USING VEGETATION INDICES FROM SATELLITE IMAGES TO ESTIMATE EVAPOTRANSPIRATION AND VEGETATION WATER USE IN NORTH-CENTRAL PORTUGAL

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Thesis: Using vegetation indices from satellite images to estimate evapotranspiration and vegetation water use in North-central Portugal.

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Abbreviations:

CESAM: Centro de estudos do ambiente e do mar
CPD: Casa do Padre study site
ET: Actual evapotranspiration
ETc: Crop evapotranspiration
EET: Effective evapotranspiration
EVI: Enhanced vegetation index
I: Interception
Kc: Crop Coefficient
LOU: Lourizela study site
MODIS: Moderate Resolution Imaging Spectroradiometer satellite
NDVI: The Normalized Difference Vegetation Index
NIR: Near-Infrared
P: Precipitation
PAR: Photosynthetically active radiation
PET: Potential evapotranspiration
QA: Quality assessment
QA SDS: Quality assessment Science Data sets
SNIRH: Sistema Nacional de Informação dos Recursos Hidricos
SPI: standardized precipitation index
ST: Soil Moisture storage
SWAT: Soil and Water Assessment Tool
UA: Universidade de Aveiro
VHL: Van Hall Larenstein
VIS: Visible-Infrared
WUR: Wageningen University

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ABSTRACT

Recent research has shown the remarkable potential of the use of remote sensing in retrieving evapotranspiration from natural and agricultural surfaces. The time courses of the main biophysical variables which affect crop photosynthesis and water consumption can be assessed using remote sensing data that will provide the spatial distribution of these variables over a region of interest (Duchemin et al. 2006). In this context, this study will investigate the feasibility of using vegetation indices Normalized difference vegetation index (NDVI) and Enhanced vegetation index (EVI) derived from MODIS remote sensing data to provide indirect estimates of: (1) crop coefficients, which represent the ratio of effective (EET) to potential evapotranspiration (PET) and (2) crop evapotranspiration (ETc). Discuss the potential of vegetation indices derived from satellite data to do the estimation of crop coefficients and crop evapotranspiration and analyze the dynamics of these paramenters in response to plant phenology and water availability to be used as drought indicators. The NDVI vegetation index showed better reliability for water use from vegetation in the study area than the EVI. Using NDVI, crop coefficient (Kc) and crop evapotranspiration (ETc) time-series from 2002 to 2012 were built for the study sites and compared with the SPI drought index and the results may indicate that the NDVI will be suitable to analyze the impact of the drought on the vegetation. Effective evapotranspiration (EET) patterns derived from the MODIS satellite (land surface evapotranspiration product MOD16) were analyzed and compared with measured effective evapotranspiration from experimental plots, to analyze the reliability of this product in the study area. The MODIS product did not provide satisfying results in showing evapotranspiration patterns that were comparable with EET calculations from the experimental plots but more extensive time-series of MODIS would be recommendable to increase the overlap period of MODIS and field observation EET values.

Key words: MODIS Satellite, NDVI, EVI, Evapotranspiration, Eucalyptus, Pine, Drought.

1 INTRODUCTION AND BACKGROUND OF THE STUDY

Nowadays hydrological models that try to represent the physical processes observed in the field (process-based models) are widely accepted, especially due to their elevated potential for testing the current understanding of hydrological and soil erosion processes and impacts of possible climate and land-use change scenarios (Beven, 2000). However, an important problem to overcome in the application of these types of hydrological models is their elevated data input requirements.

As an example, the SWAT model (Arnold *et al.*, 1998), one of the most used hydrological models in the last years, requires 57 parameter values (input variables) to make good simulations of soils and land-use. All of these 57 parameters have to be included in the model and cover each soil layer and land use type. Exploratory modeling work in forested catchments of North-central Portugal revealed that little to no information is available for almost half of the selected model input variables (Tuinenburg *et al.*, 2006). There is a lack of detailed information on soil type distribution and properties for the entire study area and a basic soil characteristic like saturated hydraulic conductivity was measured at no more than a handful of not-precisely recorded locations. There is also a lack of data on hydrological processes which can help calibrate and validate models. For example, the lack of information about some water balance components, like evapotranspiration (ET), makes it difficult to apply the proper application of hydrological models and the obtaining of good results is limited by the uncertainties of the input data. This means problems occur with calibrating the equifinality, which means that similar modeling results can be obtained using different sets of input data when only adjusting model parameters to hydrograph measurements.

Well known is the importance of landuse in the hydrological cycle. The major components from hydrological cycle could be measured in the field with sufficient accuracy for individual water balances calculated for different types of catchments, but evapotranspiration is the most difficult component to be measured, and indirect assessments could be made of evaporative losses (Edwards *et al.*, 1976). According to Zhang et al. (2001) one of the main processes responsible for changes in water yield after alterations in landuse is the evapotranspiration and the knowledge of evaporation patterns and water use of vegetation is important information for calibration and validation of eco-hydrological models.

Because of the importance of evapotranspiration in making proper calibration models this research will aim at collecting data of the evapotranspiration by use of satellite images of vegetation condition and landuse changes over a time series. The problem is that this has not been done before in the region, and thus it is not certain at the beginning of the work that this can be done at all.

2 RESEARCH QUESTIONS AND OBJECTIVES.

The objective of this research is to obtain a time-series of one decade of evapotranspiration patterns that will be useful in eco-hydrological modeling. Effective evapotranspiration (EET) patterns derived from satellite vegetation indices will be analyzed and compared with measured evapotranspiration from experimental plots. Observed crop coefficients (K_c) (the ratio between the vegetation's daily potential evapotranspiration and the reference evapotranspiration of a standard crop) will be compared with K_c calculated from satellite vegetation indices (NDVI and EVI). The evolution of calculated K_c from satellite data in the last decade will be used to analyze the impact of droughts on the vegetation's water use, i.e. its crop evapotranspiration (ET_c).

This research will have the following research questions.

Main research question:

Can the vegetation indices NDVI and EVI from MODIS satellite be used, together with observed data, to give reliable estimations of ET_c or water use in eucalypt, pine and mixed forest in north-central Portugal?
Does the land surface evapotranspiration product from MODIS (MOD16) has a good enough representation of EET to be applied in the study area?

Secondary research question:

Satellite vegetation indices reflect the state of the vegetation and can be used as indicators of water stress identifying the areas with more or less water demand. It is however not known exactly how well these vegetation indices can be used to determine water shortages.

This leads to the following research question:

How is the response from NDVI and EVI vegetation indices to drought? Can these indices be indicators of drought severity?

3 METHODS

3.1 Water balance

The water balance is an accounting of the inputs and outputs of water. The water balance of a place, whether it is an agricultural field, watershed, or continent, can be determined by calculating the input, output, and storage changes of water at the Earth's surface. The major input of water is from precipitation and the output is the evapotranspiration.

The water balance components are (Ritter, 2006):

Precipitation (P): Precipitation in the form of rain, snow, sleet, hail, etc. is the primarily supply of water to the surface. In dry locations, water can be supplied by dew and fog.

Effective evapotranspiration (EET): Evaporation is the phase change from a liquid to a gas releasing water from a wet surface into the air above. Similarly, transpiration represents a phase change when water is released into the air by plants. Evapotranspiration is the combined transfer of water into the air by evaporation and transpiration. Effective evapotranspiration is the amount of water delivered to the air from these two processes. Effective evapotranspiration is an output of water that is dependent on moisture availability, temperature and humidity.
Effective evapotranspiration can be thought of as "water use", and is water that is actually turned into vapour by evaporation or leaf transpiration. The amount is determined for the environmental conditions of a place. Effective evapotranspiration increases as temperature increases if there is water to evaporate and for plants to transpire. The amount of evapotranspiration also depends on how much water is available, which depends on the field capacity of soils. In other words, if there is no water, no evaporation or transpiration can occur.

Another important concept to take into account is the **Potential evapotranspiration (PET):** The environmental conditions at a place create a demand for water. Especially in the case of plants, as energy input increases, so does the demand for water to maintain life processes. Potential evapotranspiration is the amount of water that would be evaporated under an optimal set of conditions, like an unlimited supply of water. Potential evapotranspiration can be thought of as the water needed for evaporation and transpiration given the local environmental conditions. One of the most important factors that determine water demand is solar radiation. As energy input increases the demand for water, especially from plants increases. Regardless if there is, or isn't, any water in the soil, a plant still demands water. If it doesn't have access to water, the plant will likely wither and die.

Soil Moisture Storage (ST): Soil moisture storage refers to the amount of water held in the soil at any particular time. The amount of water in the soil depends on the soil properties like soil texture and organic matter content. The maximum amount of water the soil can hold is called the field capacity. Fine grain soils have larger field capacities than coarse grain (sandy) soils. Thus, more water is available for actual evapotranspiration from fine soils than from coarse soils. The upper limit of soil moisture storage is the field capacity, the lower limit is 0 when the soil has dried out. The change in soil moisture storage **(ΔST)** is the amount of water that is being added to or removed from what is stored. The change in soil moisture storage falls between 0 and the field capacity.

A general water balance equation (Chow *et al.*, 1988) is:

$$P = Q + ET + \Delta S$$

Where P is precipitation, Q is runoff, ET is evapotranspiration and ΔS is the change in storage (in soil or the bedrock).

This equation uses the principles of conservation of mass in a closed system, whereby any water entering a system (via precipitation), must be transferred into either evapotranspiration, surface runoff (eventually reaching the channel and leaving in the form of river discharge), or stored in the ground.

The crop coefficient (K_c) can be considered as an indicator of water use by the vegetation. To understand what the crop coefficient is, two concepts should be take into account:

1) Potential evapotranspiration (PET): is the evapotranspiration rate from a reference surface with full availability of water. The reference surface is a hypothetical grass reference crop with specific characteristics. This concept was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available, soil factors do not affect PET and the only factors affecting PET are climatic parameters that can be computed from weather data and the FAO Penman-Monteith method is recommended for determining this parameter (Allen *et al.*, 1998).

2) Crop Evapotranspiration (ETc): The crop evapotranspiration under standard conditions, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.

The crop coefficient (Kc) can be calculate as (Allen *et al.*, 1998):

$$Kc = ETc / PET$$

This index of vegetation water use can be used to compare water requirements during mild and severe droughts. The values obtained from observed data can be compared with satellite values from vegetation indices (NDVI and EVI) to perform an estimation of crop coefficients from satellite data.

3.2 Satellite data

3.2.1 What is MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths. These data will improve our understanding of global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere. MODIS is playing a vital role in the development of validated, global, interactive Earth system models able to predict global change accurately enough to assist policy makers in making sound decisions concerning the protection of our environment (MODIS, 2013).

3.2.2 MODIS vegetation indices.

Vegetation indices are used for global monitoring of vegetation conditions and in products displaying land cover and land cover changes. These data may be used as input for modeling global biologic, geochemical and hydrologic processes and global or regional climate. These data also may be used for characterizing land surface biophysical properties and processes, including primary production and land cover conversion.

MODIS core mission, standard VI products include the Normalize Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) to effectively characterize bio-physical and biochemical states and processes from vegetated surfaces. There are complete, global time-series records of 6 VI products from each of the Terra and Aqua MODIS sensors, at varying spatial (250m, 1km, 0.05 degree) and temporal (16-day, monthly) resolutions to meet the needs of the research. The VI products can be validated with pixel reliability flag to show the quality accuracy of the pixels.

Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a graphical indicator that can be used to analyse remote sensing data (not necessarily positioned at a space platform), and is used to carry out remote sensing measurements of vegetation. In other words the sensor can detect if the target surface has live vegetation cover or not.

The data products provided are the Normalized Difference Vegetation Index (NDVI), Band 1 (red), Band 2 (near infrared) and cloud data when available (NDVI, 2013). The composite values are based on data quality and the maximum NDVI for the compositing period. The NDVI is a ratio of the red and near infrared reflectance. It is useful for assessing the health and density of vegetation. NDVI values near 0 such as -0.1 to 0.1 indicate barren areas of rock, sand or snow. Higher values of 0.1 to 0.4 indicate sparse vegetation of grassland and shrubs. Dense vegetation like tropical rainforests or temperate forest is indicated by NDVI values approaching values of 1 (Weier and Herring, 2013). By using time-series of NDVI observations, one can examine the dynamics of the growing season and monitor phenomena such as drought.

Plants and trees absorb solar radiation for their photosynthesis, which is called their photosynthetically active radiation (PAR). This is a source of energy which the live green plants are able to use when the sun sends solar radiation of a spectral range (wave band) of between 400 to700 nanometers. This spectral range corresponds more or less with the visible light for the human eye. This visible light corresponds with colour band 1 of the NDVI sensor. Plants are evolved to scatter (reflect and transmit) solar radiation of over 700 nanometers, which falls within the invisible light range, represented by Band 2. Otherwise they would get overheated (Gates, 1980).

Live green plants appear relatively dark in the PAR and relatively bright in the near-infrared, (NIR) while clouds and snow tend to be very bright in the red and dark of the infrared spectrum. This means that plants can be distinct from clouds and snow and that different wavelengths can detect differences in vegetation cover. Visible light is strongly being absorbed by the pigment (chlorophyll) from the plant leaves and near-infrared is being reflected by the cell structure of the leaves. This means the more leaves a plant has; the more these wavelengths of light are influenced. To calculate the vegetation cover the differences in reflectance has to be looked upon (Crippen, 1990).

The formula to detect the NDVI is stated as follows:

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}$$

Where: NIR is near-infrared and VIS is visible-infrared.

To distinct forests from other vegetation in general, if the reflected radiation is much higher in near-infrared wavelengths than in the visible wavelengths, then the vegetation in that pixel is likely to be dense and probably covered with forest. Therefore NDVI is directly related to the photosynthetic capacity and energy absorption of plant canopies (Sellers, 1985).

Enhanced Vegetation Index (EVI)

The enhanced vegetation index (EVI) was developed to improve the distinction in vegetation from satellite images. It is an 'optimized' index designed to enhance the vegetation signal with improved sensitivity particularly in the high biomass regions like the forests. It reaches improved vegetation monitoring by getting a better view through the canopy layer of the trees and by reducing the atmospheric influences.

In other words, where the Normalized Difference Vegetation Index (NDVI) is only chlorophyll sensitive, the EVI is dependent of canopy structural variations. These variations are the leaf area index (LAI), canopy type, plant appearance, and the canopy structure. Another difference between the NDVI and the EVI is that in case of snow the values of NDVI decrease while EVI values increase with all its consequences. The EVI additionally separates the soil and atmospheric influences from the vegetation signal by including a feedback term for simultaneous correction.

3.2.3 Use of MODIS to perform evapotranspiration estimations.

The use of satellite products to estimate several environmental variables (Schubert *et al.*, 2012) as well as vegetation dynamics (Knox *et al.*, 2013) is widely extended in the last decades due to the increasing temporal resolution and spatial coverage.

MODIS data was applied successfully in several regions to estimate evapotranspiration. Previous studies showed that over a wide range of natural biomes, NDVI was well correlated with both the biomass productivity as the EET over time (Field, 1991). MODIS with daily coverage has the ability to provide near-real time remote sensing coverage of biomass intensity (Huete *et al.*, 2002; Nishida *et al.*, 2003; Mu *et al.*, 2007). Nagler et al. (2005) found good correlations between vegetation indices from MODIS like NDVI and EVI and evapotranspiration.

Rossi et al., (2007) showed preliminary results that point at the potential of developing tools to monitor crop water needs at a regional scale by means of MODIS images. Recent works in Portugal used satellite data with good results for the estimation of actual evapotranspiration (Cherif *et al.*, 2013) or maximum and minimum temperatures (Benali *et al.*, 2012).

3.2.4 Obtaining and processing MODIS data

The MODIS satellite data to use was obtained from the Oak ridge National Laboratory DAAC for the National Aeronautics and Space Administration (NASA). The data was ordered by selecting a global subset of the preferred location of each study site using the global coordinate system WGS84 to give the coordinates for the central pixel and the system select an area corresponding to 3km from the center pixel for the NDVI/EVI subset.

The final subset comprehends data from March 2000 to April 2013 for NDVI/EVI product with a pixel resolution of 250 x 250 m, and from January 2002 to September 2012 for the EET/PET product, with a pixel size of 1 x 1 km in ASCII format. Beside this information, the ASCII files with the vegetation indices values contain values for each pixel of vegetation index quality, pixel reliability, and different color reflectance values: Near Infrared, Mid-Infrared, red and blue, and the azimuth angle of the satellite at the moment of the measurement.

Table 1. Product MOD13A1: 16-day 250/500-m VI (Solano *et al.*, 2010)

Science Data set	Units	Data type	Valid range	Scale factor
XYZm 16-days NDVI	NDVI	int 16	-2000, 10000	0.0001
XYZm 16-days EVI	EVI	int 16	-2000, 10000	0.0001
XYZm 16-days VI Quality detailed QA	Bits	uint 16	0,65534	NA
XYZm 16-days red reflectance (Band 1)	Reflectance	int 16	0, 10000	0.0001
XYZm 16-days NIR reflectance (Band 2)	Reflectance	int 16	0, 10000	0.0001
XYZm 16-days Blue reflectance (Band 3)	Reflectance	int 16	0, 10000	0.0001
XYZm 16-days MIR reflectance (Band 7)	Reflectance	int 16	0, 10000	0.0001
XYZm 16-days view zenith angle	Degree	int 16	-9000, 9000	0.01
XYZm 16-days sun zenith angle	Degree	int 16	-9000, 9000	0.01
XYZm 16-days relative azimuth angle	Degree	int 16	-3600, 3600	0.1
XYZm 16-days composite day of the year	Day of year	int 16	1, 366	NA
XYZm 16-days pixel reliability summary QA	Rank	int 8	0, 3	NA

The supplied data from MODIS are 16-day composite records for the NDVI/EVI for each pixel within the selected area that had to be multiplied by a 0.0001 factor to adapt it to the real NDVI/EVI values that range from 0 to 1 (MODIS, 2013).

The MODIS Land Products are assessed through the Quality Assessment (QA) metadata objects and by the QA Science data sets. The QA objects are codes of single words or numeric numbers and are therefore useful for data ordering and screening processes. The QA SDS document contains the pixel quality on a pixel-by-pixel basis and is therefore useful for data analysis. In the QA SDS there are two kinds of pixel level metadata implementations of Quality Assessments of the MODIS land products. These are the Vegetation Index Quality Assessment (VI QA) and the pixel reliability QA. The VI QA contains numeric values that contain a code. When the code was over 10.000 the values were considered abnormal and therefore unusable. This threshold was obvious, as the vast majority of values were around 2 or 3 thousand and only some had values around 35000, which could clearly be seen in a graphical presentation.

The pixel reliability gave values of -1 (no value) 0, 1, 2, 3 and 4 of which only the 0 was fully reliable. The value 1 of the pixels was considered marginal data, which was useful but other quality assessments had to be checked. Value of 2 could be related to snow and ice coverage disturbance and values of 3 are disturbances by clouds and therefore not useful. A reliability value of 4 indicated that when there was no observation done within the composite date, the pixel was attributed with a value by making use of historical data of the location. At the chosen location within the time series only 0, 1, 2 and 3 QA values were found. This pixel reliability quality assessment could be applied for both NDVI and EVI. It is used to describe if pixels were generated by using historical filling criteria (Solano *et al.*, 2010).

To have a broader idea of the average NDVI or EVI values of the eucalypt and pine areas, a total of 9 pixels were processed, including the central pixel for the two study sites coordinates. Quality checks were performed for each of the 9 pixels in the eucalypt and pine sites at their NDVI, EVI, VI Quality, Pixel reliability and Azimuth values and deviations were removed. After the removal of all NDVI or EVI values of each of the nine central pixels that did not pass quality checks, graphs of the time-series of the pixels were made.

As the visualization of the data still showed extreme deviations in the graphical performance like sudden shifts in NDVI or EVI patterns, an additional mathematical calculation would be applied. This preferred filter was the 3-P filter which is a widely applied filter in NDVI and EVI calculations to reduce noise (extreme values) and reconstruct high-quality time-series for further applications (Gu *et al.*, 2009). The effect of the 3-P filter is a more “smooth” appearance of a time-series without extreme noise. The filter replaces each temporal value with a weighted average, considering the original value at 50% weight, and the previous and subsequent temporal values at 25% weight each. In this case the pixel NDVI/EVI values of each 16-day composites were taken and multiplied with previous and subsequent values. The result of this filter application would be graphs containing less noise.

After having created the NDVI and EVI temporal pattern for each pixel of the eucalypt and pine locations the pixels were combined to acquire a mean value for each of the two areas (0,56 km^2 each). Each mean value then had to be reviewed on being acceptable, or influenced negatively by dubious pixel values. To demonstrate to what extent certain pixel values were deviating, standard deviation graphs were created of NDVI and EVI of Pine and Eucalypt. Finally the mean values of the NDVI and EVI derived from MODIS were visualized. These values were compared to the values of the observed data from the field of the pine and eucalypt locations. The dubious temporal pixel NDVI values were removed to improve the mean NDVI value.

3.2.5 Estimation of temporal series of Kc using MODIS vegetation indices

To estimate the crop coefficient (Kc) using the vegetation indices, transpiration crop coefficients (Kc) were compared with NDVI and EVI following the method of Duchemin *et al*. (2006) that was adapted to the study site and the 16-day composite values.

According with Duchemin *et al.* (2006) a filtering of the Kc values need to be done and only the Kc values that did not present high evaporation values, nor high water stress can be used. Only these observed values can be expected to be correlated with the vegetation indices, since they represent only crop transpiration under low water stress conditions. To perform this filtering, in case of the high evaporation and interception, a different rainfall threshold value was selected for eucalypt (90 mm) and pine (160 mm). The rainfall saturation point criteria stated that when the measured precipitation was higher than the threshold value, the Kc value for this period would not be taken into account.

Plotting the suitable observed Kc values against the mean of the vegetation indices an equation will be adjusted to relate this two parameters and it can be applied to all the MODIS vegetation indices data to generate temporal series of Kc for pine and eucalypt.

3.2.6 MODIS vegetation indices as indicator of drought.

The rainfall values from the Pousadas climatologic station were analyzed to identify possible drought periods. A first approach was done by calculating the 25^{th} percentiles of rain for each month within the period 2002/2012 and identifying the months under this percentile as dry months and comparing this with the Kc vales obtained. To see if there was a relation between the drought periods and the Kc mean values estimated via satellite, the actual Kc values were set out against the annual monthly Kc mean and put in a graph with the drought periods.

The Standardized Precipitation Index (SPI) was calculated for the study period (Mckee *et al.*, 1993), as a more accurate method to determine drought. This index defines the drought based on standardized precipitation, which is the difference of the precipitation from the mean over a specified time series divided by the standard deviation. The mean and standard deviation are defined by use of past records. It is calculated in the following sequence. A monthly precipitation data set should be prepared, preferably an undisturbed period of 30 years or more, but in this case only 9 years were available. The monthly SPI can be calculated by taking each average of the past 3, 6, 12, or 48 month records up to the present monthly precipitation and subtract the average precipitation of the whole period divided by the standard deviation from the monthly SPI. The data set is moving in the sense that each month a new value is determined from the previous months. In the present work the SPI for 12 months was calculated and analyzed for the study area; this period was selected to avoid exclusion of the summer dry periods in the SPI. The SPI values were attributed into climate bands to visualize the different climatic situations like the drought or wet periods (Mckee *et al.*, 1993). Table 2 shows distinction of the climatic situations in function of the SPI values.

Table 2. Climate situation defined by the Standardized Precipitation Index (SPI) values.

SPI value	Climate situation
From 1 to (-1)	Normal precipitation
From 1 to 1.5	Moderately wet or dry
Until 2 or (-2)	Very wet or severely dry
Above 2 or below -2	Extremely wet or dry

By adding the calculate values of Kc or ETc and its respective average monthly values along the study period for pine or eucalypt to the SPI graph, the corresponding reaction of the Kc or ETc on drought severity was shown. To draw conclusions, the vegetation history in the study sites, such as tree harvest and fires, was compared with these SPI/Kc and SPI/ETc graphs and important moments were marked by break lines.

3.2.7 Evaluation of MODIS Land Surface Evapotranspiration product (MOD16)

The land surface evapotranspiration product: MOD16 ET, is one of the several products already produced by MODIS and can be used for water balance calculations for hydrologic management, as drought or fire risk mapping (MODIS, 2013). MODIS16 ET give the values of transpiration from vegetation and evaporation from canopy and soil surfaces and is computed globally every day at 1km resolution using MODIS landcover, MODIS leaf area index (LAI) and MODIS Fractional Photosynthetically Active Radiation (FPAR) data. The meteorology used is from the Global Modeling and Assimilation Office (GMAO). The MOD16 ET datasets are estimated using Mu *et al.* (2011) building on previous Mu *et al.* (2007) datasets. The ET algorithm is based on the Penman-Monteith equation (Monteith, 1965). Surface resistance is an effective resistance to evaporation from land surface and transpiration from the plant canopy.
To evaluate the product the overlapped records from the MODIS ET product were compared with the observed EET values from the study sites.

3.3 Study area

Portugal is located in the Mediterranean region and it is affected by interactions between mid-latitude and tropical processes. The geographic position of the country, in a North-South orientation of the main land, which stretches over about 800 km, creates several different climatic zones, from dry to humid Mediterranean, to alpine to semi-arid or steppe climates. Furthermore the country is very mountainous with mountain ranges of over 1000 meters high up to almost 2000 meters. This means that there is a large differentiation in vegetative zonation.

In Northern Portugal the vegetation is highly affected by human influences as the forested hills are planted and harvested for their wood or otherwise used for agriculture (Figure 1). The afforestation plan developed during the last decades in Portugal supported the afforestation of 420 thousand hectares from 1938 to 1977 and the favored species were *Pinus pinaster* Aiton. and *Eucalyptus globulus* Labil. *(Baptista, 1993; Coelho, 2003; Jones et al., 2011).* These changes caused an important decrease of agricultural lands in favor of forest and scrublands (Daveau, 1995; Serra *et al.*, 2008; Geri *et al.*, 2010). The production of eucalypt in the coastal region of Central and North Portugal is double that of pine (Soares *et al.*, 2007). Between 1995 and 2010 eucalypt plantations in Portugal increased considerably in comparison with pine and in 2010 the dominant species is the eucalypt with 812 thousand hectares representing 26% of the Portuguese continental area (Icnf, 2013).

Figure 1. Caramulo Mountain range landscape examples.

The study area is located in the foothills of the Caramulo mountain range within the Vouga River Basin in north-central Portugal (Figure 2). Within the study area, two catchments were selected for this work. The Serra de Cima catchment (SDC) has an area of 0.52 km^2 and consists predominantly of commercial eucalypt plantations (*Eucalyptus globulus* Labil.), and the stand selected is the so-called Casa do Padre (CDP). The other stand selected (LOU) belongs to the Lourizela catchment (LOU) with 0.65 km^2 dominated by commercial forest plantations of *Pinus pinaster* Aiton. Both catchments were intermittently monitored since the 1990's and fully reactivated by the University of Aveiro in October 2009 within the HIDRIA project (reference PTDC/CTE-GEX/71651/2006). The historic sequence of the known changes of landuse and management operations in the study sites is shown in Table 3.

Table 3. Historic sequence of landuse changes in the study sites.

EUCALYPT PLOTS (Casa do Padre: CDP)	TERRACES (close to the CDP plots)	PINE PLOTS (Lourizela: LOU)
	Before 1975 - Adult pine.	
	1975 - Ploughed and Eucalypt planted	
Before 1986 – Eucalypt (unknown rotation)	1986 - Forest fire. Cut and natural regeneration	
1986 – Forest fire, cut and natural regeneration		
1988 –Ploughed and eucalypt planted		
	1998 - Cut and natural regeneration	1990 - Adult pine (Planted between 1950 and 1960 = 30-40 years old)
		July 1991 - Forest fire.
		After 1991 - Natural regeneration and Pine plantation
2003 – Cut and natural regeneration		
	December 2009 - Cut.	
	January 2010 - Built terraces and Eucalypt planted	
		Before April, 14 2011 - Forest fire close to the plots

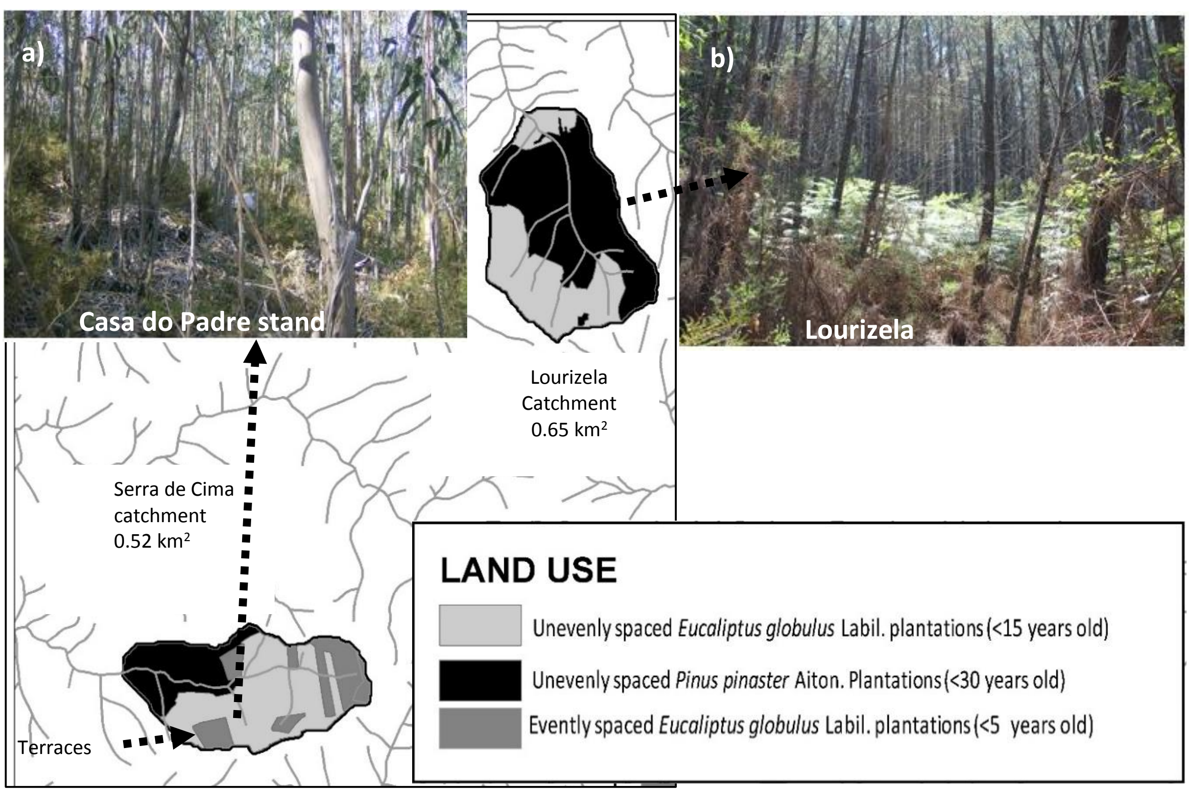

Figure 2. a) *Eucalyptus globulus* Labil. in Casa do Padre stand and b) *Pinus pinaster* Aiton. in the Lourizela stand.

3.3.1 Meteorological and climate information

A climate station from the University of Aveiro team (Figure 3) is operating in the study area since 2004 recording precipitation solar radiation, air and soil temperature, relative humidity, wind speed and direction. The records of this station were used to create climate time-series from 2002 to 2012 using the closer stations from the "Sistema Nacional de Informação dos Recursos Hidricos" (SNIRH) to complete the missing values and the climate data was used to calculate the Potential Evapotranspiration (PET) in the study area.

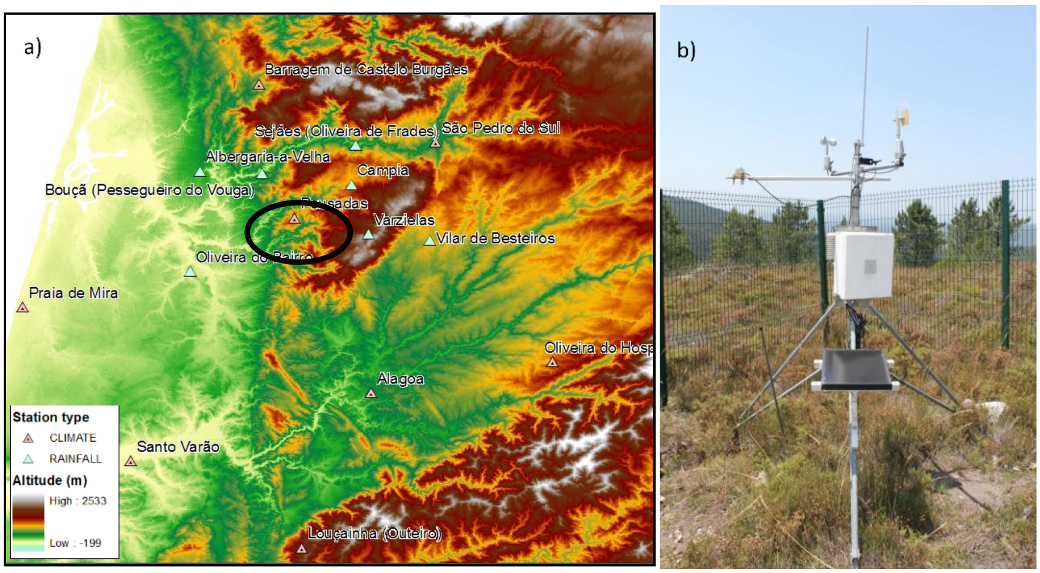

Figure 3. a) Location of Pousadas climate station and surrounding SNIRH stations in the study area; b) Pousadas climate station

In addition to the meteorological information, information about effective evapotranspiration (EET) is available from the two different tree stands (Eucalypt and Pine) calculated from on-site soil moisture measurements for the period from February 2010 to September 2012. Measured data for interception was calculated using daily rainfall and the Gash interception model, adapted for the study sites (de Coninck, 2003; Fernandes, 2008). Additionally, the Crop coefficient (Kc) transpiration value was calculated by dividing the transpiration by the potential evapotranspiration, while the Kc for ET_c was obtained by dividing the EET by the PET (Allen *et al.*, 1998).

4 RESULTS

4.1 Obtaining and processing MODIS data

After obtaining the MODIS subsets graphs of the NDVI and EVI of both eucalypt and pine could be created as can be seen in Figures 4a and 4b. In these results there are still some quality gaps, as for instance can be seen at the NDVI of the eucalypt at the 18th of December 2000 composite. As NDVI values in temperate to semi-arid zones have common distribution values between 0.6 and 0.8 while EVI values in the same physical region should lie somewhere between 0.2 and 0.4 (MODIS, 2013) the dubious values out of this range should be removed.

A first impression of NDVI and EVI patterns shows that the Casa do Padre Eucalypt measurements seem to be following the Lourizela pine measurements to a large extend on both NDVI as EVI. Quality gaps seem to overlap composite dates though the deviation seems higher for eucalypt. In the beginning of 2005 and 2010 and the spring of 2012 NDVI values seem low for the eucalypt while Pine does not show high fluctuations in these given periods.

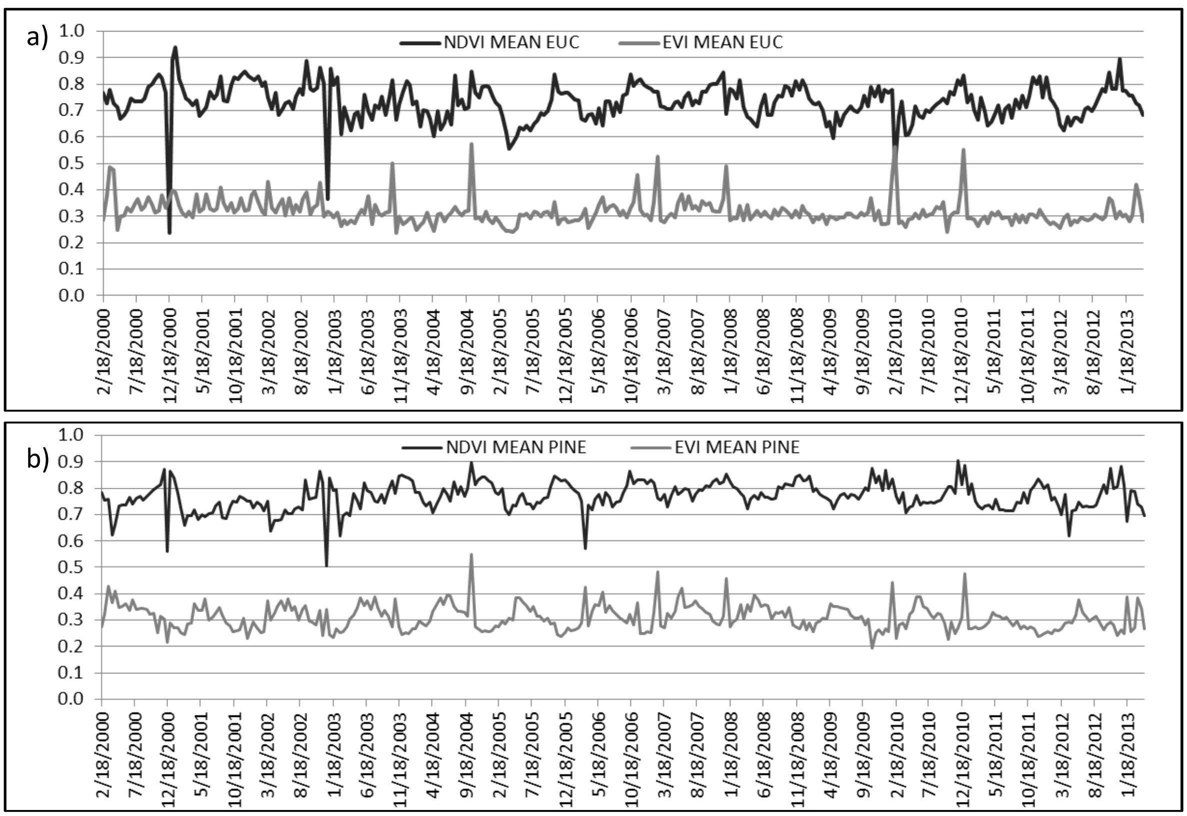

Figure 4. Unfiltered NDVI and EVI of the Casa do Padre Eucalypt (a) and the Lourizela Pine (b).

After filtering the data with the Vegetation index quality assessment and Azimuth angle filtering most of the dubious values for the pine and eucalypt NDVI and EVI were took out but was still necessary the application of the 3-P filter (Gu *et al.*, 2009) to select only the trustworthy pixels to calculate means the NDVI/EVI of eucalypt and pine and obtain the right patterns.

These patterns however still contained wrong information due to the fact that some pixels influenced the mean values negatively. Therefore the analysis of each pixel distribution of NDVI and EVI was done and those pixels that performed remarkably out of order to the mean were removed as can be seen in Figure 2a and 2b. For instance, in the Casa do Padre site (Eucalypt), the pixels in the lower right corner (NDVI/EVI (3-P+PR+Q) 338 and NDVI/EVI (3-P+PR+Q) 339) had much lower values then the other pixels in that area and Google Earth images shown that, at this location, the value was highly influenced by the presence of a road.

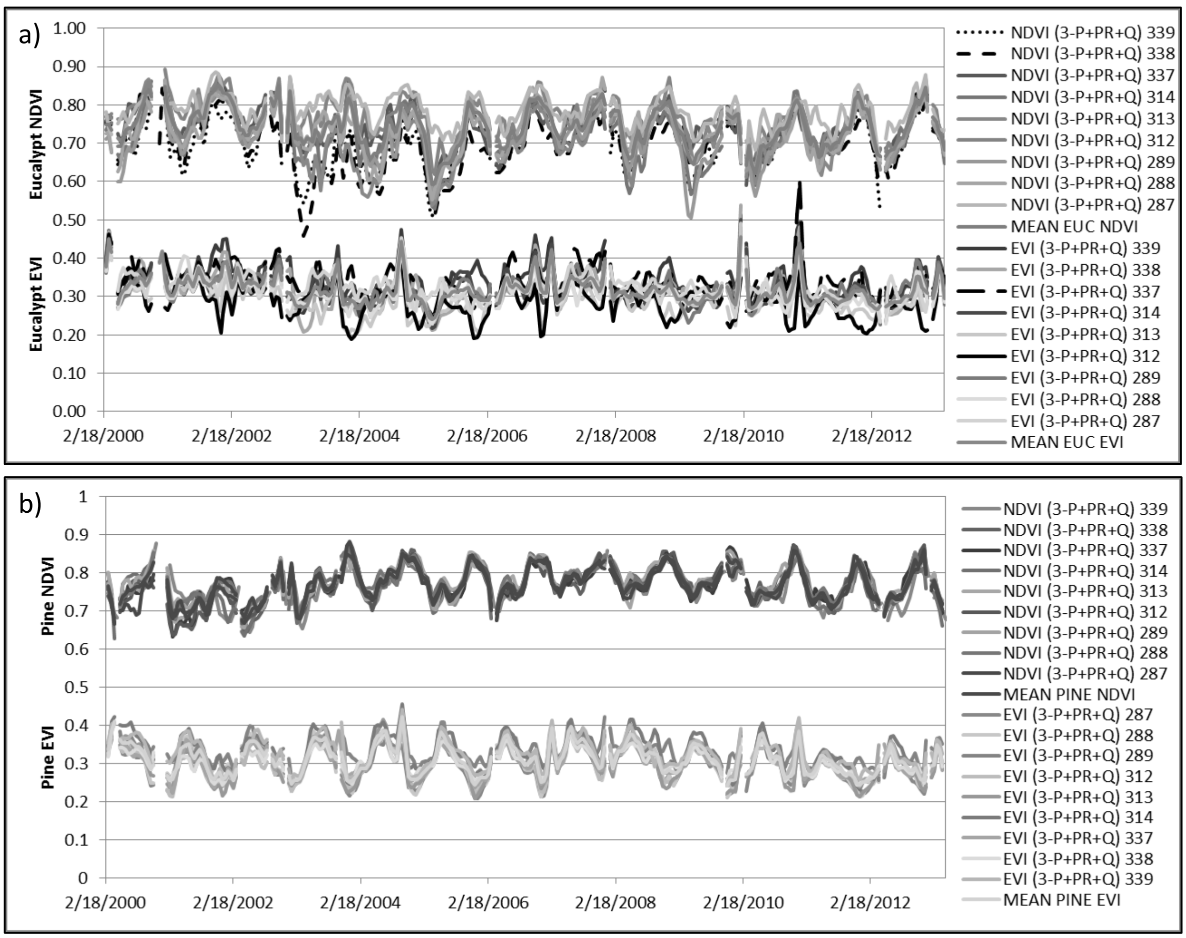

Figure 5. Eucalypt location removal of dubious pixels to improve mean NDVI and EVI values (a). The pixels in black (NDVI 339, 338, EVI 337, 312) fell out of the selection of calculating a mean NDVI/EVI pattern for the eucalypt location. The pine location did not have dubious pixel patterns (b).

After all the filtering trustworthy mean patterns are observed in Figure 6. It can be observed that up to April 2003 the NDVI of eucalypt are over the values of pine, but after this time the pine has higher values. This should either mean that pine has developed gradually within these years to a more mature status while eucalypt patterns stay unchanged, or that there are other unknown reasons causing this effect. Looking at the known historic sequence of the two locations (see Table 3 in Methods chapter) there would be no indication of reason why this shift would take place so we could assume that the values from before April 2003 were not correct for unknown reasons and should not be taken into account.

Furthermore the eucalypt shows a remarkable low value for the spring of 2005 and in the same time the EVI of eucalypt stays much below the pine values.

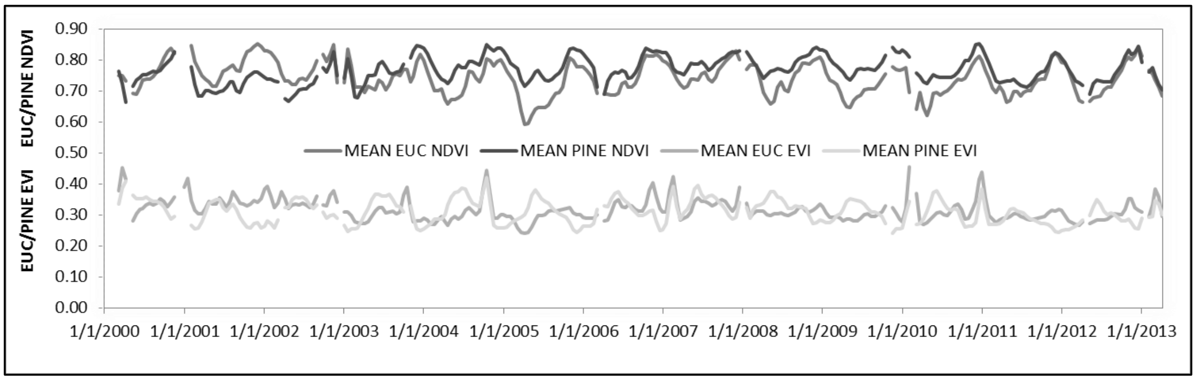

Figure 6. Mean NDVI and EVI of Eucalypt and Pine sites after applying all filters and removal of dubious pixels.

Observed temporal were processed to acquire equal 16-day composite records as MODIS data. The observed transpiration and potential evapotranspiration patterns of eucalypt and pine in relation to precipitation can be seen in Figures 4a and 4b. The existence of a data gap from February to August 2011 in the eucalypt site is to highlight, due to the stealing of the soil moisture sensors that could not be replace until July 2011.

In these figures it can be seen that potential evapotranspiration is highest in summer as it assumes a continuous availability of water. On the other hand transpiration of measured values stays behind in summer because of the precipitation and consequent soil water deficits. Pine and eucalypt seem to show comparable patterns, with some exceptions. For eucalypt the transpiration values were normally distributed in the first year; the transpiration increased parallel with the PET, and decreased in spring with reduced rainfall and reached lowest values in July and August after which the precipitation increased in autumn and transpiration and PET become parallel again.

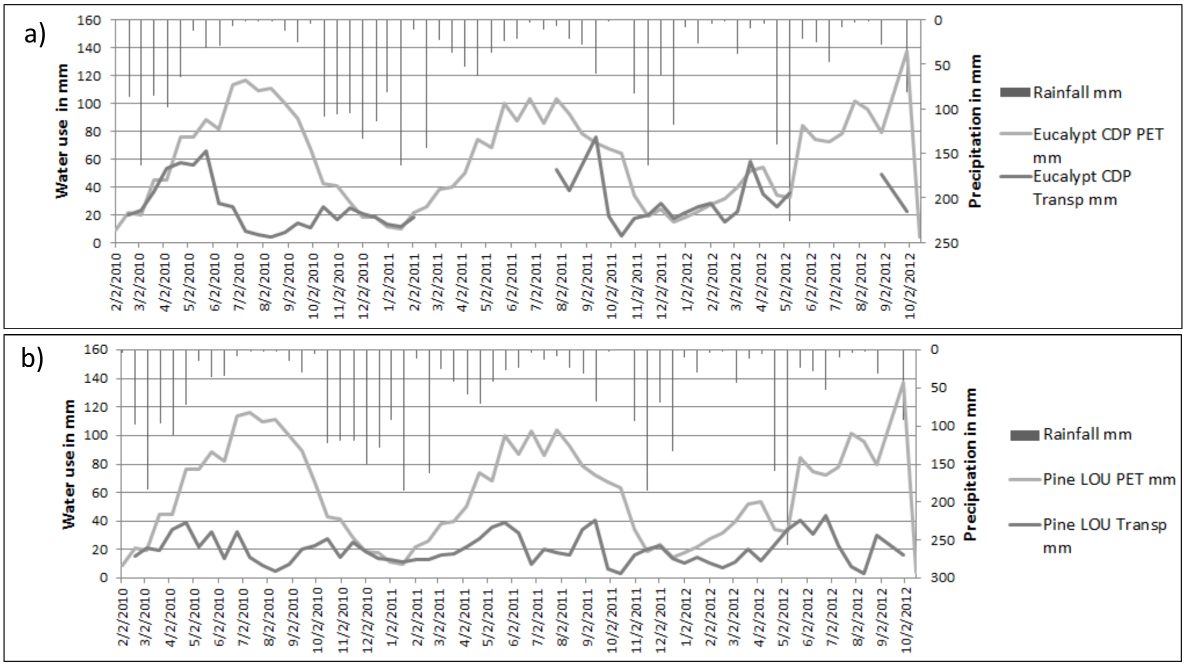

Figure 7. Potential evapotranspiration and transpiration in mm in relation to the precipitation for eucalypt (a) and pine (b).

The next year 2011 was an abnormal year, however, since spring was very dry. Then the rain increased until May and June, followed by a normal dry summer, but a wet September month. After that October was very dry. The transpiration values for eucalypt were very high in August and September, but with an information gap from February until July, the spring-summer period transpiration pattern can only be guessed. The year 2012 again lacks information as the whole summer period of June, July and August are missing and November and December as well. The only period worthy is January until May and it seems to follow the normal pattern until April. In general it could be stated of eucalypt that transpiration values are highest in March until June, with a large decrease in July and August. In autumn the transpiration depends on the amount of precipitation and can be very high also.

When looking at the transpiration pattern of pine it could be seen that, for each consecutive year, transpiration was at a minimum in July-August and highest in spring, with an increase in autumn. The only unusable transpiration value was in the period of September-October 2011 when very high rain values were followed by almost no rain in this whole month. In general it could be said of the Lourizela pine site that the transpiration values follow the water availability values, with low transpiration in the driest months and high transpiration in spring and early summer when water is still plenty, though differences in response are not as pronounced as for the Casa do Padre eucalypt in that same period.

4.2 Estimation of temporal series of Kc and ETc using MODIS vegetation indices

After comparison of both vegetation indices, the NDVI index showed the best reliability to be applied in the estimation of the crop coefficients (Kc) for pine and eucalypt in the study area (Figure 8a). Only one outlying value of the eucalypt Kc transpiration was removed, so the eucalypt equation changed from a 0.3669 to 0.6769. There was no apparent cause for incorrect valuation of this point being the 21st of March 2012, but it was a clear outlier and the correlation changed in such a number that the removal was accepted. The equation adjusted using the Kc transpiration and the NDVI mean value during the observation period (February 2010-September 2012) was applied to the rest to the MODIS NDVI series to get the Kc temporal series.

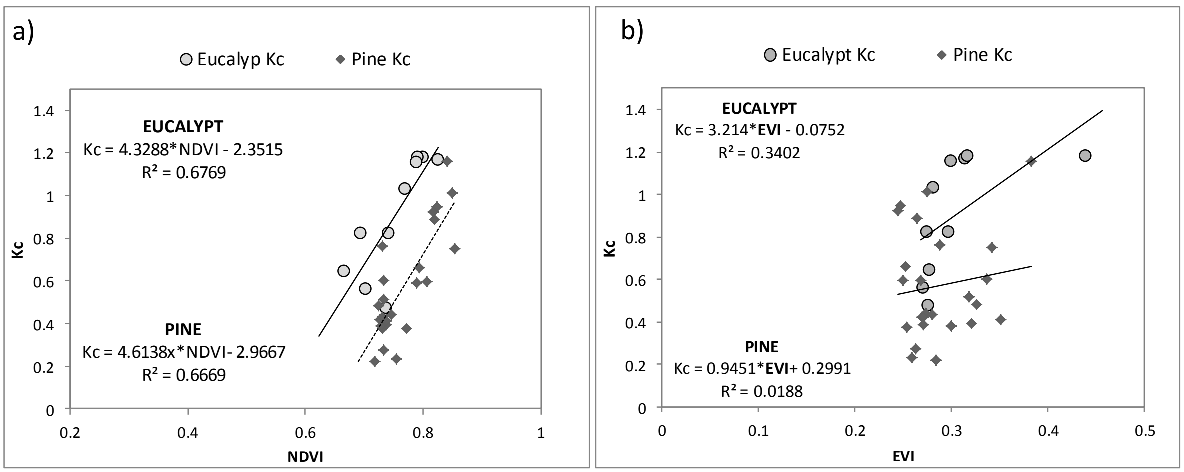

Figure 8. Correlation between MODIS NDVI (a) and MODIS EVI (b) in relation to the Kc for eucalypt and pine.

In the Figure 8a it can be observed that the trend lines for Eucalypt and pine are parallel to each other, although eucalypt had a higher crop coefficient than pine and therefore a higher water use, with equal NDVI values; and likewise pine gave lower outcomes with equal NDVI.

The comparison between the Kc values obtained for eucalypt and pine show a clear correlation in both types of tree during the study period (Figure 9) and only the values from January 2002 to March 2003 show some type of anomaly and should be neglected because of quality disturbance for unknown reasons in the NDVI records that showed very low values not linked to a known drought period or forest fire within the coordinates that could have influenced these low values, as already described earlier. So the rest of the comparisons and calculations will be based on the values from April 2003 for both types of tree.

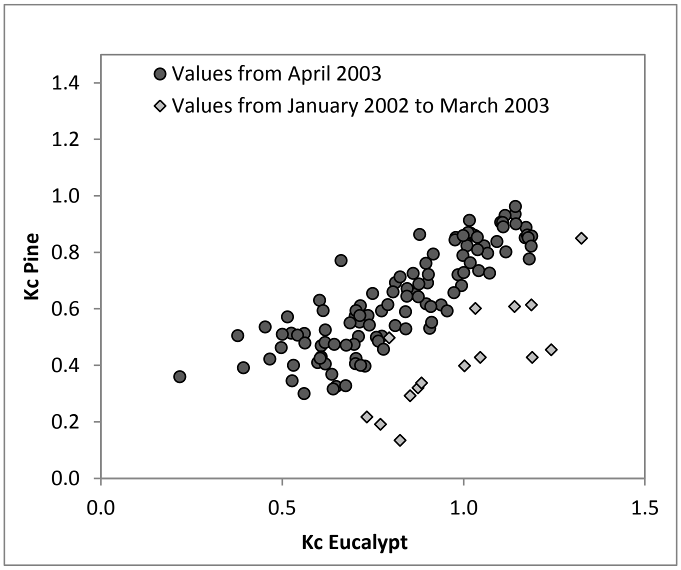

Figure 9. Distribution graph of crop coefficients of eucalypt and pine starting in January 2002 and starting in April 2003.

In Figure 10 the temporal evolution of the Kc for pine and eucalypt calculated from the MODIS NDVI vegetation index can be observed. The values obtained for the Kc for pine and eucalypt in the study area range from approx. 0.3 to 0.9 for Pine and 0.2 to 1.2 for Eucalypt. In general, the higher values were observed during the months of October and November and the lower values recorded in April and May. A clear drop in the Kc values is observed for during the spring months of 2005, clearly related with the existent drought in that year.

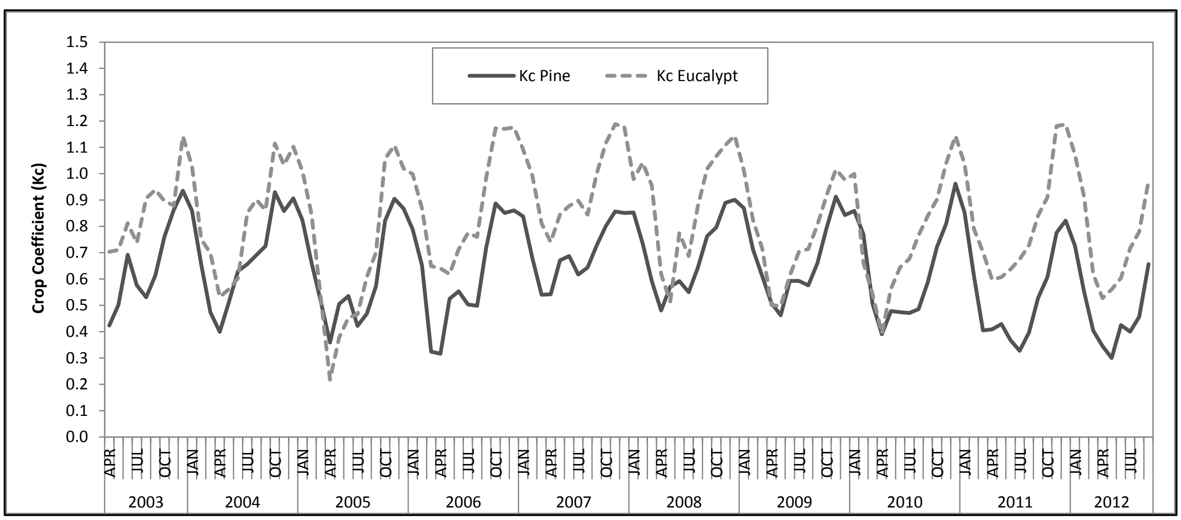

Figure 10. Crop coefficient (Kc) values for Pine and Eucalypt obtained from MODIS NDVI.

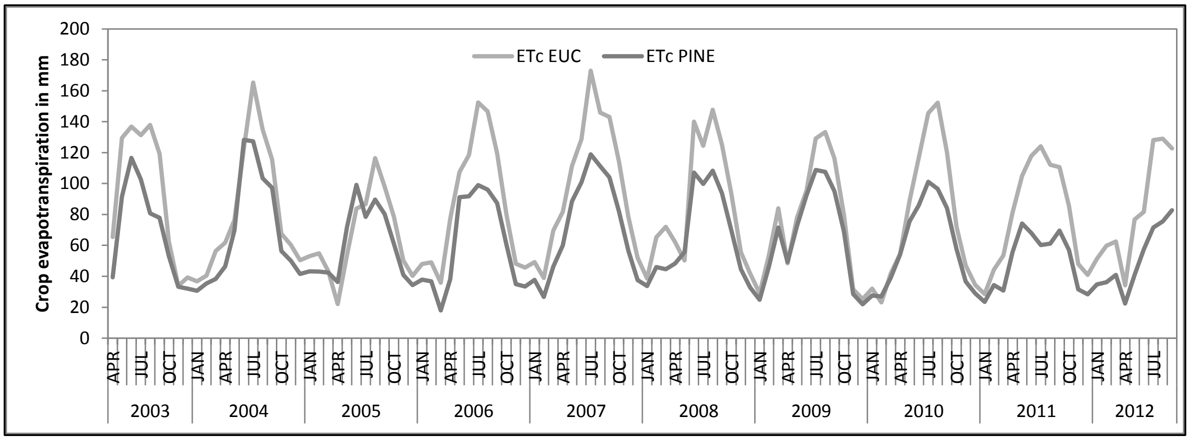

Figure 11. Crop evapotranspiration (ETc) series for Pine and Eucalypt obtained from MODIS NDVI.

The monthly values of ETc obtained from the satellite estimations (Figure 11) range from 20 to 180 mm with the maximum values in July and August and minimum values from January to February. The lowest values were also observed during 2005.

4.3 MODIS vegetation indices as indicators of drought.

The monthly Kc and ETc values were compared with the rainfall statistics during the study period: mean rainfall and standard deviation and 25th and 75th percentile searching for a relation between the Kc obtained from satellite and drought periods.

In Figure 12a the eucalypt shows 4 periods worth mentioning in which the monthly Kc values are below the mean Kc values. These are March-December 2005, April 2009 until November 2010, February-September 2011 and March-August 2012. In the Figure 12b the pine shows below average values in the period March-April 2006, June-November 2011 and April-July 2012. The 2006 lower values seem to correspond with a long drought period but in 2011 the drought only lasted from July until August while the low Kc values started earlier and lasted longer.

Figures 12c and 12d show the same comparison using the crop evapotranspiration (ETc). The mean ETc show larger differences between the high and low seasons and there are some remarkable patterns. The eucalypt (Figure 12c) show low ETc values from March to December 2005. Other periods to highlight with low ETc are from November 2009 to April 2010, from December 2010 to March2011 and from April to June 2012.

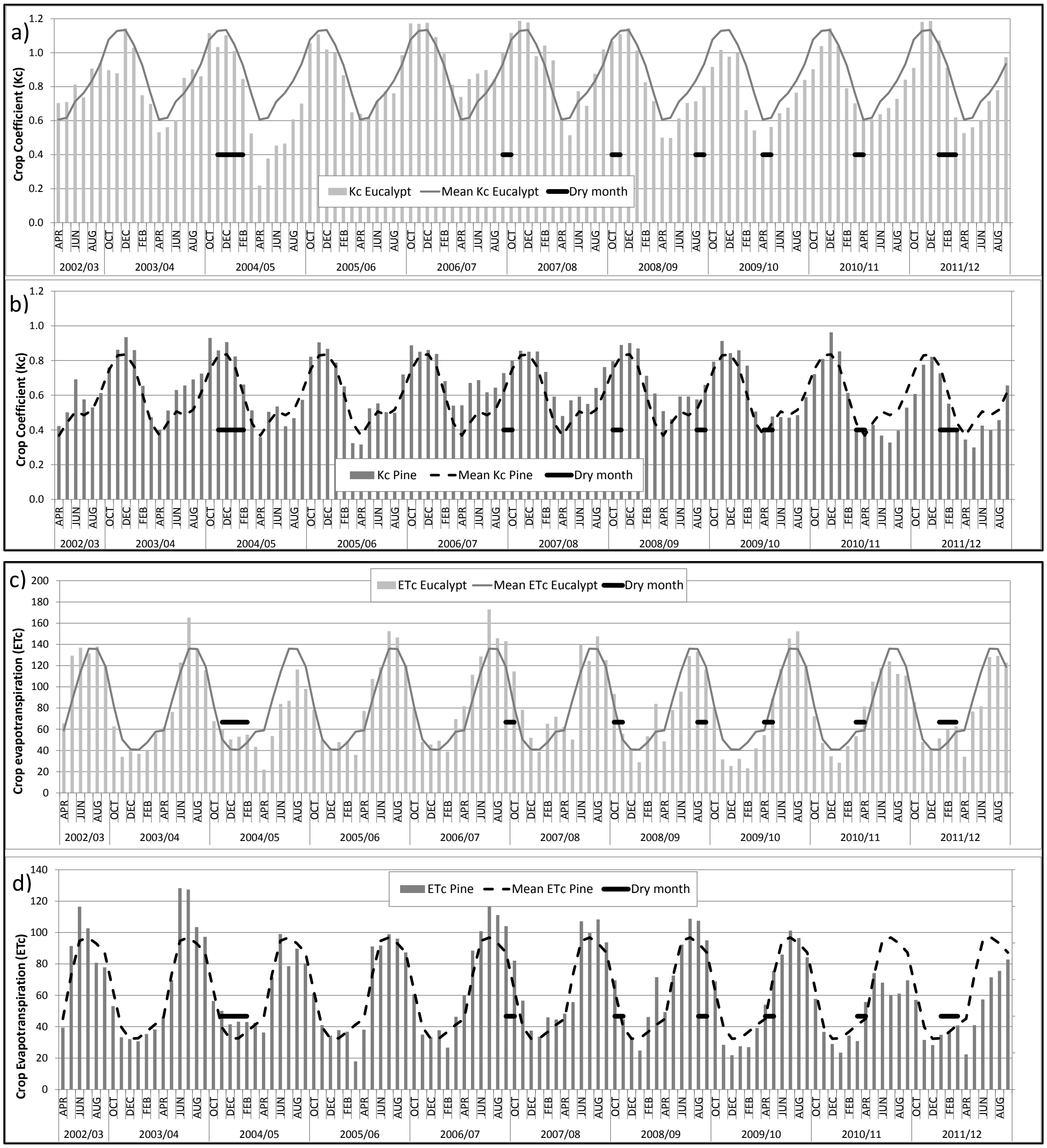

Figure 12. Eucalypt (a) and Pine (b) monthly Kc related to the average Kc for that period and drought periods and Eucalypt (c) and Pine (d) monthly ETc related to the average ETc for that period and drought periods.

In these periods the below mean values are smaller than in case of the Kc and the periods are shorter. In case of the pine (Figure 12d) below mean values are observed in April and July 2005, March and April 2006, January 2009, November 2009 until February 2010, January until March 2011, June until September 2011 and from April to September 2012. Of these the June-September 2011 period is very remarkable and as the highest ETc mean occurs in July and August, the actual ETc did not increase after May. Both the ETc and the Kc graphs show below mean values in the same period, but the highest values of the mean Kc pattern occur three months later than the highest ETc mean values, in November-December.

Using as drought indication the monthly rainfall values under 25th percentile of monthly precipitation did not coincide with the low Kc levels. Using the Standardized Precipitation Index for 12 months, the drought severity during the study period was identified. The SPI over the data period (2002-2012) provided monthly time-aggregated values, which means that each monthly value is the mean of the total of the previous 12 months. Therefore the monthly SPI values were representative of the long term climatic conditions. In Figure 10 the patterns of the 12 monthly SPI can be seen in relation to the Kc and monthly mean Kc of eucalypt and pine. In this graph it is made clear that the long drought periods have their most severe moment from July to October in 2005 and from February to April in 2012. The Kc values of the eucalypt and pine to lesser degree, go under the mean Kc values before the highest drought severity moment of 2005. At the moment of highest severity the calculated Kc are recovering to the level mean Kc in 2005. Looking to the pine Kc graph, the two droughts identified by the SPI reflected very different reactions in the Kc. Despite the drought in 2005 is longer than the one in 2012, the drop of the Kc is clearer in 2012 and started already before the drought period. After April 2011 the Kc of pine goes under the mean before the highest severity and remains under the mean line after. This may illustrate the effect of a wildfire that happened in this area in April 2011 and that can be the cause of the low Kc values before the drought started.

Besides the 2005 and 2012 pattern changes, there is another below the mean Kc observable in the eucalypt location from December 2009 onward. This may be explained by the existence of an eucalypt plantation that was cut and later terraces were created to plant new eucalypt trees. These management operations may cause the drop in the Kc values after December 2009 that is recovered later with the growth of the new trees. To summarize, only the 2005 eucalypt Kc response can be related with drought with some certainty, and for the other two moments other causes had to be searched.

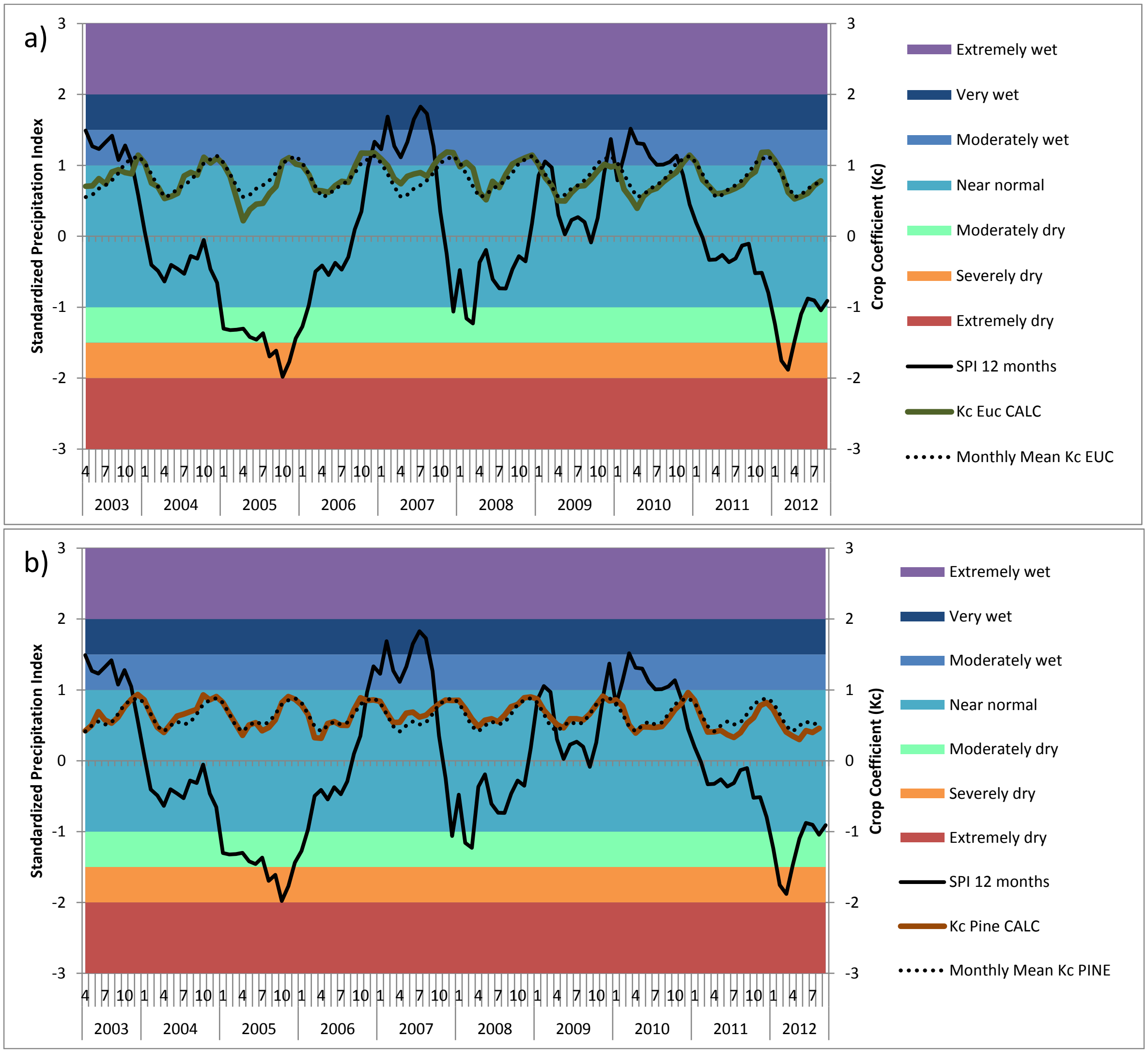

Figure 13. SPI 12 of eucalypt (a) and pine (b) in relation to calculated monthly Kc and mean monthly Kc.

Figure 14a and 14b show that the variety in the ETc values are more extreme than the Kc values. Furthermore ETc has a stronger tendency to have values in the dry class of the SPI. Both eucalypt and pine show annual lower values in the extreme dry SPI class. Figure 14a show that the eucalypt ETc are below the mean in 2005, the winter of 2010/11, summer 2011 and April-July 2012. The 2005 below mean ETc values seem to be clearly related to the drought this year as in spring ETc goes down at the same moment as the SPI and the annual recovery in summer stay below the mean for the rest of the year. For pine there is a short below average period of ETc in August 2005 and March 2006, following the extreme drought of that year. There is a very noticeable below mean period from May until August 2011 and later in April 2012 another decrease of ETc seems to follow the drought period of that year. This ETc values do not relate to any drought period.

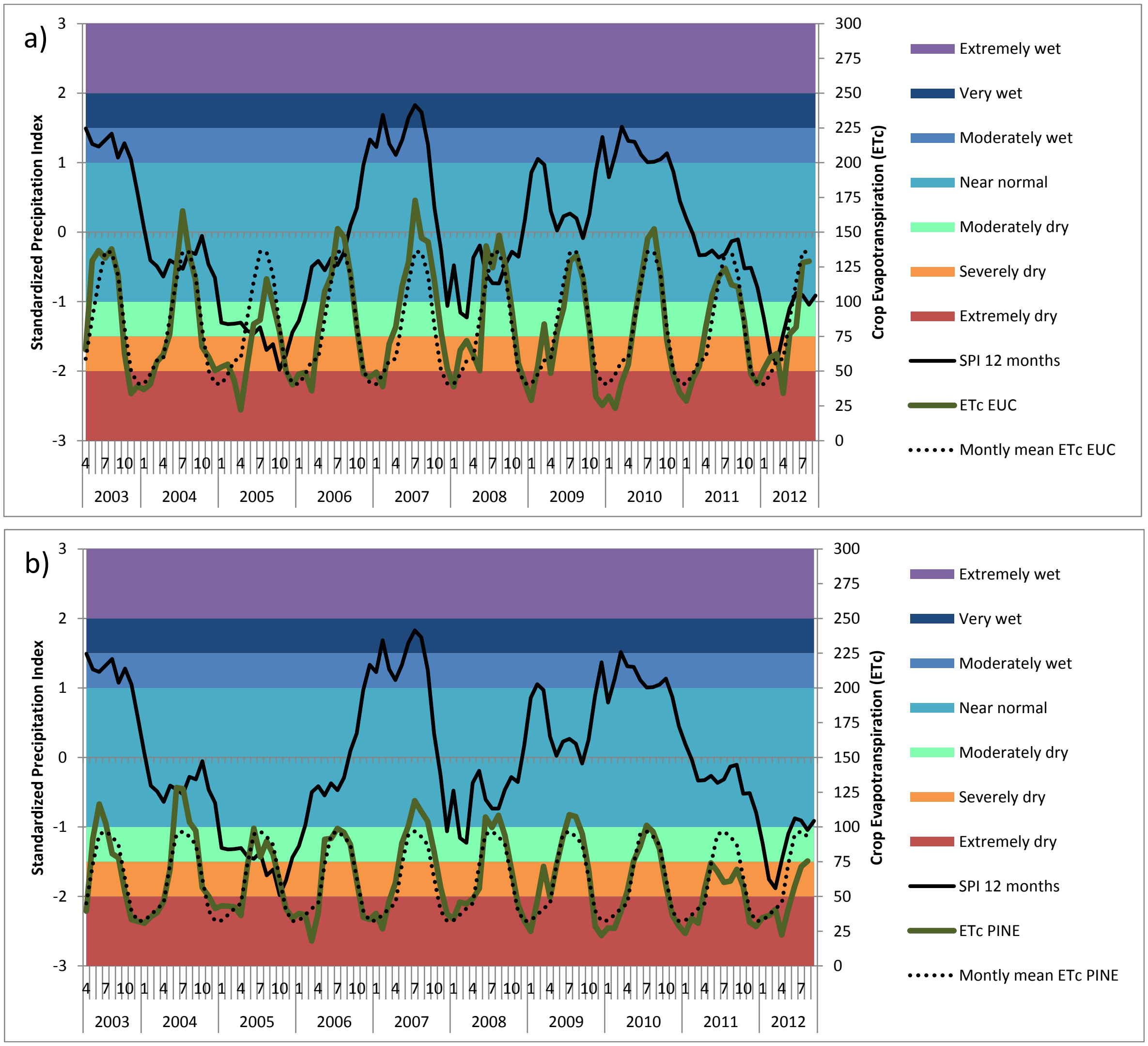

Figure 14. SPI 12 of Eucalypt (a) and Pine (b) in relation to calculated monthly ETc and mean monthly ETc.

4.4 Evaluation of the MODIS Land Surface Evapotranspiration product (MOD16)

To evaluate the reliability of the MODIS EET product in the study area, the comparison of the EET values provided by the MODIS product and the EET observed values was made for both stands from February 2010 (beginning of the observed data) to December 2011 (ending date for the MODIS EET product at present time). The result of this comparison can be observed in the Figure 15.

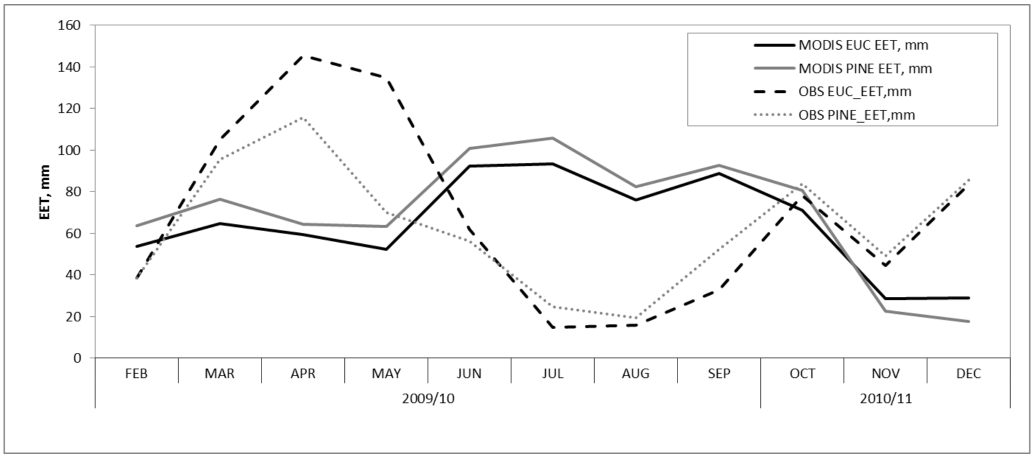

Figure 15. Eucalypt and pine evapotranspiration patterns of MODIS data and observed data.

As can be observed in the graph, the MODIS EET patterns of eucalypt and pine do not follow the observed values of EET for the same period. MODIS EET shows an extraordinary increase for both eucalypt and pine for the February to April period of 2010, while observed EET values stay more or less unchanged until May of that year. The MODIS EET starts to decrease after April; however eucalypt only starts to drop back much in June and July. In the same time observed EET increases and remains at higher values until October. From June until October observed EET data remains at their highest level while MODIS EET remains at their lowest. In October both MODIS and observed pine and eucalypt decrease, though in December the MODIS EET values increase again. From these 11 Months of temporarily matching values only 2 months showed similar in-or decrease patterns (March and November).

5 DISCUSSION

After filtering the Kc data according with Duchemin *et al.* (2006), the relation between the EVI and the crop coefficient did not present a good adjustment; the one with the NDVI was acceptable, despite that the observed data is limited to 2 hydrological years.

Overall, it can be stated that the Kc values calculated from NDVI in this work agree with those in the literature. The estimated Kc values from the MODIS NDVI for eucalypt in the Caramulo mountains range from 0.2 to 1.2, values which fit within the range proposed by David *et al.* (1997) although with a decreased lower bound (but only during the exceptionally dry spring of 2005). The main difference is that the dry period in the Caramulo study area start earlier than in David et al. (1997), although that study was carried out in South Portugal, near Lisbon. For eucalypts, David et al. (1997) report ET values becoming progressively lower as the dry season develops, despite the increase in PET, with the dry period between May and August. The ratio between measured sap-flow and ET estimated via the Penman-Monteith method ranged from 1.05 to 0.55 between the start and end of the wet period. (Myers *et al.*, 1999) also describe a similar range of variation of Kc, between 1.2 and 0.4. For maritime pines, the FAO 56 report (Allen *et al.*, 1998) proposes a Kc value of 1 for conifer trees, but states that the value can lower considerably under dry conditions. Mediterranean plants can usually see a drop of Kc in summer of 50 to 60% (Nunes, 2008), so a minimum value of 0.5 during the drier season would seem reasonable. The results obtained from the NDVI estimations of Kc for pine range from 0.3 to 0.9, being slightly lower than the ones in the literature.

According with these results, the NDVI vegetation index may be suitable to calculate vegetation water use in the study area, but a higher number of observations will increase the reliability of the method and the validation.

The comparison between the crop coefficients calculated for both landcovers showed clear differences between pine and eucalypt stands with higher water use for eucalypts than for pine and making possible the differentiation of each stand.

Both methods used to identify dry periods using precipitation (Standardized precipitation index 12 months and 25th percentile of monthly rainfall within the study period) showed good results identifying the droughts during the study period. The longest drought period was from January 2005 until February 2006. During this period, the drought was moderate from January 2005 to July 2005 changing to severe drought until December 2005 and again to moderate until February 2006. The drought of 2012 started in January as moderate until the end of February and change to severe until April 2012 when the rain started again and this stopped the dry period reaching normal conditions June. This second drought had less impact on plant development, due to the fact that there was an unusual wet spring in 2012. The use of SPI of 12 months as indicator of drought and its comparison with the crop coefficient (Kc) obtained from the NDVI vegetation index show good results and clearly identify the drought in 2005 as the one which clearly affected vegetation development. Crop evapotranspiration in relation to SPI12 performs even better as both drought periods can be observed clearly. For 2005 the low evapotranspiration values of eucalypt and pine can both be observed and reactions to fire and drought can be distinct for the two locations in 2011 and 2012. The 2012 drought therefore can only really be observed by use of the ETc and not with the Kc.

The comparison between the MODIS MOD16 product and observed EET values for the two study sites shows clear differences in the monthly patterns that may suggest poor reliability of the MODIS product of EET to be applied in the study area. The main limitation for this comparison is that the overlapping period between the MODIS product and the observed values was limited to 11 Months in 2010, as the starting date of the EET observed values began in February 2010 and by the date where this work was done, the MODIS MOD16 product ends in December 2010. A longer period with the MODIS MOD16 product EET values may increase the performance of the method and may be stated the need of on-site observations from the study sites to make good estimations of EET. However, the differences between both datasets during this period are large enough to suggest that this disparity will continue in the near future. The motives of the disparity require further exploitation, but it can be suggested that the low soil water storage capacity in the study sites (and therefore the low water availability in summer) is an important factor which might not be taken properly into account by MOD16.

6 CONCLUSIONS

The MODIS NDVI product showed a good reliability to perform the estimations of crop coefficients (Kc) and crop evapotranspiration (ET_c), while the EVI cannot be used for this purpose in the study area. The estimated Kc values from the MODIS NDVI for eucalypt in the Caramulo Mountains range from 0.2 to 1.2 and the Kc values for pine range from 0.3 to 0.9.

When comparing with widely used drought indices like the Standardized Precipitation Index (SPI), the time-series of crop coefficients (Kc) and crop evapotranspiration (ETc) estimated from MODIS NDVI are able to identify drought periods. The use of this parameters to determine the drought severity is not clear in the study area or at least, not during the study period. A more extended observed data set will be need to improve the results obtained in this work.

The evaluation from the EET patterns obtained from the Land Surface evapotranspiration product from MODIS does not fit properly the observed EET patterns in the study area. Further studies are necessary regarding this topic, namely a wider observed dataset and a longer time-series of the MODIS16 product that will allow a better interpretation of the results and confirm the correct EET patterns.

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