t=1}^{i} zi}{(0.309t+2.691)} \qquad (19)$$

Nevertheless, this is an unrealistic cumulative procedure because the single wet month during a given dry summer should not have any great influence on the severity of a drought that had continued for long period (Palmer, 1965). For this reason Palmer redefined K, the climatic characteristic, weighted the moisture departure. K is actually a refinement of K', which is Palmer's general approximation for the climate characteristic of a location (Wells, 2004).

$$K'i = 1.5\, log_{10}\left(\frac{\frac{\overline{PEi}+\overline{Ri}+\overline{ROi}}{\overline{Pi}+\overline{Li}}+2.8}{\overline{Di}}\right) + 0.5 \qquad (20)$$

Where $\overline{Di}$ is the average moisture departure for the appropriate month, and

$$Ki = (17.67)/(\sum_{j=1}^{12} \overline{Dj}K'j) * K'i \qquad (21)$$

The value 17.67 is an empirical constant that Palmer obtained using data from nine different places in seven different states. In this way, the Z index is defined by the equation 22:

$$Z = dK \qquad (22)$$

20. Calculation of the Drought Severity Index Palmer:

The Z index can be used to calculate the PDSI for a given month, using equation 23.

$$Xi = 0.897X_{i-1} + \left(\frac{1}{3}\right)Zi \qquad (23)$$

As it can be guessed, PDSI has advantages and disadvantages. First, it is the first comprehensive drought index that is widely used. It is effective in large areas with uniform topography and it is readily available and standardized; on the other hand, it is very unsuitable for very mountainous areas or areas with extreme climatic events (Richard A. Smith, 1993). In addition, PDSI does not consider snow and ice, and does not take into account the runoff until the saturation of both layers (Kogan, 1995).

From the computational point of view, the PDSI has different weaknesses:

- The potential evapotranspiration is not computed with the Thorntwaites's formula;
- The soil profile is not divided into only two layers;
- Available Water Content (AWC) is considered constant.
- Palmer assumed that the potential precipitation is equal to AWC; thus the potential run-off (PRO) is equal to the total soil moisture at the beginning of the month (S'). In reality, there is no relationship between P and AWC (Kingtse, 2006).

The sc-PDSI results in a process that is slightly more complicated than the "original" PDSI, with the aim to replace all the empirical constants in the previous procedure. The sc-PDSI replaces the empirically derived climatic characteristic K and the duration factor with values automatically calculated based upon the historical climatic data of a location (Wells, 2004).

Systematically, the procedure used by Wells (2004) to replace all empirical constant in Palmer's computation is:

I. Calculate all moisture departures;
II. Calculate all moisture anomalies using K' (same of Palmer);
III. Calculate the duration factors (using the least squares method for extremely wet and dry conditions), using the moisture anomalies computed in the previous step;
IV. Calculate the PDSI using the moisture anomalies and duration factors computed in steps 2 and 3;
V. Find the 98th and 2d percentile values of the PDSI;

VI. Compute the new moisture anomalies using the equation 24:

$$K = \begin{cases} K' \left({-4.00}/{2nd\ percentile} \right), if\ d < 0 \\ K' \,{(4.00)}/{2nd\ percentile}, if\ d \geq 0 \end{cases} \qquad (24)$$

VII. Calculate the SC-PDSI.

In 1968, Palmer developed the Crop Moisture Index (CMI); it uses a meteorological approach to monitor week-to-week crop conditions. Whereas the PDSI monitors long-term meteorological wet and dry spells, the CMI was designed to evaluate short-term moisture conditions. It is based on the mean temperature and total precipitation for each week, as well as the CMI value from the previous week. The CMI responds rapidly to changing conditions, and it is weighted by location and time. Because it is used to monitor short-term moisture conditions affecting a developing crop, the CMI is not a good long-term drought-monitoring index. For example, a beneficial rainfall during a drought may allow the CMI value to indicate adequate moisture conditions, while the long-term drought at that location persists

As the PDSI is the most used drought index in North America, the Standard Precipitation Index (SPI) is the most used in Europe. It is a statistical indicator comparing the total precipitation received at a particular location during a period of n months with the long-term rainfall distribution for the same period at that location (Kee, 1993). SPI was developed by T.B. McKee, N.J. Doesken and J. Kleist, of the Colorado State University, in 1993, and the main difference from PDSI is that it considers only precipitation. It is based on the probability of recording a given amount of precipitation, and the probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median), as defined by NOAA (National Climatic Data Centre). The used classification system is shown in table 3; a drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

Table 3: SPI values and relative magnitude of drought defined by McKee, 1993.

SPI value	Drought Magnitude
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

From the mathematical and statistical point of view, the SPI index is defined as (from *ConsorzioLAMMA*):

$$Z = \mathrm{SPI} = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad t = \sqrt{\ln\left[\frac{1}{(H(x))^2}\right]} \quad \text{for} \quad 0 < H(x) \leq 0.5$$

$$Z = \mathrm{SPI} = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \qquad t = \sqrt{\ln\left[\frac{1}{(1 - H(x))^2}\right]} \quad \text{for} \quad 0.5 < H(x) < 1$$

(25)

Where H(x) is the cumulative probability of precipitation and c and d are constants.

In Figure 16 the gamma distribution and the cumulative probability used for the computation of the SPI index are reported, starting from the precipitation recorded.

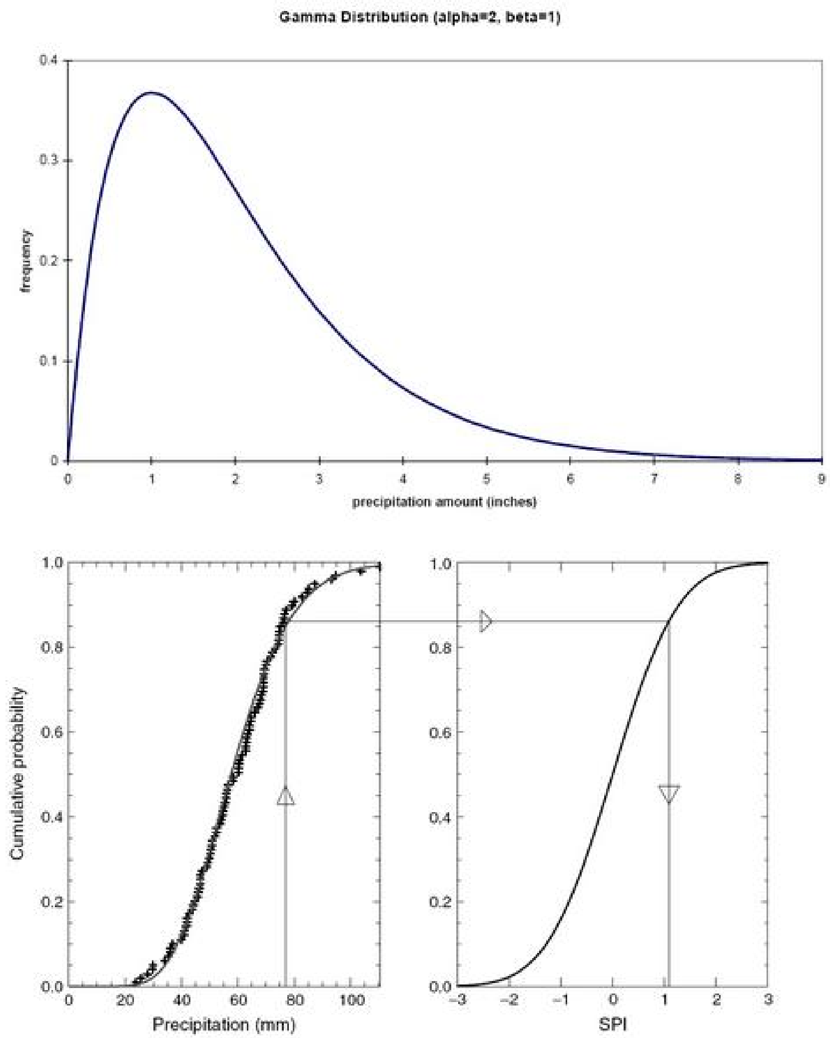


Figure 16: Probability gamma distribution and cumulative probability (ConsorzioLAMMA).

1.4.5 HEAT STRESS INDICATOR:

Bristow and Abrecht developed the calculation of the High Temperature Degree Hours (HDH) in 1991 (Bristow, 1991). The method defines an amount of high-temperature above a critical temperature (indicating a threshold of stress), using only minimum and maximum daily temperatures for the computation. A sine function is used to designate the changing of temperatures during the day. The equations 26, 27 and 28 are used to calculate HDH (based on Bristow and Abrecht).

$$t1 = \frac{D}{\pi} * \left(\frac{asin(Tc - Tmin)}{Tmax - Tmin}\right) \ldots \qquad (26)$$

$$t2 = D - t1 \qquad (27)$$

$$HDH = (Tmin - Tc) * (t2 - t1) - (Tmax - Tmin) * \left(\frac{D}{\pi}\right) * \left(cos\left(\pi * \frac{t2}{D}\right) - cos\left(\pi * \frac{t1}{D}\right)\right) \qquad (28)$$

Where t1 and t2 (expressed in hours) are intermediate variables, D in day length (h), Tc is the critical temperature (°C), T min and T max the minimum and maximum temperature respectively (°C) for the current day.

2 MATERIALS AND METHODS:

The area and its weather characteristic is described, as well as the soil moisture content and the computation of the programs used to determine both potential evapotranspiration, meteorological drought indices (PDSI, sc-PDSI and SPI), hydrological drought index (HPDI) and agricultural drought index (CMI). The steps to compute the High Degree Hours (HDH) index using an excel file is described (Fig 17).

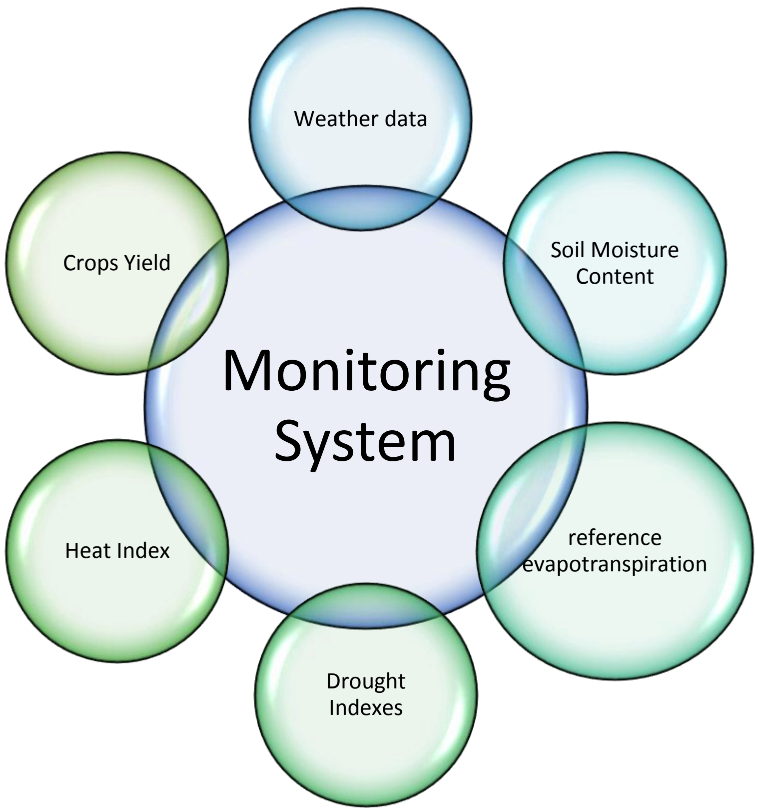


Figure 17: Parameters, which need to be monitored for heat and drought assessment. Weather data are recorded by the weather station; soil moisture content is recorded by the FDR-Sensor; reference evapotranspiration is computed with FAO "ET0 calculator program"; Drought indexes are computed with program in C++ provided by "Greenleaf Project"; Heat Index (high degree hours) is calculated in excel.

2.1 AREA DESCRIPTION:

The Marchfeld region is the largest plain of Lower Austria, with an extension of about 45 km in length and 30 km in width. It is part of the Vienna Basin and it is delimitated to the south by the River Danube, to the east by the River March/Morava, to the north by the hilly regions of the Weinviertel and to the west by the Bisamberg Hill (alt. 385 m). Gross-Enzersdorf (latitude 48° 12´N, longitude 16° 34´E and altitude 153 m above the see level) is situated in the Marchfeld region, where the experimental research centre of BOKU is located (fig.18).

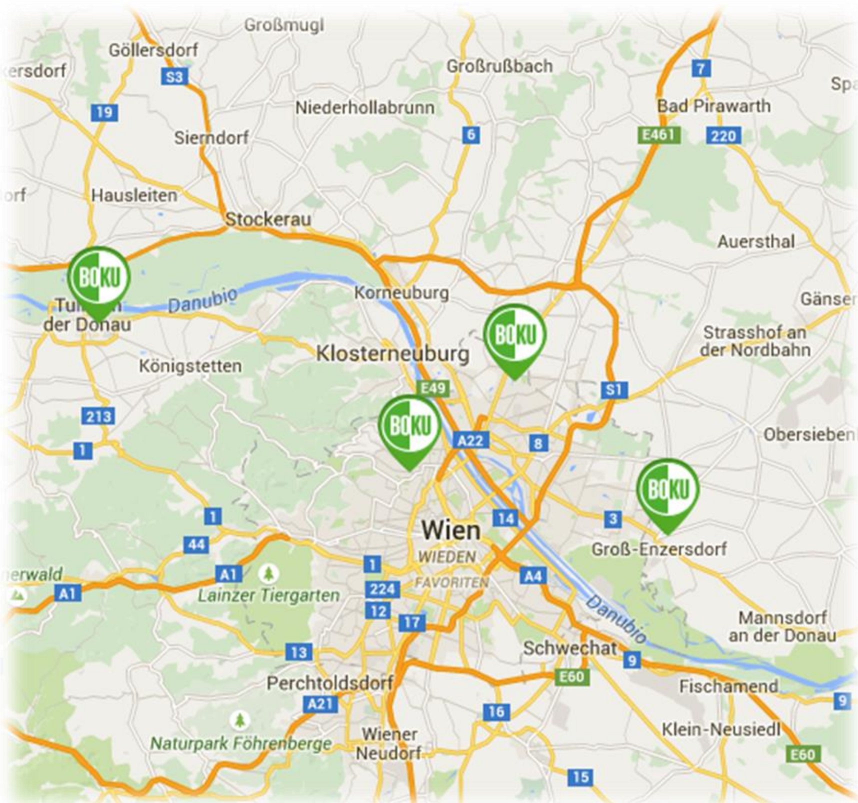


Figure 18: BOKU locations near Vienna

In this location the lysimeter and a weather station (Zentralanstalt für Meteorologie und Geodynamik, ZAMG) are situated. The web page of the lysimeter station, with the main features regarding the station, is reported in figure 19 (from http://ihlw.boku.ac.at/lysi/).

Figure 19: web page of lysimeter and weather station (http://ihlw.boku.ac.at/lysi/index.php?page=start/home)

The weather data (mean temperature, maximum temperature, minimum temperature, relative humidity, wind velocity at 2 m. above the surface and precipitation) of every day since 1990 until 2013 are collected by the meteorological weather station (Zentralanstalt für Meteorologie und Geodynamik, ZAMG). Evapotranspiration data are recorded by the lysimeter, from 1990 to 2013. The volumetric water content is recorded from 2005 to 2012 with a FDR-sensor (SENTEK Capacitance Sensor), but data are missing for the following periods: from 23rd November 2007 to 22nd January 2008; from 18th December 2008 to 4th February 2009; from 29th November 2012 to 12th December 2012. The weather and the lysimeter station, where the data are collected, are shown in figure 20.

Figure 20: Lysimeter and weather station in Gross-Enzersdorf

The soil at the experimental field in Gross-Enzersdorf could be classified as the soil type 19 according to the Austria Soil Classification, ÖBK (Milada Štastná, 2002). The soil is described as chernozem on fine calcareous sediments over gravel and sand (Milada Štastná, 2002). Following the Unified Soil Classification System (USCS), soil texture is sandy loam to loamy sand (Reinhard Nolz, 2009).

The characteristics regarding water availability of the soil to the plant such as Field Capacity (Fc), the Permanent Wilting Point (PWP) and the Available water content (AWC) are reported in table 4.

Table 4: Considered values for field capacity (FC), permanent wilting point (PWP) and available water content (AWC) are reported in percentage (%). These approximated values are obtained by personal communication with Priv.-Doz. Dr. Bodner, Gernot (July 2015).

FC	PWP	AWC
%	%	%
32	10	22

The water content is recorded by the FDR-Sensor at the following soil depths: 10 cm, 30 cm, 50 cm, 70 cm, 90 cm, 110 cm, 130 cm, 150 cm.

The soil moisture (mm) for the soil layer between *i* (between 1 and n) is calculated using equation 29:

$$SM_{i-n.} = SM_{0-1} + \sum_{i=1}^{n} \frac{\theta_i + \theta_{i+1}}{2} * \Delta z \qquad (29)$$

Where θ_i is the percentage of water content for the *i*-soil depth (i=1 for soil depth at 30 cm, i=2 for soil depth at 50 cm, and so on); Δz is the soil layer depth, equals to 200 mm andSM_{0-1} in the soil moisture of the top layer, between 0 and 19 cm depth; it is considered constant for simplicity. The procedure followed in represented in figure 21.

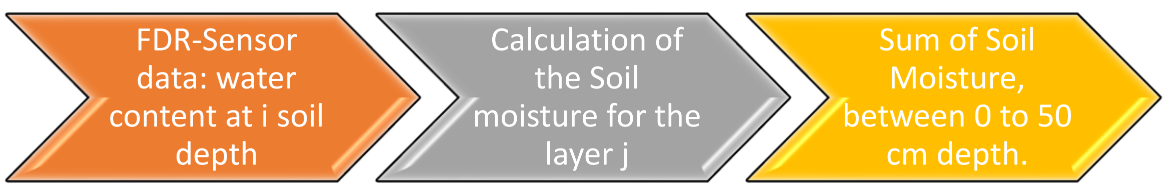


Figure 21: Procedure to calculate the soil moisture between 0 and 50 cm soil depth. Starting from the water content recorded by the SDR-Sensor, the soil moisture for each layer i is calculated, and the result is obtained by the sum of the soil moisture in each layer.

2.2 POTENTIAL EVAPOTRANSPIRATION COMPUTATION:

The potential evapotranspiration is obtained with the use "ET0 calculator software" (Version 3.2, September 2012, in Fig.22) of the Food and Agricultural Organization of the United Nations (FAO, Land and water division), importing the data collected in Gross Enzersdorf's station. The ET0 calculator software by means of the FAO Penman-Monteith equation (equation 30) assesses the potential evapotranspiration. This method has been selected by FAO as the reference because it closely approximates grass ETo at the location evaluated, is physically based, and explicitly incorporates both physiological and Aerodynamic parameters (Allen, 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)}$$

(30)

Where:

ETo reference evapotranspiration [mm day-1],

Rn net radiation at the crop surface [MJ m-2 day-1],

G soil heat flux density [MJ m-2 day-1],

T mean daily air temperature at 2 m height [°C],

u2 wind speed at 2 m height [m s-1],

es saturation vapour pressure [kPa],

ea actual vapour pressure [kPa],

es-ea saturation vapour pressure deficit [kPa],

D slope vapour pressure curve [kPa °C-1],

g psychrometric constant [kPa °C-1].

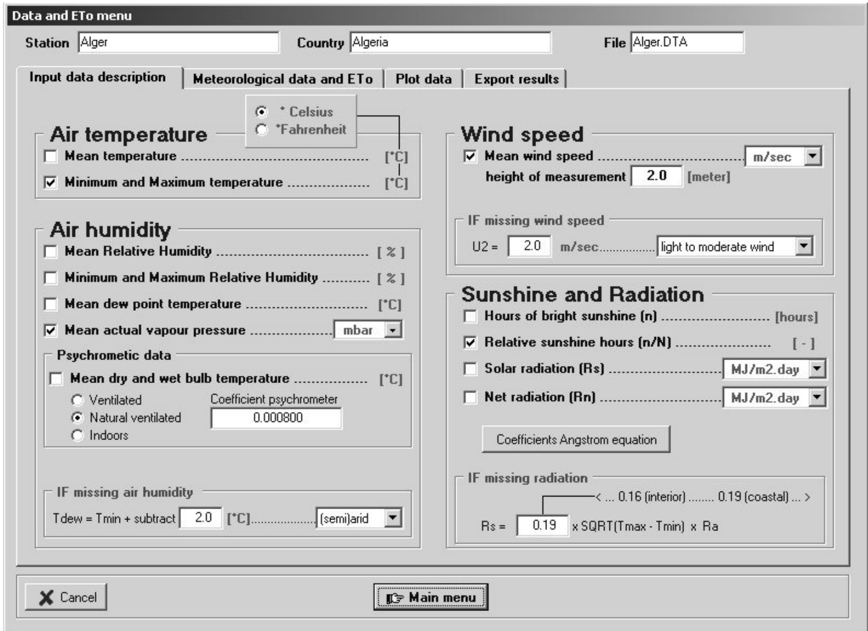


Figure 22: ET0 calculator software starting page. The main input are the air temperature, the air humidity, the wind speed and, finally, the sunshine and the radiation. The units of the data can be selected.

The description of the program and the main steps to use the program are presented, following the « Reference Manual IV 32, version 3.2, September 2012 », provided by FAO when the program is downloaded.

• Data base management section in which the Path (directory and folder where data files are stored), can be changed. There is the possibility to Select a data file or create a new file in which meteorological data from climatic stations are stored or to Import climatic data from file. The data create in a new file must be in *.DSC (files describing the station) and *.DTA (files containing meteorological data).

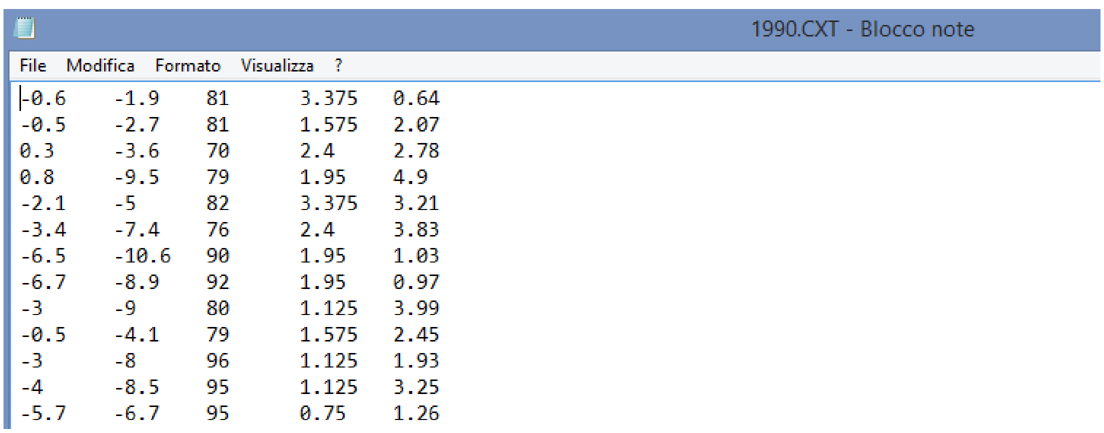
• Selected climatic station: the name of the selected file and the corresponding name of the climatic Station and Country are updated. Is possible to add the Station characteristics, expand or shorten the Data range, change the thresholds of the Data limits and examine the available meteorological data.

• ETo calculation section contains the ETo Calculator. In the corresponding Data and ETo menu, the climatic parameters used to calculate ETo can be selected and results can be exported as reports. The climatic data are imported in free format text files (*.CXT); a text file is a file with extension CXT in which climatic data for a specific period is saved in columns. It is a copy from a spreadsheet. Once a text file has been selected, the program displays:

- The number of data lines (rows) which should correspond with the specified time range (from-to);

- The number of climatic parameters, which corresponds with the number of columns of the text file.

The input file (figure 21) contains the maximum air temperature in degree Celsius (column1), the minimum air temperature in degree Celsius (column2), the mean Relative humidity in percentage (column3) and the wind speed in meter per second measured at 2 m above soil surface (column4).



-0.6	-1.9	81	3.375	0.64
-0.5	-2.7	81	1.575	2.07
0.3	-3.6	70	2.4	2.78
0.8	-9.5	79	1.95	4.9
-2.1	-5	82	3.375	3.21
-3.4	-7.4	76	2.4	3.83
-6.5	-10.6	90	1.95	1.03
-6.7	-8.9	92	1.95	0.97
-3	-9	80	1.125	3.99
-0.5	-4.1	79	1.575	2.45
-3	-8	96	1.125	1.93
-4	-8.5	95	1.125	3.25
-5.7	-6.7	95	0.75	1.26

Figure 23: example of input file for "ET0 calculator program": in the first column in reported the maximum air temperature (°C), in the second column the minimum air temperature (°C), in column 3 the relative humidity (percentage) and finally, in column 4 the wind speed (m/s) at 2m.above soil surface.

2.3 DROUGHT INDICES COMPUTATION:

Soil moisture content, evapotranspiration and weather parameters mentioned are compared with the drought indices calculated with the following program (http://greenleaf.unl.edu/downloads/).

The GreenLeaf Project

The GreenLeaf project it represents a revolution in software for agricultural decision support. Instructions provided by "PDSI User's Manual, version 2.0" are followed; this program runs from a DOS command and thanks to it is possible to obtain the PDSI (Palmer Drought Severity Index), self-calibrated PDSI (sc-PDSI), the HPDI (Hydrological Palmer Drought Index), the Z index and the CMI (Crop Moisture Index). For the mentioned weakness of PDSI (see section "1.3.4 Drought quantification"), different indices are computed and compared. The computational steps followed by the program are described:

- Carry out a hydrologic accounting by months for at least 25 years of data (data from 1980 to 2013 are used); in the case there are not available data, it can be represented in the input files by using the number -99.00;
- AWC is very important to the calculations of the PDSI;
- Prepare the followed named input files to calculate the monthly PDSI: monthly_T ; monthly_P; mon_T_normal; parameter.
- To calculate the weekly CMI, four files are needed: weekly_T; weekly _P; wk_T_normal; parameter.

The data provided directly by the weather station (ZAMG) are from 1990 to 2013; the outputs are more precise, higher are the amount of input data provided. For the following reason, precipitation and temperature data from 1980 to 1990, related the same area, are provided by Priv.-Doz. Dr. Bodner, Gernot.

The files monthly_T and monthly_P hold the temperature or precipitation data for a station. Each line starts with the year and is followed by 12 (52 in case of weekly file) temperature (or precipitation) entries. In mon_T_normal (Fig.24) and wk_T_normal files, the normal temperature data for a station is reported. It has only 12 (or 52) entries, all on one line. The values in the file are the normal, or average, temperature over all the years on record for each of 12 months (or 52 weeks). The parameter file contains two numbers: the first number should always be the Available Water Holding Capacity and the second number should be the latitude of the station, in decimal degrees (AWC: 180; Latitude: 48.20).

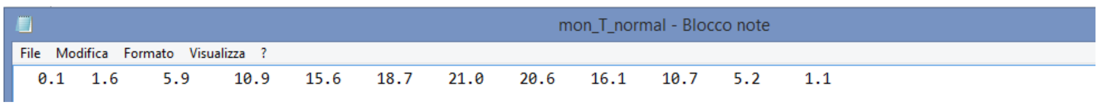


Figure 24: mon_T_normal file input example; entry values of the monthly mean temperature, between 1980 and 2013.

The SPI (Standard Precipitation Index) is obtained using the program provided by The National Drought Mitigation Centre at the following link: http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx

As for the previous program described, it is compiled in C++ for PC. The input file contains only one folder, organized in 3-column format: Year, month and monthly precipitation value (in this case, missing values data are written as “0”). The program outputs are organized in one file containing the actual SPI.

2.4 HEAT STRESS INDEX COMPUTATION:

The weather station located in Gross-Enzersdorf recorded daily maximum and minimum temperatures between 1990 and 2013. The formulae 26, 27 and 28 reported in section 1.3.4, are easily to implement in an excel file.

Figure 25 shows the organization of the excel sheet: the date is reported in the first column, followed by the values of the daily maximum and minimum temperatures (in column 2 and 3, respectively), expressed is °C.

Date	Maximum Temperature, Tmax	Minimum Temperature, Tmin
JJJMMDD	°C	°C

Figure 25: Excel file preparation to calculate HDH index. In the first column, the date is reported; in the second and third columns the maximum temperature and the minimum, respectively, are reported in °C.

The day length D (h) and the critical temperature Tc (°C) are fixed parameters. The respectively values are shown in table 7.

Table 5: Parameters chosen values

Critical Temperature, Tc	Day length, D
°C	h
27	12

t1, t2 and HDH are calculated, following the method proposed by Bristow and Abrecht. The formulae 26, 27 and 28 are reported as written in formulae 29, 30 and 31 respectively, in the excel file:

$$t1 = IF\ \left(Tmax > Tc; \frac{D}{\pi} * arcsen\left(\frac{Tc - Tmin}{Tmax - Tmin}\right); 0\right)\ \ (29)$$

$$t2 = IF\ (t1 = 0; 0; D - t1)\ \ (30)$$

$$HDH = (Tmin - Tc) * (t2 - t1) - (Tmax - Tmin) * \left(\frac{D}{\pi}\right) * \left(cos\left(\pi * \frac{t2}{D}\right) - cos\left(\pi * \frac{t1}{D}\right)\right)\ \ (31)$$

The Accumulation of the HDH index (“HDHcum”) is calculated as the sum between the values of the day before and the HDH index of the respectively day.

2.5 CROP YIELD:

The purpose of the study is to understand how the most widely crops cultivated in Gross-Enzersdorf (winter wheat, spring barley, maize and sugar beet) respond to different conditions; sometimes they can be more affected by drought, other times by heat stress.

Crop Yield is defined as a measurement of the amount of a crop that was harvested per unit of land area. It is usually expressed in ton/ha or in kg/ha.

Correlations between the yield of these crops collected by farmers and the different parameters (precipitation, evapotranspiration, soil moisture, and drought and heat indices) are calculated.

Winter wheat yields from the years 2000, 2002, 2004, 2006, 2007, 2008 and 2009 are collected in Gross-Enzersdorf and are provided by Priv.-Doz. Dr. Bodner, Gernot. Yield data regarding maize, sugar beet and spring barley were not available. The comparison between the weather data collected, drought and heat indexes and the crops yield represents the core of the study. For this reason, Dr. Macaigne, Peggy, has provided the yield data regarding the three crops mentioned from the nearest area, Hollabrunn. Hollabrunn (longitude 16°3', latitude 48°37') is a city in Lower Austria, 264 m.a.s.l. and the weather conditions are similar to Gross-Enzersdorf.

Average Yield data reported by AGROFAO for the four crops mentioned are reported and are shown in table 8.

Table 6: Mean planting and harvesting periods and mean Yield for Winter Wheat, Spring Barley, Sugar Beet and Maize (from AGROFAO).

Crop:	**Planting:**	**Harvesting:**	**Yield (kg/ha):**
Winter Wheat	March	July	3400
Spring Barley	March	July	3200
Sugar Beet	April	October	52700
Maize	May	October	6200

The CORRELATION function of excel is used in order to determine correlations between the data analysed and computed, as explained in the previously section. The Excel CORREL function calculates the Pearson Product-Moment Correlation Coefficient for two sets of values; it is a statistical measurement of the linear association between x and y. The equation 32 give the Pearson product-moment correlation coefficient (r):

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}$$

(32)

Where x and y are the sample means of the two arrays of values. A value of r close to +1 indicates a strong positive correlation, and a value of r close to -1 indicates a strong negative correlation. No correlation subsists if r is close to 0.

3 RESULTS AND DISCUSSION:

3.1 WEATHER DATA:

The weather data recorded at the weather station of Gross-Enzersdorf, from 1990 to 2013, are presented. The average values of monthly precipitation recorded in Gross-Enzersdorf between 1990 and 2013 are shown in fig. 26. The figure shows that the monthly mean values of precipitation increase during the summer period from May to September.

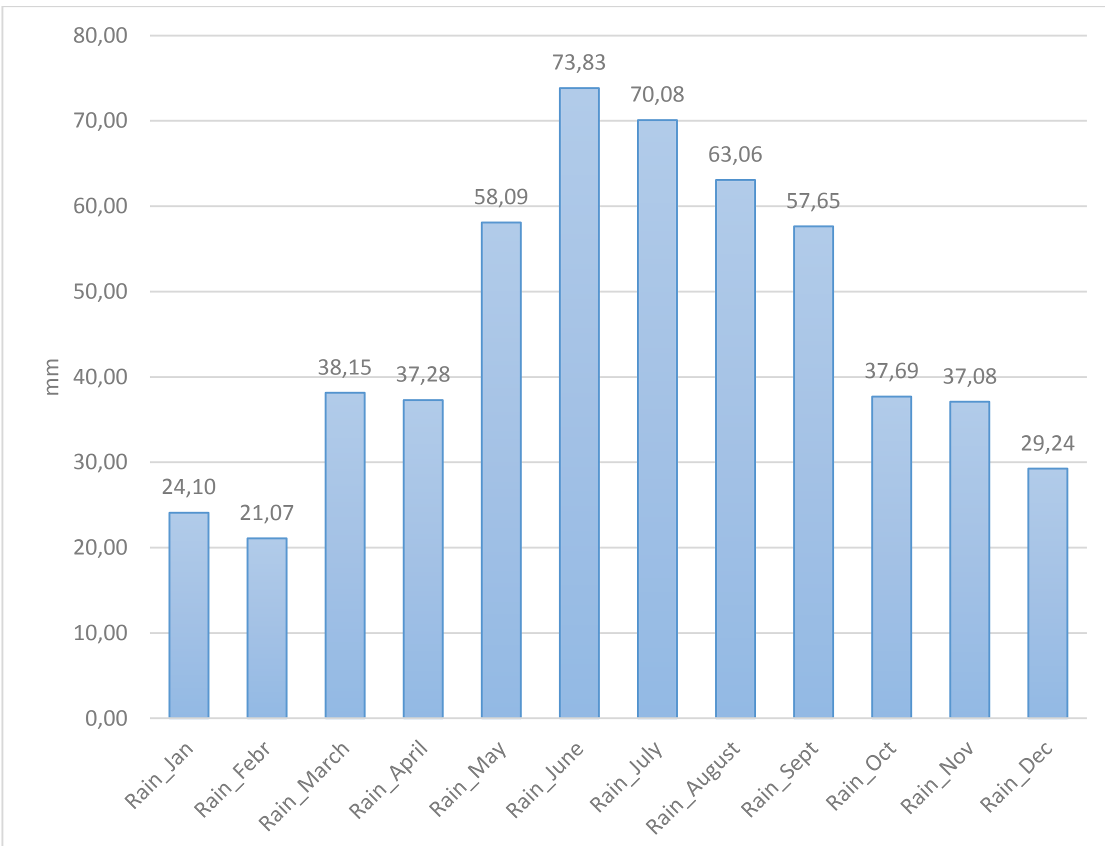


Figure 26: average values of monthly precipitation from daily data recorded between 1990 and 2013.

Yearly cumulated precipitation recorded from 1990 to 2013 is presented in fig.27. In 1992, 1994, 1998, 2001, 2003 and 2011 the yearly precipitations are lower compared to the other years.

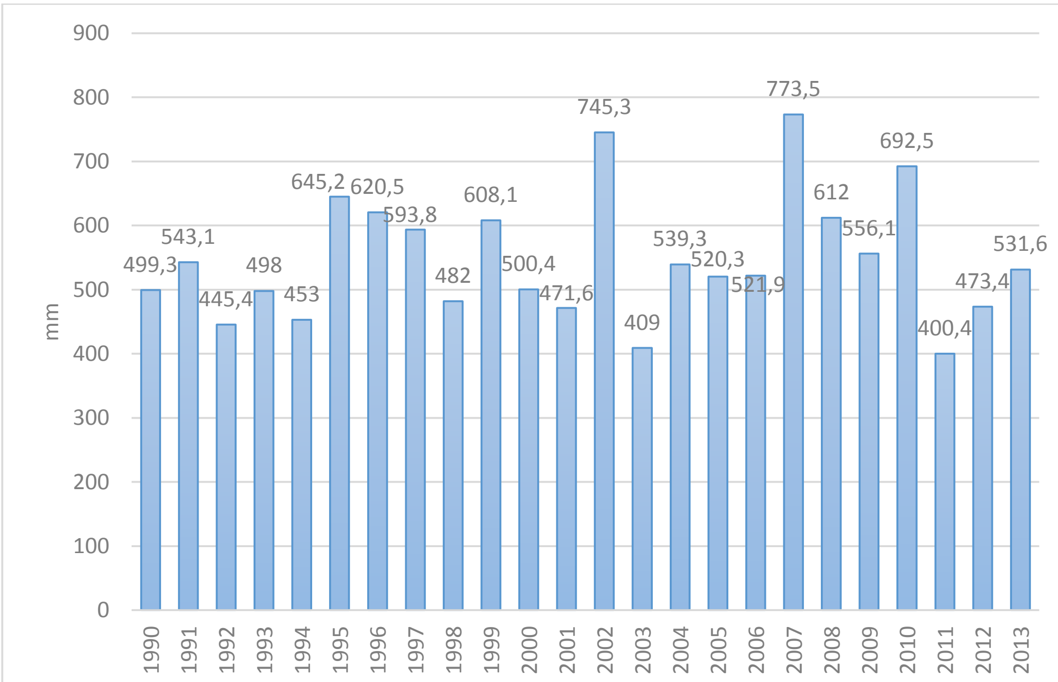


Figure 27: Yearly cumulated precipitation from daily data recorded between 1990 and 2013.

Daily temperatures were also analysed, especially during summer periods. Mean monthly temperatures from1990 to 2013 are reported in fig.28. On the figure, July represents the month in which temperatures are the highest, while January is the month in which temperatures are the lowest.

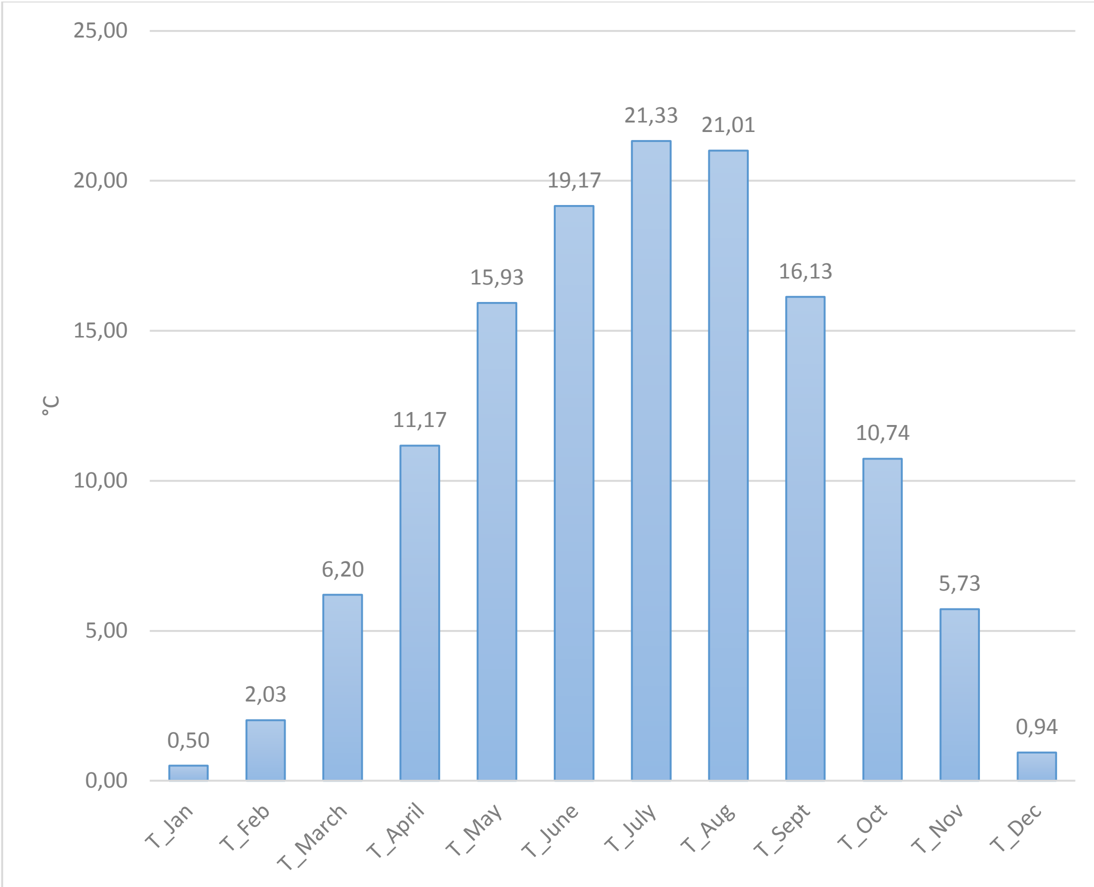


Figure 28: Average monthly mean temperatures from 1990 to 2013.

The average temperature during the hottest month (July) is equal to 21.33°C.

No significant correlation between the monthly cumulated precipitations and mean monthly temperatures has not been found using the Pearson Product-Moment Correlation Coefficient (Excel CORREL function) for the time period 1990-2013.

3.2 POTENTIAL EVAPOTRANSPIRATION:

The potential evapotranspiration has been computed using the program "ET0 calculator Software" (provided by FAO) for the time series between 1990 and 2013 as shown figure 29.

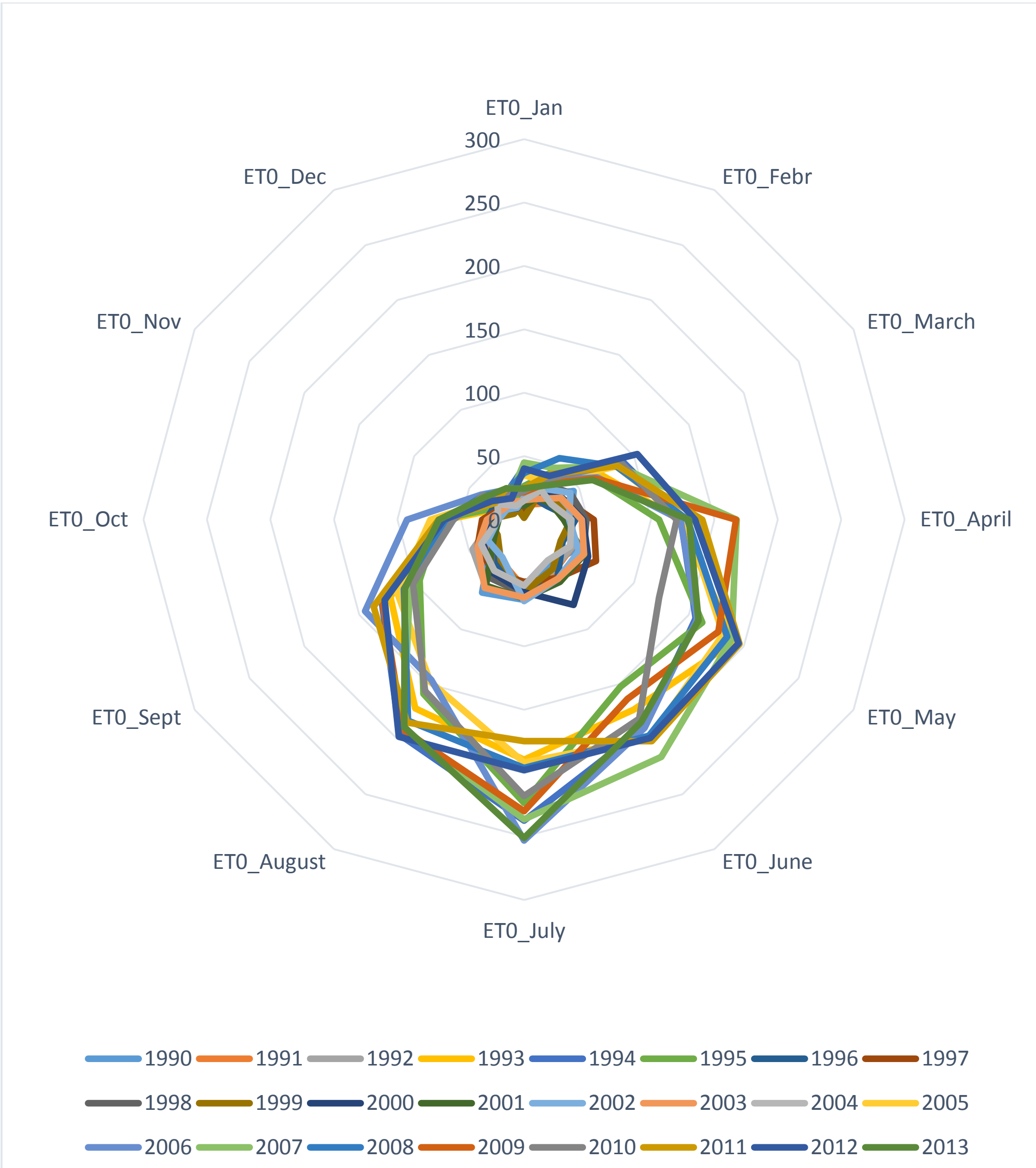


Figure 29: Potential Evapotranspiration (mm) obtained with the use of "ET0 calculator software" from 1990 to 2013.

The highest potential evapotranspiration is always computed during the month of July. A net increase of the amount of the monthly potential evapotranspiration for the entire year has been observed from 2001.

3.3 DROUGHT INDICES:

The main results of the different drought indices obtained with the program provided by "GreenLeaf Project" are shown in this chapter.

The output values obtained by the computation of PDSI are shown in figure 30.

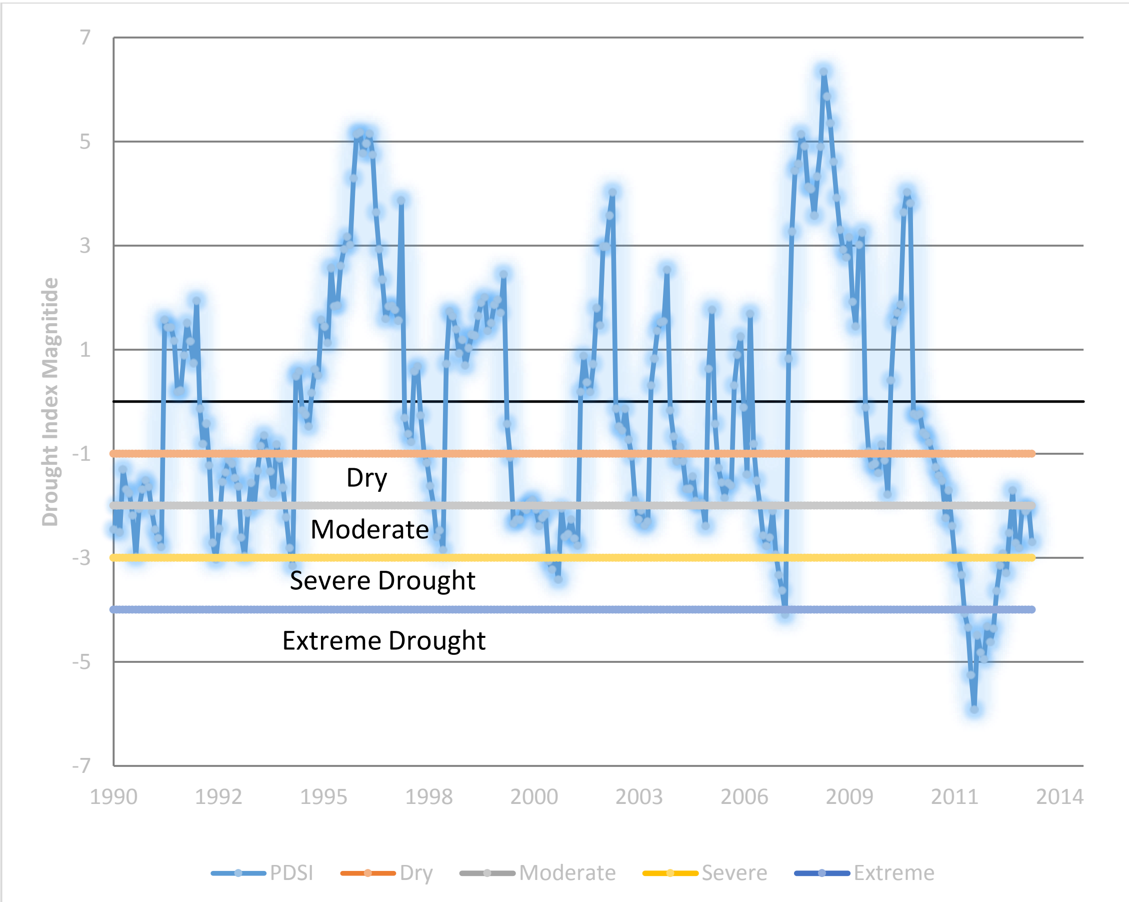


Figure 30: Monthly PDSI from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "dry" periods, the zone between grey and yellow lines defines "moderate" drought periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods.

The values of the magnitude of drought, defined by Palmer are reported in table 9.

Table 7: Magnitude of drought for PDSI values (Palmer, 1965).

PDSI values for the 11 drought (or wet) categories:	
4.0 and above	Extreme moist spell
3.0 to 3.99	Very moist spell
2.0 to 2.99	Unusual moist spell
1.0 to 1.99	Moist spell
0.5 to .99	Incipient moist spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.0 to -1.99	Mild drought
-2.0 to -2.99	Moderate drought
-3.0 to -3.99	Severe drought
-4.0 and below	Extreme drought

The number of days from 1990 to 2013 classified as extreme drought, severe drought, and mild, moderate or without any drought are reported in table 10.

Table 8: Number of days classified as extreme, severe, moderate, mild and incipient dry drought using PDSI, from 1990 to 2013.

CLASSIFICATION	NO DROUGHT	INCIPIENT DRY SPELL	MILD DROUGHT	MODERATE DROUGHT	SEVERE DROUGHT	EXTREME DROUGHT
DAYS	135.00	35.00	54.00	59.00	12.00	11.00

The number of days that does not present drought are higher; on the other hand, from figure 30, the extreme drought periods are recorded only during the last years (from April 2012).

As explained, PDSI has different weakness. For this reason, others drought indices are considered, as the self-calibrated PDSI (fig. 31).

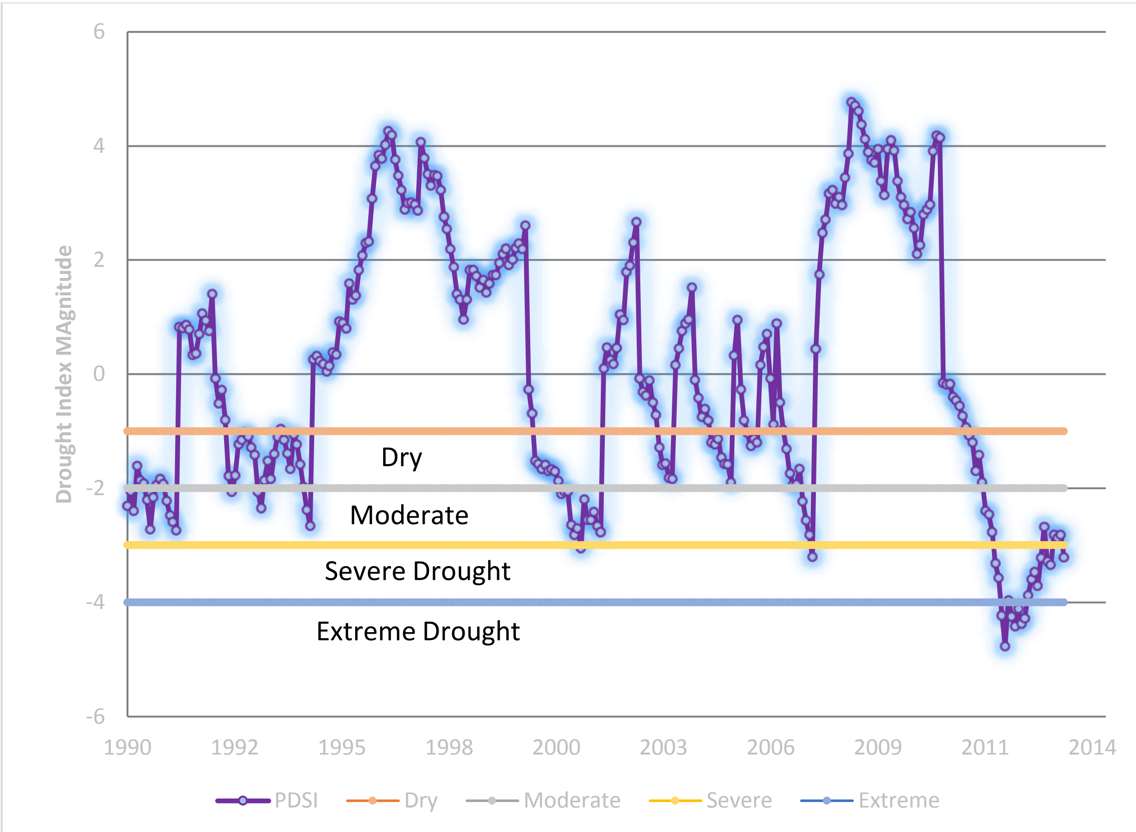


Figure 31: Monthly sc-PDSI computed from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "dry" periods, the zone between grey and yellow lines defines "moderate" drought periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods

The magnitude of the sc-PDSI is the same of the values indicated in table 9 for the original PDSI. The same methodology described for the original PDSI is followed and the number of days from 1990 to 2013 classified as extreme drought, severe drought, mild, moderate and without any drought are reported in table 11.

Table 9: Number of days classified as extreme, severe, moderate, mild and incipient dry drought using sc-PDSI, from 1990 to 2013.

Classification	No drought	Incipient Dry Spell	Mild Drought	Moderate Drought	Severe Drought	Extreme Drought
days	156.00	32.00	60.00	37.00	13.00	7.00

The two indices are compared in fig. 32.

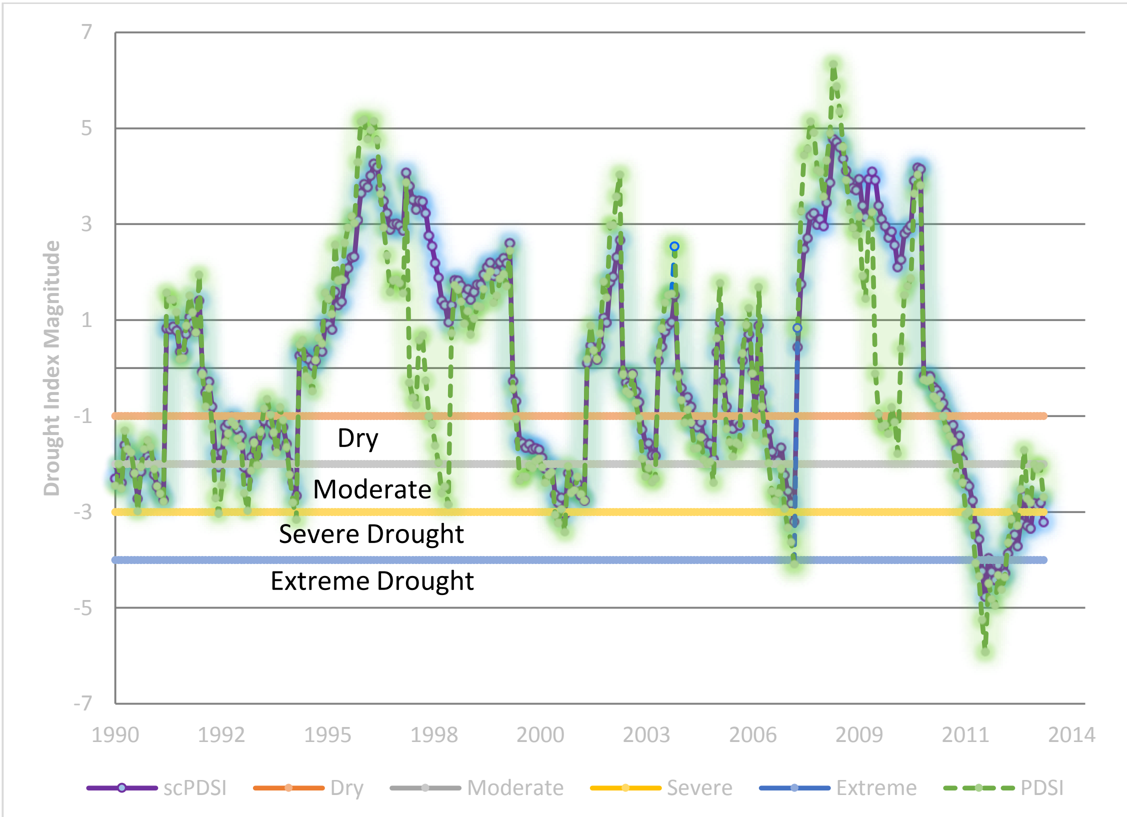


Figure 32: Comparison between monthly PDSI and monthly sc-PDS from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "dry" periods, the zone between grey and yellow lines defines "moderate" drought periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods

Different results between original and sc-PDSI are noticeable from February 1998 until July 1998 and from November 2010 to July 2010. Sc-PDSI is considerable stronger than PDSI. PDSI is weak during winter period (Kogan, 1995) and the differences reported between the two indices are due to this reason. The sc-PDSI presents less severe, moderate and mild drought period, compared with the results obtained with the original index.

In figure 33 the correlation between original and sc-PDSI (R^2=0.7769) is shown:

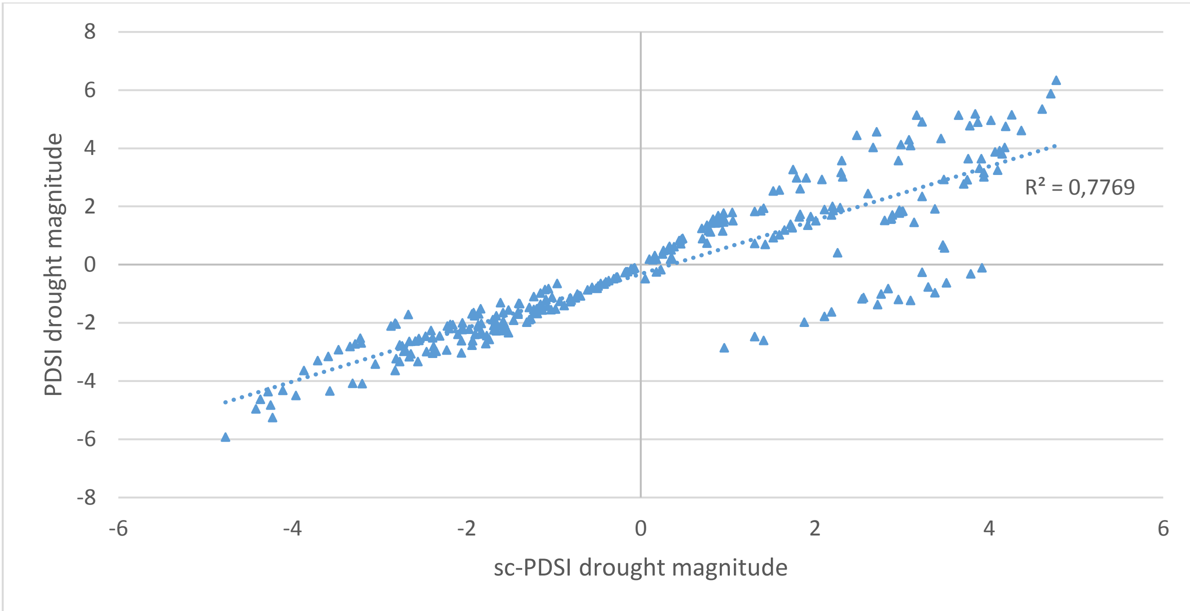


Figure 33: sc-PDSI vs PDSI: The figure present the correlation between the two indexes. Data between 1990 and 2013 are analyzed.

Sc-PDSI shows positive correlation with the amount of rainfall during summer periods (r=0.55 in May, r=0.56 in June). The sc-PDSI shows, also, strong negative correlation with the maximum temperature during the hottest months, July and August (r=-0.70 in July, r=-0.66 in August), and it is shown in figure 34.

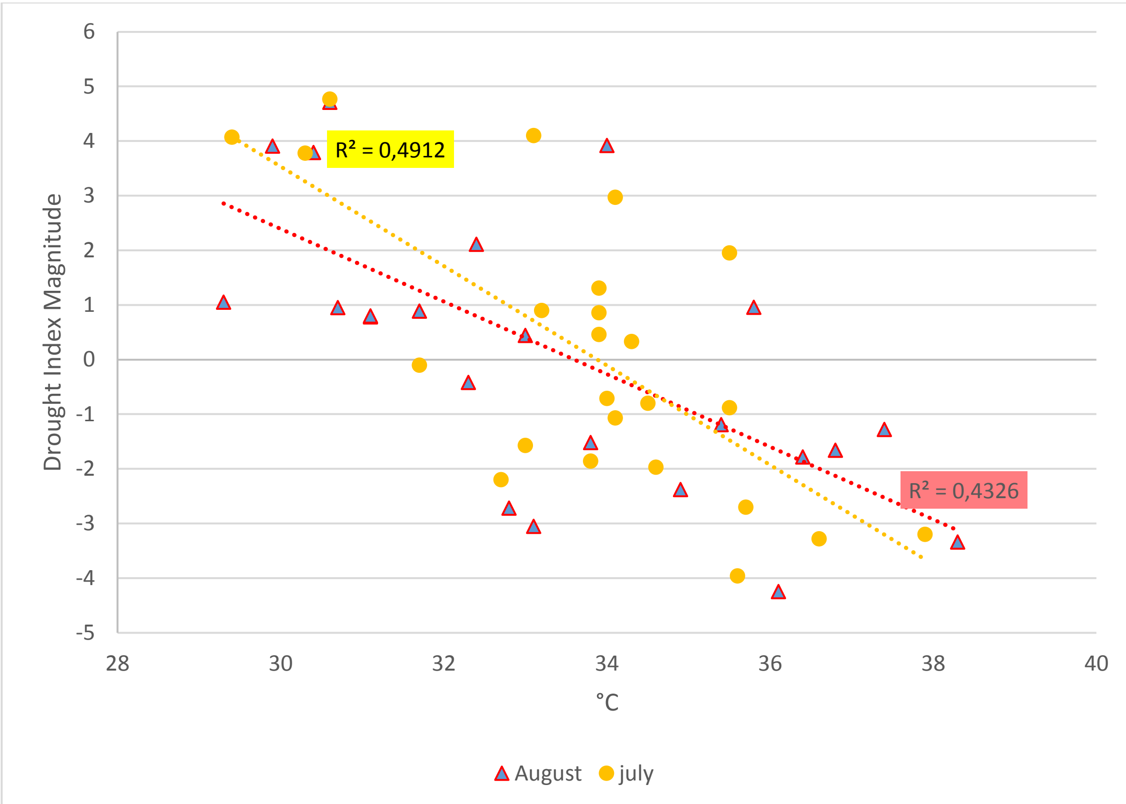


Figure 34: Maximum temperature (Tmax) vs sc-PDSI from 1990 to 2013: the figure shows the negative correlation between the Maximum temperatures (°C) and the sc-PDSI in July and August, between 1990 and 2013.

The Hydrological Palmer Drought Index (HPDI, or HDSI) is reported in figure 35, compared with the original PDSI. The HDSI indicates the hydrological impact of drought.

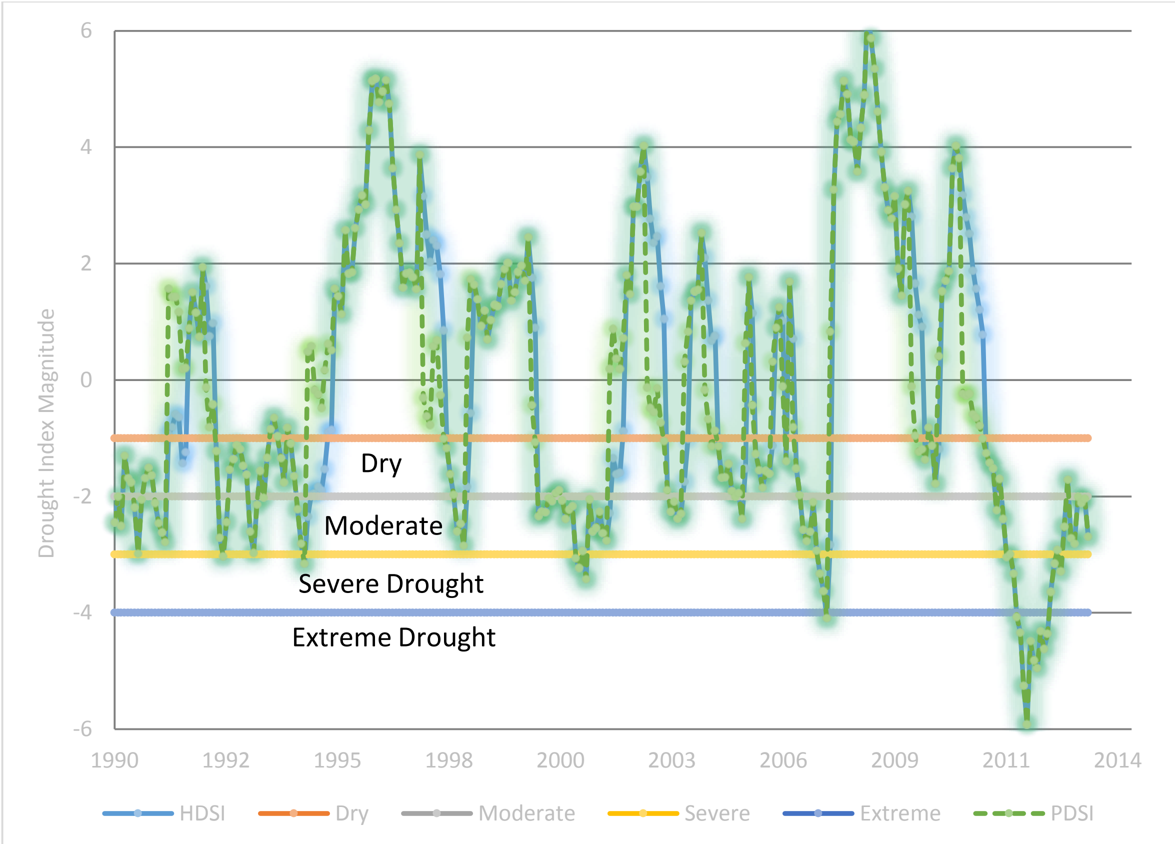


Figure 35: Monthly HDSI and monthly PDSI results from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "dry" periods, the zone between grey and yellow lines defines "moderate" drought periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods

In figure 36, the comparison between the sc-HDSI and sc-PDSI is shown.

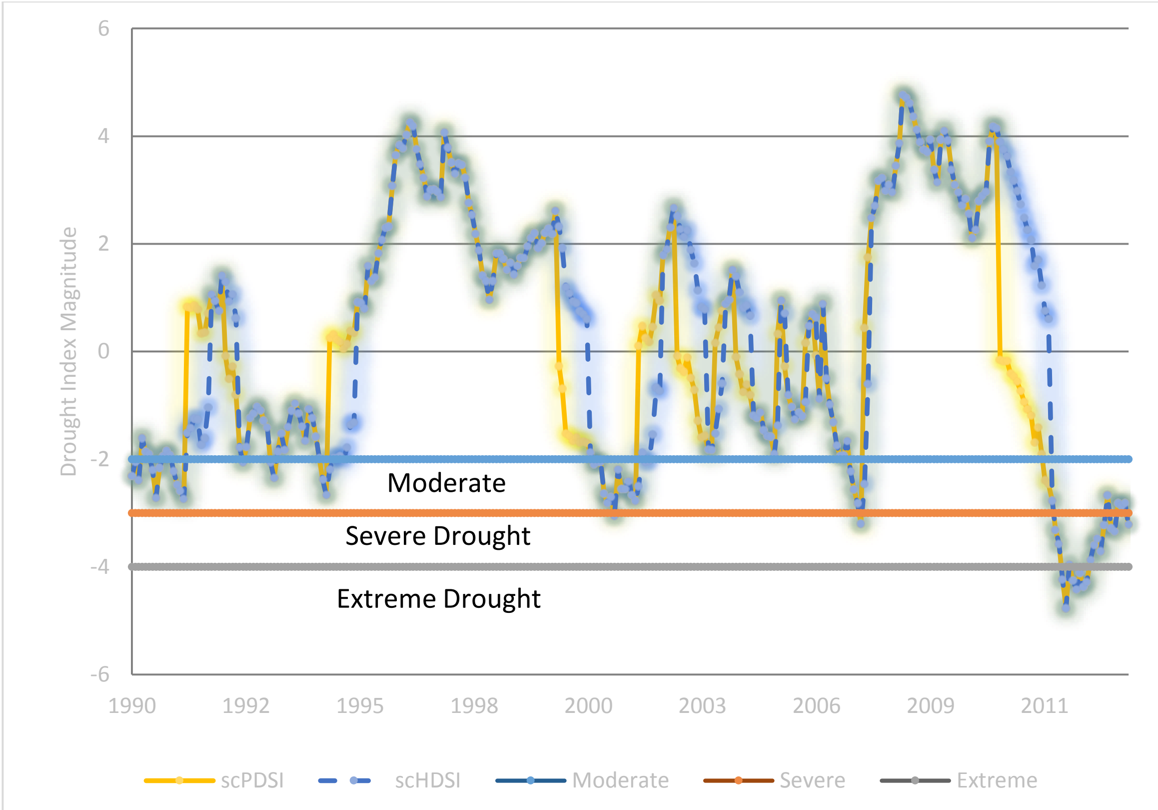


Figure 36: monthly sc-HDSI and monthly sc-PDSI from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "dry" periods, the zone between grey and yellow lines defines "moderate" drought periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods.

The number of days classified following the Palmer criteria (reported in table 9) for the HDSI and the sc-HDSI are shown in table 12:

Table 10: Number of days classified as extreme, severe, moderate, mild and incipient dry drought by sc-HDSI and original HDSI from 1990 to 2013.

Classification	**No drought**	**Incipient Dry Spell**	**Mild Drought**	**Moderate Drought**	**Severe Dought**	**Extreme Drought**
sc-HDSI	154	10	63	41	13	7
HDSI	127	13	63	62	12	11

Both PDSI and HDSI (as well as for the “self-calibrated” related indices) are based on a water balance model. The two indices differ mainly in defining the end of a drought (Demuth, 2006): the PDSI considers a drought end as soon as an uninterrupted rise in moisture condition begins; the HDSI waits until the soil moisture deficit has finished (Demuth, 2006). HDSI changes more slowly than PDSI and it has sluggish response for drought (*http://www.in.gov/dnr/files/ws-Final_droughtindices.pdf*).

As well as long-term drought are calculated by PDSI (and sc-PDSI), short-term droughts are calculated by the Palmer Z-Index (Palmer, 1965). The Z-Index corresponds to monthly drought conditions with no memory to previous monthly deficits or surpluses. This is beneficial because it is possible to have a short-term moist period in the midst of a long-term drought or vice versa. Because the Z-index is not affected by moisture conditions in the previous month, its values can vary dramatically from month to month, as it is from figure 37 (the PDSI varies more slowly, although heavy rain events can dramatically change PDSI values).

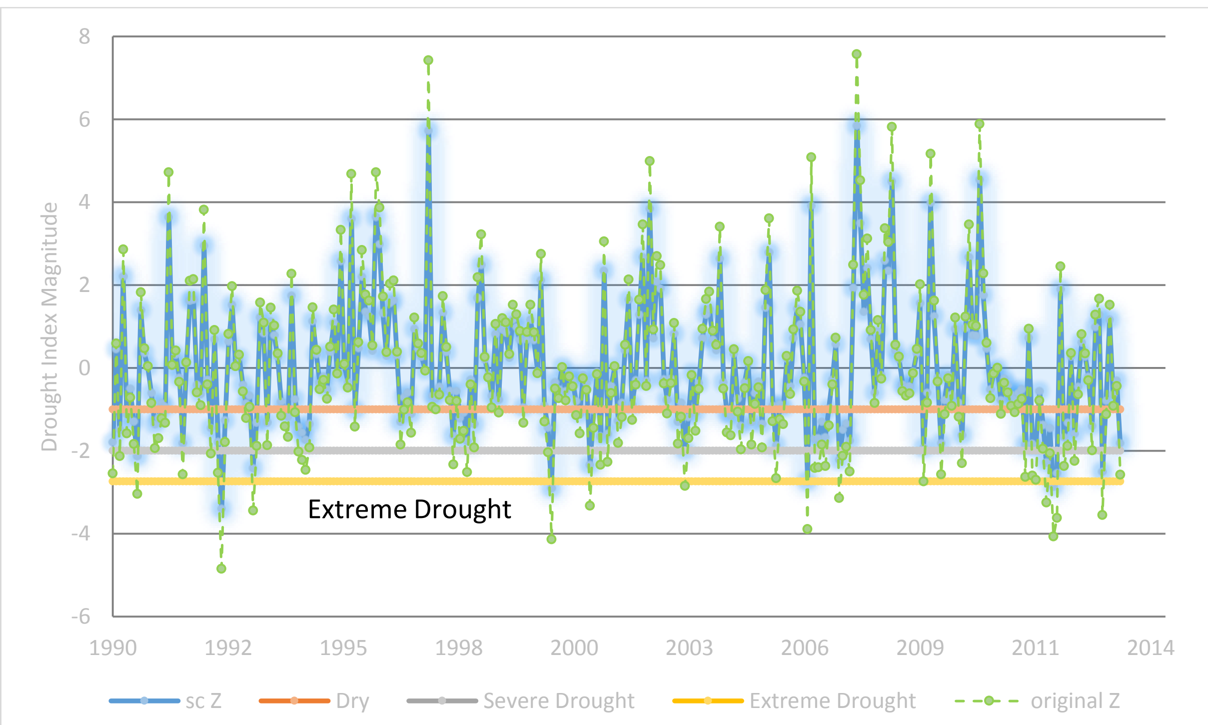


Figure 37: Original and self-calibrated Z-index from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines “dry” periods, the zone between grey and yellow lines defines “severe” drought periods, and finally the zone below the yellow line defines “extreme” drought periods.

As it is possible to notice, the Z index classification is different from the PDSI, and the relative values are reported in table13 (Palmer, 1965).

Table 11: Z index values (Palmer, 1965).

Z index values for dry and wet periods

3.50 and above	Extreme wetness
2.50 to 3.49	Severe wetness
1.00 to 2.49	Mild to moderate wetness
-1.24 to .99	Near normal
-1.99 to -1.25	Mild to moderate drought
-2.74 to -2.00	Severe drought
-2.75 and below	Extreme drought

Figure 37 shows how the original and self-calibrated Z-index follow the same trend. The original Z index classify more “extreme” drought periods than the sc-Z index; the last one is more precautionary.

The last Climatological drought index computed is the SPI. The magnitude of drought defined by SPI values are reported in table 14, and in figure 38 the results obtained are shown.

Table 12: SPI index classification (Kee, 1993)

SPI value	Drought Magnitude
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

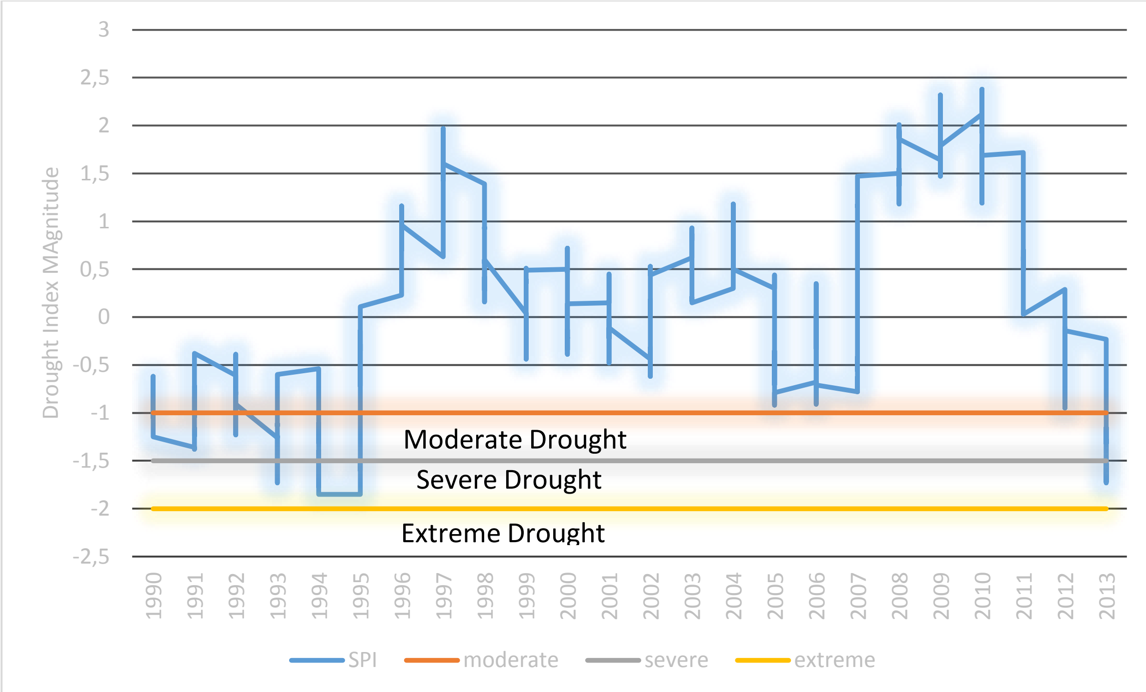


Figure 38: Monthly SPI Index results from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "moderate" drought periods, the zone between grey and yellow lines defines "severe" drought periods, and finally the zone below the yellow line defines "extreme" drought periods.

The classification of the drought magnitude is different from the one used by Palmer. SPI index does not classified "Incipient dry spell" and "mild drought". Table 15 reported the main differences between PDSI and the self-calibrated one.

Table 13: Numbers of days from 1990 to 2013 classified as "No Drought", "Incipient dry spell", "mild Drought", "moderate Drought", "Severe Drought" and "extreme Drought" for the three main climatological drought indices studied: PDSI, sc-PDSI and SPI.

Index	**Classificat ion**	**No drought**	**Incipient Dry Spell**	**Mild Drought**	**Moderat e Drought**	**Severe Drought**	**Extreme Drought**
sc-PDSI	days	156	32	60	37	13	7
PDSI	days	135	35	54	59	12	11
SPI	days	243	-	-	31	12	0

The SPI does not take into account the evapotranspiration, and this limits its ability to capture the effect of increased temperatures on soil moisture demand and availability, as explained in "*climatedataguige.ucar.edo*". The great differences between SPI and PDSI are in agreement with the results reported in table 15.

Sc-PDSI and SPI indices have different values to classify extreme, severe and moderate drought periods; figure 39 represents the sc-PDSI in the left axis and the same degree of severity is reported in the right axis for the SPI index.

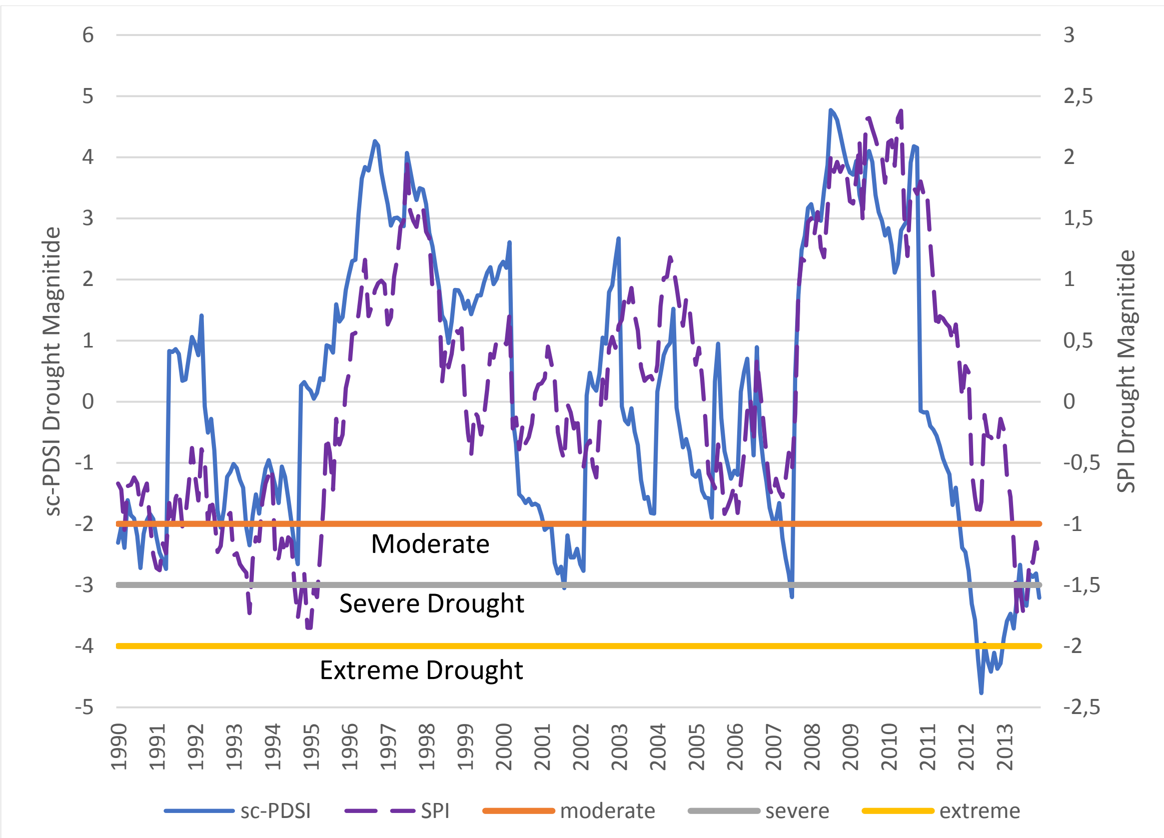


Figure 39: Monthly SPI (right axis) and monthly sc-PDSI (left axis) comparison. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "moderate" drought periods, the zone between orange and grey lines defines "severe" drought periods, and finally the zone below the yellow line defines "extreme" drought periods.

The trends of the two index are different between February 1993 and September 1993, between April 1994 and April 1995, June 200 and December 2001, May 2007 and August 2007 as well as November 2010 and May 2013. The main differences are reported during the summer periods, when the evapotranspiration is higher. The relationship between SPI and sc-PDSI (r= 0.72) is shown in figure 40:

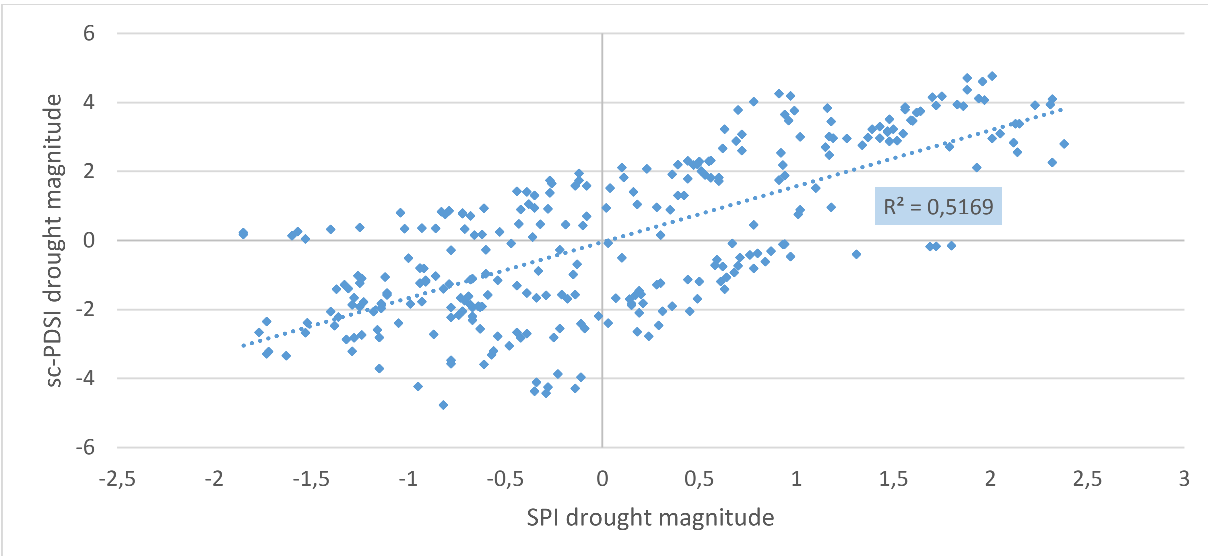


Figure 40: SPI vs sc-PDSI. The figure shows the correlation between the two indices. Data between 1990 and 2013 are analysed.

Finally, the weekly results regarding the Crop Moisture Index (CMI) are shown in figure 41.

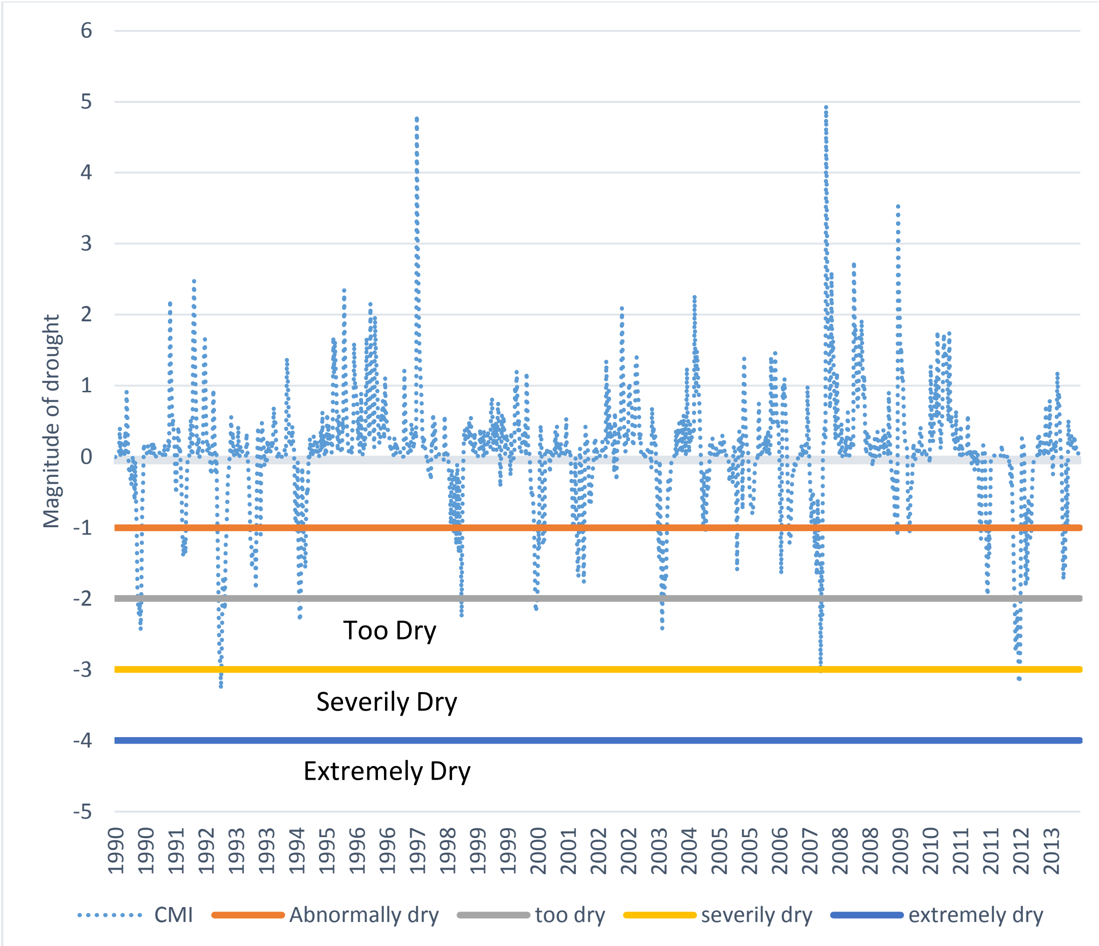


Figure 41: Weekly CMI from 1990 to 2013. The main values of the magnitude of drought are shown: the zone between the orange and the grey lines defines "abnormally dry" periods, the zone grey and yellow lines defines "dry" periods, the zone between yellow and blue lines defines "severe" drought periods, and finally the zone below the blue line defines "extreme" drought periods.

The classification adopted by Palmer in 1968 to classify the magnitude of the drought is reported in table 16; in general, the classification of "moderate", "severity" and "extreme" drought periods follow the one used for the original Palmer index.

Table 14: CMI Classification: the table shows the magnitude of the drought related to the CMI values. Palmer developed the classification in 1968.

CMI values when the index increased or did not change from the previous week.	
3.0 and above	Excessively wet, some fields flooded
2.0 to 2.99	Too wet, some standing water
1.0 to 1.99	Prospects above normal, some fields too wet
0 to .99	Moisture adequate for present needs
0 to -.99	Prospects improved but rain still needed
1.0 to -1.99	Some improvement but still too dry
-2.0 to -2.99	Drought eased but sill serious
-3.0 to -3.99	Drought continues, rain urgently needed
-4.0 and below	Not enough rain, still extremely dry
CMI values when the index decreased	
3.0 and above	Some drying but still excessively wet
2.0 to 3.99	More dry weather needed, work delayed
1.0 to 1.99	Favorable, except still too wet in spots
0 to .99	Favorable for normal growth and fieldwork
0 to -.99	Topsoil moisture short, germination slow
-1.0 to -1.99	Abnormally dry, prospects deteriorating
-2.0 to -2.99	Too dry, yield prospects reduced
-3.0 to -3.99	Potential yields severely cut by drought
-4.0 and below	Extremely dry, most crops ruined

The CMI (developed by Palmer in 1968) is based on a meteorological approach, as the PDSI. The CMI is designed to evaluate short-term moisture conditions, whereas the PDSI monitors long-term meteorological wet and dry spells. CMI is based on mean temperature and the total precipitation for each week. It can be used to compare moisture conditions since it responds rapidly to changing conditions.

The CMI is not a good long-term drought-monitoring tool as the PDSI, because it is designed to monitor short-term moisture conditions. For example, a beneficial rainfall during a drought may provide misleading information about long-term conditions, while the long-term drought at the location persists. The two indexes, CMI and PDSI, are shown in figure 42.

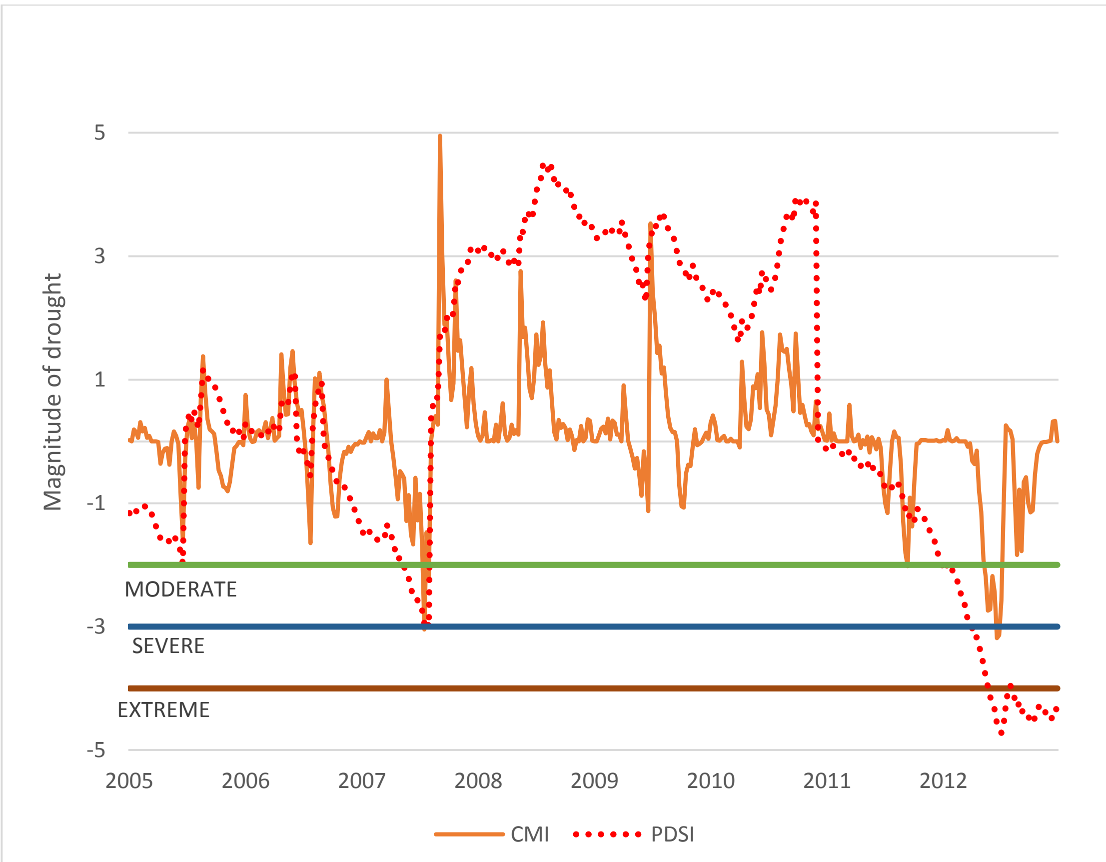


Figure 42: Comparison between monthly CMI and monthly PDSI from 2005 to 2012. The main values of the magnitude of drought are shown: the zone between the green and the blue lines defines "moderate" drought periods, the zone between blue and brown lines defines "severe" drought periods, and finally the zone below the brown line defines "extreme" drought periods.

The trend of PDSI and of CMI is not the same; on the other hand, both indices indicate the same periods of moderate, severe and extreme drought.

As well as short term droughts are calculated by the Palmer Z index, figure 43 shows the Z Index (in the right axis) and the CMI (in the left axis).

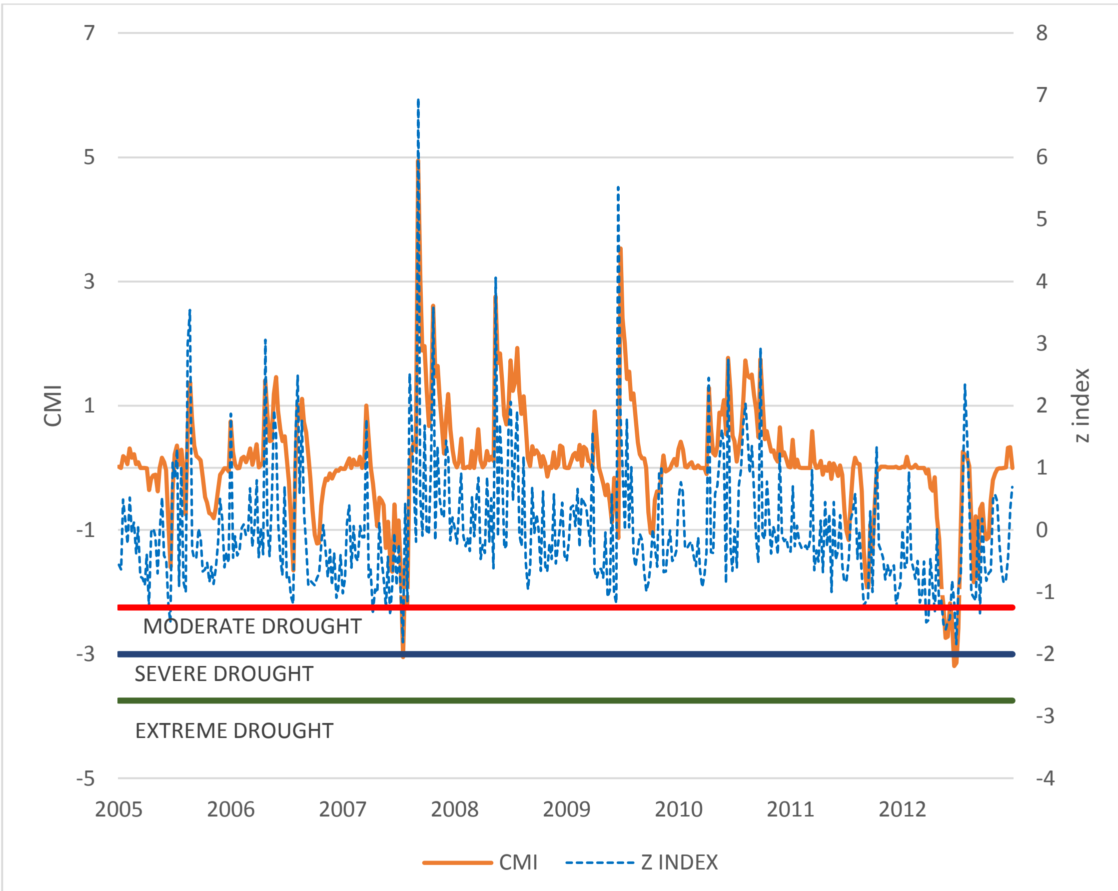


Figure 43: Comparison between weekly CMI and weekly Z index between 2005 and 2012. The main values of the magnitude of drought are shown: the zone between the red and the blue lines defines "moderate" drought periods, the zone between blue and green lines defines "severe" drought periods, and finally the zone below the green line defines "extreme" drought periods.

The relation between Z index and CMI seems to be closer than the one between CMI and PDSI; the trends are similar and both indices indicate the same moderate drought periods in 2007 and 2013, even if Z index is influenced by more variations. The relationship between the two indexes is shown in figure 44:

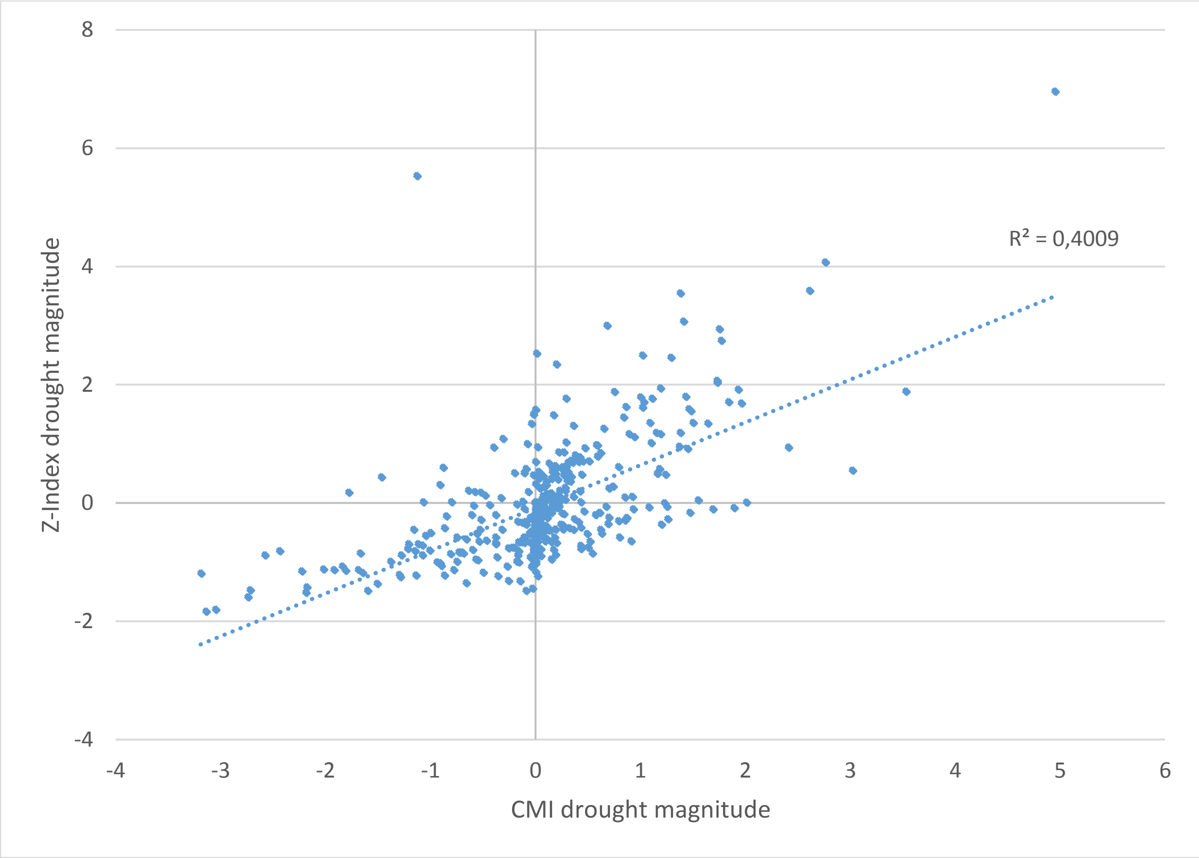


Figure 44: CMI vs Z-Index. The figure shows the correlation between the two indexes. The weekly data analysed are from 1990 to 2013

The attention is focus between 2005 and 2012 to compare the CMI with the soil moisture content between 0 and 50 cm soil depth; only the soil layer between 0 to 50 cm depth is considered because no important results were obtained for deeper soil layers. The soil moisture (millimetre) for the soil layer between 0 (soil surface) and 50 cm depth is calculated using equation 29.

Figures 45-52 show the soil moisture from 0 to 50 cm of soil depth (in the right axis) and the CMI (in the left axis), from year 2005 to year 2012; the line representing the permanent wilting point (equal to 50 mm) is normalized in order to be at the same height of the Palmer value that indicates a “severe” drought.

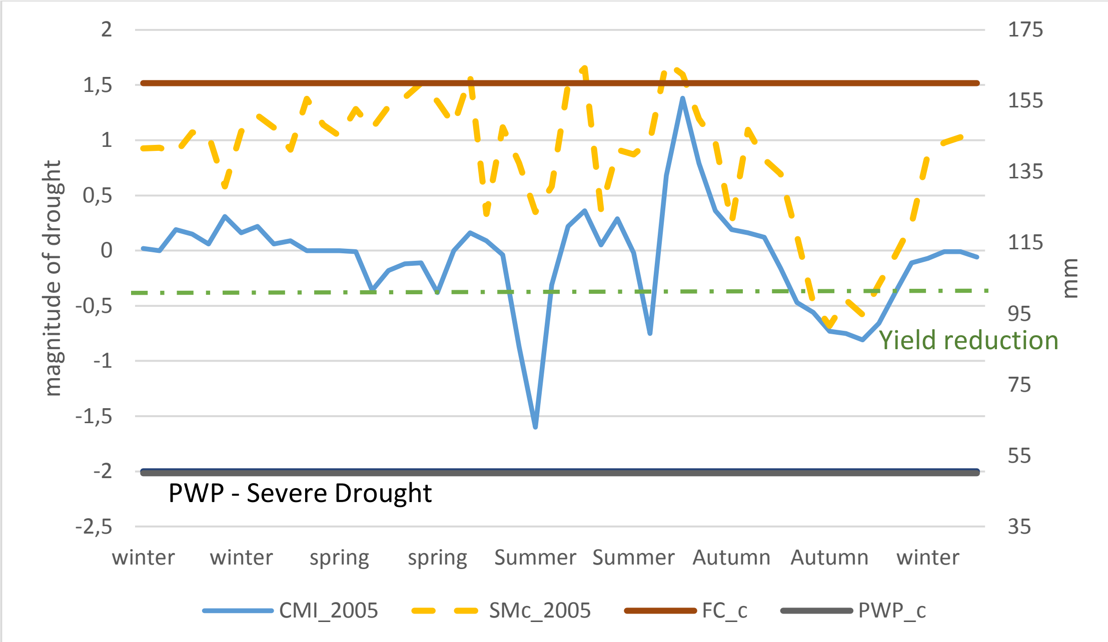


Figure 45: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2005 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. The two parameters do not show "severe" drought.

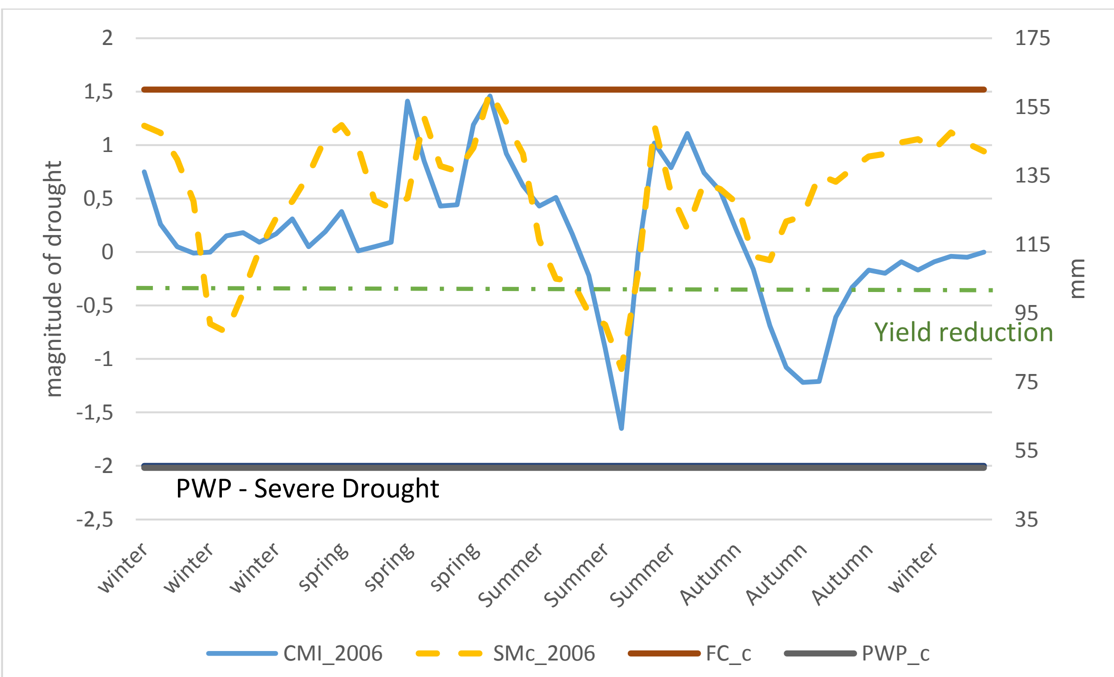


Figure 46: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2006 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. The two parameters not show "severe" drought. They increase and decrease at the same time, following the same pattern.

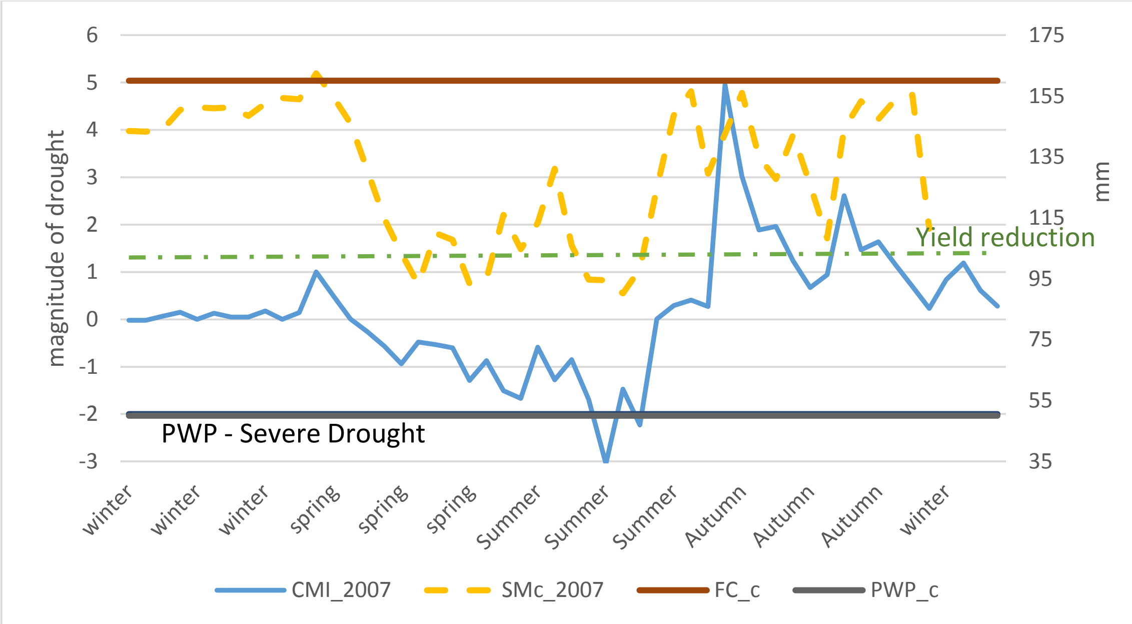


Figure 47: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2007 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. CMI indicates "severe" drought during summer, but the soil water content does not show the same extreme situation.

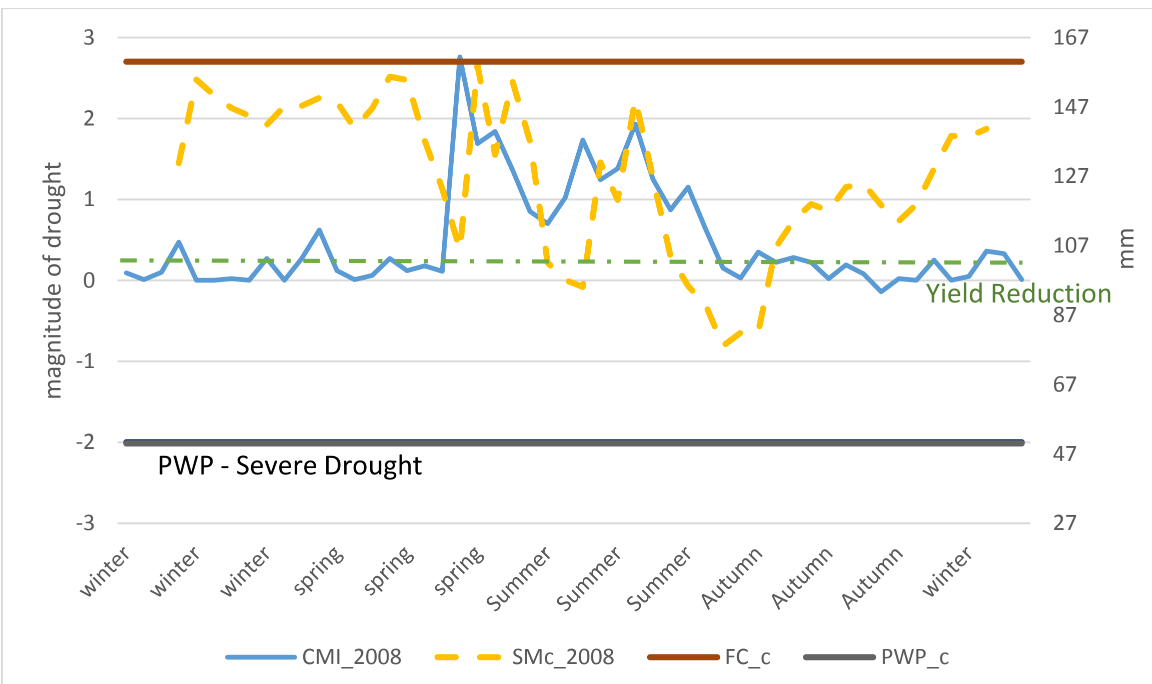


Figure 48: Soil moisture between 0 to 50 cm depth (mm) and CMI in 2008 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. The two parameters increase and decrease in the same way, and both of them do not show "severe" drought periods.

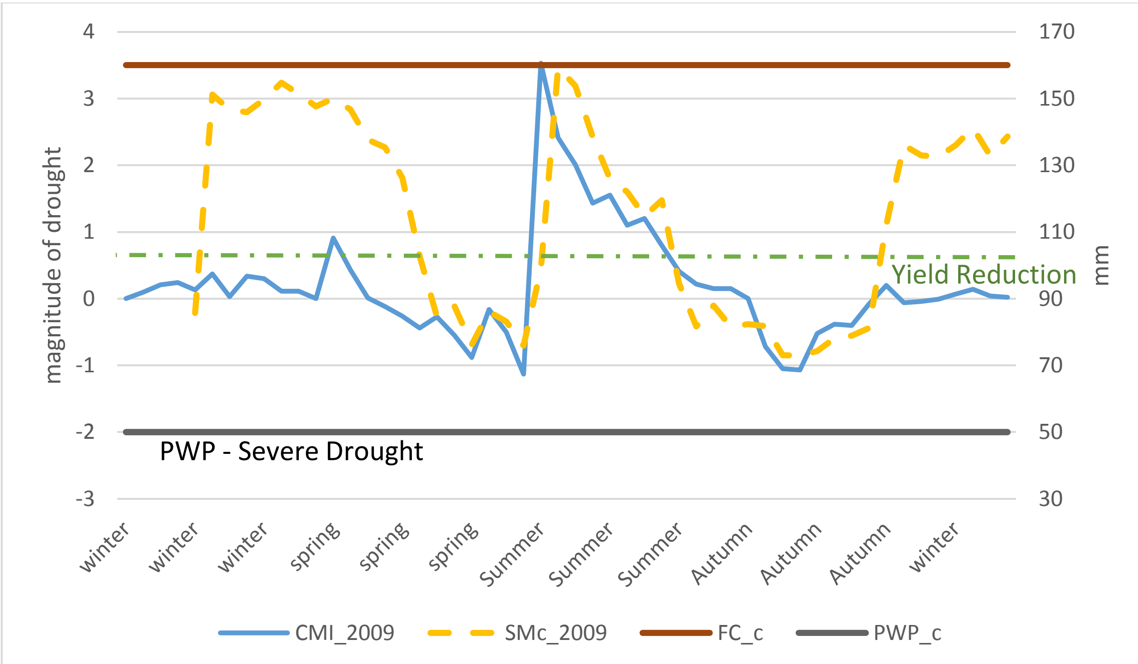


Figure 49: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2009 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. During summer, the values of the two parameters overlap well. Differences are reported during winter and autumn, but both parameters do not shown "severe" drought.

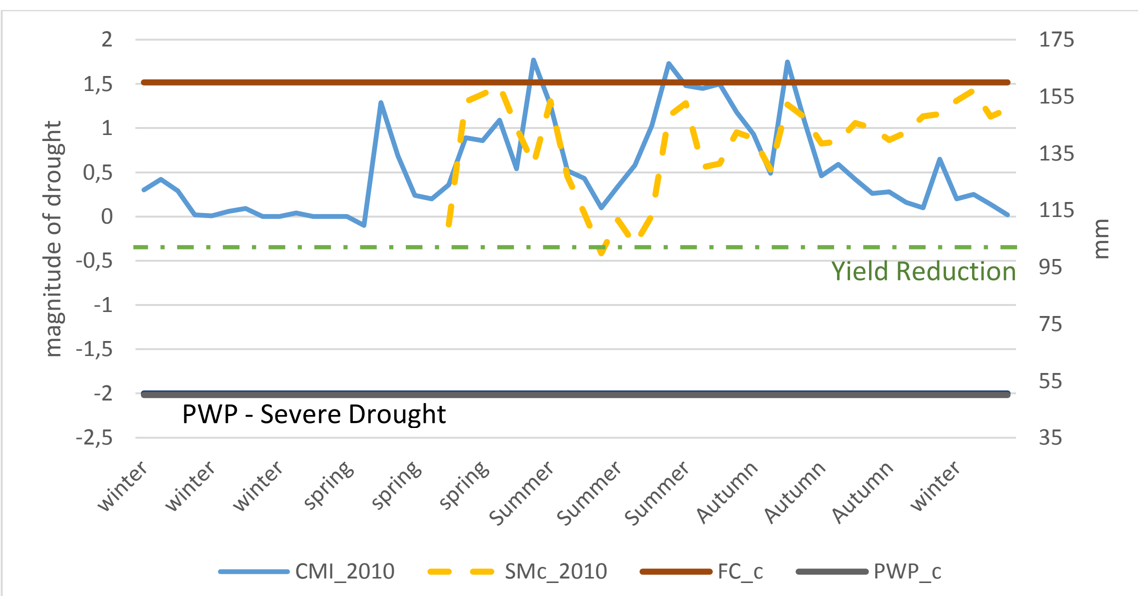


Figure 50: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2010 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. The two parameters increase and decrease in a similar way and both of them do not show "severe" drought periods.

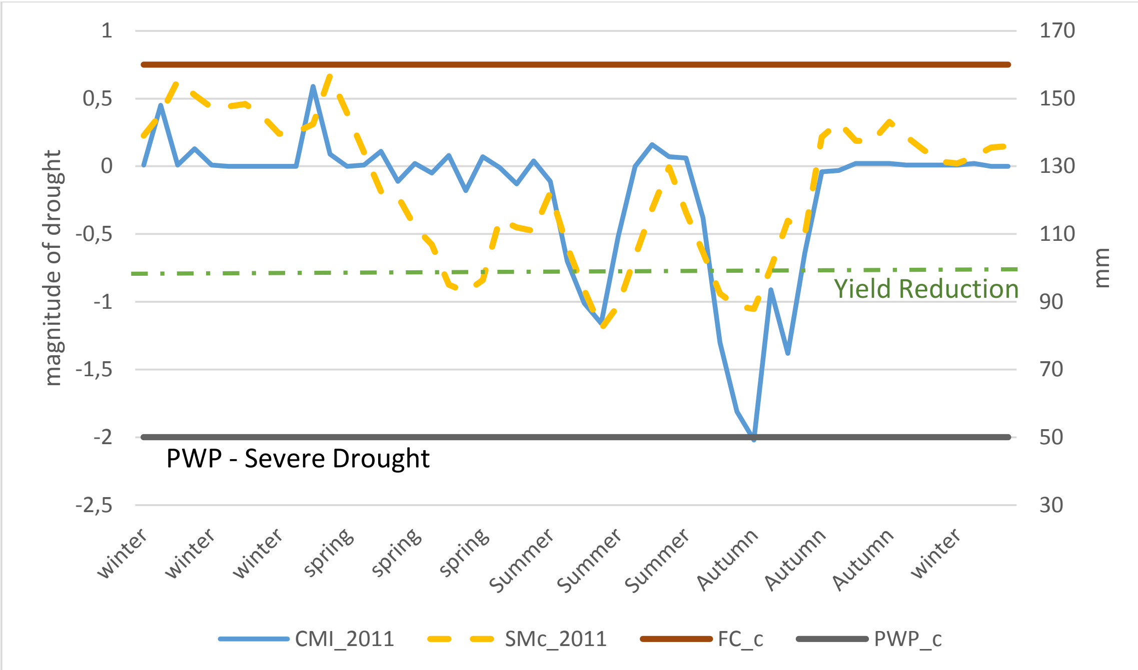


Figure 51: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2011 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. The two parameters increase and decrease in a similar way, except during autumn.

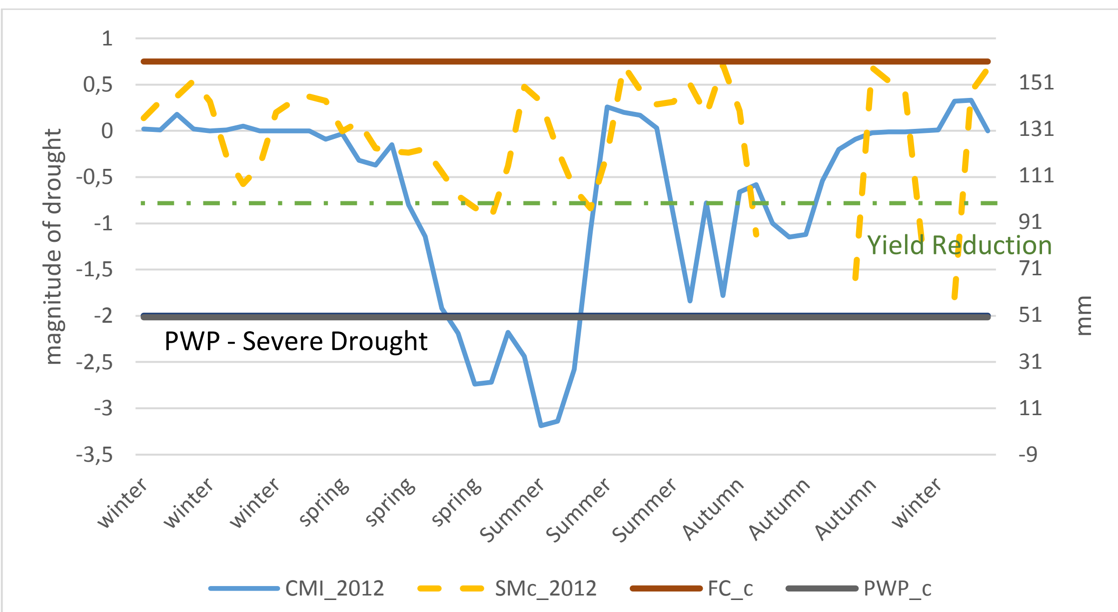


Figure 52: Soil Moisture between 0 to 50 cm depth (mm) and CMI in 2012 (weekly data). The line representing the permanent wilting point is at the same level of the Palmer value that indicates a "severe" drought. CMI shows a severe drought period during the summer, even if the Soil Moisture does not report the same situation.

The definition of the term permanent wilting point, reported by the Glossary of Soil Science terms (Soil Science Society of America, 2001), is the follow: "*permanent wilting point indicates the largest water content of a soil at which indicator plants, growing in that soil, wilt and fail*". Then, when the water content in the soil reaches the permanent wilting point, the crop wilts in an irreversible way. The reduction of the expected crop yield is usually defined when the water in the soil is around the 40% of the available water content. Considering the soil layer between 0 and 50 cm depth (FC= 160 mm; PWP= 50 mm; AWC= 110mm), the depletion (reduction of the expected yield) starts when the soil moisture is lower than 99 mm. The relationship between the periods classified as "severe" drought by the CMI and the soil moisture at the depletion-point is more consistent than the one between periods classified as affected by "severe" drought and soil moisture below the PWP.

CMI and Soil Moisture follow a similar trend; during summer 2007 and summer 2012 there are differences. However, relationship between the two parameters is confirmed by the results obtained with the correlation (r is higher than 0.70). In figure 64 the correlation between Soil Moisture and CMI is shown during summer periods

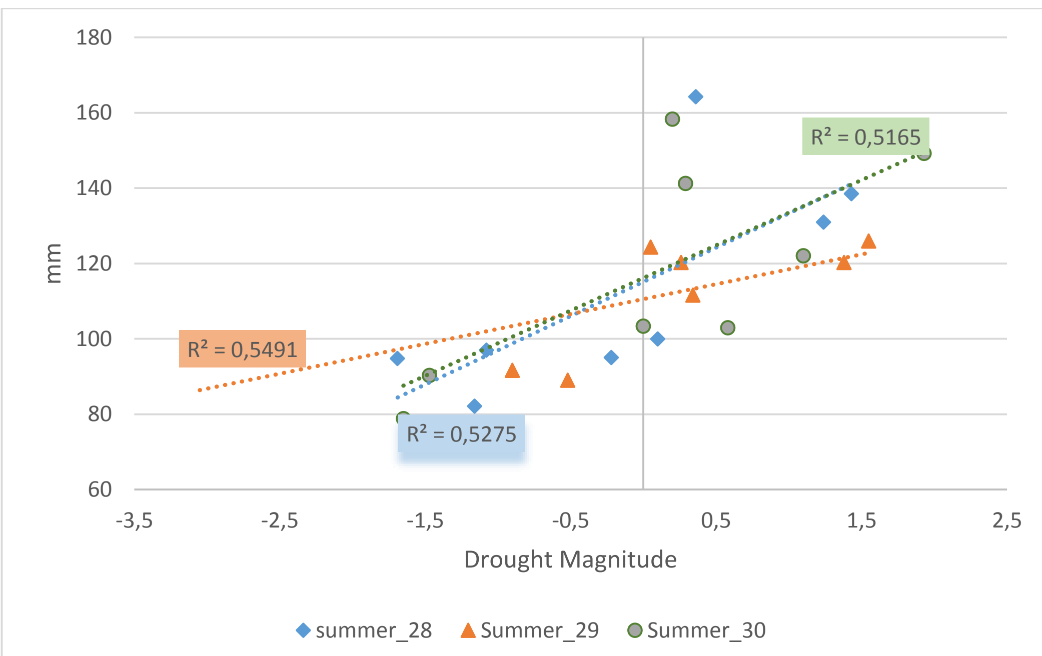


Figure 53: CMI vs Soil Moisture (mm) between 0 and 50 cm soil depth. Values reported are related to the week number 28, week number 29 and week number 30 for each year, from 2005 to 2012.

3.4 HEAT INDEX:

The results obtained with the computation of the HDH index with excel file are shown in figure 54. The amount of precipitation is shown in the right axis; instead, the HDH index is in the left axis.

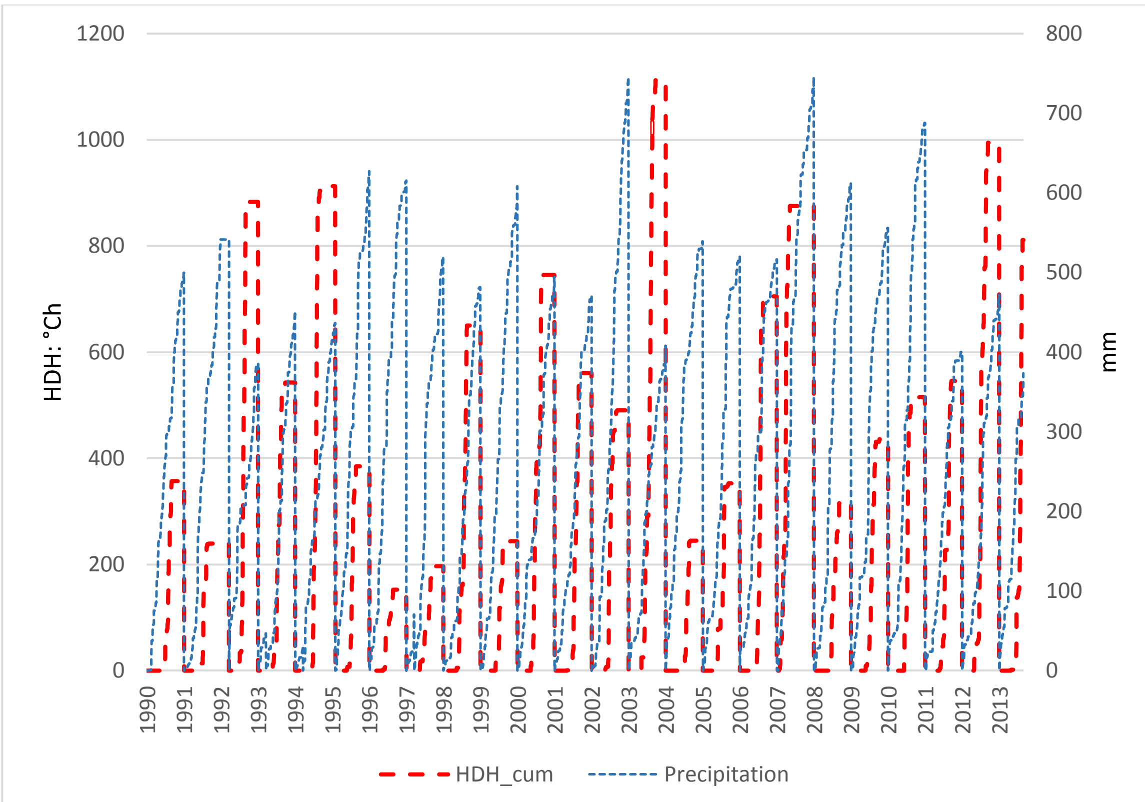


Figure 54: Results obtained from HDH calculation. The figure shown HDH index in the right axis and the precipitation in the left one, from 1990 to 2013

The periods with highest HDH values are in 2003 and 2012. The lower amount of precipitation is recorded during 2003 and 2011. On the other hand, the highest amount of precipitation is recorded in 2002 and 2007.

3.5 CROP YIELD VULNERABILITY:

3.5.1 WINTER WHEAT:

Yields data for winter wheat are shown in figure 55. Yield data are collected from the fields in Gross-Enzersdorf (data are provided by Priv.-Doz. Dr. Bodner, Gernot), related the following years: 2000, 2002, 2004, 2006, 2007, 2008 and 2009.

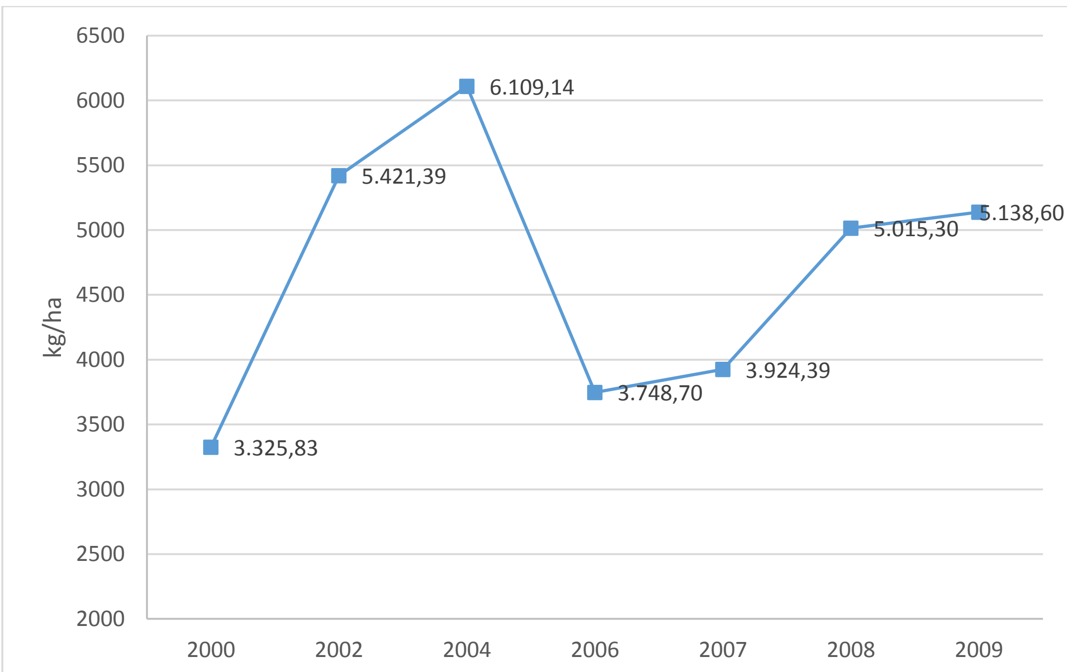


Figure 55: Winter Wheat Yields data from Gross-Enzersdorf, of the following years: 2000, 2002, 2004, 2006, 2007, 2008 and 2009.

The highest production was in 2004, year in which the lowest HDH was computed since 1990.

The data shown are compared with the drought indicators: strong correlation exists between the yield data and long terms drought indicators, as sc-PDSI (r=0.92) and SPI (r=0.92).

Winter wheat yields data show a strong positive correlation also with the amount of precipitation (r=0.94).

There is a good correlation also with short-term drought indicators, as Z and sc-Z (r=0,78 and 0,60 respectively), CMI (r=0,60). The results are presented in figure 56.

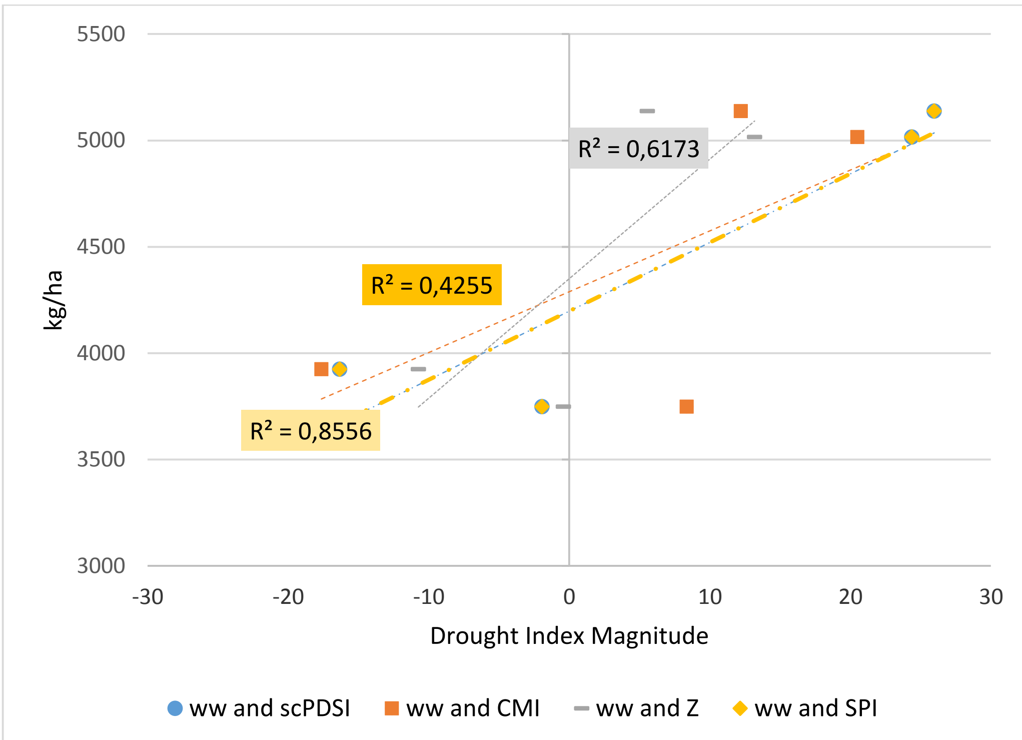


Figure 56: Winter wheat (ww) yields data vs drought indexes (sc-PDSI, CMI, Z index and SPI) for the years: 2000, 2002, 2004, 2006, 2007, 2008 and 2009.

A negative correlation between winter wheat yield and HDH subsist (r=-0.68), as is shown in figure 57.

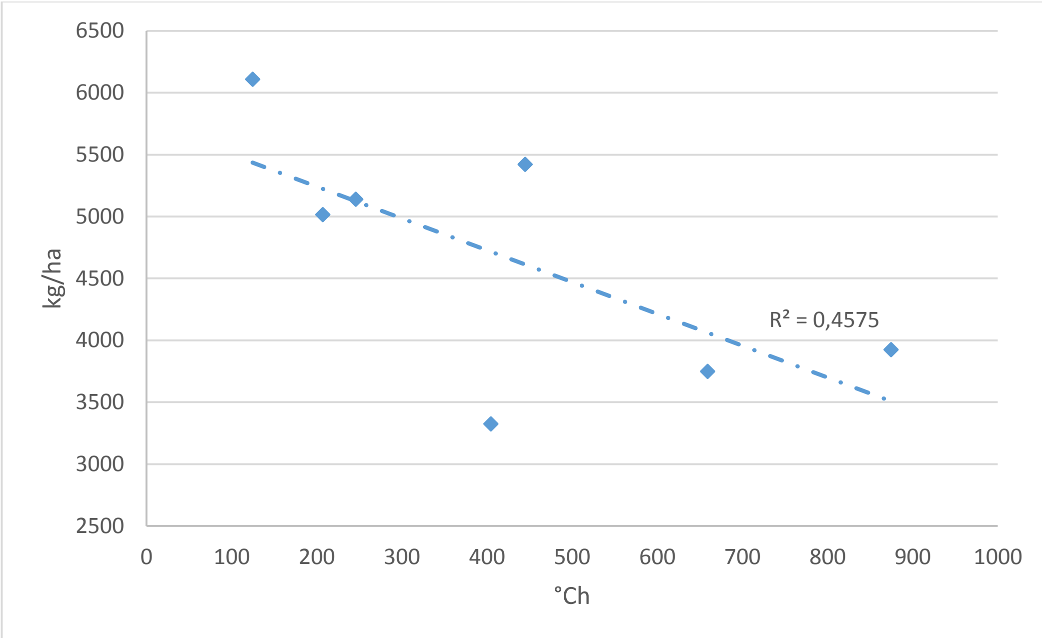


Figure 57: Yields data of winter wheat (kg/ha) vs HDH (°Ch) for winter wheat for the following years: 2000, 2002, 2004, 2006, 2007, 2008 and 2009.

Negative correlation between two variables means that when one variable is increasing, the other is decreasing. This is the case between yield data and HDH index: higher is the values of HDH index (higher is the heat stress), lower is the yield observed.

The results show that the crop mentioned is extremely sensitive to the absence of water; winter wheat is sensitive also to the heat stress. No correlation subsist between the crop yield and potential evapotranspiration or the evapotranspiration recorded by the lysimeter.

3.5.2 SPRING BARLEY:

Yields data for spring barley are reported in figure 58; they are collected in the station of Hollabrunn (provided by Dr. Macaigne, Peggy) and they refer to 2006, 2007, 2008, 2009 and 2010.

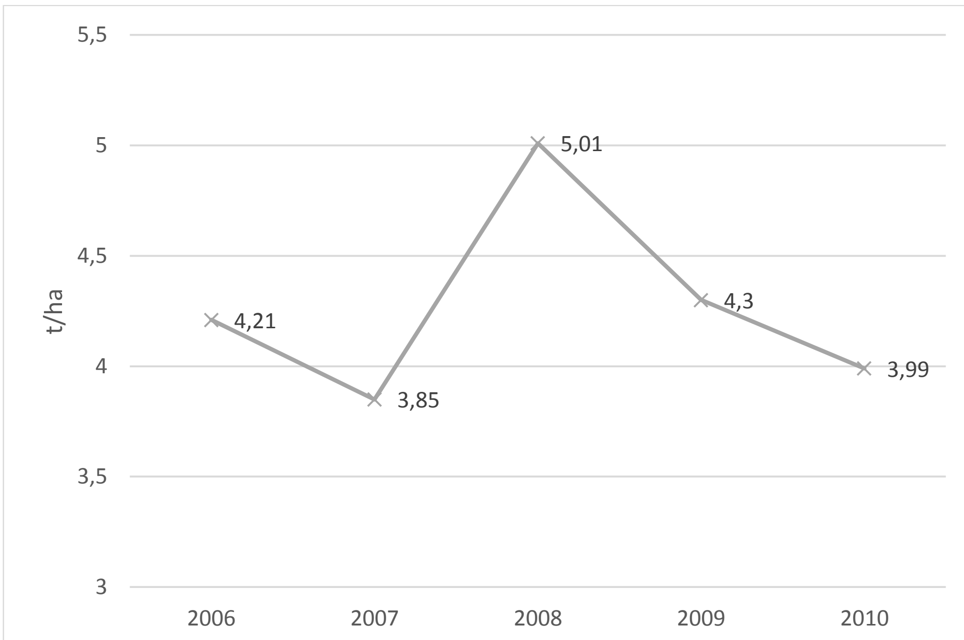


Figure 58: Spring Barley Yields data from Hollabrunn, between 2006 and 2010.

Spring barley yield has a correlation with long-term drought indices, as sc-PDSI (r=0.62), and SPI (r=0.60). On the other hand, the cumulated values of sc-PDSI and of SPI are very similar and from figure 59, where both of them are reported, is difficult to see differences. Very good correlation exists also between yields data and the amount of precipitation (r=0.71).

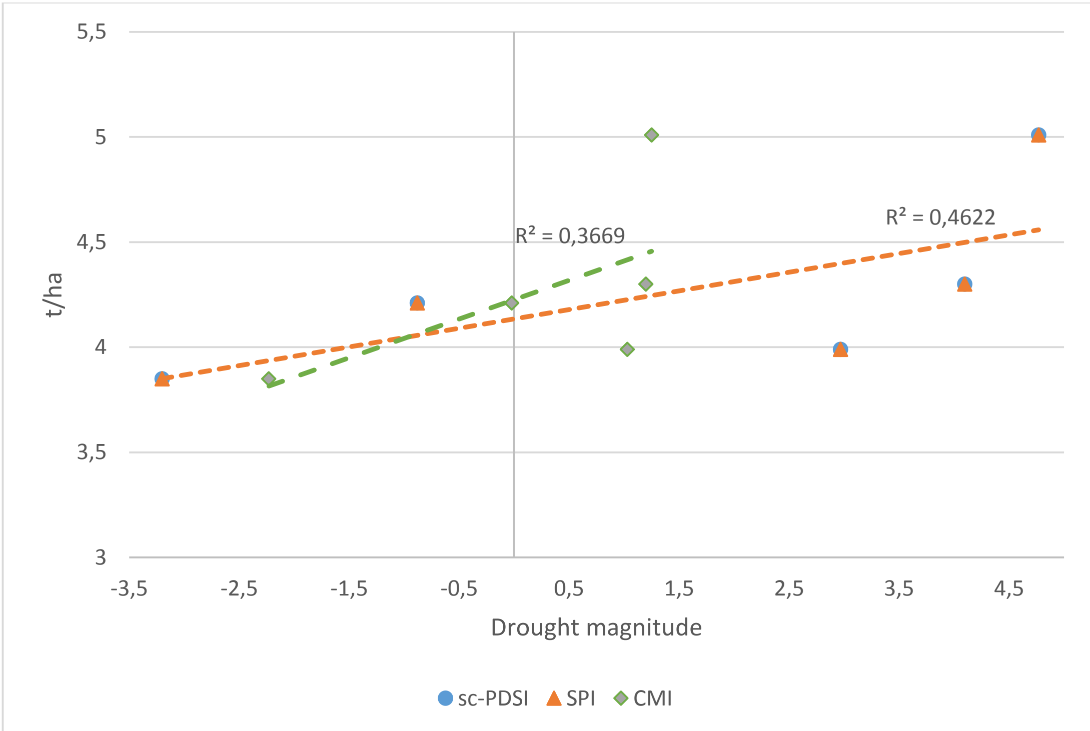


Figure 59: Spring Barley Yields data vs sc-PDSI, SPI, and CMI, between 2006 and 2010. Sc-PDSI and SPI values overlap in the figure.

Winter wheat yield shown a stronger correlation with long-term drought indices, rather than with short-term drought indicators. Spring Barley shows the contrary: the correlation is stronger between yield and CMI (z=0.73), original and sc-Z index (r equals to 0.83 and 0.70 respectively) than the one calculated for sc-PDSI and SPI.

The results are represented in figure 60:

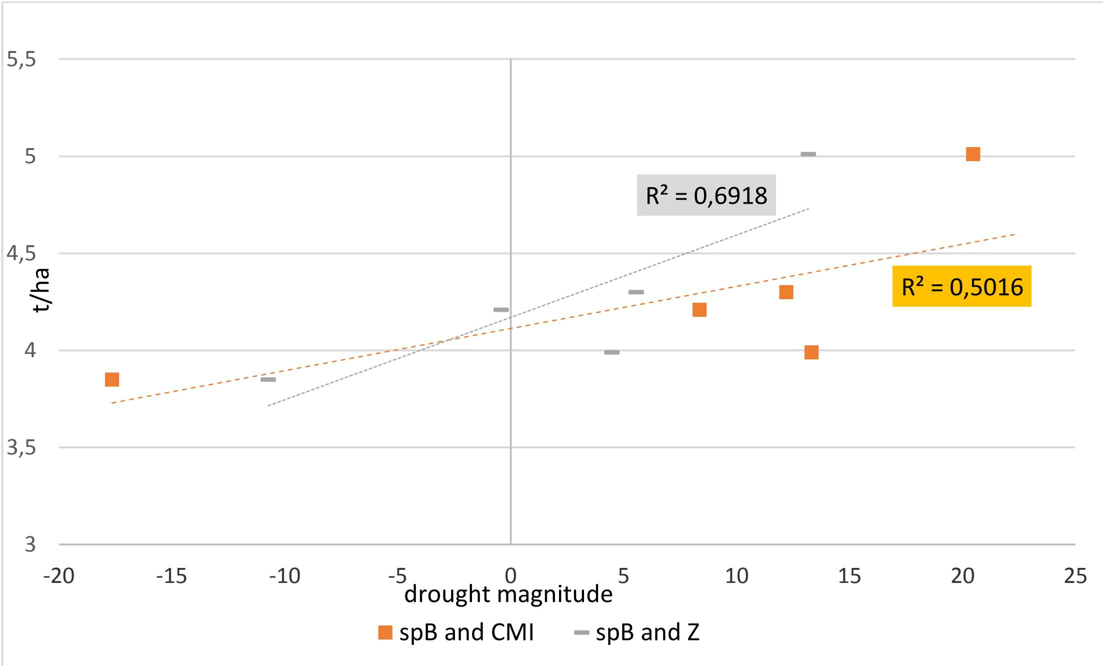


Figure 60: Spring Barley Yields data vs cumulated CMI and Z index between 2006 and 2010.

Finally, the good correlation between the crop yield and the HDH index (r=-0.72) is shown in figure 61:

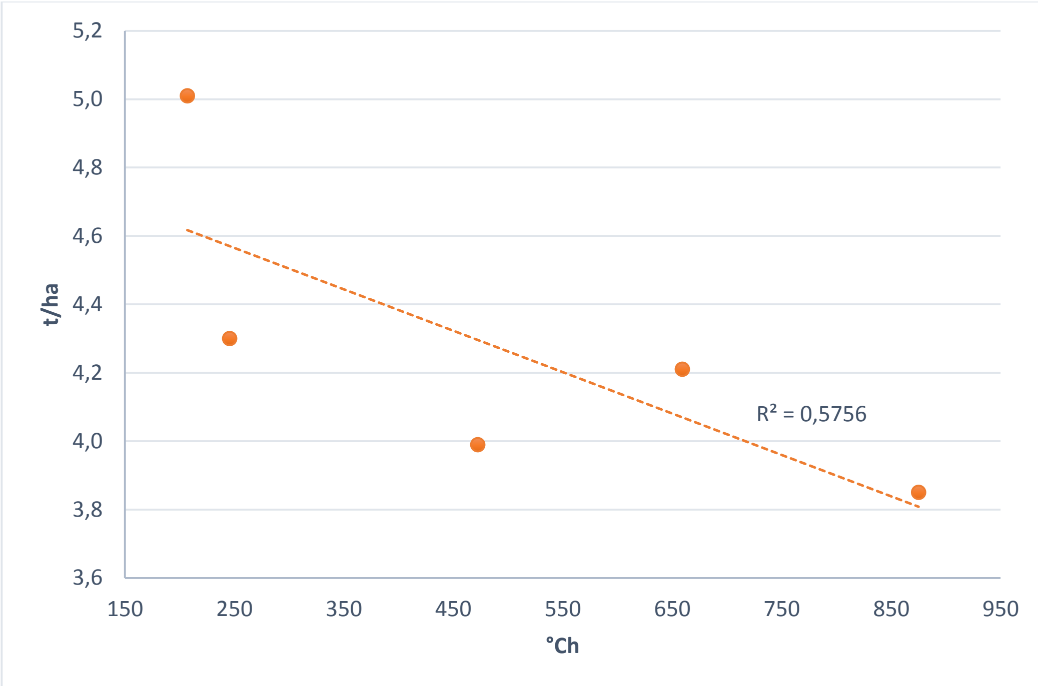


Figure 61: Spring Barley (spB) yields data vs HDH (°Ch) between 2006 and 2010

Spring Barley is very sensitive to both heat stress and water soil content in the soil, in fact, the highest production for the crop was observed in 2008, year in which the HDH registered is very low.

3.5.3 SUGAR BEET:

Yields data for sugar beet are reported in figure 62; they are collected in the station of Hollabrunn (data provided by Dr. Macaigne, Peggy) and they refer to the following years: 2006, 2007, 2008, 2009 and 2010.

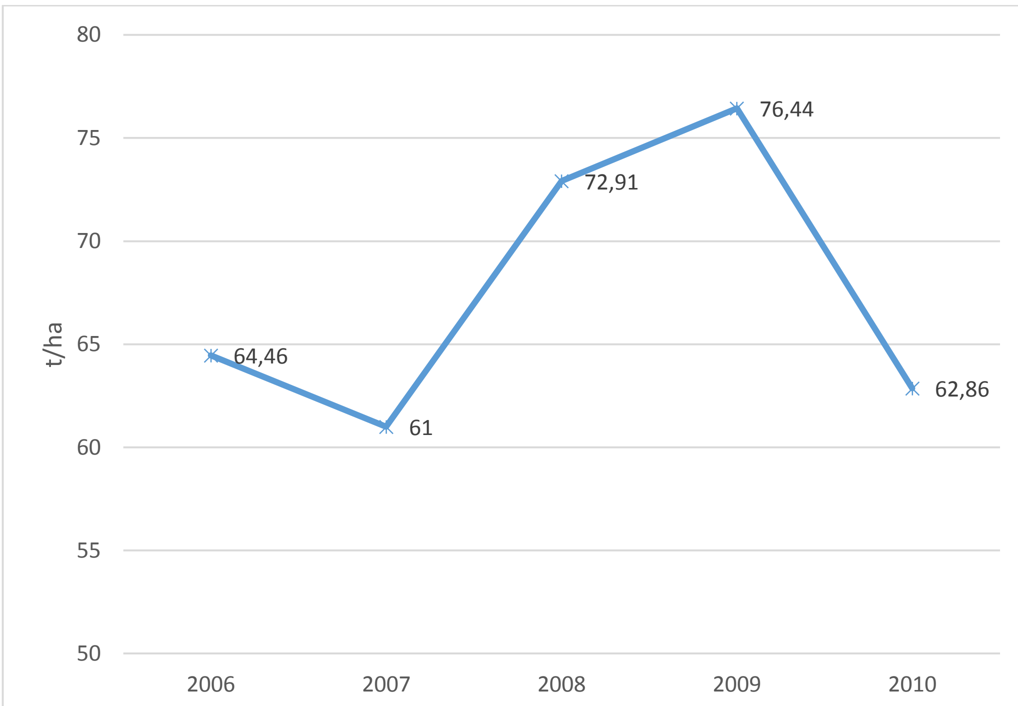


Figure 62: Sugar Beet (sugb) yields data from Hollabrunn between 2006 and 2010.

The yield trend shows an increasing of the productivity in 2009.

Sugar beet yields do not shown a good correlation with long-term drought indices: sc-PDSI and SPI.

Negative correlation subsists between yields data and precipitation amount (r=-0.66); any correlation exists with potential evapotranspiration.

Yields data of the crop have not any correlation with short-term drought indicators, as CMI and Z index, as well as for soil moisture content.

Yield data related to Sugar beet and HDH reported a strong negative correlation (r=-0.787). The results are shown in figure 63.

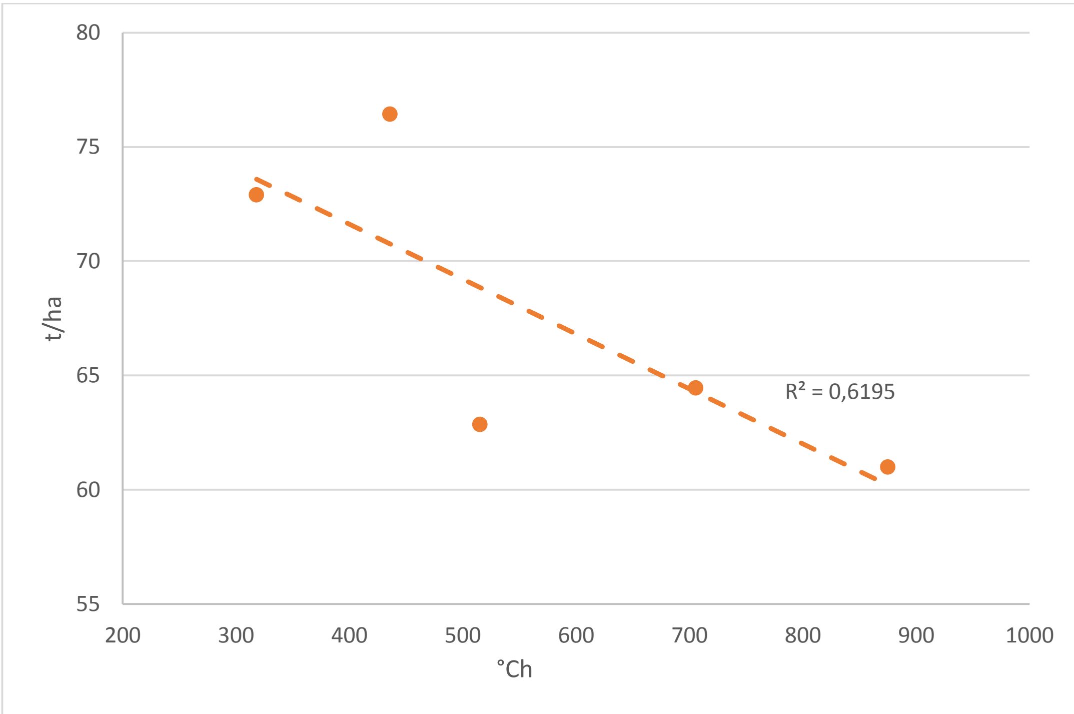


Figure 63: Sugar beet yields data vs HDH index (°Ch) from 2006 to 2010.

3.5.4 MAIZE:

Yields data for maize are reported in figure 64; they are collected in the station of Hollabrunn (provided by Dr. Macaigne, Peggy) and they refer to 2006, 2007, 2008, 2009 and 2010.

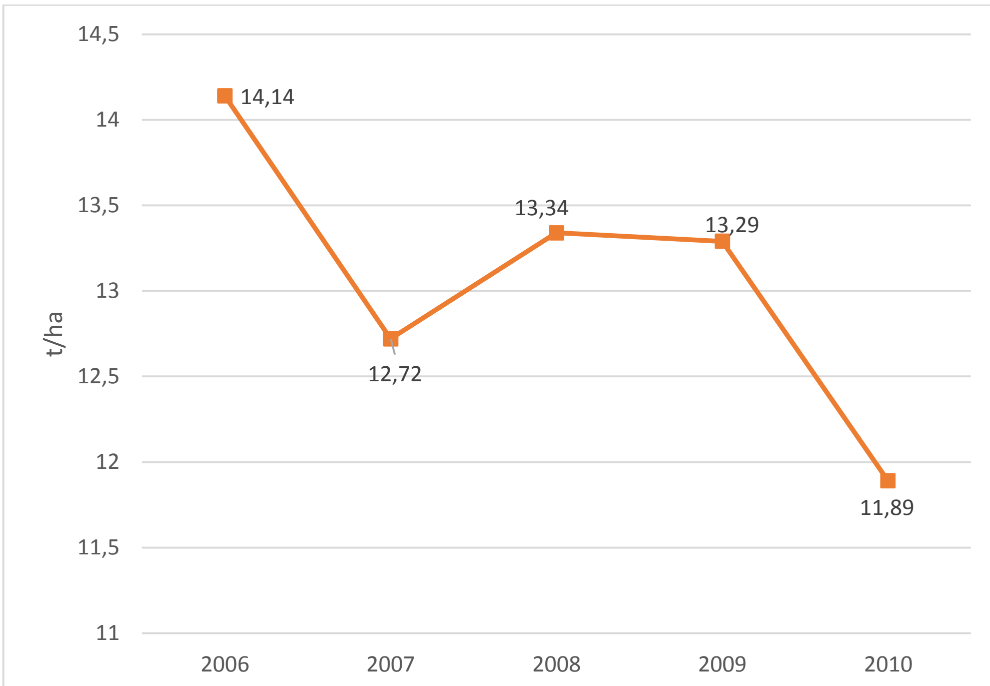


Figure 64: Maize (m) yields data from Hollabrunn between 2006 and 2010.

Maize is the crop, compared to winter wheat, spring barley and sugar beet, which shows the most severe yield reduction.

Maize yield does not show any correlation with long-term or short-term drought indices. Correlation between maize yields and soil moisture content have been found (r= 0.67). The results are shown in figure 65.

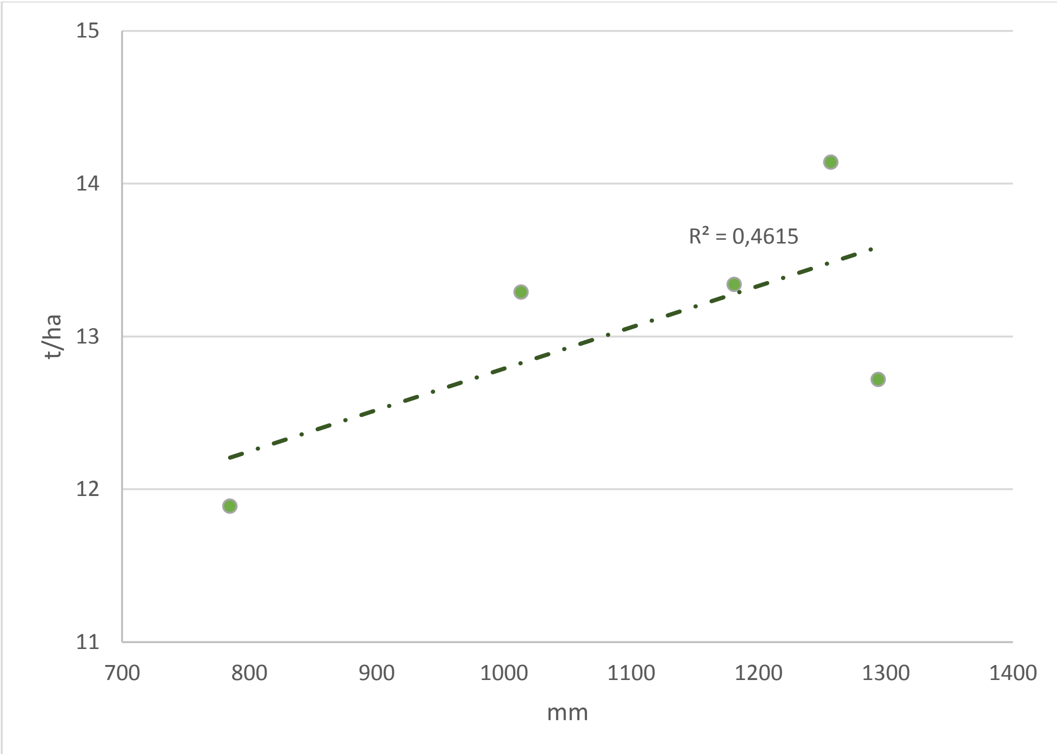


Figure 65: Maize yield vs Soil Moisture accumulated (mm) during the month of October (harvesting period for maize) between 0 and 50 cm soil depth.

Maize is most susceptible to soil water content variations; negative correlations between maize yields and both CMI (r=-0.40) and Z index (r=-0.62) confirm the previously observations.

Any correlation exists between maize yields and HDH index.

4 CONCLUSIONS:

In the study first the relationship between weather parameters, long and short term drought indices and water content in the soil of Gross-Enzersdorf (latitude 48° 12´N, longitude 16° 34´E and altitude 153 m above the see level) was analyzed. This is one of the main agricultural area in Marchfeld region and the main crop cultivated, and considered in the study, are winter wheat, sugar beet, maize and spring barley.

Palmer Drought Severity Index, PDSI, (Palmer, 1965), self-calibrated PDSI (Wells, 2004) and Standard Precipitation Index, SPI (Kee, 1993) , are well known long term drought indicators. PDSI and sc-PDSI are computed using a software provided by “GreenLeaf Project”, using DOS command. Original and self-calibrated Hydrological Drought Severity Index, HDSI (Palmer, 1965) are also tested using the same software; the results are very similar to original and sc-PDSI. SPI is compiled in C++ for PC using a software provided by the National Drought Mitigation Center. The indexes are computed considering the time period between 1980 and 2013. Between PDSI and sc-PDSI a very good correlation is obtained (r= 0.78); a good correlation is obtained also between sc-PDSI and SPI (r= 0.72). The drought indices are analysed considering the results obtained from 1990 to 2013: SPI, PDSI and sc-PDSI show that the area of Gross-Enzerdorf was not affected by extreme drought periods before 2012 (Figure 66). Even if the SPI results show less harmful scenario, the trend of the three drought indexes are worse in the last years (2012 and 2013).

Figure 66: Long-term drought indices. Monthly mean precipitation and monthly mean temperature from 1980 to 2013 are the input data used to calculate PDSI, sc-PDSI, HDSI and sc-HDSI. Monthly mean precipitation is the input data to calculate SPI. All the mentioned indexes show extreme drought periods in 2012 and 2013.

Short-term drought indexes are the Crop Moisture Index (CMI, developed by Palmer in 1968), the original and self-calibrated Z index (Palmer, 1965). These indexes show extreme and severe dry periods mainly during August 1992, July 2000, July 2006, July 2012 and 2013. They also show worst scenario during recent years (2012 and 2013). Short term drought indices can be considered good indicators of soil water content during summer; correlation functions between soil moisture in the soil layer 0-50 cm depth and CMI, as well as between soil moisture in soil layer 0-50 cm depth and Z index, are higher than 0.7 during summer. The main results are reported in figure 67.

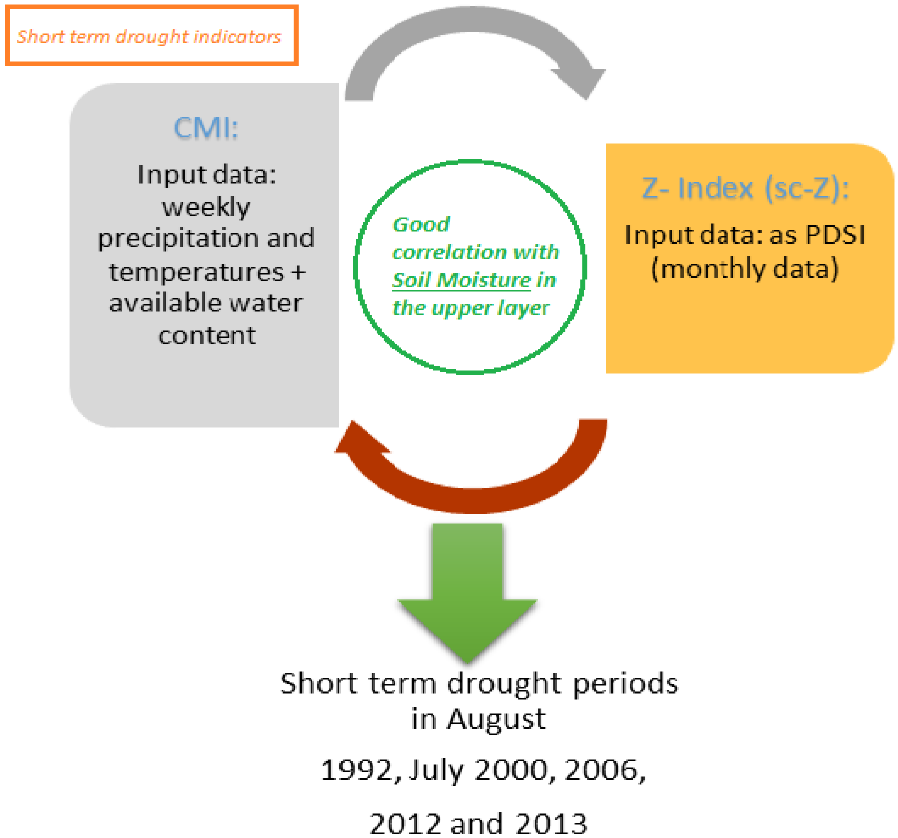


Figure 67: Short-term drought indices. For CMI the Input data are weekly mean precipitation and weekly mean temperature from 1980 and 2013. For Z-Index the input data are the same of PDSI. Outputs are analysed between 1990 and 2013 and they show drought periods in August 1992 and on July 2000, July 2006, July 2012 and July 2013.

High Degree Hour Index, HDH (Bristow, 1991) is also tested; the method defines an amount of high-temperature above a critical temperature (indicating a threshold of stress). The periods with highest HDH calculated values are 2003 and 2012.

The core of the study is to understand how the yields of the most widely crops cultivated in Gross-Enzersdorf (winter wheat, spring barley, maize and sugar beet) respond to soil moisture conditions and to drought or heat stress. Winter wheat yields data for Gross-Enzersdorf are provided by Priv.-Doz. Dr. Bodner, Gernot. The yield data are provided for the following years: 2000, 2002, 2004, 2006, 2007, 2008 and 2009 from 2006 to 2010. Yield data regarding maize, sugar beet and spring barley were not available in Gross-Enzersdorf and for this reason, the yield data regarding the three crops mentioned have been provided from the nearest area: Hollabrunn (longitude 16°3’, latitude 48°37’). The city is located also in Lower Austria, 264 m.a.s.l. and the weather conditions are similar to that of Gross-Enzersdorf.

Yield data are compared with long term (sc-PDSI, PDSI, SPI) and short-term drought indexes (CMI, Z-index, sc-Z-Index), with soil moisture between 0-50 cm depth and with heat stress index (HDH). The main results obtained are shown in table 17: “++” indicates a very good correlation between crop yields and the parameter considered ($r>0.7$); “+” means that a good correlation was obtained ($0.55<r<0.69$), and finally, “NC” means the absence of correlation (No-Correlation)

Table 157: Results obtained with the correlation function between crop yields and the relative parameters reported in the first column: long-term drought indices are PDSI, sc-PDSI and SPI; short-term drought indices are CMI, Z index and sc-Z index. "++" indicates a very good correlation between crop yields and the parameter considered (r>0.7); "+" means that a good correlation was obtained (0.55<r<0.69), and finally, "NC" means the absence of correlation (No-Correlation).

	Winter Wheat	*Spring Barley*	*Sugar Beet*	*Maize*
				
Long term drought indices	+ +	+	NC	NC
Short term drought indices / Soil moisture	+	+ +	NC	+
HDH index	+	++	++	NC
ET0	NC	NC	NC	NC
ET lysim.	NC	NC	NC	NC

Winter wheat is usually harvested in July. Very good correlation exists between the yield data of the crop and long terms drought indicators, as sc-PDSI (r=0.92) and SPI (r=0.92). There is a good correlation also with short-term drought indicators, as Z and sc-Z (r=0,78 and 0,60 respectively) and CMI (r=0,60). A good correlation between winter wheat yields and HDH exists (r=-0.68). The results, obtained comparing winter wheat yields with drought and heat stress indicators, show that the crop is extremely sensitive to the absence of water; winter wheat is sensitive also to the heat stress. No correlation exists between the crop yield and potential evapotranspiration.

Spring Barley is also harvested in July. Spring barley yield has a good correlation with long-term drought indices: scPDSI (r=0.62), and SPI (r=0.60). Spring Barley shows a very good correlation between yield and short-term drought indicators. The short-term drought indicators, which can be consider also good indicators regarding soil moisture, are CMI (z=0.73), original and sc-Z index (r equals to 0.83 and 0.70 respectively). Spring Barley is very sensitive both to heat stress (r= 0.72) and water soil content in the soil.

Sugar beet usually is harvested in October. There is no correlation between yield data and long-term drought indices. Yields data of the crop have not any correlation with short-term drought indicators, as CMI and Z index, as well as for soil moisture content. A very good correlation is observed between yield data and HDH index (r=-0.787).

Maize is harvested in October; the crop, compared to winter wheat, spring barley and sugar beet, shows the most severe yield reduction between 2006 and 2010. Maize yield does not show any correlation with long-term drought. A good correlation between maize yields and both CMI (r=-0.40) and Z index (r=-0.62) is confirmed also by the correlation with the soil moisture between 0 and 50 cm depth (r= 0.67). Any correlation is observed between maize yields and HDH index.

The results summarize in table 18, show the different ability to tolerate drought and heat of the crops considered in the study.

The objective of the study was describe in the Introduction; in table 18 a starting point for the development of a database on crop specific drought and heat vulnerability and impacts is shown, based on the results reported in table 15.

Table 18: Starting development of a database on crop specific drought and heat vulnerability and impacts under Austrian and climate change conditions for major crops (winter wheat, spring barley, maize and sugar beet).

	Winter Wheat	*Spring Barley*	*Sugar Beet*	*Maize*
				
Vulnerability	Long and Short Term Drought	Short Term Drought and Heat stress	Heat stress	Short Term Drought
Approaching modelling	Soil moisture; CMI; Z Index	CMI, Z-index; HDH index	HDH Index	Soil moisture, CMI, Z-Index

In general, both drought indicators and heat indicator can assist and enhance understanding of crops performances, to obtain higher and stable yields under stress. In particular, Winter wheat is more vulnerable to drought; then drought indexes should be taken in account for cultivar development. Spring Barley is vulnerable to both drought and heat stress, and Sugar Beet only to heat stress. Finally, Maize is more vulnerable to drought than to soil moisture, hence short-term drought indices should be considered for crop development.

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