Quantifying spatial and temporal patterns of the water related yield gap, using synoptic data and a dynamic Crop Growth Model (PSn)

A Case Study of Sunflower in Andalucia, Spain

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By

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Abstract

Various approaches and methods have been developed to quantify yield gap constraints to crop production. Among land factors, water plays an important role in determining yield gap, especially in regions where land management factors are homogeneous. The aim of this study is to quantify the spatial and temporal patterns of the water related yield gap by using synoptic data and a dynamic Crop Growth Model.

A combination of data from weather station and remote sensing data (from MODIS imageries) were applied to calculate the potential and water limited yields of sunflower in Andalucia for 5 years (2001 – 2005) by Production Situation Model (PSn) level 1 and 2. Point results were extrapolated to the region using regression models with Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) from MODIS imageries. PSn model successfully identified the variability of potential and water limited yields of sunflower in space and time. Using remote sensing data, it is possible to extrapolate this variability to broader scale.

The output maps of water limited yield gap prove that water is a main limiting factor causing yield gap for sunflower in Andalucia. For every year, this factor contributed more than 60% to overall yield gap of sunflower in most areas. Thus, less than 40% of overall yield gap was caused by other limiting factors of land and management. Map produced by this study could be a reference for farmers and decision makers in improving the production of sunflower in Andalucia.

Keywords: PSn model, Water limited yield, yield gap, sunflower, Andalucia

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Table of contents

List of figures

List of tables

1. Introduction

1.1. Background

Analysis of meteorological (weather data) can provide near real time performance assessments of crops. Monitoring crops can lead to timely interventions. To forecast the crop yields, various datasets need to be collected such as synoptic, soil, remotely sensed, agricultural statistic data etc. These data can provide inputs to derive several indices or indicators to assess crop performances and to predict the possible crop production.

Crop forecasting through computer programs (models) that use weather data to estimate the potential and water limited production of the crop in space. In combination with actual farm production, it is possible to identify and quantify the crop yield gap. Across years, analysis of yield gaps can produce outputs such as maps and statistical data that present the gap of a certain crop in space and the behaviour of this gap between years.

As other crop production systems, sunflower cultivation in Andalucia, Spain, is affected by some main biophysical (weather, soil) factors. With rain-fed condition of cultivation for most of sunflower in Andalucia and mechanised practices in most of modern farms in Spain, the main factors causing the gap of sunflower would come from land factors such as weather and soil. Study of the water limited yield gap can provide information of the main yield gap for sunflower in space (how it is variable from site to site) and time (how it is changing through time by site). By having such data, some possible recommendations could be provided for intervention or planning procedures (for both farmers and decision makers).

1.2. Spatial and Temporal Patterns of Water Related Yield Gaps

Various approaches and methods have been developed to research on yield gap constraints to improve crop production and assist to gain food security. One of attractive methods is called “Comparative Performance Analysis” (CPA)(De Bie, 2000). The principle of this method is to identify and quantify all factors of land and management that cause a gap between actual and potential yield of a certain crop in an area. In this method, factors as shown in table 1 can be identified and their impact also can be quantified.

Table 1: Definition of factors effecting crop yields in land use system (modified from (Ngo The, 2000))

Land Factors	Management Factors
• Rainfall (estimated by farmers) • Soil quality (estimated by farmers) • Soil PH (tested by researchers) • Soil texture (identified by researchers) • Infiltration rate (estimated by farmers and tested by researchers)	• Land preparation • Planting time • Weeding • Pest control • Water irrigation • Fertilizer application

• Temperature and climate (experienced by farmers)	• Manure application • Harvesting time and practices

In some regions (such as European countries) where the land management (operation sequence) is almost homogeneous from plot to plot, land factors become main constraints for yield gap of certain crop. Among all the land factors, climate/weather plays the most important role in deciding yield gap of crop. The climate decided how much solar radiation, temperature and rainfall volume etc the crop could have in certain plot to growth. It is very clear in reality that we (and the farmers) cannot modify the crop production by changing some climate factors like solar radiation and temperature. However, it is possible to close the yield gap caused by water shortage (rainfall) through supplying more water by irrigation system. The question here is how much and where the water related yield gap takes place and how to quantify this gap in space and time.

Recently, some researchers have used the data from remote sensing (temperature, rainfall, NDVI) for estimating the crop production for food security purposes (Metternicht, 2003; Rugege, Bouma, Skidmore, & Driessen, 2002; Venus, 2000). These researches have been found to be very useful for crop production estimation and contributed to improve the crop growth simulation techniques as well as crop modelling methods. Although it has been very practical of using those RS data for estimating the crop production, these spatial factors (derived from satellite images or from weather station based data) have not been used as based attributes for mapping the yield gap and improving the methodology of yield gap analysis.

Beside the CPA, the “Production Situation Model” (PS-n) can be used with weather based data (temperature, precipitation, relative air humidity and ETo etc) to estimate crop potential and water limited yields in study areas (points). The principle of this model presents a simplified Land Use System in which crop production and yield are solely determined by availability of light, the temperature, the photosynthetic mechanism and other factors.

The main idea of this research is to combine the use of Production Situation Model (with data from weather stations), remote sensing data and techniques to quantify the water related yield gap of sunflower following CPA logic.

1.3. Justification

CPA has been found as a useful and credible method for yield gap analysis for any specific crop in any land use system. CPA complements established land use study methods and forms an addition to “researcher’s toolkit” in which each method has specific strengths and merits (De Bie, 2000). However, the study on yield gap and farming system needs to be done systematically and integrated with other disciplines. Some spatial aspects such as rainfall can be included in CPA and GIS analysis of yield gaps (Ngo The, 2000).

Moreover, observations from satellites and weather stations have been found useful to infer the required data such as canopy temperature and daily, monthly precipitation (Venus & Rugege, 2004). These data (T, Prec, Eo, ETo etc) can be used as inputs for some crop growth models such as Production Situation Model (PSn) for crop yield estimation. In addition, Production Situation Model can be used to calculate the potential (PS1) and water limited (PS2) yields of certain crop from point to point (plot to plot) (Driessen & Konijn, 1992). By comparing with actual yield collected from the farms, the gap between potential and actual farm yield can be quantified.

On the other hand, yield assessment using AVHRR and MODIS data has been demonstrated in a number of studies for many years. Statistic model using simple regression techniques between collected in the fields and various expressions of NDVI has shown that vegetation index from satellite images could explain very well the yield variance (Rasmussen, 1998). This assessment method can be used to extrapolate the water limited yield of sunflower from points to all sunflower areas in Andalucia. Other researches also proved that Land Surface Temperature (LST) derived from satellite images can be used as inputs for some crop growth simulation models (WOFOST) for yield estimation of some crops (winter wheat and sunflower) (De Wit, 2004). This method in combination with others (Ouedraogo, 1995; Venus & Rugege, 2004) would be useful to apply for extrapolating the potential yields of sunflower (calculated by PS1) from weather station based points to all sunflower cultivation areas in Andalucia.

This research is trying to combine the weather based data with remote sensing data (MODIS imageries) in order to quantify the water related yield gaps in space and time by following CPA logic.

1.4. Research Objective

The objective of this research is to quantify the spatial and temporal patterns of the water related yield gap by using synoptic data and a dynamic Crop Growth Model (Production Situation – PSn)

1.5. Research Questions

- What are the general potential yields of sunflower in Andalucia during five year period (2001 to 2005)?
- Can Gross Primary Productivity (GPP) from MODIS be used to extrapolate sunflower's yield from points to broader scale?
- How much is the yield of sunflower reduced due to water shortage?
- Where does the highest water limited yield reduction (gap) take place for sunflower in Andalucia?
- What is the fraction of water limited yield gap to overall gap by year?
- Where are the areas of low and high gaps for sunflower in Andalucia?

1.6. Assumptions

In order to conduct this research and test the hypothesis, the following conditions have been assumed:

- Land management (land use) for cultivating sunflower is considered homogeneous throughout Andalucia.

- Soil is not a limiting factor for sunflower production in Andalucia.

1.7. Hypothesis

This research is going to test the following ***Hypothesis:***

Ho: The weather based estimation data from Production Situation Model cannot be used to quantify a component of yield gap of sunflower.

Ha: The weather based estimation data from Production Situation Model can be used to quantify a component of yield gap of sunflower.

In the other way, the hypothesis of this research can be described in figure 1.

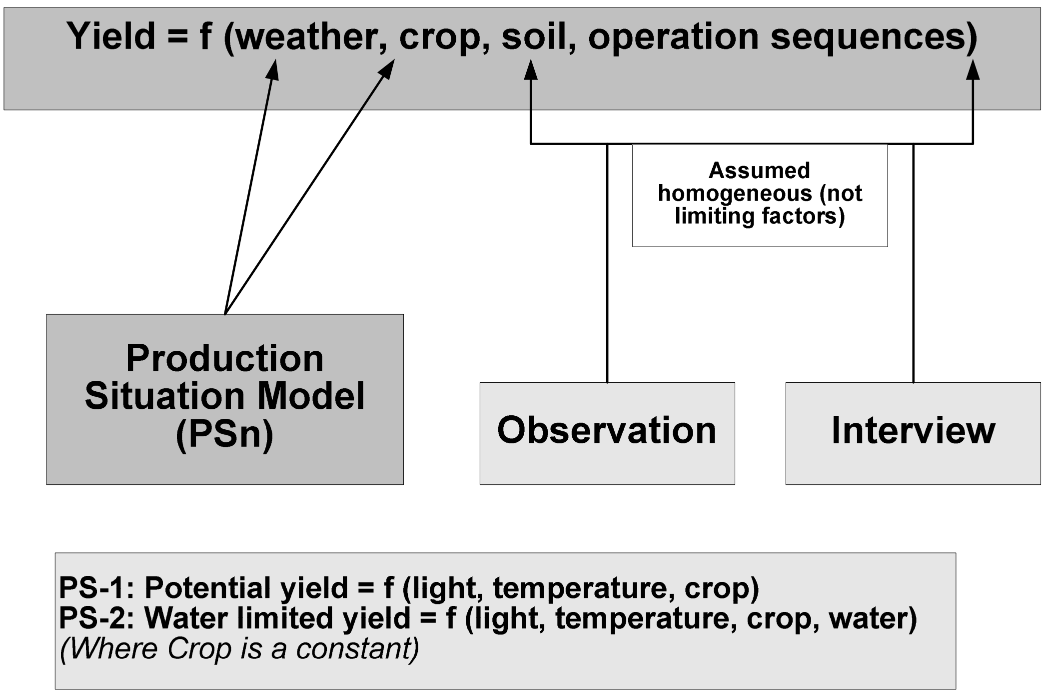


Figure 1: Overview of research hypothesis

2. Literature Reviews

2.1. Conceptual Base to Study Water Related Yield Gap

The land provides conditions for crop growth while land use reflexes the interests of the holder through the operation sequence. The purpose of land use is expressed in terms of the products and/or benefits aimed at in a land use system. The goals of the holder, however, are specified with reference to holding level. Goals can be food production or income generation (De Bie, 2000). In a land use system, the crop production is determined by land and land use factors. All limiting factors (that are responsible for yield gap) are called yield constraints (De Datta, 1988). Improving management operation and removing limiting factors (problems) lead to yield increases (figure 2).

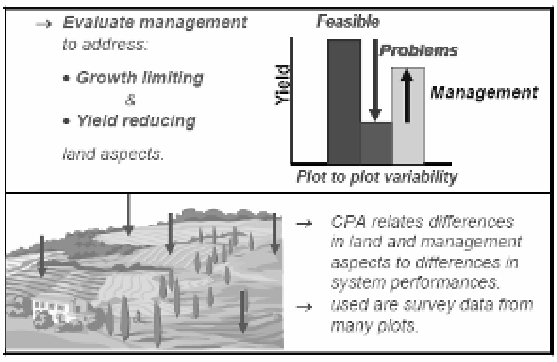


Figure 2: Comparative Performance Analysis (CPA) is an Approach to Study Yield Gaps and Yield Constraints to estimate Quantified Production Functions (De Bie, 2002)

In a land use system where environmental and management limitations do not exist, these are conditions for potential production of a certain crop. However, land always has some limitations concerning water and nutrients as well as yield reducing factors like pets, weeds and diseases (Zook, 1997). Through agriculture practices, land users always want to improve the crop production through minimizing the problems (constraints) and adopting appropriate management methods. Good management aims to reduce impacts of land constraints. The gap between potential (feasible) farm yield and actual farm yield in a given site of a given crop can be narrowed and quantified by understanding the functions of yield constraints and management of a land use system.

2.2. Land Use System Concept

A combination of one land unit and one land utilization type (with one set of land use requirements) constitutes a Land Use System (LUS) (Driessen & Konijn, 1992). Earlier, FAO (1983) defined a system as "a collection of elements and their relationships, selected for the effect on their environment; a system processes boundaries, internal relationships and external inputs and outputs". De Bie (2000) defined a Land Use System as "a specific land use, practised during a period of time on a known unit of land that is considered homogeneous in land resources".

Two terms often used to denote the agricultural land use systems are "Cropping System" and "Agro Ecosystem". In another way, A land use system can be seen as a system that is composed by two main elements: Land and Land Use where land use purpose and operational sequences characterized land use (De Bie, 2000).

To simplify this definition for cropping system in Andalucia, Spain, a land use system (LUS) can be described by figure 3.

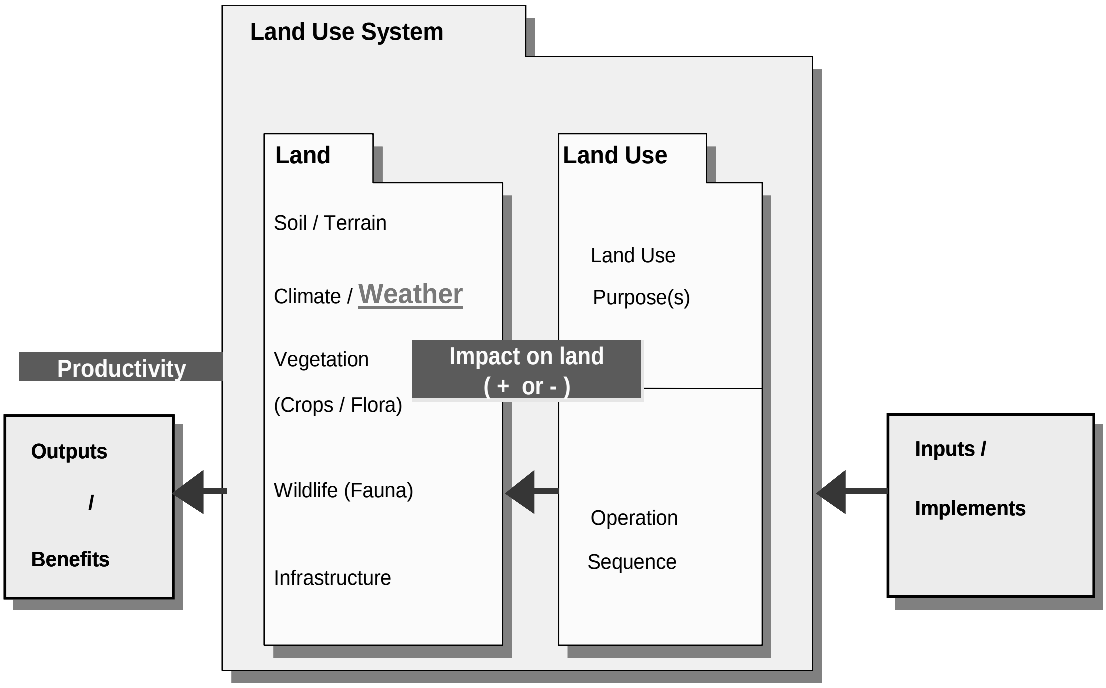


Figure 3: Land Use System (LUS) concept - (De Bie, 2000)

In this system, the land use purposes decide the specific outputs of the system (what the system will produce) meanwhile, the inputs, land factors and operation sequence decide the productivity of the system (how much the system can produce). At local and regional scales, where land use purposes and the operation sequence (land management) are homogenous, the land factors (soil, weather etc) will play an important role in determing which system will produce more than another. The gap between potential farm yield and actual farm yield is then mainly decided by the land factors of those systems.

2.3. Yield Potential, Yield Constraints and Yield Gaps

"Yield potential" is the maximum production of a crop cultivar that can be achieved in a given environment. Solar radiation during the growing season, temperature and crop characteristics determine the yield potential (Dobermann & Charles, 2004). To achieve the yield potential, the crop must receive optimum levels of water and nutrients and be completely protected against weeds, pests, diseases, and other management factors that may reduce growth.

Growth limiting factors such as water and nutrients determine the attainable yield. Yield potential is reduced by insufficient supply of water either from inadequate rainfall or from failure to supply water. Lack of nutrients either from poor soil quality or failure of applying external inputs is also a factor causing yield reduction. As it has been applied all over the world, management can be used to control availability of both water and nutrients (Dobermann & Charles, 2004).

The other constraints may further reduce crop yield, like pests, diseases, weeds, water-logging or poor soil qualities. Better management can limit the negative impacts of those constraints and through that increase the crop yield to the level of the yield potential.

The yield gap can be identified as the difference between the maximum attainable yield and the farm-level yield, in which the maximum attainable yield is defined as the yield of experimental/on-farm plot without physical, biological constraints of land and with the best-known management practices for a given time in a given ecology. Meanwhile, the farm-level yield is the average farmer's yield in a given target area at a given time in a given ecology (FAO, 2004).

Yield gap can also be further broken down into 3 components – Gap I – is the gap between theoretical potential yield and experiment station yield for which scientists conceive and breed potential varieties. The second component - Gap II – is the gap between experiment station yield and potential farm yield and it is caused by factors that are generally not transferable such as environmental conditions and some of the built in component technologies that are available at research stations. The third component of yield gap – Gap III – is the gap between the potential farm yield and the actual farm yield and it is mainly caused by differences in management practices (figure 4). This component is manageable and can be narrowed by increasing efforts in research and extension services as well as by appropriate governmental interventions, particularly institutional issues (FAO, 2004).

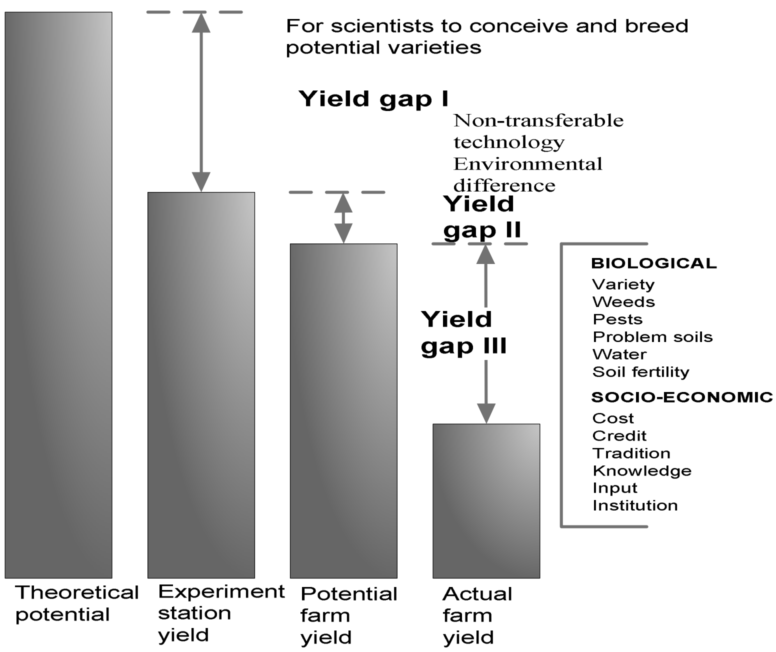


Figure 4: **Yield gap components (source: FAO 2004)**

For most crops, the factors causing yield gaps can be classified according to their nature and the degree to which they contribute to yield gaps. They are (De Bie, 2002):

- Land factors: climate/weather, soil, terrain, water, flora and fauna etc
- Management (land use) factors: land use purpose and operational sequences (tillage, variety/seed selection, water, nutrients, weeds, pests and post-harvest management).

Studies on yield gap will help to identify the yield determining constraints, yield limiting constraints and yield reducing constraints of a certain crop and through that, to control those constraints/factors with better management. To understand the causes of yield gap is not only helpful to increase the crop production but also to improve the efficiency of land and labour use, reduce production costs and increase sustainability (FAO, 2004).

In this research, for sunflower in Andalucia, Spain where land management (land use) is almost homogeneous in every land use system (through farmer interview results), so the land factors have become the main factors causing the yield gap of sunflower from farm to farm. In this situation, the yield gap component can be modified as figure 5.

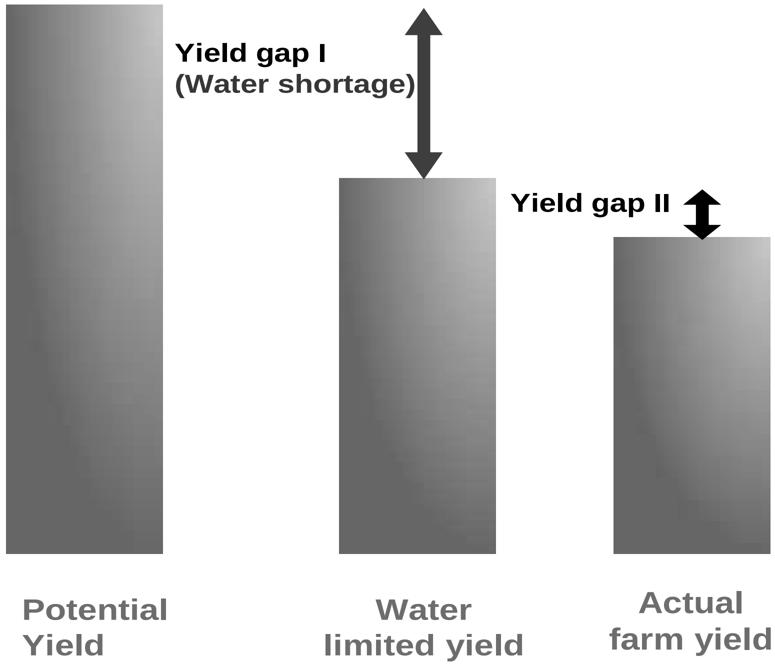


Figure 5: Modified Yield Gap Components for Sunflower in Andalucia

In this system, the Gap I (caused by water shortage) can be quantified by comparing yield potential and water limited yield with an assumption that other factors do cause the second gap.

2.4. Comparative Performance Analysis

The Comparative Performance Analysis (CPA) is a quantitative method for yield gap analysis. CPA is used to identify the major yield constraints and quantify the yield gap functions. CPA considers on-farm production situations assuming land users to operate at several technological levels. The key feature of CPA is to relate differences in land and land use to the differences in system performance (figure 6).

CPA considers environmental conditions and management aspects as they occur in specific study areas (De Bie, 2002).

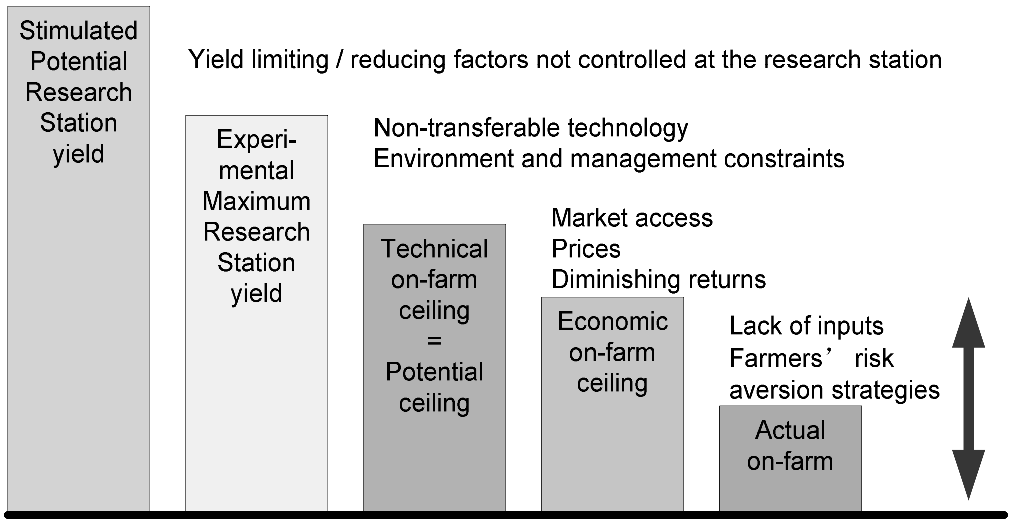


Figure 6: Partial yield gaps and their dominant constraints (De Bie, 2002)

To have a successful CPA, the following conditions are necessary:

- The study must focus on a particular land use class.
- The land use systems surveyed must reflect the entire prevailing range of environmental conditions and all types and levels of technology practised (De Bie, 2000).

Basically, the CPA can be characterised by descriptive functions:

Production = f(land, land use)

In this research, this function can be presented as:

Yield = f(weather, crop, soil, operational sequence)

Where crop and operational sequence are constants; soil is not considered as a limiting factor for sunflower yield in the study area.

2.5. Production Situation Model

A production situation is a hypothetical land-use system, with one or only a few relevant land qualities. Land qualities not considered in the definition of a production situation are assumed not to constrain the performance of the system. Land-use is defined by the choice of crop and a fixed set of management attributes. A production situation is not an actual land-use system and the production calculated is not the actual production but the production potential (Driessen & Konijn, 1992).

Models of production situations (PS-n) are composed of a number of sub-models, each matches one land-use requirement against one land quality and translating the outcome of the matching into realized or lost production potential.

The simplest production situation (PS-1) quantifies crop performance, within the physiological possibilities of the crop, as a function of the only land qualities that a farmer cannot modify as the availability of solar radiation and the temperature. All other land qualities are assumed to fully satisfy the corresponding land-use requirements. Production situation PS-1 constitutes the highest level in the hierarchy of production models. The production calculated is the highest that can be realized on an experimental field; it is the biophysical production potential.

At the second highest level (PS-2), the assumption of optimum water supply is waived and the land quality 'moisture availability' is quantified and matched against the consumptive water needs. The result of this matching is incorporated in the calculation of the production potential. In other words, crop production in production situation PS-2 is determined by the amount of intercepted radiation, the temperature and the availability of water. All other land qualities or limitations that influence production in normal farming (availability of nutrients, competition by weeds, occurrence of pests and diseases, harvest losses) are assumed not to constrain crop performance. The outcome of a PS-2 analysis is the water-limited production potential (Driessen & Konijn, 1992).

Basically, Production Situation Model used in this research can be characterized by following functions:

PS-1: ***Yield = f(light, temperature, Crop), and***

PS-2: ***Yield = f(light, temperature, Crop, water)***

Where: light, temperature and water are dependent variables, which are different from point to point. The calculation of PS-1 and PS-2 uses the inputs of weather data including: Daily maximum temperature; daily minimum temperature; daily rainfall, daily relative humidity of atmosphere; number of sun hours per day; daily potential evaporation rate and daily potential evapotranspiration rate. Meanwhile, crop is a constant that depends on the parameters of each crop such as Tsum (heat requirement for full development of crop); Tleaf (heat sum for development of leaf tissue); LAI (leaf area index); Ec(org) – efficiency of conversion etc.

In this research, PS-1 is used to estimate the potential yield of sunflower for 40 weather station sites in Sevilla province (point maps) for five years (2001 to 2005). From these 40 sites, the estimated yields are extrapolated by using remote sensing data from MODIS. Meanwhile, PS-2 is used to calculate the water limited yield of sunflower for 40 weather stations sites.

In addition, Remote Sensed PSn model is also used with additional input of canopy temperature to calculate daily PSn yield of sunflower and through this calculation, the water sufficiency coefficient is also derived as daily values. In principle, the Remote Sensed PSn model can be characterized by following function (Venus & Rugege, 2004):

PS-n ***Yield = f(light, temperature, crop, canopy heating)***

2.6. Gross Primary Productivity (GPP) Estimation from Remote Sensing - MODIS17

The MODIS GPP algorithm (MODIS17) is a light use efficiency model that requires daily inputs of incoming Photosynthetic Active Radiation (PAR), minimum temperature over the 24 h period, and daytime average vapour pressure deficit (VPD). Currently, these meteorological data are provided by the NASA Data Assimilation Office (DAO) based on a general circulation model that is continuously assimilating observations from space and ground stations (Turner, Ritts, & al, 2006).

In the Model of MODIS17, the GPP (kg C/km2) is calculated following the method that is described in figure 7.

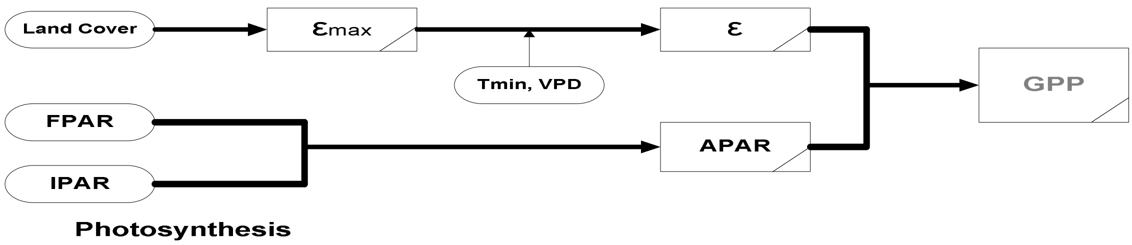


Figure 7: The logic behind MODIS17 algorithm in calculating 8 day average GPP (Heinsch, Reeves, & Votava, 2003)

Where:

PAR: Photosynthetic Active Solar Radiation

FPAR: Fraction of Incident PAR absorbed by the surface

IPAR: Incident PAR on the vegetative surface

APAR: Absorbed PAR where: APAR = IPAR*FPAR

ε: Conversion Efficiency of PAR (depending on vegetation types – Land Cover, unit: kg C MJ-1)

εmax: The maximum radiation conversion efficiency

Tmin: The daily minimum temperature at which ε = 0.0 (at any VPD)

VPD: Vapour Pressure Deficit

The core science of the algorithm is an application of the described radiation conversion efficiency concept to predictions of daily GPP, using satellite-derived FPAR (from MODIS15) and independent estimates of PAR and other surface meteorological fields (from DAO data) (Heinsch, Reeves, & Votava, 2003).

For any given pixel of the global set of 1 km land pixels, estimates of GPP are calculated. To calculate GPP, an 8-day estimate of FPAR from MODIS15 and daily estimated PAR from DAO are multiplied to produce APAR for the pixel.

Based on the at-launch land cover product (MODIS12), a set of Biome-specific radiation efficiency parameters are extracted from the Biome Property Look-up table, and the conversion efficiency of PAR is calculated as follows:

ε = εmax * TMIN_scalar * VPD_scalar

Where TMIN_scalar and VPD_scalar are ranged from 0 to 1

ε is combined with estimates of APAR to calculate GPP (kg C day-1) as

GPP = ε * APAR

Where APAR = IPAR * FPAR. IPAR (PAR incident on the vegetative surface) must be estimated from incident shortwave radiation (SWRad, provided in the DAO dataset) as

IPAR = (SWRad * 0.45)

While GPP is calculated on a daily basis, 8-day summations of GPP are created and these summations are made available to the public. The summations are named after the first day of the 8-day period (Heinsch, Reeves, & Votava, 2003).

2.7. Potential, Actual Evapotranspiration and Water Sufficiency Coefficient

Potential evapotranspiration (ETp): the potential evapotranspiration concept was first introduced in the late 1940s and 50s by Penman and it is defined as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile". Nowadays, ETp is characterized by maximum possible evapotranspiration that is approximately equal to evaporation over a water body.

Based on FAO, 1998, the ETp was defined as the maximum possible evapotranspiration according to prevailing atmospheric condition and vegetative properties. The land surface should be well supplied by water such that soil moisture forms no limitation to the stomatierous aperture. One major difference with the reference crop is that the biophysical properties of potential evaporating vegetation are spatially and temporally variable. The Reference Evapotranspiration ETo is a special case of ETp with fixed properties.

The Actual Rate of Evapotranspiration (ETa) caused by conditions of the atmosphere, the real vegetation development (also due to various types of stress functions) and the actual soil moisture and soil temperature regimes in the root zone of the vegetation (Simmers, 2003)

The Water Sufficiency Coefficient (or water uptake correction factor) is the relative rate of transpiration and represents the sufficiency of the land quality “water availability”:

cfH2O = TR/TRM

Where:

cfH2O: is the water sufficiency coefficient (relative rate of transpiration by plants exposed to water stress)

TR: is actual rate of transpiration (cm/day) with ETa = TR + Ea (actual rate of evaporation)

TRM: is maximum rate of transpiration (cm/day) (Driessen & Konijn, 1992)

The difference between analysis of PS1 and PS2 is that cfH2O is 1.0 in production situation PS1 and between 0 and 1 in production situation PS2. It is presented in this equation:

Fgass = Fgc * 30/44 * cfH2O

Where:

Fgass: is gross rate of assimilate production by a field crop

Fgc: is gross rate of CO_2 reduction by a reference crop

30/44: is ratio of molecule masses of CH_2O and CO_2

cfH2O: is water sufficiency coefficient (=1 in PS1)

In a plant environment, it is difficult to determine how much soil water loss is through evaporation from soil surfaces and how much is through transpiration from plants. Therefore, water extracted by these two process is usually combined and called evapotranspiration (Ayele, 2000).

From the above functions, it is possible to derive:

CfH2O = ETa/ETp

Where:

ETa: is actual evapotranspiration

ETp: is potential evapotranspiration

And for daily PS2 calculation:

Water limited yield = Potential yield*cfH2O

From this equation, it is possible to derive the following equation:

NPP = GPP*cfH2O (Venus & Rugege, 2004)

2.8. Land Surface Temperature (LST) Estimation from Remote Sensing – MODIS11A2

LST over eight days is the averaged LSTs of the MODIS11A1 product over eight days. This level 3 LST product at 1km spatial resolution is a tile of eight-day LST product gridded in the sinusoidal projection. A tile contains 1200 x 1200 grids in 1200 rows and 1200 columns. The exact grid size at 1km spatial resolution is 0.928km by 0.928km (Wan, 2007).

Every pixel of the eight-daily MODIS11A2 LST has a value of averaged land surface temperature in daytime and night time representing a period of eight days. The unit of temperature presents in the images is degree Kelvin (K), with valid ranges from 7500 to 65535 (pixel value) and scale of 0.02 (this scale is used to calculate the real value of LST from pixel value: Real value of LST = Pixel value*0.02).

LST in general can be considered and used as canopy temperature in remote sensed Crop Growth Simulation model to calculate the water limited yield of crop (PS2). In this model, PS1 yield was calculated as traditional method of PS1 model with inputs of weather data by points. Meanwhile, the model would use the LST as canopy temperature as the inputs for PS2 calculation based on the hypothesis that the sensible heat component of the energy balance equation is approximated from the instantaneous temperature difference between air temperature and canopy temperature of a crop surface (Venus & Rugege, 2004). By this method, the calculated Water Sufficiency Coefficient (cfH2O <=1) is a value that presents the situation of water shortage (crop tress) for the crop and simulates how much the daily yield potential reduces due to the water stress.

3. Methods and Materials

3.1. Study Area

Andalucia is an autonomy region located in the south of Spain. It is composed of 8 provinces including: Sevilla, Malaga, Almeria, Cadiz, Cordoba, Granada, Huelva and Jaen, stretching from Southeast to Southwest of the country. The total natural area is of 87,300 sq km (17.3% of Spanish territory) with total population estimates of 7 million people (20% of Spanish total population).

Andalucia is the home of olive and sunflower cultivation in Spain. Besides that, the main agricultural crops of this region include wheat, barley, fruit, grape and vegetable. Due to the influence of specific climate condition (hot in summer and cold in winter), Andalucia has produced very good products and olive (fruit and oil) and grape wine meanwhile it provides most of sunflower oil in EU. Figure 8 presents the agricultural area in Andalucia which is home of grape, olive, wheat and sunflower.

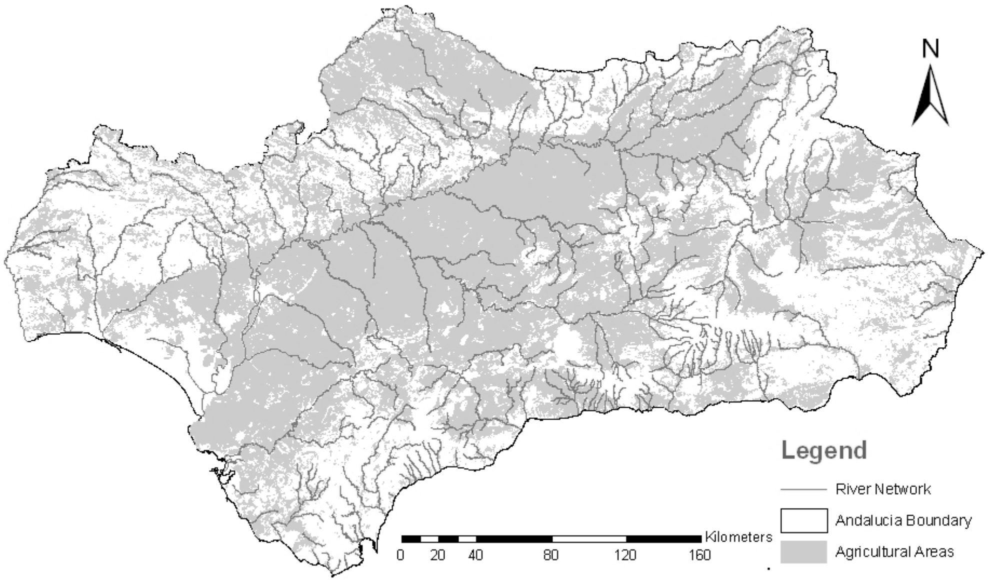


Figure 8: Agricultural Map of Andalucia Region (Modified from Corine map)

In terms of climate, Andalucia has the hottest (around 45^{o}C) and driest summer in Spain. Even those, as a whole, the region enjoys above average yearly rainfall in the context of Spain, and in the west, it is relative wet in winter due to the influence of Atlantic Ocean. The provinces of Cadiz, Huelva and the Sierra de Cazorla received around 1000 mm of rainfall per year, meanwhile the areas where olive growing (Sevilla, Cordoba and Jaen), the average rainfall was 500 to 700 mm/year. Much of Andalucia has in excess of 300 days of sun a year.

As the Atlantic's rain-laded clouds move east they lose much of their moisture, ending in the badlands of Almeria. In particular, Cabo de Gata with barely 150mm of rain a year is the driest corner in the Peninsula. The distribution of average annual rainfall in Andalucia is shown in figure 9.

Among the provinces, Almeria and Sevilla have the highest average temperatures in Spain with 18.6ºC and 18.7ºC, respectively (Huelva with 18.3ºC and Cadiz with 18.2ºC). Meanwhile, Granada, lying at the foot of the Sierra de Cazorla, is the coolest at an average of 15.1ºC. Parts of Almeria compete with southern Alicante for the warmest spot. The average annual temperature of Andalusia as a whole is recorded to be above 16 ºC. The coldest month is January (12.5 ºC in Málaga, 6.4 ºC in Granada) and the hottest is August (28.5 ºC in Écija). The maps of average temperature of Andalucia in January and July are presented in figure 10 and figure 11.

Figure 9: Average annual rainfall map of Andalucia (Sources: Junta de Andalucia)

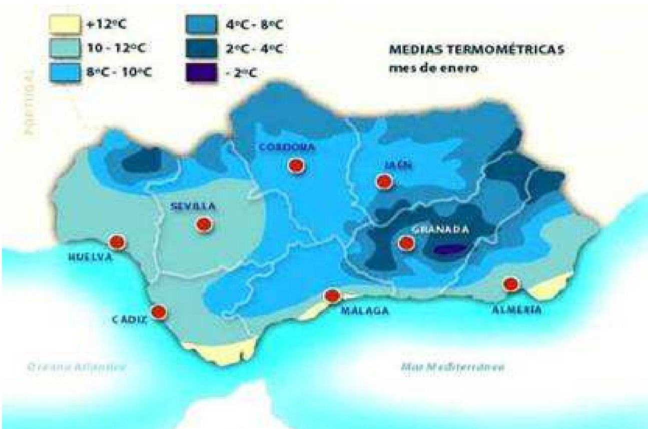


Figure 10: Map of average temperature in January, Andalucia (Sources: National Institute of Meteorology, Spain)

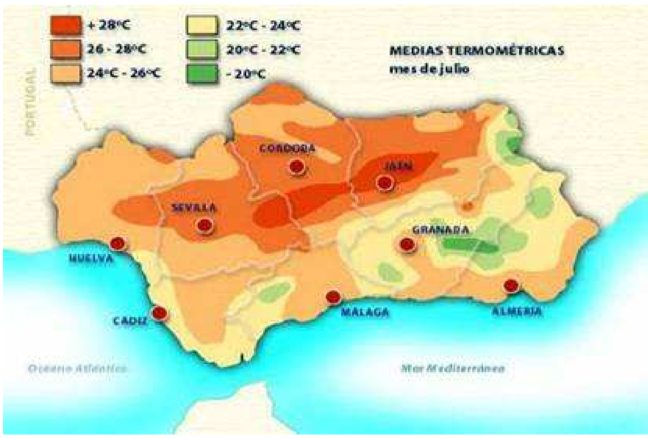


Figure 11: Map of average temperature in July, Andalucia (Sources: National Institute of Meteorology, Spain)

The highest temperature recorded in Spain is 47.4 ºC in Sevilla on 6 th August 1946. There are a number of other figures of around 47ºC, at Écija , also known as the ‘sartén or frying pan of Andalucia in the province of Seville, with 47.0ºC in 1959 and again in 1967.

(Source-internet: http://www.iberianature.com/material/wild_nature_sites/climate_andalusia.htm)

3.2. Sunflower in Andalucia

The products of sunflower are mainly used for edible oil, meal, industrial application, non-oil seed, and forage (Putnam et al., 1990). Sunflower was probably first introduced to Europe through Spain, and spread through Europe as a curiosity until it reached Russia where it was readily adapted. In Spain, sunflower occupied about more than one million ha (1,100,000 ha in 1997) (Fernandez, 1998), It is cultivated in Andalucia (42.8% of the total sunflower crop surface in the country), located in the South of the Peninsula and Castilla la Mancha (20.8%) and Castilla-León (18.4%) in the Centre. Yields varied between 750 kg/ha produced in Aragón (located in the North-east of the Centre of the country) and the 3,360 kg/ha in Andalucía. The country average yield corresponds to 980 kg/ha. In 1997, In Andalucia, 75% of sunflower was cultivated in rain-fed land. In this traditional way, a little work is usually carried out and a little or no fertiliser is applied, since sunflower is supposed to be able to use the fertiliser that remains in the soil after cereal growth (Fernandez, 1998). But up to date (2007), sunflower was cultivated in more irrigated land with better management although the total areas for this crop had been reduced in Adalucia. In 2005, sunflower was planted in Adalucia with total of 192,529 ha including 12,955 ha with irrigation and 179,574 ha in rain-fed land, according to Adalucica agricultural statistic data (Junta De Andalucia).

From 2001 to 2005, the average yield of sunflower in Spain was 1000 kg/ha (meanwhile the average yield in Europe was 1700 kg/ha), 960 kg/ha in 2006 and 1100 kg/ha in year 2007 (MARS, 2007). Figure 12 presents the potential total biomass of sunflower (kg/ha) for the years of 1999, 2006 and 2007.

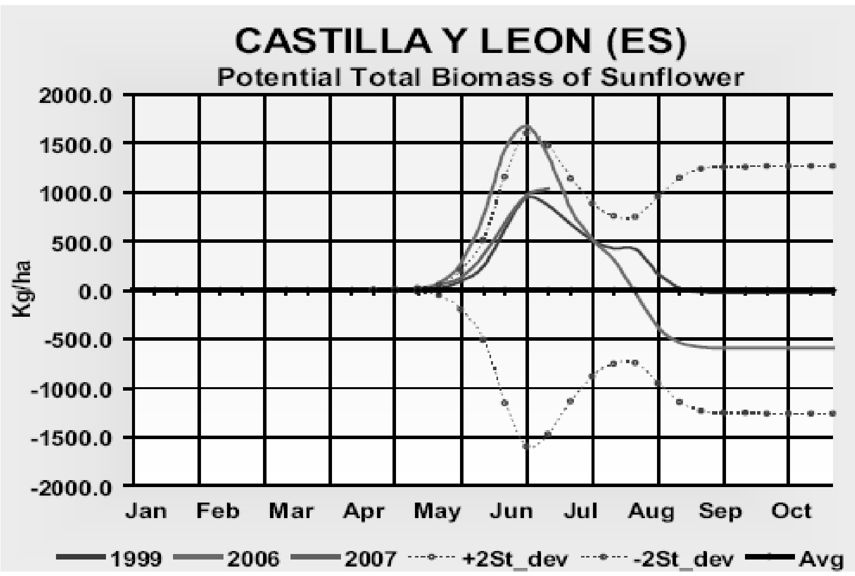


Figure 12: The estimated potential total biomass of sunflower in Spain through time (source (MARS, 2007).

Normally, in Andalucia, sunflower was planted (sowed) in the 1st or 2nd week of March (depend on the situation of rainfall by year) and harvested in the second half of July or early August. Most of the farm, during the growing period, did not treat sunflower with fertilisers nor irrigate with water (only treated with herbicides when necessary). The production was mainly defined by natural condition such as soil and weather factors but not by agricultural technologies like for other crops.

3.3. Data Used

The following data (in table 2) have been used in this research:

Table 2: Data used for the thesis research

Data Description		Type of Data	Scale/Pixel Size	Coverage	Time Range	Sources
Remote sensed images and Aerial photographs						
1	SPOT-VGT NDVI images	Raster format	1000m	300 layers	1998 to 2006	Junta De Andalucia
2	Aerial Photographs	Raster format	0.6m	1000 photos	2004	Junta De Andalucia
3	Digital Elevation Model (DEM)	Raster format	90m	1		SRTM
Maps						
5	Andalucia boundary	Polygon	1:2,800,000	1		Junta De Andalucia
6	Provincial boundary	Polygon	1:2,800,000	8		Junta De Andalucia
7	Road network	Polyline	1:2,800,000	Andalucia		Junta De Andalucia
8	River network	Polyline	1:2,800,000	Andalucia		Junta De Andalucia
9	Land cover map (Corine)	Polygon	1:10,000,000	Andalucia	2000	Corine land cover, Spain, CNIG - EEA
Remote Sensing and weather station based data						
10	Sevilla weather stations	Point		40 stations		Junta De Andalucia
	Daily weather data (T, PREC, ETo etc)	Access database		40 points	1990 to 2007	Junta De Andalucia
11	Estimated daily land surface temperature from MODIS	HDF format	1000m	Andalucia	2000 to 2005	EOS Gateway, NASA
12	Estimated 8-daily Gross Primary Productivity (GPP) from MODIS	HDF format	1000m	Andalucia	2001 to 2005	EOS Gateway, NASA
13	8-daily ETa and ETo	DAT – raster	5500m	All Europe	2000 to 2006	University of Montana

		format				
Others						
14	Actual production data of sunflower in Andalucia by field	Polygon	1:2,700,000	Andalucia	2001 to 2005	Ministry of Agriculture, Spain
15	Crop statistic data in Andalucia by municipality	Access database		Andalucia	1998 to 2006	Junta De Andalucia
16	GPS data from fieldwork	Polyline, point	1:440,000	Andalucia	2007	
17	Field survey information	Excel table		Sevilla	2007	
18	Interview data of farm yield	Point	1:440,000	Sevilla	2007	

3.4. Field Data Collection

3.4.1. Sampling Schemes

In order to make a random sampling scheme, a crop map of sunflower for the study area was developed. This map was made through image classification of SPOT-VGT NDVI images in combination with crop statistic data and Corine (land cover map) with GIS analysis.

SPOT-NDVI images of Andalucia region with all 300 layers from 1998 to 2006 were classified to 45 classes by unsupervised classification method (the number of classes were identified and decided through divergence analysis). The derived raster map was converted to polygon map and used the mask of agricultural area from the land cover (corine) map of 2000 to select the area that present the crop of sunflower. This map then was intersected with municipality map to identify the area of each NDVI class in each municipality. The attributable of the result was joined with agricultural statistic data of sunflower in Andalucia for multi variable regression analysis in SPSS. A step-wise linear regression model was developed as:

$$\mathbf{Y = a1*N1 + a2*N2 + \ldots + a45*N45}$$

Where:

Y is the area of sunflower in each municipality (from statistic data)

N1 to N45 is the area of each NDVI class present in each municipality

And a1 to a45 are the coefficients denoting the fraction of sunflower in each NDVI class (0 to 1).

Based on the result of this model, a crop map of sunflower was developed to present the faction of sunflower by every 1 square km in Andalucia (figure 13).

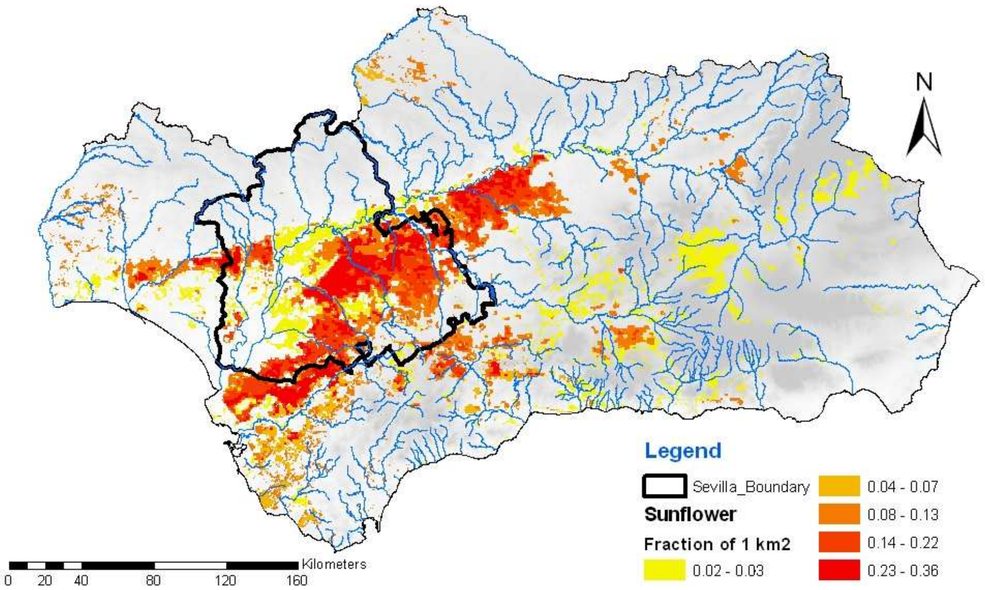


Figure 13: Crop map of Rain-fed Sunflower in Andalucia

From the crop map of sunflower, it is very clear to observe that most of sunflower is planted in Sevilla province. Based on the result of the crop map and based on the reality that the time is limited for the data collection in the field, Sevilla province has been chosen for sampling schemes of data collection instead of whole region of Andalucia.

Based on the crop map of Sevilla province, the method of strata sampling scheme was applied. The buffer zones were created around the main towns with a distance of 20 km from every town. These buffer zones were chosen to conduct the interview with farmers for data collection (figure 14). Due to high fraction of sunflower in these areas, the interviews have been conducted randomly in any farm of the strata.

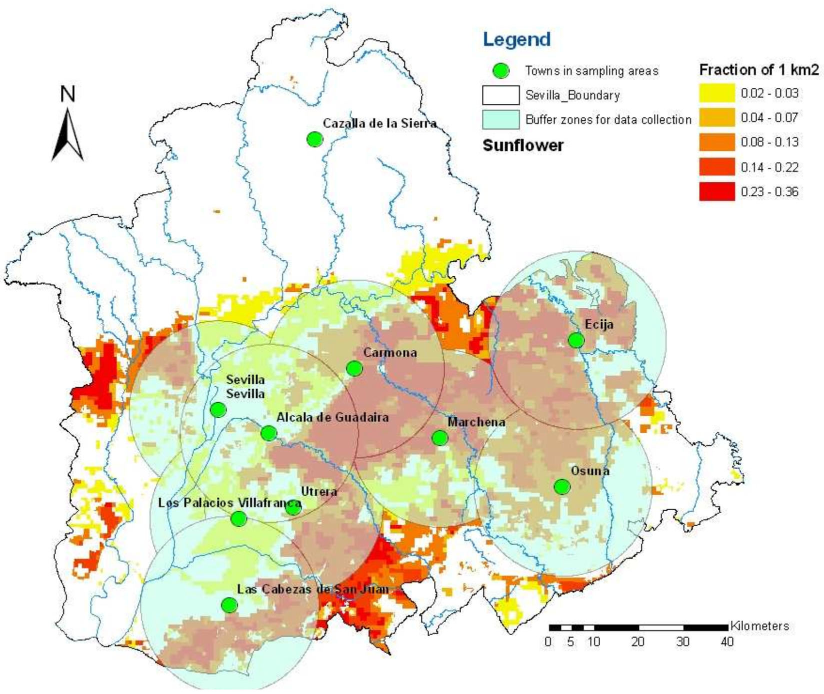


Figure 14: The strata sampling schemes for data collection

3.4.2. Field Data Collection

Most of field data were obtained by two traditional methods: observation and through interview. The observation was used to collect data that related to land at plot size such as soil quality and current operations on the field. Meanwhile, the interview (by semi-structured method) was applied to obtain the data related to land use operations (management) such as land preparation, soil treatment, planting time, fertilizer application, water shortage and yield etc (the format of interview and observation sheet is presented in the appendices). All the data from interview were used to discuss about the variable of land and land use operation and to develop the assumption for the research. In this fieldwork, statistical data of sunflower actual production in Andalucia (from Ministry of Agriculture, Spain) from 2001 to 2005 were also collected. In this data, the actual production of a certain crop (sunflower, wheat etc) is recorded for different random selected strata of 700 m x 700 m in Andalucia.

Additional data for this research are data from weather stations in Sevilla province. The data were collected are air temperature (daily maximum and minimum), precipitation, Eo, ETo, Air humidity etc. These data later are used as the inputs for PS-n model to estimate PS1 and PS2 yields for all weather station based points. In addition, satellite imageries concerning products of 8-day Gross Primary Productivity (GPP) and daily Land Surface Temperature (LST) in Andalucia region were also downloaded from MODIS (NASA – EOS Gateway - http://delenn.gsfc.nasa.gov/ims-bin/pub/secured/nph-ims.cgi/u39543).

3.5. Research Methods

3.5.1. Basic Flowchart

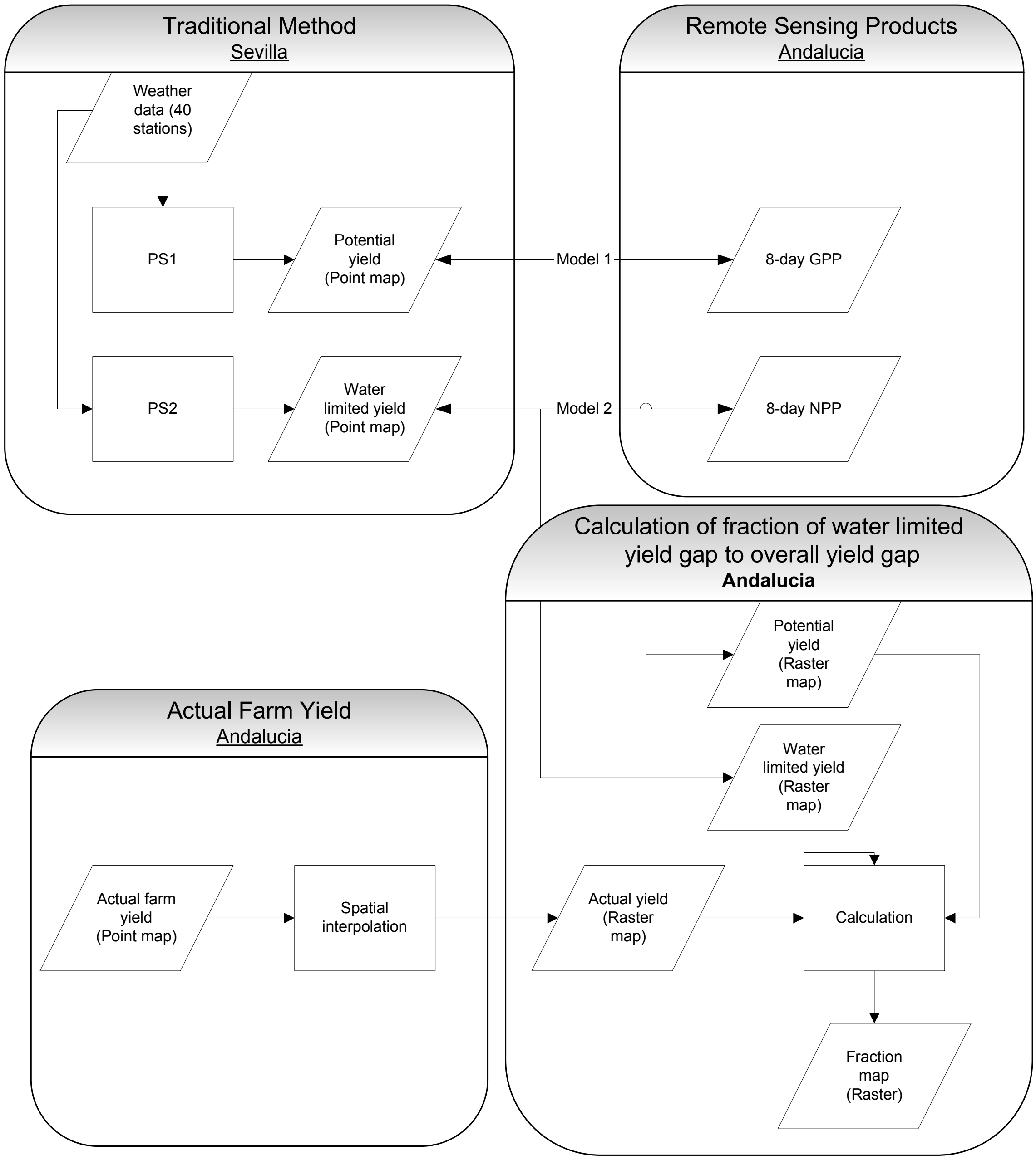


Figure 15: Overview of research method

3.5.2. Operational Flowchart

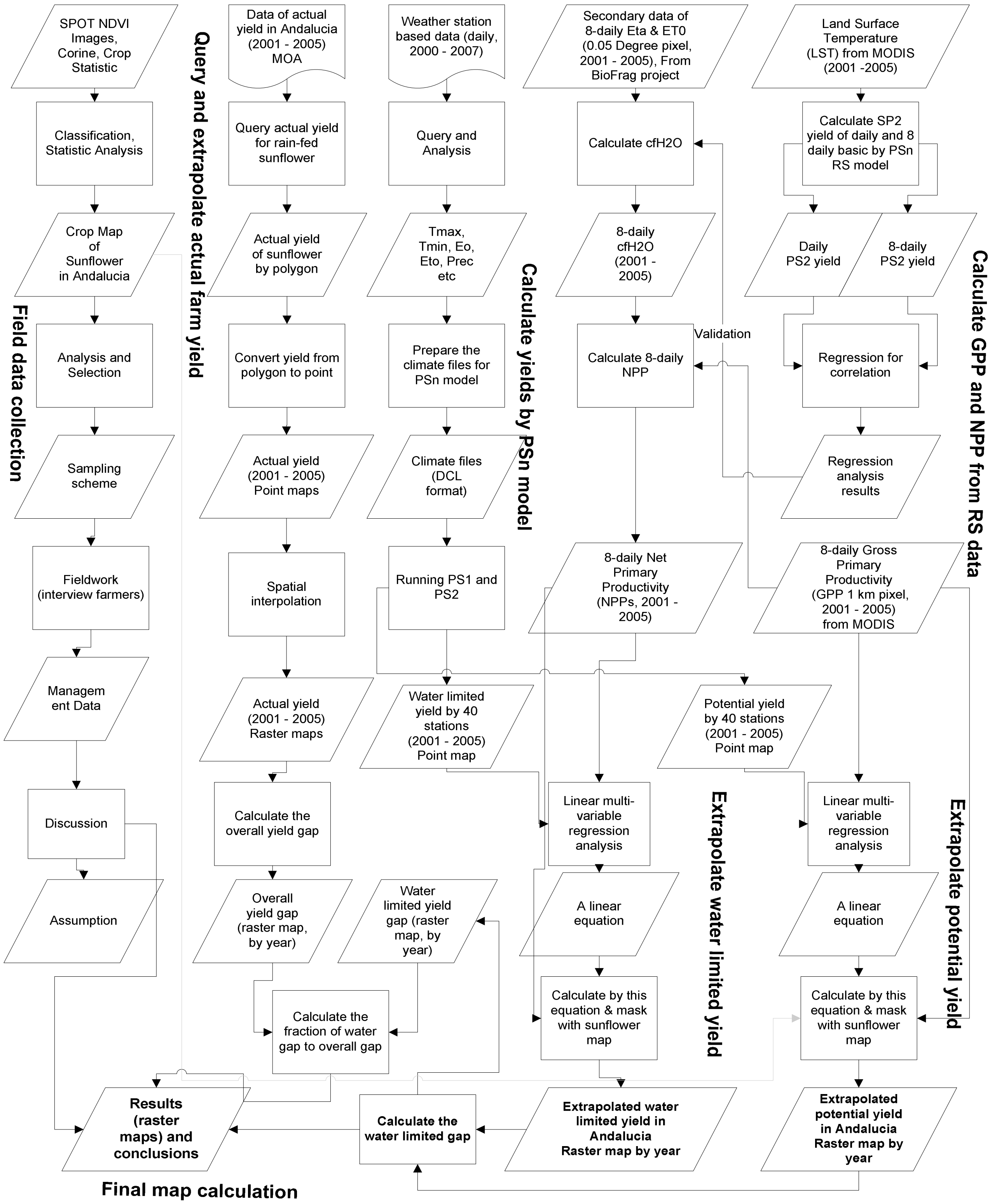


Figure 16: Detailed operational flowchart

3.5.3. Software Used

The following software and programs are used for data analysis in this research:

- SPSS – version 15.0: for statistic analysis
- ArcGIS – version 9.2: for GIS analysis
- Erdas Imagine – version 9.1: for remote sensing/image processing and analysis
- ArcPad for Windows – version 7.1: for GPS support
- Microsoft Office 2003
- Model selected: Production Situation Model (PSn) (Driessen & Konijn, 1992)

Note: All output maps of this research are presented in coordinate system of ED_1950_UTM_Zone_30N

3.5.4. Data used for PSn model

In PS1, the model calculates the yield potential based on temperature, solar radiation and crop parameters of sunflower. Meanwhile PS2 will analyse the water limited yield with more complicated procedures that deducts yield potential by water limited yield reduction (daily). This yield reduction is determined by rainfall, RHA, Eo and ETo during growing period.

In order to run the PSn models PS1 and PS2, the following data were used:

- Daily Minimum and Maximum air Temperatures – Tmin and Tmax (^{0}C)
- Daily Rainfall – PREC. (cm/day)
- Relative Humidity of Atmosphere **-** RHA (0 – 1)
- Potential Evaporation **-** Eo (cm/day)
- Daily Sunshine **-** SUNH (h/day)
- Reference Evapotranspiration **-** ETo (cm/day)

In this research, Tmax, Tmin, PREC, SUNH, RHA, Eo and ETo are queried from database of 40 weather stations in Sevilla province (figure 17). This research used the data from year 2001 to 2005 for final analysis. All available data have been queried for each station and for every year then converted to the units that are suitable for PSn model inputs.

In addition, a crop file of sunflower was also developed. This crop file was in DAT format and developed based on the characteristics of sunflower such as Tsum, Tleaf, SLAmax, SLAmin (Specific Leaf Area) etc (Driessen & Konijn, 1992).

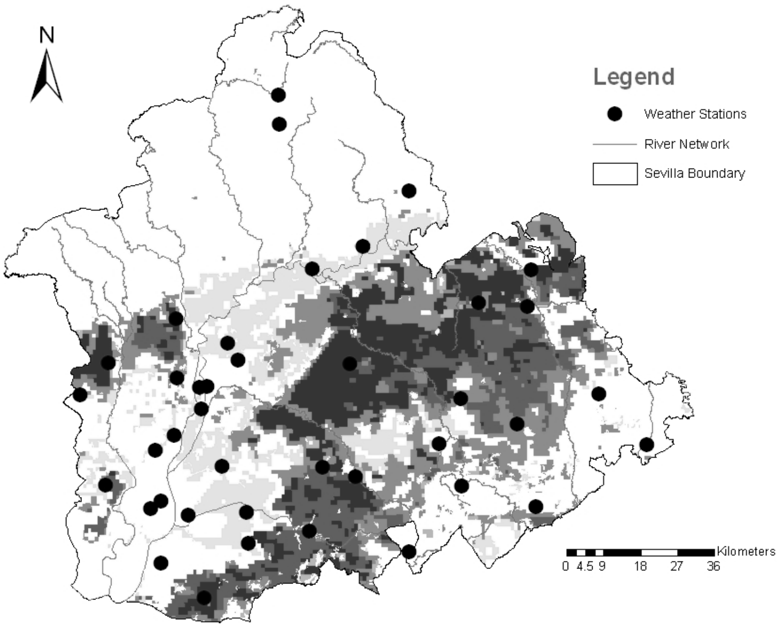


Figure 17: Weather stations in Sevilla province

For both PS1 and PS2, the model will use the constant parameters of sunflower provided as a model input. In this research, the crop parameters (biophysical characteristics) of sunflower are developed based on the literature reviewed data (Driessen & Konijn, 1992) in consultation with local situation of sunflower in Andalucia (Tsum, Tleaf and Relative Development Stage – RDS of crop etc). In order to have better accuracy for model calculation of yield potential and water limited yield, a crop file of sunflower has been developed and modified (in DAT format) as follows (figure 18).

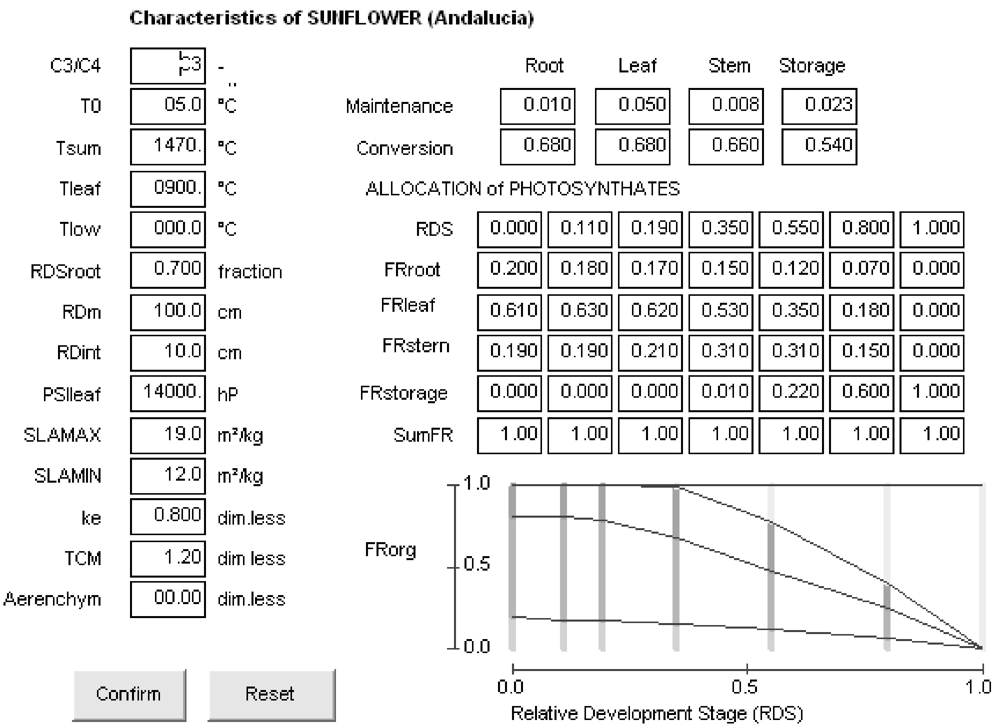


Figure 18: Crop characteristics of sunflower in Andalucia for PSn model

List of abbreviation in figure 18:

C3/C4 is group of photosynthetic mechanism

T0 is threshold temperature for development (^{0}C)

Tsum is heat requirement for full development (^{0}C)

Tleaf is heat sum for full development of leaf tissue

RDSroot is relative development stage root growth stops (fraction)

RDm is maximum rooting depth (cm)

RDint is equivalent rooting depth at germination or planting (cm)

PSIleaf is critical leaf water head (cm)

SLAmax is maximum specific leaf area (m^2/kg)

SLAmin is minimum specific leaf area (m^2/kg)

Ke is extinction coefficient for visible light

TCM is maximum turbulence coefficient

Maintenance – R(org) is relative maintenance respiration rate (kg/kg/day)

Conversion – Ec(org) is efficiencies of conversion (kg/kg)

FR(org) is mass fraction of assimilate production allocated to organs

RDS is crop relative development stage (0 -1)

In PS2 – Water limited yield calculation, as assumed that the water is the main constraints for yield gap, so the soil is not considered as a limiting factor. In this research, the soil is considered as a constant for all analysis and calculation of PS2 and the model calculates water limited yield of sunflower using sandy soil as the inputs in all the points. The parameters of sandy soils for PS2 model is described in figure 19.

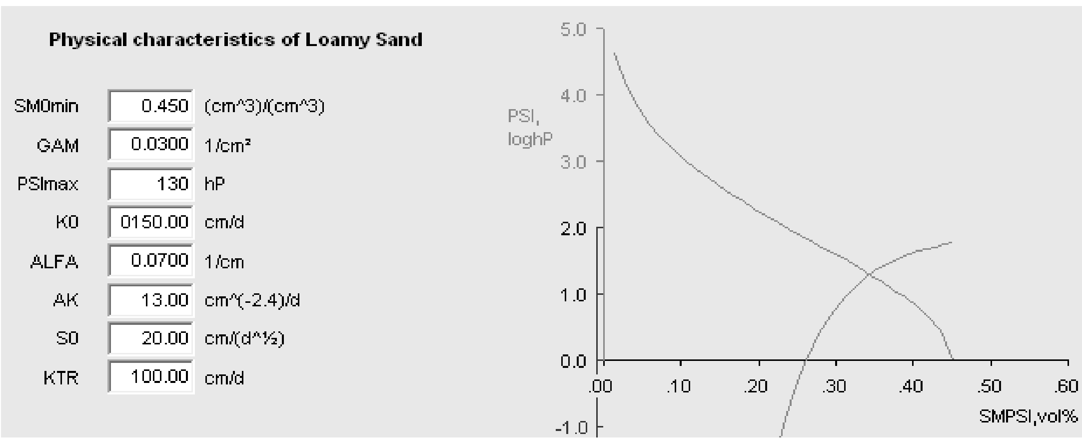


Figure 19: Physical characteristics of Loamy sand soil for PS2

List of abbreviation in figure 19:

SM0min is minimum total pore fraction of soil material (cm^3cm^{-3})

GAM is texture-specific constant (cm^{-2})

PSImax is texture-specific suction boundary (cm)

K0 is saturated hydraulic conductivity (cm/day)

ALFA is texture-specific geometry constant (cm^{-1}).

AK is texture-specific empirical constant ($cm^{-2.4}$/day)

S0 is reference sorptivity (cm $day^{-1/2}$)

KTR is permeability of the transmission zone of soil material (cm/day)

SMPSI is volume fraction of moisture in soil (%)

SPI is matric suction of rooting zone (cm)

3.5.5. Query and Extrapolation of Actual Farm Yield

The actual farm yields for every year were queried from secondary data provided by Ministry of Agriculture, Spain. Based on the strata of 700 m x 700m, the rain-fed sunflower actual farm yields were queried and presented by polygon maps. These maps then were converted into point maps based on the principle: one point in point map represents one polygon in polygon map.

The spline interpolation method was used to extrapolate the actual farm yield from sampling points to whole sunflower cultivation of Andalucia in raster format. The spline tool works in the principle of estimating values using mathematical function that minimizes overall surface curvature. The result is in smooth surface that passes exactly through the input points. Conceptually, it can predict ridges and valleys in the data and it is the best method for representing the smoothly varying surface of phenomena such as temperature (Childs, 2004).

Based on the principle that crop productivity is mainly defined by temperature and rainfall factors, it is the most suitable method for interpolating the actual farm yield from points to raster maps. Instead of using elevation of each point as Z value in interpolation process, the actual farm yield value was used as the magnitude value that decides the value of each cell in output map. For further analysis with other potential and water limited yield maps, the mask of sunflower crop map was used in the interpolation process and pixel size of 1000 m was applied for the output interpolated raster map.

For quality control, the buffer zone of 30 km around each point of actual farm yield was also applied. This method provides better accuracy for the output raster map but the area of sunflower in output map would be reduced which is depended on the number of points from input map for each individual year.

3.5.6. Yield Calculation by PSn Model

For every year, Potential yield and water limited yield of sunflower were calculated by PS1 and PS2 to produce the point maps of sunflower in Andalucia (2001 – 2005).

Based on the fact that most of sunflower was planted from 1st week to 2nd week of March in Andalucia (interviewed result data), the PSn model was run with following inputs:

Table 3: Input parameters for PSn model calculation

Inputs	PS1	PS2
Crop	Sunflower profile (.CRP)	Sunflower profile (.CRP)
Weather	Weather profile (.DCL)	Weather profile (.DCL)
Soil texture		Loamy sand profile (.DAT)
Planting time	Day 70 (Julian day)	Day 70 (Julian day)
Harvesting time	Day 184 (Julian day)	Day 184 (Julian day)
Seeding rate	5 kg/ha	5 kg/ha
Seed mortality	0%	0%
Day-length sensitivity	12 hours	12 hours
Phreatic level in the soil		300 cm
EC ground-water in the soil		0.1 dS/m

3.5.7. Calculation of Gross Primary Productivity (GPP) and Net Primary Productivity (NPP) from Remote Sensing Data

3.5.7.1. GPP from MODIS Images and Extrapolation of Potential Yield of Sunflower

The 8-day basic Gross Primary Productivity MODIS images with resolution of 1 km have been downloaded from EOS Gateway. Based on the growing period of sunflower in Andalucia, the MODIS's GPP images were collected from day 65 to day 185 (Julian day – from March to July) for every year from 2001 to 2005 for Andalucia area. Each image contains the information of total GPP (sum up) for every 8-day period (kg of carbon/1 square km pixel).

The 16 period images were used for the purpose of extrapolation of potential yield of sunflower from PS1 calculated points to whole sunflower cultivation areas in Andalucia. As PS1 model calculates potential yield based on the Photosynthetic Active Radiation (PAR) from daily temperature and solar radiation provided by synoptic data, meanwhile MODIS17/A3 model also calculates the GPP based on the PAR (Heinsch, Reeves, & Votava, 2003), it is possible to assume that there is a linear correlation between GPP from MODIS at different periods and potential yield of sunflower calculated by PS1. All GPP images (of every year) were overlaid with weather station point map. GIS Spatial Analyst tool was used to extract the pixel values (GPP) to the points of weather station map. These values of GPP of each 8-day image from all the points together with potential yield values were entered into SPSS for identifying the correlation between GPP and potential yield. A step-wise multiple regression analysis was conducted to develop a model of:

Y = a1*X 1 + a2*X2 +… + a16*X16

Where:

Y: Potential yield of sunflower in Andalucia (dependent variable)

X1 to X16: Value of GPP of 16 periods from MODIS in the same location with potential yield point in Andalucia (independent variables)

And a1 to a16 are coefficients

This equation was then used to extrapolate the potential yield map of sunflower in Andalucia from points to raster format. The equation was used to calculate the potential yield from 8-day GPP images. The result of each year then was masked with crop map of sunflower in Andalucia to produce the final potential yield map of sunflower for every year.

In general, it is possible to describe the extrapolation method by flowing flowchart:

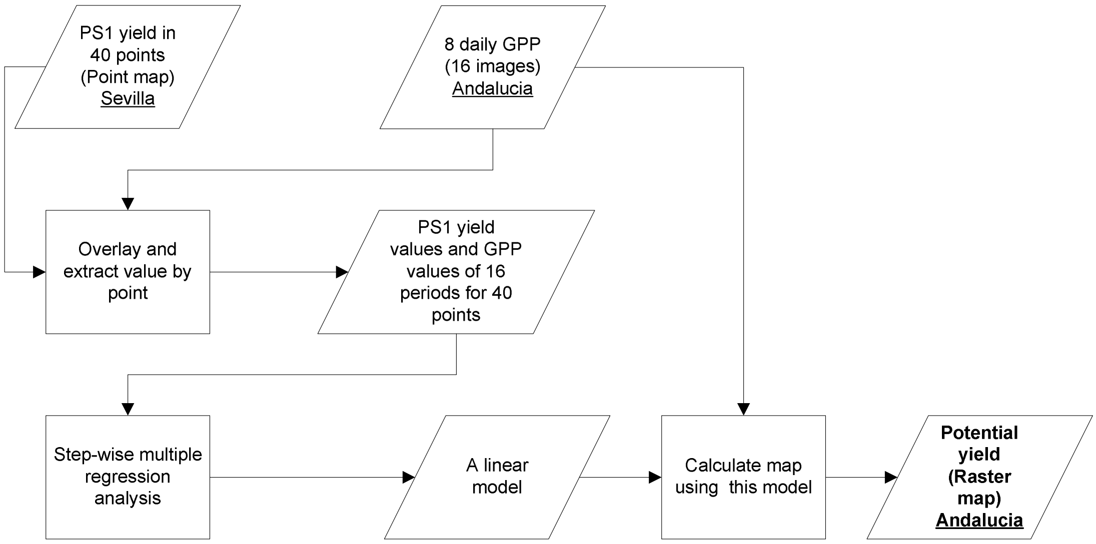


Figure 20: Flowchart for potential yield extrapolation method (every year)

3.5.7.2. Calculation of Land Surface Temperature (LST) from MODIS Images

The MODIS satellite images with resolution of 1 km were downloaded from EOS gateway. The LST images were also collected from day 65 to day 185 for every year (2001 to 2005). ArcGIS software was used to extract the daily values of LST from images for 40 the weather station points (by year). In order to get the real value of LST in degree Celsius for PSn model analysis, the following function was applied to calculate for every point (daily value):

LST in degree of Celsius = LST pixel value * 0.02 – 273

3.5.7.3. Calculation of cfH2O and NPP

Land Surface Temperature derived from MODIS was used as inputs of canopy temperature for remote sensed PSn model (Mendez Jocik, 2004; Venus & Rugege, 2004) to calculate the PSn yield of sunflower in 40 weather station based points. By this procedure, the water sufficiency coefficients are calculated as daily values. These cfH2O coefficients were then used to test the following hypothesis

Water limited yield calculated for each 8-day period is not much different from summed up of daily calculated water limited yield from 8 days. In another way this hypothesis can be presented as:

> **(Summed up potential yield of 8 days) * Average cfH2O of 8 days = Water limited yield for 8-day period (Y variable) and**
>
> **(Daily potential yield * daily cfH2O) * 8 = Summed up of daily water limited yield for 8 days (X variable).**
>
> Test: Y is not so different from X

To test this hypothesis, the output data of year 2001 were added into SPSS for the linear regression analysis to identify following indices:

- Root Mean Square Error (RMSE) between 2 variables.
- Correlation (coefficient) between 2 variables.
- R squared of the regression
- T value of the regression

If all the indices show the strong relationship between 2 variables (high value of R square, P value < 0.05 etc), it is possible to conclude that the 8 daily cfH2O can be used to calculate water limited yield from potential yield instead of using daily values. By this method, the monthly cfH2O was also calculated and tested for monthly water limited yield with summed up of daily water limited yield of one month.

If the hypothesis is tested successfully, the secondary data of 8-daily ETa and ETo from the FSES project of ITC can be used to calculate the cfH2O for every 8-day period (from 2001 to 2005) for Adanlucia (because ETa and ETo were available on 8 daily value). The 8 daily values of cfH2O represent the water stress of the crop in every 1 square km of the study area for every 8-day period.

Based on 8-day basic value of cfH2O, it is possible to calculate the Net Primary Productivity of every pixel for total 8-day period from 8 daily GPP (downloaded from MODIS) by following equation:

8 daily NPP = 8 daily GPP * cfH2O of 8-day period

The NPP values (in images) later will be used for the purpose of extrapolation of water limited yield from point maps to raster maps.

3.5.7.4. Extrapolation of Water Limited Yield

Water limited yield was calculated by PS2 model and produced a potential yield maps by points. For further analysis of spatial and temporal patterns of yield gap caused by water shortage, it was necessary to extrapolate these point maps into raster maps of sunflower in Andalucia.

Because the NPP calculated from GPP and cfH2O, it represents the water stress of the crop in the area and through this principle, it is possible to assume that there was a linear relationship between NPP values and water limited yield values. The 16 images of NPP (from day 65 to day 185 of Julian days) calculated form GPP were used to extrapolate for water limited yield map of every year. All NPP images were overlaid with weather station point map. GIS Spatial Analyst tool was used to extract the pixel values (NPP) to the points of weather station map. These values of NPP of each 8-day image from all the points together with water limited yield values were entered into SPSS to identify the correlation between NPP and water limited yield. A step-wise multiple regression analysis was conducted to develop a model of

Y = b1*X 1 + b2*X2 +… + b16*X16

Where:

Y: Water limited yield of sunflower (dependent variable)

X1 to X16: Value of NPP of 16 periods in the same location with water limited yield point in Andalucia (independent variables)

And b1 to b16 are coefficients

This equation was then used to extrapolate the water limited yield map of sunflower in Andalucia from points to raster format. The equation was applied to calculate the water limited yield from 8-day NPP images. The result of each year then was masked with crop map of sunflower in Andalucia to produce the final water limited yield map of sunflower for every year. This extrapolation procedure has the same principles as potential yield extrapolation method.

3.5.8. (Raster) Calculation of Spatial and Temporal Patterns

In order to quantify the spatial and temporal patterns of yield gap for sunflower, the raster calculation and cell statistic tools were used to calculate following values:

- The difference between potential yield and water limited yield for every year: To quantify the yield gap pattern caused by water shortage for each year (2001 to 2005).
- The average of potential yield for five-year period: to present the general potential yield of sunflower in the study area.
- The minimum of water limited yield for five-year period: to present the lowest water limited yield pattern of sunflower in the study area.
- The difference between general potential yield and minimum water limited yield: to quantify the possible highest yield gap pattern (caused by water shortage) of sunflower in the study area.
- The difference between water limited yield and actual farm yield for each year: to quantify the yield gap caused by other factors than water shortage.
- The difference between potential yield and actual farm yield for each year: to quantify the overall yield gap pattern caused by all limiting factors for sunflower in the study area.
- The maximum of overall yield gap for five-year period: to present the highest overall yield gap of sunflower through time.

3.5.9. Calculation of Fraction of Water Limited Yield Gap to the Overall Yield Gap

To prove the hypothesis that the yield gap of sunflower in Andalucia is mainly caused by water shortage, it is necessary to quantify how many percents the gap caused by water shortage contributed (in space) to the overall gap of sunflower for each year.

For every year, the raster map of actual farm yield was overlaid with both potential yield and water limited yield raster maps. Spatial Analyst tool (raster calculator) was used to calculate:

Overall yield gap (kg/ha) = Potential yield – actual farm yield

Water limited yield gap (kg/ha) = Potential yield – water limited yield

Fraction of water limited yield gap to overall yield gap (0 – 1) = Water limited yield gap/overall yield gap

4. Results and Discussions

4.1. Land Management for Sunflower Cultivation in Andalucia

As the traditional CPA method (De Bie, 2000), land management factors were identified and analysed to quantify the degree of influence to final yield gap of sunflower. The interview results have shown that, the land managements including crop calendar and operational sequence are almost homogeneous in interviewed plots.

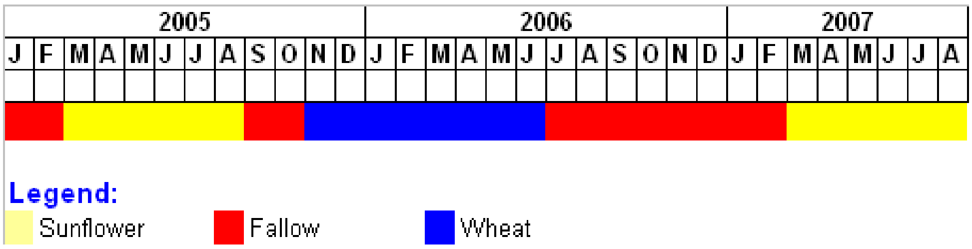


Figure 21: Crop calendar for sunflower in Andalucia (in 23 sites)

All interviewed farmers (23 farms) have reported the same sequence for their crops as a crop rotation in flowing order: Sunflower – Wheat – Sunflower (figure 21). This sequence (rotation) was applied in order to avoid crop diseases (fungus, bacteria etc) and to take the advantage of nutrition from previous crop to support later crops.

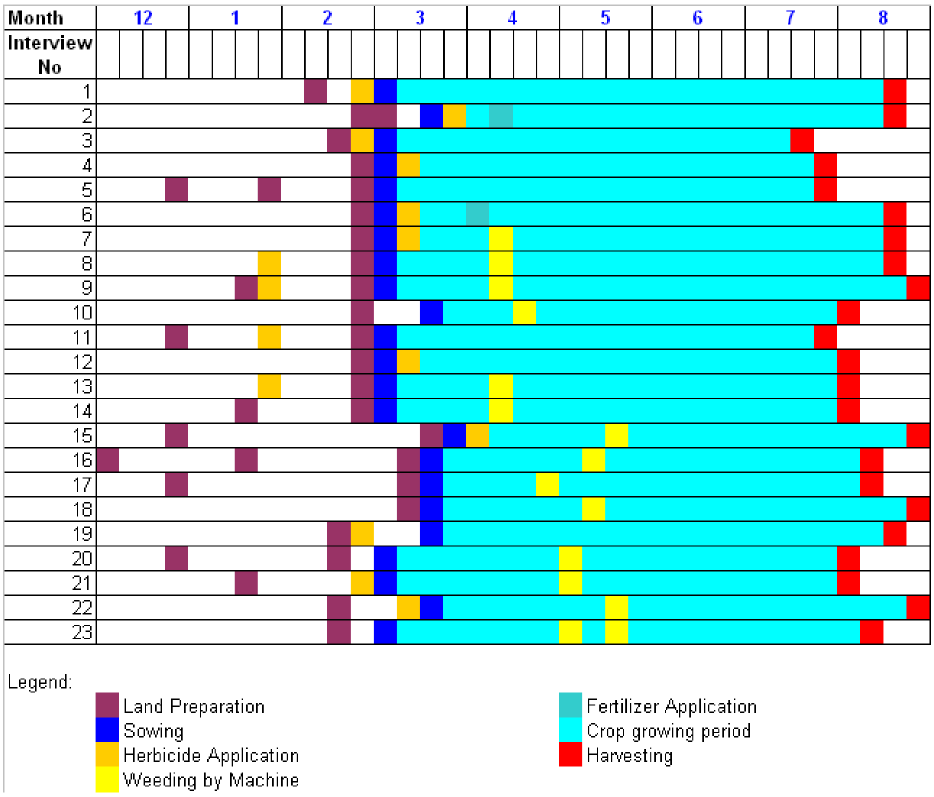


Figure 22: Operation sequence for sunflower cultivation in interviewed farms, Andalucia

In terms of land operational sequences, figure 22 shows that 65% of interviewed farmers sowed the seeds of sunflower at the same time (first week of March), meanwhile, the remaining (35%) sowed one or two weeks after.

All farmers applied machines for land preparation and for weeding. Most farmers applied herbicides (Teflan and Glitosato) in the soil before or after planting time. Nobody applied fertilizers because sunflower could use the fertilizers remaining from previous wheat cultivation, but the main reason is based on the climate condition of this area – during the growing period of rain-fed sunflower, the rain did not provide enough water (in term of intensity) that could support moisture in the soil for fertilizer application.

Another factor in operational sequence is the harvesting time. Because all farmers used machines for harvesting, and the land was not needed immediately for other following crop (needing a fallow period), so the sunflower was all collected by machine at the right time when the seeds were already ripped. Therefore, this factor actually does not influence final production of sunflower.

According to the farmers, sunflower yield are different from year to year, from plot to plot mainly based on the climate condition and soil characteristics.

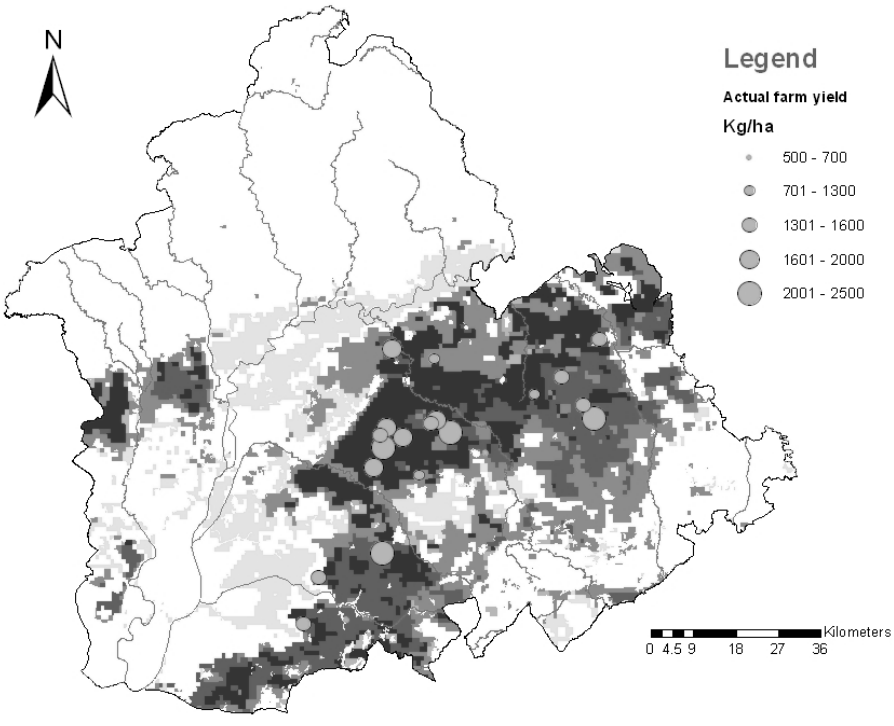


Figure 23: Actual farm yield of sunflower in interviewed farms, year 2007

Figure 23 also shows that the actual farm yields (collected by interviews) are variable from plot to plot. This variation in space can be explained by other factors that may play stronger roles in determining the yield gap of sunflower in Andalucia.

From all analysis, it is possible to come to an assumption that the land management for sunflower cultivation in Andalucia is almost homogeneous in space and time and it does not deicide the yield gap of sunflower in space and time.

4.2. The Heterogeneous of Rainfall Data Used for PSn model

Beside temperature, the rainfall is a very important factor for crop development. Especially, in non-irrigated areas, the rainfall is main source of water to provide moisture for crop's growth. Insufficiency of water in different period of time may provide different effects to the crop and through those effects, the final yields of crop are determined.

In space and time, the rainfall is also a factor that determines the variation of crop yield from plot to plot and year to year. Different amount of rainfall in different plot brings variable yield data that farmer could not modify except through the irrigation intervention.

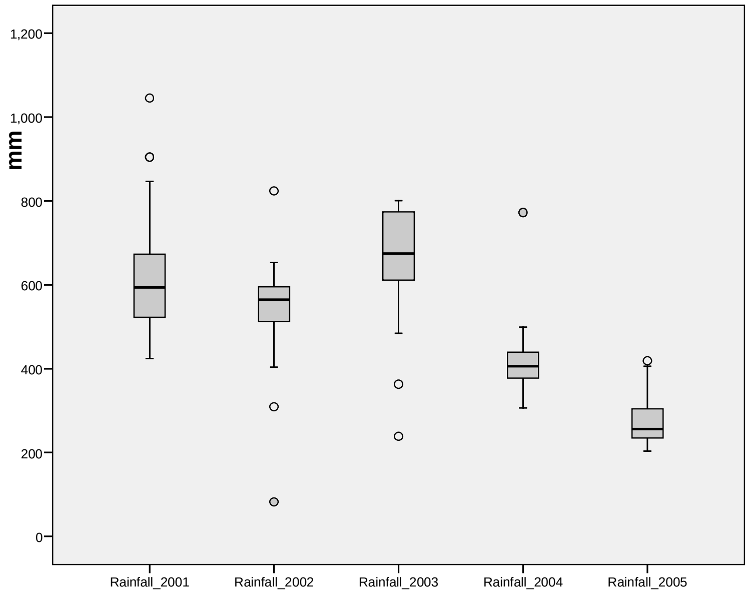


Figure 24: The box-plot shows the distribution of annual rainfall data of 40 weather stations in Sevilla province (2001 to 2005)

To study the variation of yield gap in space, it is necessary to identify the variation of rainfall data in the study plots. In 40 weather stations based points, figure 24 shows that there was a heterogeneous in annual rainfall data within all plots and between years.

Table 4: Statistic description for analysis of rainfall variable in 40 weather station points (2001 to 2005)

	N	Minimum	Maximum	Mean	Std. Deviation
Rainfall_2001	40	423	1045	628	132
Rainfall_2002	40	82	823	537	115
Rainfall_2003	40	238	800	666	120
Rainfall_2004	40	306	772	419	93
Rainfall_2005	40	203	419	272	55
Valid N (listwise)	40				

Table 4 shows that the annual rainfall varies from 423 mm to 1045 mm with Standard Deviation of 132 mm in year 2001. Across the years, the average rainfall varies from 272 mm in 2005 to 666 mm in 2003.

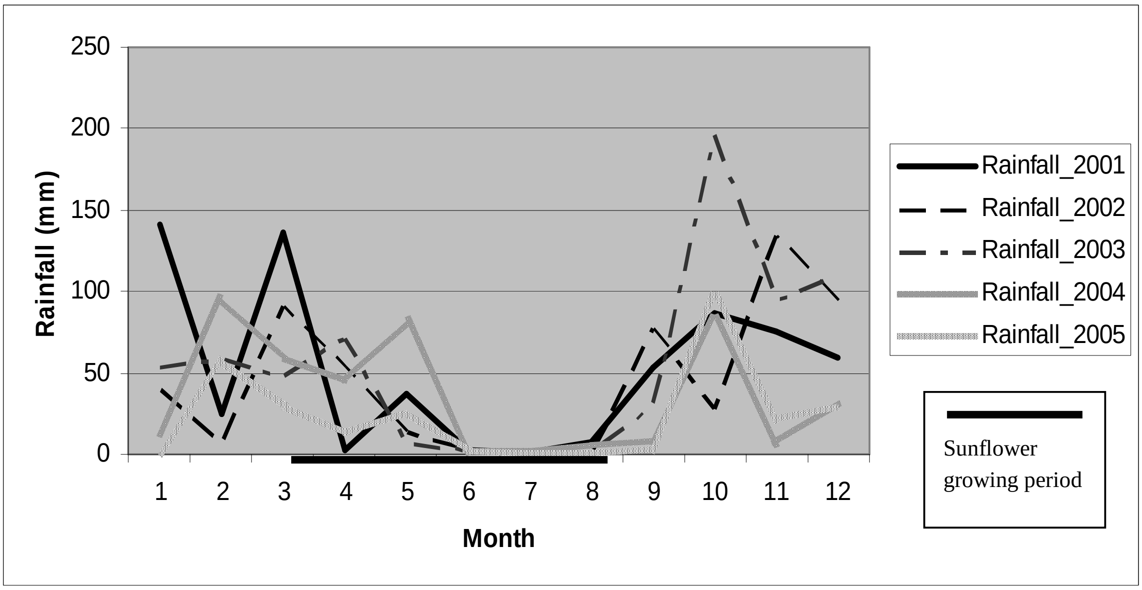


Figure 25: Distribution of monthly rainfall data for 5 years (2001 to 2005)

Figure 25 also clearly shows that during the period of sunflower growing (March to August), the rainfall was different from year to year. The lowest rainfall was in year 2005 and the best distribution of rainfall was in 2003 and in 2004 (distributed more evenly through time).

It is very clear to see that the rainfall data is quite heterogeneous from plot to plot and from year to year. These rainfall data can be used as a significant input for crop growth model (PSn) to quantify the pattern of yield gap of sunflower in space and time.

4.3. Yield Reduction of Sunflower Due to Water Shortage

4.3.1. Potential Yields of Sunflower Calculated by PS1 Model

Production Situation Model (PS1) was used to calculate the potential yield of sunflower in 40 weather station points in Sevilla province. These yield values were defined by climate factors of solar radiation and temperature (Driessen & Konijn, 1992). Based on the variation of climate in space and time, the potential yields are also variable from plot to plot and from year to year.

Figure 26 shows the result of PS1 calculation for potential yield within 40 station points for year of 2001. The potential yield of sunflower varies from 2167 to 5015 kg/ha. It proves that without consideration of other land factors, weather factors of solar radiation and temperature have played very important roles in determining the variability of yields through the area.

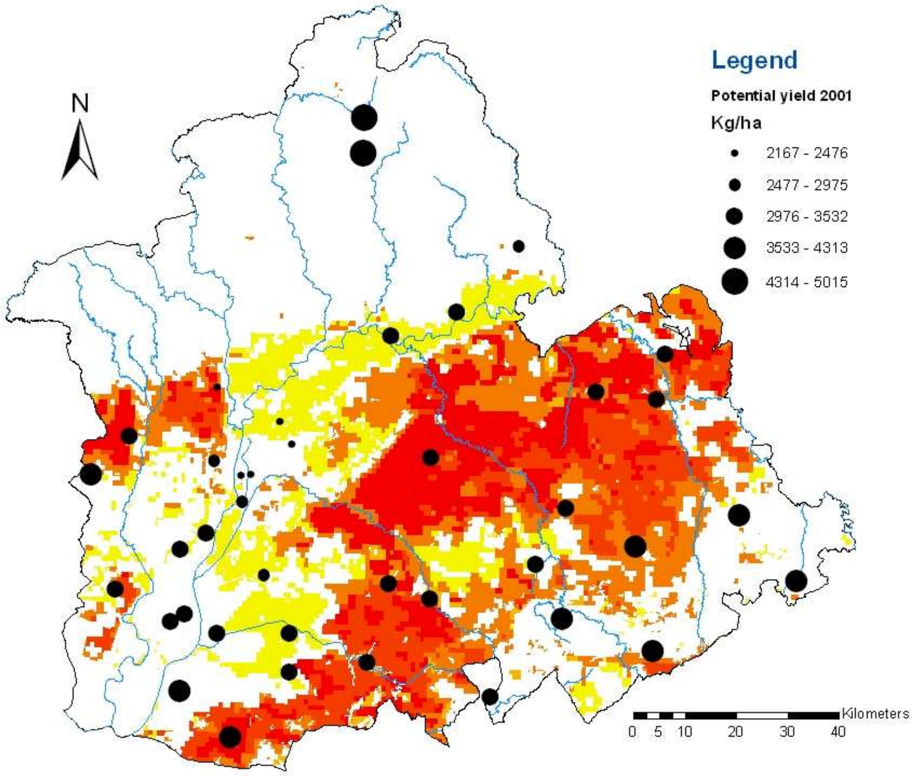


Figure 26: Point map of potential yield of sunflower in Andalucia, year 2001

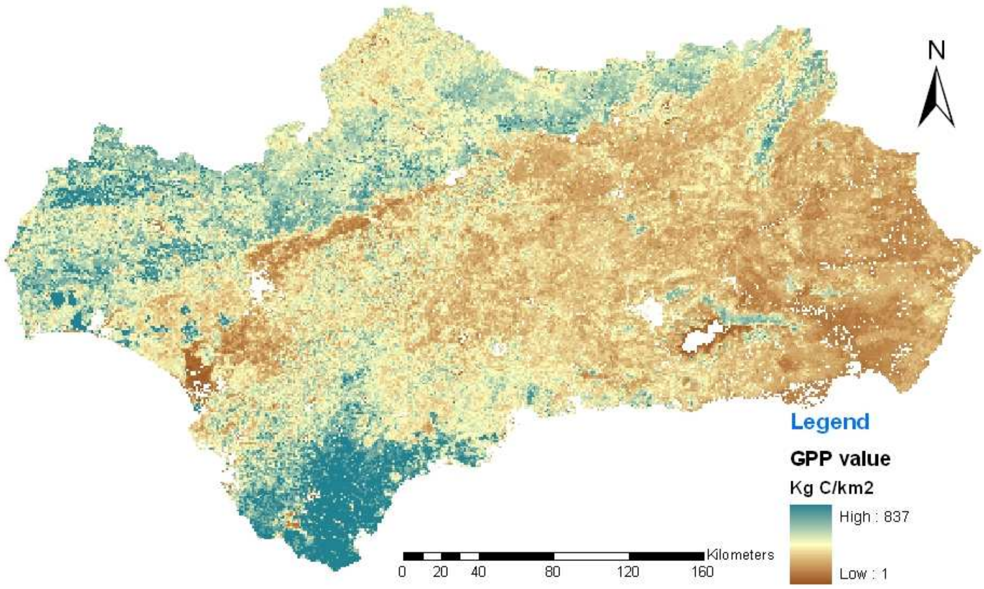


Figure 27: One of GPP images from MODIS, used for potential yield extrapolation (year 2001)

To extrapolate the point map of potential yield (40 points) to raster map of whole sunflower cultivation in Andalucia, the step-wise multiple regression has been conducted to quantify the correlation of potential yield value and GPP values (figure 27). The regression analysis (linear, step-wise) results show that there is a significant correlation between potential yield of sunflower and GPP values through many 8-day periods (16 periods):

Table 5 shows the results of this regression for year 2001. In the results, 3 linear models are recommended for quantifying the correlation between potential yields and GPP values.

Based on the R squared value (0.948), the 3rd model is selected to develop an equation for extrapolating the potential yield of sunflower from point map to raster map based on the GPP images. The correlation between potential yields of sunflower and GPP values in 2001 is:

Potential yield_2001 = 7.401*GPP81 + 11.989*GPP121 + 5.531*GPP177

Apply this equation to GPP images, the raster map of sunflower potential yield is produced and presented in figure 28.

Table 5: The regression results showing the correlation of potential yields of sunflower and GPP values - year 2001

Model	R	R Square(a)	Adjusted R Square	Std. Error of the Estimate
1	.935(b)	.874	.870	1236.49443
2	.966(c)	.934	.930	909.87978
3	.974(d)	.948	.943	816.75362

ANOVA

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	370241738.473	1	370241738.473	242.159	.000(a)
	Residual	53512146.527	35	1528918.472		
	Total	423753885.000(b)	36			
2	Regression	395605924.014	2	197802962.007	238.927	.000(c)
	Residual	28147960.986	34	827881.205		
	Total	423753885.000(b)	36			
3	Regression	401740031.054	3	133913343.685	200.744	.000(d)
	Residual	22013853.946	33	667086.483		
	Total	423753885.000(b)	36			

Coefficients (a,b)

Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**	**B**	**Std. Error**
1	GPP121	21.908	1.408	.935	15.561	.000
2	GPP121	13.203	1.883	.563	7.011	.000
	GPP81	9.887	1.786	.445	5.535	.000
3	GPP121	11.989	1.737	.512	6.901	.000
	GPP81	7.401	1.801	.333	4.109	.000
	GPP177	5.531	1.824	.198	3.032	.005

Based on the regression analysis for potential yields and GPPs values of other years, the equation for extrapolation of potential yields for each year was also developed and presented in table 6.

Table 6: Equations for potential yield extrapolation for other years, derived from regression analysis results

Year	Equation for extrapolation	R Square
2002	Potential yield_2002 = 18.187*GPP113 + 7.855*GPP177	0.941
2003	Potential yield_2003 = 13.19*GPP129 + 12.49*GPP169	0.895
2004	Potential yield_2004 = 12.393*GPP97 + 66.1*GPP177	0.940
2005	Potential yield_2005 = 17.692*GPP89 + 58.544*GPP169	0.851

Table 6 shows that there was a significant correlation between potential yields and GPP values of every year. However, it is not possible to use the coefficients and GPP periods of one year to apply for extrapolation of other years.

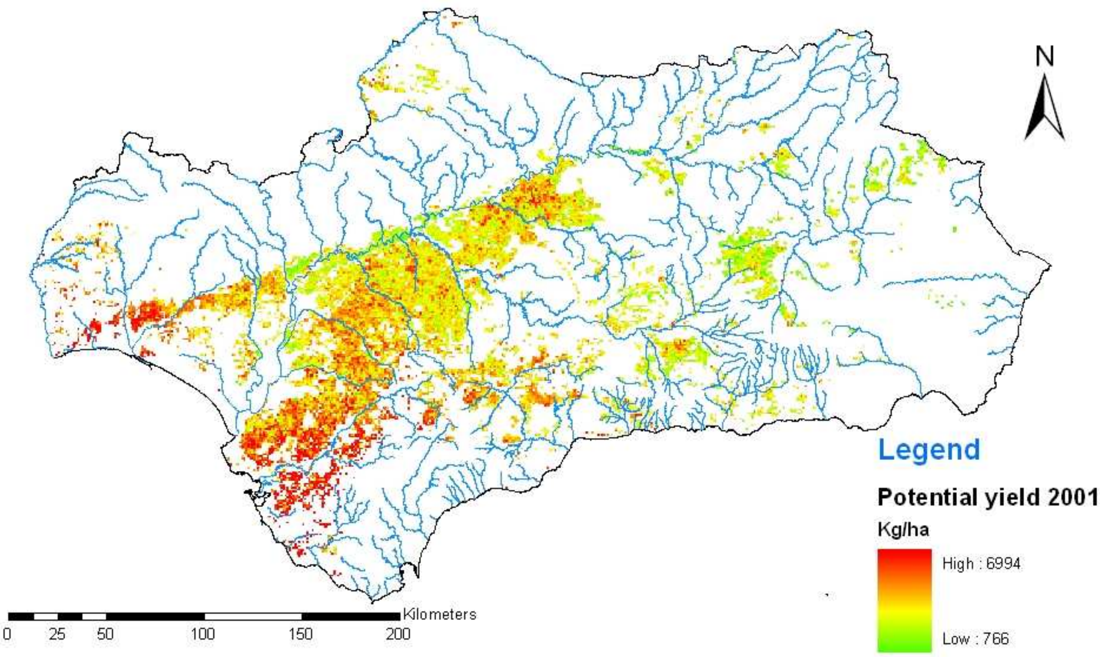


Figure 28: Raster map of potential yield of sunflower in Andalucia, year 2001

In Andalucia, for the year of 2001, the figure 28 shows that the potential yields of sunflower could vary from 463 to 6,995 kg/ha. However, in the high fraction areas for sunflower cultivation, the potential yield could gain from 2,744 to 5,253 kg/ha (based on classified map – shown in Appendices). The variation of potential yields in space will partly contribute to the variation of actual farm yield in reality.

4.3.2. Water Limited Yields of Sunflower

Water limited yield is the second level of potential yield calculation from PSn model. Depending on the availability of water for crop growth though out the relative development stages (RDS), potential yields will be reduced from 0% up to almost 100%. If water was enough for crop growing in all RDS, then PS2 yield = PS1 yield. However, in most of rain-fed crop growing areas, water is always a limited factor and in some periods of RDS, the crop always faced with water stress. In this case, PS2 yield = PS1 yield – yield reduction due to water stress (shortage).

The results of PS2 calculation for water limited yield of sunflower in 40 points of Sevilla province is showing in figure 29. It shows that as well as potential yield, the water limited yield is also variable from point to point within a year. It ranges from 484 to 3167 kg/ha in 40 points in Andalucia for the year 2001. The water limited yields were also calculates for 40 points of year 2002, and year 2005. The PS2 model was failed to calculate water limited yields for year 2003 and year 2004 due to excessive moisture values which provided by weather data.

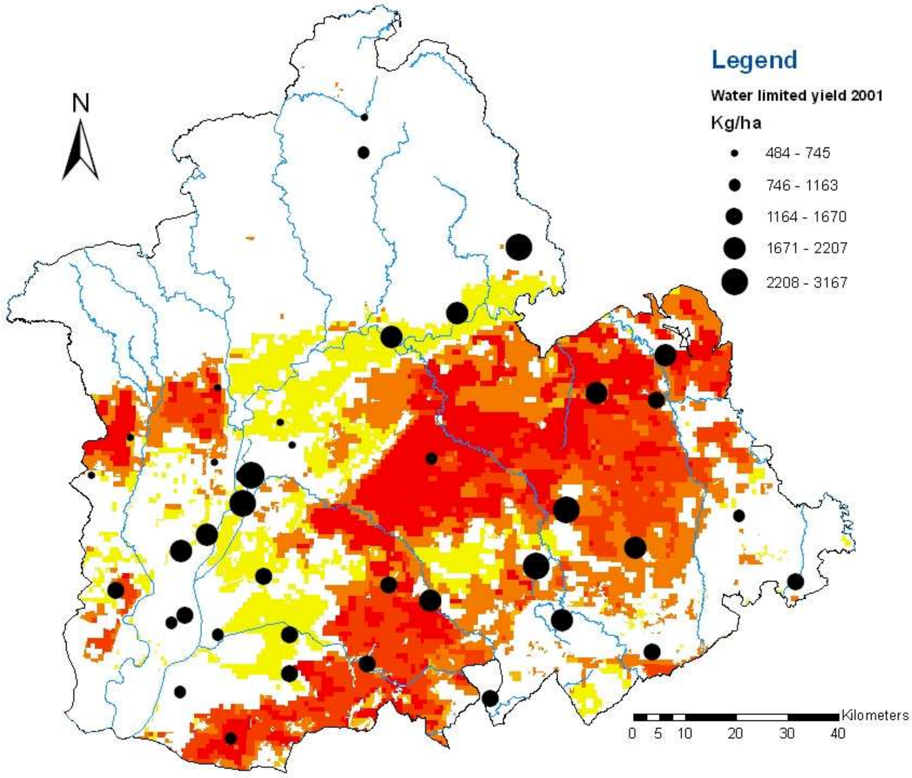


Figure 29: Point map of water limited yield of sunflower in Andalucia, year 2001

To extrapolate the water limited yield from the map of 40 points to raster map for whole sunflower area in Andalucia, the Net Primary Productivity (NPP) from remote sensing was calculated from GPP by following function:

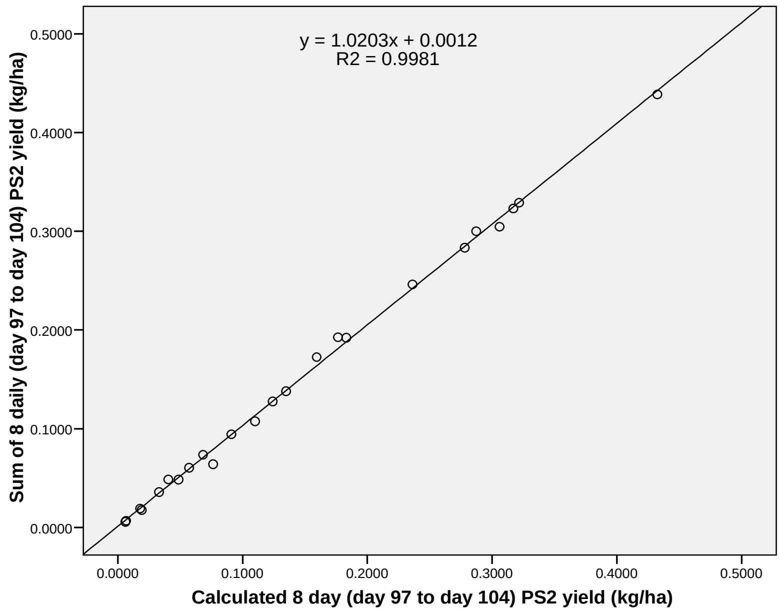
NPP = GPP*cfH2O *where:* cfH2O = ETa/ETo

To use the secondary data of ETa and ETo for calculating the cfH2O value, it is necessary to prove that the data of eight daily ETa and ETo can be used to calculate cfH2O for every eight day period and this water coefficient can be used to calculate NPP from GPP instead of using its daily value.

Figure 30; 31 show the results of regression analysis between 2 variables (daily calculated PS2 yield and 8-day calculated PS2 yield). For many 8-day periods, there were significant correlations between 2 variables (R square > 0.98). It is possible to conclude that it is not much different between these 2 variables in terms of values (RMSE) and their distribution. From the analysis results, it is significant to come to the conclusions:

- It is possible to calculate PS2 yield for every 8-day period instead of calculating the daily values. The final yield of crop for whole growing season will not be much different between 2 methods.

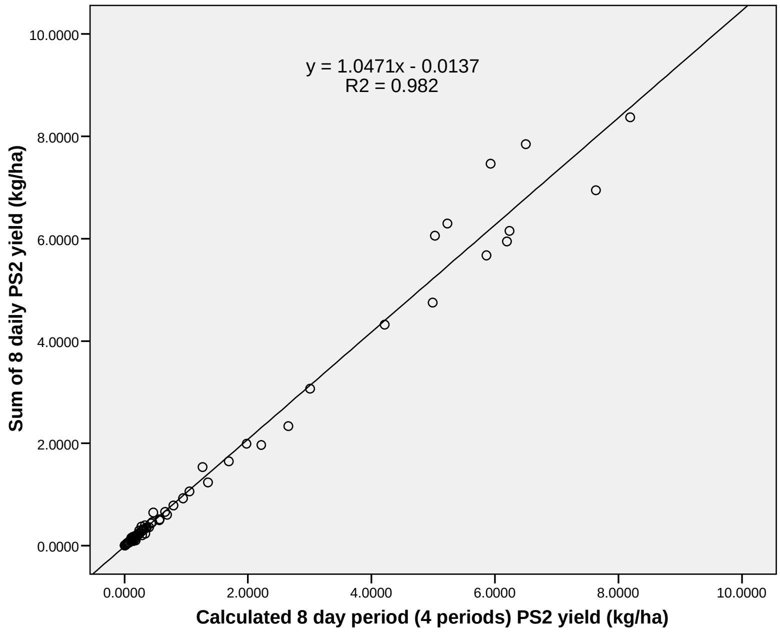
- The water sufficiency coefficient can be calculated for every 8-day period and applied to calculate PS2 yield from PS1 yield for every 8-day value instead of daily value. It is also possible to use this 8-day coefficient to calculate 8-day NPP from 8-day GPP.



Degree of freedom: 23

T value: 106

Figure 30: The chart showing correlation daily calculated PS2 and 8-day calculated PS2 yield of sunflower (from day 97 to 104)



Degree of freedom: 76

T value: 64

Figure 31: The chart showing correlation daily calculated PS2 and 8-day calculated PS2 yield of sunflower.

The same procedure was also conducted to test the correlation of daily calculated PS2 yield and monthly calculated PS2 yield. The result of the regression analysis is presented in figure 32

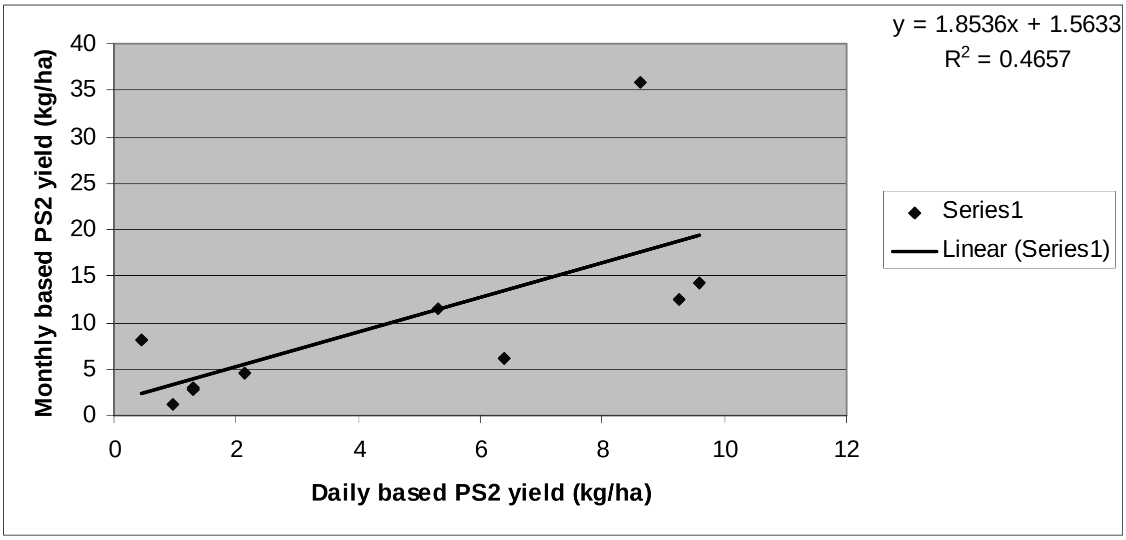


Figure 32: The correlation of daily based calculated PS2 yield and monthly based calculated PS2 yield of sunflower, year 2001.

The figure 32 shows that there was not a significant correlation between 2 variables of daily based calculated PS2 yield and monthly based calculated PS2 yield. This result proves that it is not significant to use monthly values of cfH2O to calculate monthly NPP from monthly GPP.

From the analysis results, the cfH2O for every 8-day period was calculated from secondary data of 8-day ETa and 8-day ETo. The image of calculated cfH2O of 8-day period (from day 81 to day 88, year 2001) is presented in figure 33.

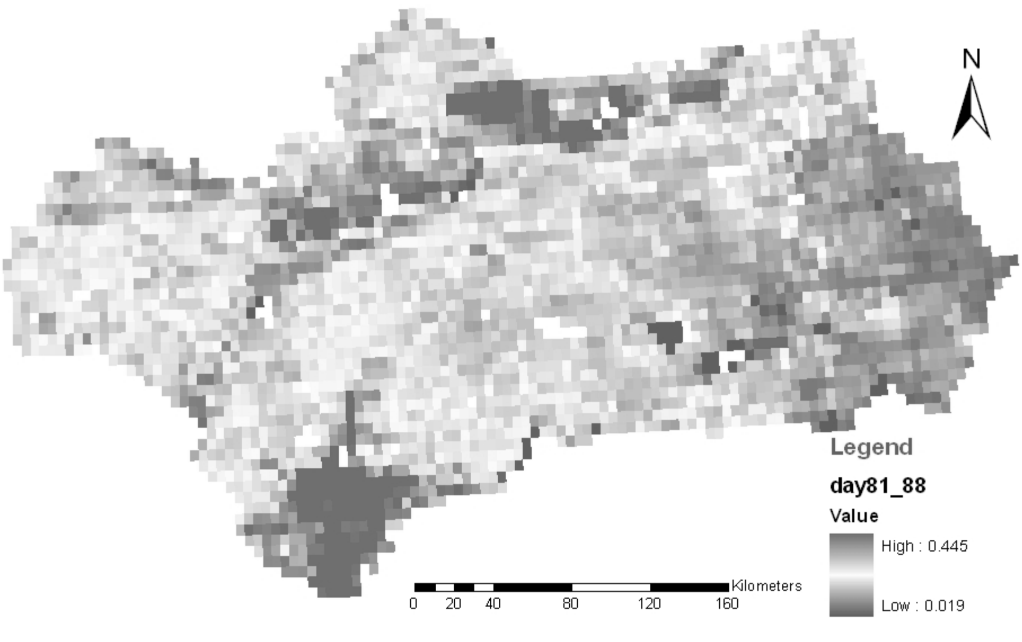


Figure 33: cfH2O calculated from ETa and ETo for 8-day period, year 2001

This value (cfH2O) was used to calculate NPP from GPP image. The image of NPP from day 81 to day 88, year 2001 is shown in figure 34.

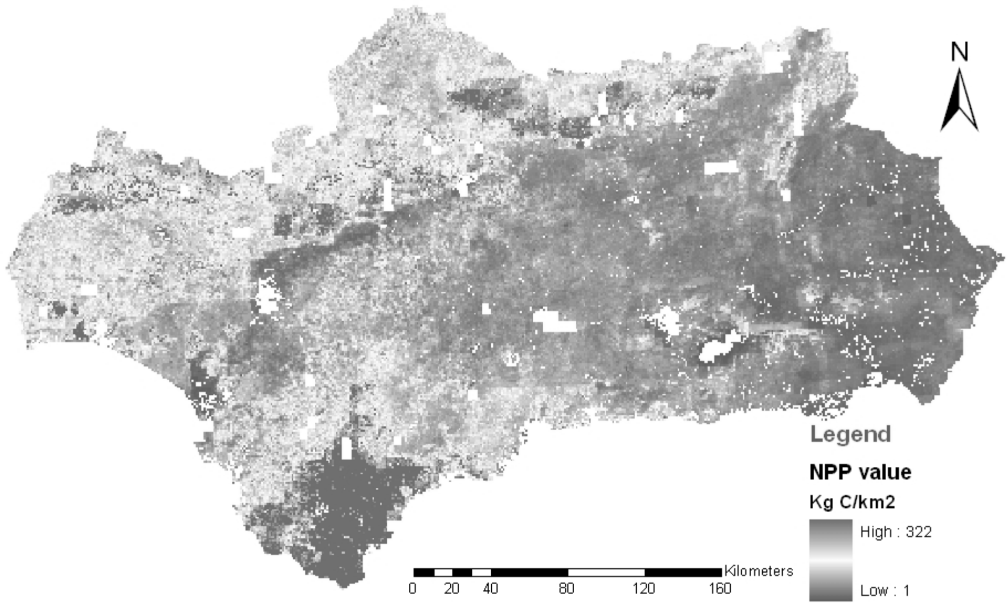


Figure 34: One of 8-day NPP calculated from GPP, year 2001 in Andalucia

The correlation between water limited yield of sunflower and NPP values through 16 eight day period is presented by statistical analysis (linear multiple regression) results which is shown in table 7:

Table 7: Results of regression analysis showing the correlation between water limited yields and NPP values, year 2001

Model	R	R Square(a)	Adjusted R Square	Std. Error of the Estimate
1	.835(b)	.698	.689	914.50616
2	.870(c)	.757	.743	831.41302

ANOVA (d,e)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	71374743.616	1	71374743.616	85.344	.000(a)
	Residual	30943896.384	37	836321.524		
	Total	102318640.000(b)	38			
2	Regression	77433725.829	2	38716862.915	56.010	.000(c)
	Residual	24884914.171	36	691247.616		
	Total	102318640.000(b)	38			

Coefficients (a,b)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	NPP81	40.270	4.359	.835	9.238	.000
2	NPP81	29.361	5.411	.609	5.426	.000
	NPP153	75.455	25.486	.332	2.961	.005

Based on R square value (0.87), the second model is selected to develop an equation for extrapolating the water limited yield of sunflower from point map to raster map based on the NPP images. The correlation between water limited yield of sunflower and NPP values in 2001 is presented in the equation as follows:

Water limited yield (2001) = 29.361*NPP81 + 75.486*NPP153

Apply this equation into the NPP images, the raster map of water limited yield of sunflower year 2001 is produced and presented in figure 35.

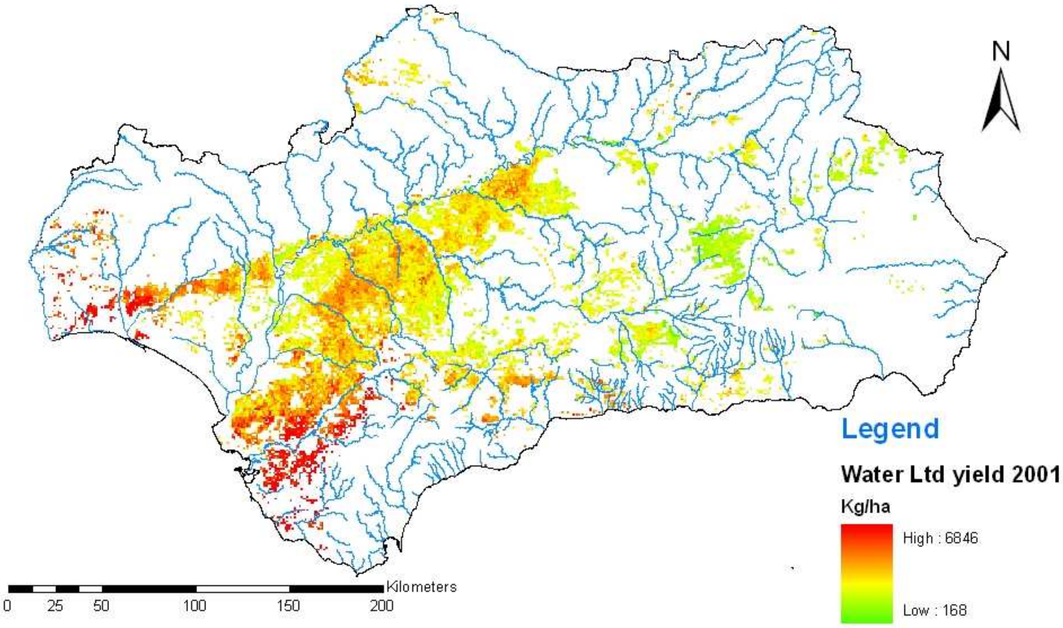


Figure 35: Raster map of water limited yield of sunflower in Andalucia, 2001

Figure 35 shows that the water limited yield of sunflower in Andalucia, year 2001 was distributed from 168 to 6,864 kg/ha. However, in the high fraction areas of sunflower, the water limited yield was mostly in the range of 1000 to 2500 kg/ha (classified yield map – shown in Appendices).

Other equations were also developed from regression analysis for extrapolating the water limited yield for the year of 2002 and 2005. These equations are shown in table 8.

Table 8: Equations for water limited yield extrapolation for year 2002 and 2005

Year	Equation for extrapolation	R Square
2002	Water limited yield_2002 = 15.169*NPP129 + 10.283*NPP185	0.775
2005	Water limited yield_2005 = 13.569*NPP65 + 98.028*NPP137	0.644

4.3.3. Yield Reduction of Sunflower Due to Water Shortage

The result of raster calculation (potential yield minus water limited yield) for every year shows the patterns of water limited yield gap. A raster map of these patterns for year 2001 is presented in figure 36.

This figure shows that the patterns of yield gap caused by water shortage was very variable in space for year 2001(from 32 to 4,574 kg/ha). This gap varied from 2 to 5,599 kg/ha for year 2002 and from 0 to 4,980 kg/ha for year 2005 in Andalucia. Comparing with the crop map of sunflower, in the high sunflower fraction areas, the water limited yield gaps are smaller than other low sunflower fraction areas (classified yield gap map – shown in Appendices). The possibility for sunflower to be cultivated more in high fraction areas may come from the suitability of climate (in terms of water availability) in these areas.

It is also clear to observe that in many areas, there are big numbers of yield reductions due to the water shortage. This result partly contributes significant evidences to prove the hypothesis that the water is the main cause of yield gap for sunflower in Andalucia. The water limited yield reduction map for every year is the result of quantifying the spatial patterns of yield gap caused by water shortage (where and how many kg/ha). Comparing with actual farm yields will help to quantify the fraction of this gap (how many percent in overall yield gap).

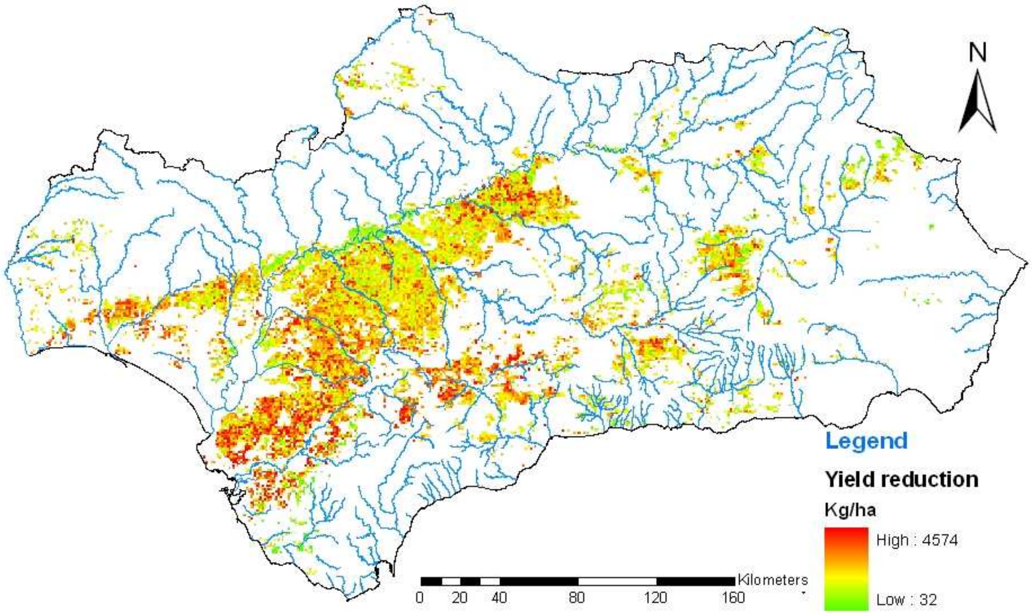


Figure 36: Yield reduction of sunflower in Andalucia due to water shortage, year 2001

4.4. The Patterns of Highest Water Limited Yield Gap of Sunflower

To identify the patterns of highest water limited yield gap in Andalucia, the average potential yield map of sunflower for 5-year period was produced and presented in figure 37.

It shows that for 5-year period, the potential yield of sunflower could be ranged from 968 to 6861 kg/ha (based on quality control for GPP and NPP images, there were some areas that have no value in extrapolated yield maps, these areas have been removed out of the maps during the process of raster calculation).

The average potential yield map of sunflower represents the possibility of the yield the sunflower could be achieved during 5 years without any limited factors from land and land management. In order to identify (where) and quantify (how much) the highest yield gap caused by water shortage during 5 years, it is necessary to calculate the lowest (minimum) water limited yield during the same period.

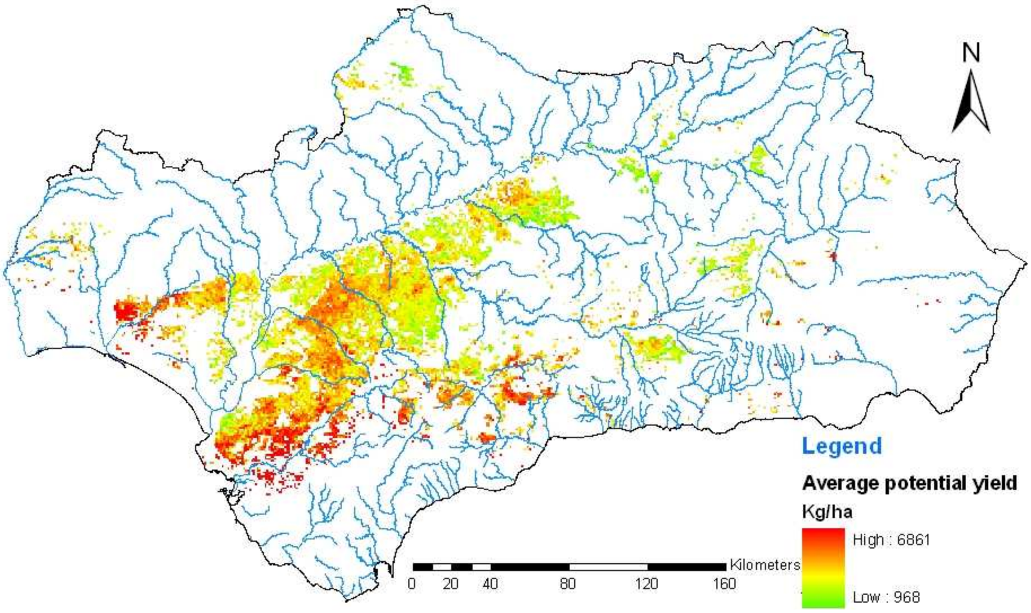


Figure 37: The average potential yield map of sunflower for 5 year period (2001 - 2005)

The cell statistic tool was used to calculate the minimum water limited yield of sunflower for 5-year period. The map of this result was developed and presented in figure 38.

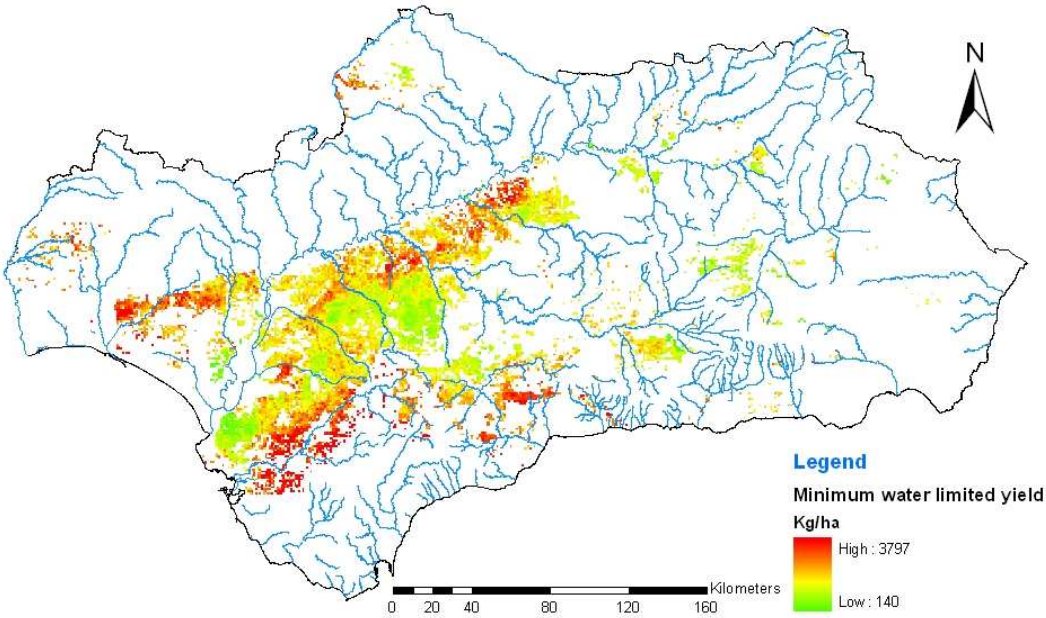


Figure 38: The lowest water limited yield of sunflower from 2001 to 2005 in Andalucia

Figure 38 shows that, for 5 year period, the minimum water limited yield could be from 140 to 3797 kg/ha although, it could be reached up to nearly 7,000 kg/ha in some year.

Based on the general (average) potential yield map and minimum water limited yield map, the patterns of highest yield gap caused by water during 5 year period was quantified. These patterns of gap were reclassified into 3 main classes which present the low, medium and high gap areas. The classified areas of gap are shown in figure 39.

The area (in ha) was calculated for each pattern and shown in table 9.

Table 9: The calculated area of gap level caused by water shortage in Andalucia from 2001 to 2005

Classes	Range of water limited yield gap (kg/ha)	Gap level	Area (ha)	Fraction to total area (%)
1	766 – 1,500	Low	54,905	5.07
2	1,500 – 2,500	Medium	746,771	68.99
3	2,500 – 4,815	High	280,767	25.94

The table 9 shows that in general, most of area of sunflower in Andalucia (68.99%) has the water limited yield gap (yield reduction) from 1,500 to 2,500 kg/ha. In the map (figure 39) this pattern is visualized in yellow colour.

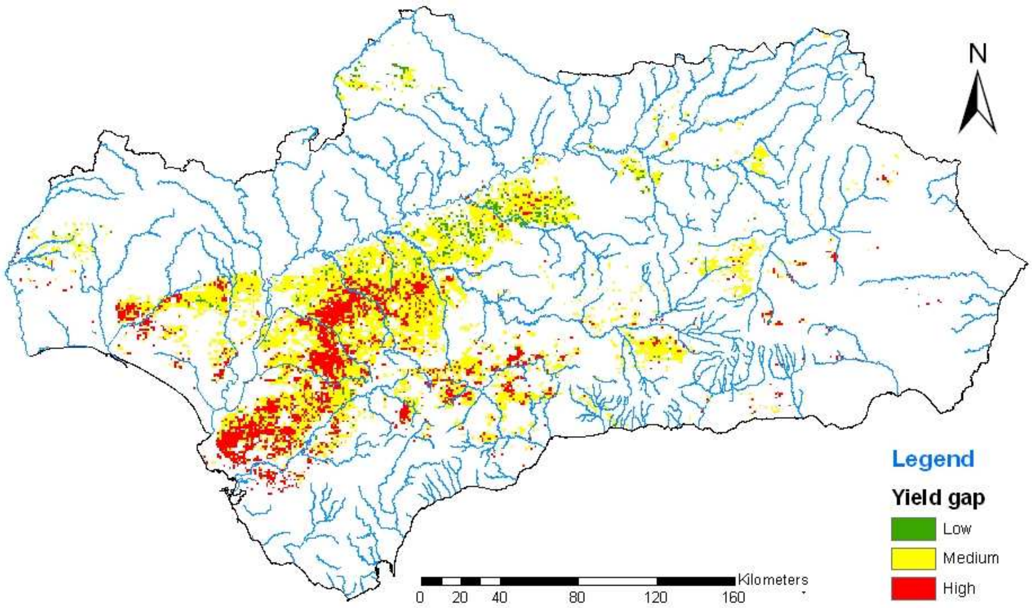


Figure 39: the classified 3 main gap patterns caused by water shortage for sunflower from 2001 to 2005 in Andalucia

It is also possible to observe that the low gap pattern mainly presents in the northern part of Andalucia meanwhile the high gap pattern mainly presents in the southern and western parts of Andalucia.

4.5. Quantification of Overall Yield Gap of Sunflower

4.5.1. Actual Farm Yield of Sunflower

To quantify the overall yield gap of sunflower for every year, the actual farm yield of sunflower is used for following calculation:

Overall yield gap = Potential yield – Actual farm yield

The point data of sunflower actual farm yield for every year (2001 – 2005) were derived from the agricultural yield maps (from Ministry of Agriculture, Spain) and shown in figure 40.

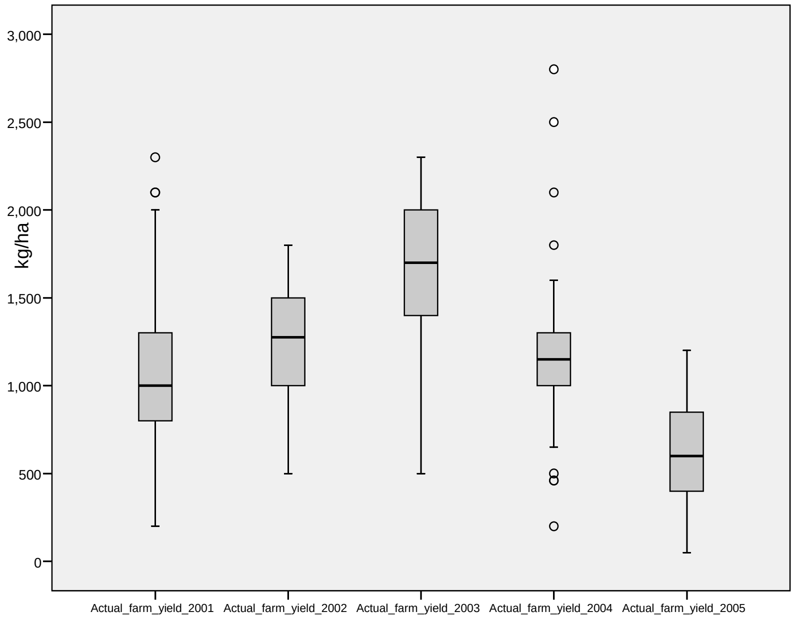


Figure 40: The distribution of actual farm yield of sunflower in Andalucia from 2001 to 2005

Figure 40 shows that the actual farm yield of sunflower in Andalucia is mainly in the range of 500 to 1,500 kg/ha (except year 2003). The actual farm yield is lower than potential yield due to the presence of 2 main yield gaps:

First Gap is caused by the shortage of water (water stress) during growing period.

Second Gap is caused by other land and management factors.

And **Overall gap = First gap + Second gap**

4.5.2. Extrapolated Raster Map of Actual Farm Yield of Sunflower

Spatial interpolation method (Spline tool in ArcGIS) was used to extrapolate the actual farm yields from point map to raster map for each year. For quality control, all the areas with the distance is bigger than 30 km to the actual farm yield points, have been removed from the output raster map. The raster map of actual farm yield for year 2001 is developed and shown in figure 41.

The map shows that in 2001, the actual farm yield was ranging from 21 to 2253 kg/ha. However, in most of the areas, the yield was lower than 1770 kg/ha (classified yield map).

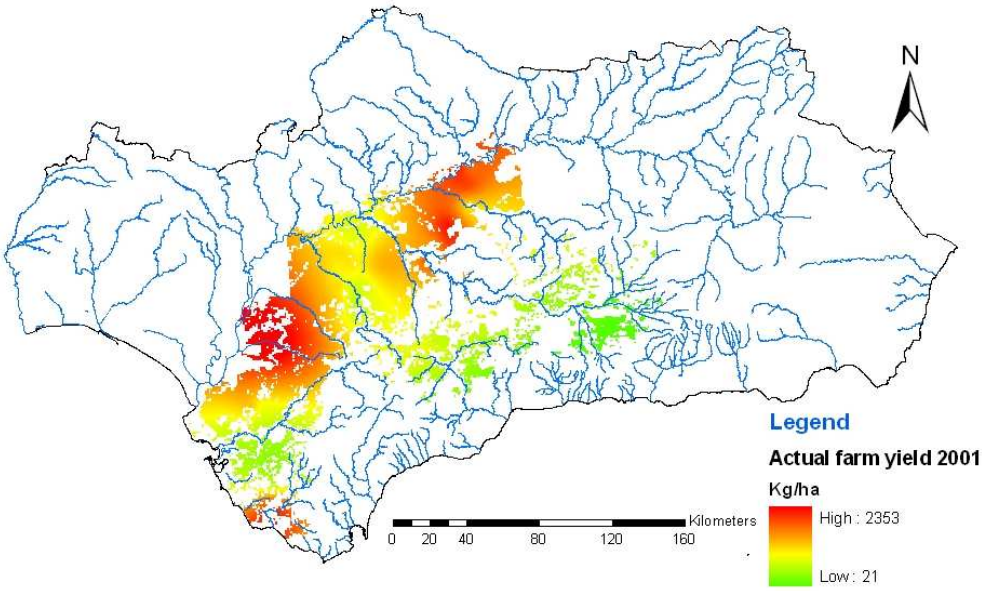


Figure 41: Raster map of actual farm yield of sunflower in Andalucia, 2001

4.5.3. Quantification of Overall Yield Gap of Sunflower

The patterns of overall yield gap for each year were quantified by following equation:

Overall yield gap = Potential yield – Actual farm yield

One of the resulted maps, the overall yield gap patterns (total yield reduction) for year 2001 was developed and presented in figure 42.

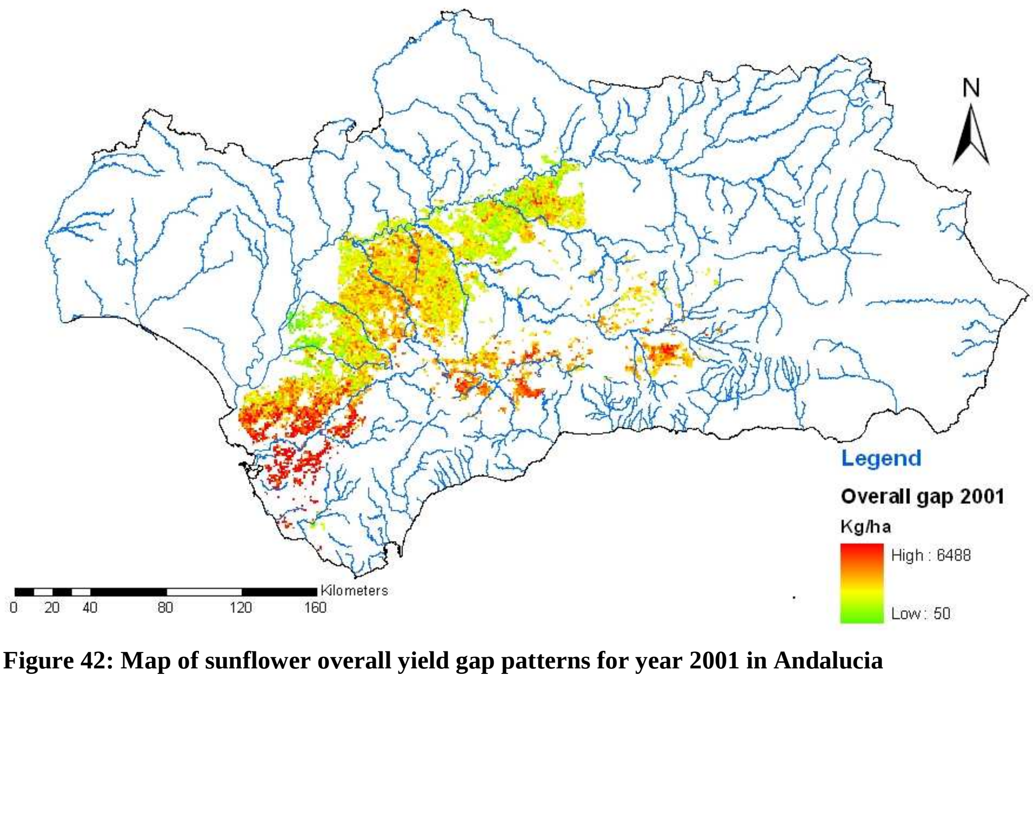


Figure 42: Map of sunflower overall yield gap patterns for year 2001 in Andalucia

In 2001, the yield of sunflower was reduced from 50 to 6488 kg/ha. In most of sunflower areas, the yield reduction by all limiting factors took place from 1300 to 3600 kg/ha (by natural breaks). However, it does not represent the highest yield gap for sunflower in Andalucia for 5-year period. A plot that had a low yield gap in year 2001 may not have the low yield gap in 2002 and vice versa. In order to quantify the patterns of highest overall yield gap in Andalucia for 5-year period, the available results of overall yield gap maps for 3 years (2001, 2002 and 2005) were used to calculate the maximum overall yield gap of each year. The maximum value (yield gap data) of each pixel was selected to produce the map of highest overall yield gap patterns throughout 5 years.

Patterns of highest overall yield gap = Maximum of (overall yield gap_2001, overall yield gap_2002, overall yield gap_2005).

The result of this calculation (map) was then classified into 2 classes of overall yield gaps (low gap and high gap) based on mean value of yield gap data (2,885). The classified map of overall yield gaps of sunflower for 5-year period is shown in figure 43.

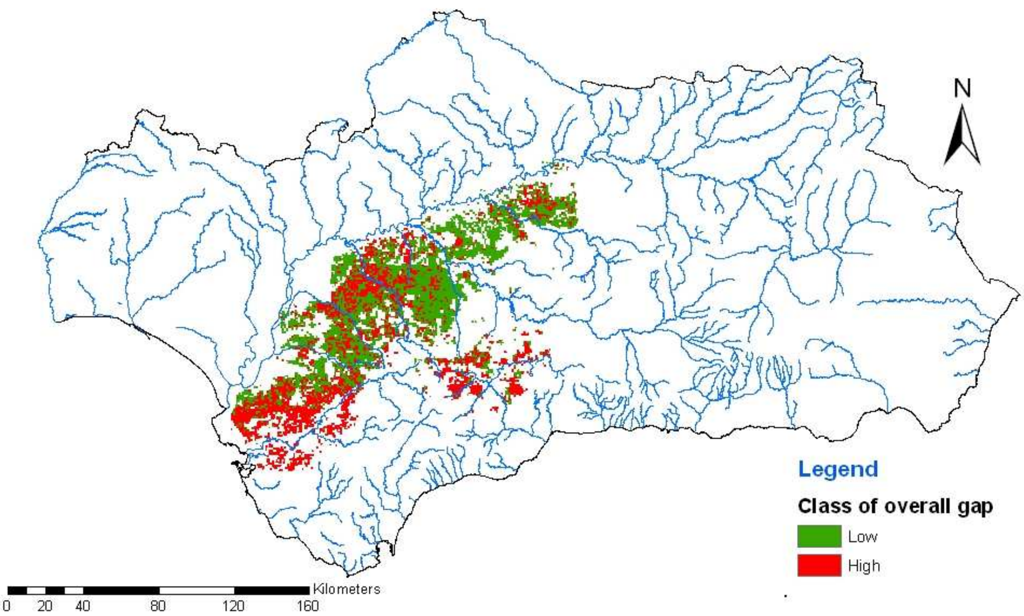


Figure 43: Map of classified maximum overall yield gap for 5 year period in Andalucia

Figure 43 shows that in space (Andalucia) and in time (throughout 5 years), the yield gap of sunflower could be quantified and classified into 2 main classes. The criteria and other information of each class are presented in table 10.

Table 10: The calculated area of gap level caused by all limiting factors in Andalucia from 2001 to 2005

Classes	Range of overall yield gap (kg/ha)	Gap level
1	908 –2,885	Low
3	2,885 – 6.517	High

The information in table 10 shows that if the mean value of overall yield gaps was selected as the break, the yield gap can be classified into 2 main classes - the low gap patterns (smaller than 2,391 kg/ha) and the high gap patterns (bigger than 2,885 kg/ha) in Andalucia.

4.5.4. Quantification of the Patterns of Yield Gap Caused by Other Factors than Water Shortage

To quantify the patterns of second yield gap (caused by other factors) for sunflower, the raster calculation tool was used to subtract the actual farm yield from water limited yield.

Second yield gap (kg/ha) = Water limited yield – Actual farm yield

The result of these calculations produced the maps of the second yield gap. The map of year 2002 is presented in figure 44.

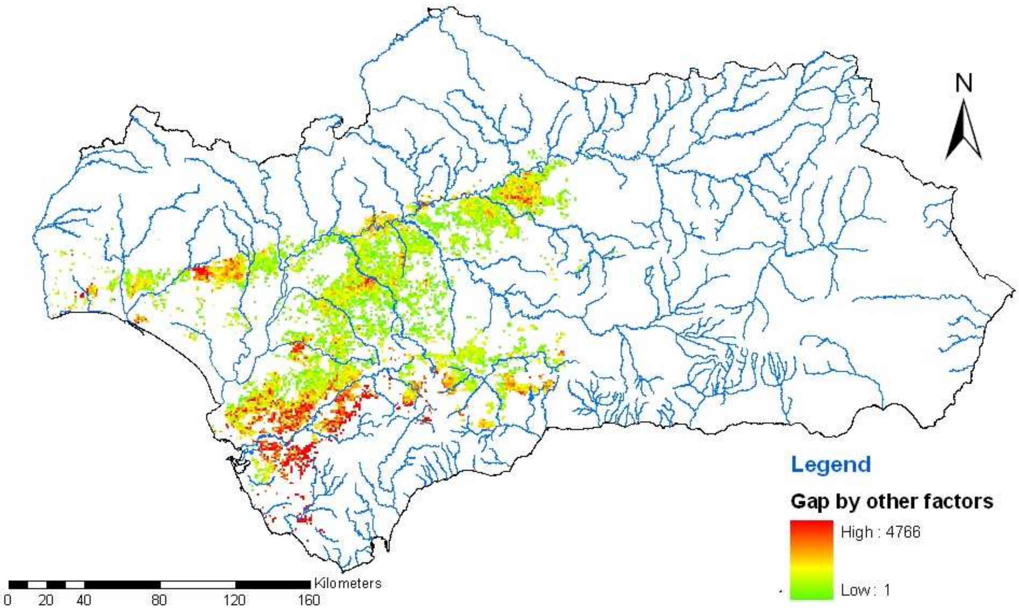


Figure 44: Map of yield gap caused by other factors, 2002

This map can provide the information on the patterns of the second gap in space (where and how much). The yield reduction caused by other factors took place from 1 to 4766 kg/ha in 2002. However, in most of areas, the gap is smaller than 1500 kg/ha.

4.6. Calcualtion of Fraction of Water Limited Yield Gap to Overall Yield Gap of Sunflower

To quantify the faction of water limited yield gap compared to overall yield gap of sunflower for every year (this fraction could be different from year to year based on the variability of climate through time), the actual farm yield of sunflower is used for following calculation:

Water limited yield gap = Potential yield – Water limited yield

Overall yield gap = Potential yield – Actual farm yield, and

Fraction of water limited yield gap = Water limited yield gap/Overall yield gap.

The raster calculation tool was used to quantify the faction of water limited yield gap to overall yield gap of sunflower for each year. For quality control, all pixel with value is bigger than 1, have been removed from the output maps.
The result of these calculations produced the fraction map of water limited yield gap for year 2001, year 2002 and year 2005. These maps are presented in figure 45, 46 and 47.

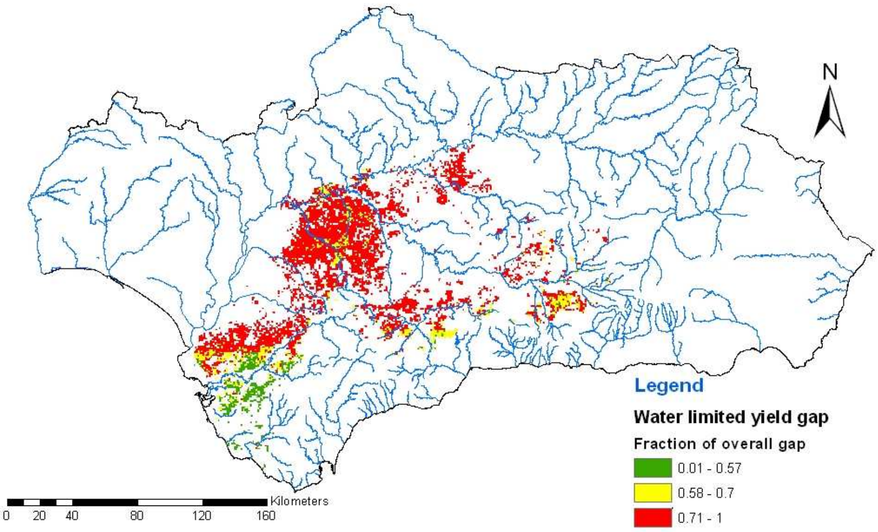


Figure 45: Map of fraction of water limited yield gap to overall yield gap for sunflower, year 2001

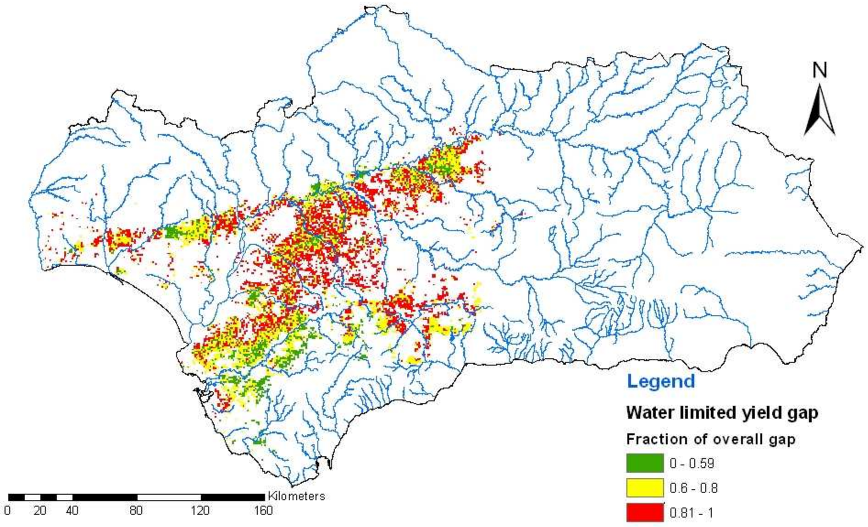


Figure 46: Map of fraction of water limited yield gap to overall yield gap for sunflower, year 2002

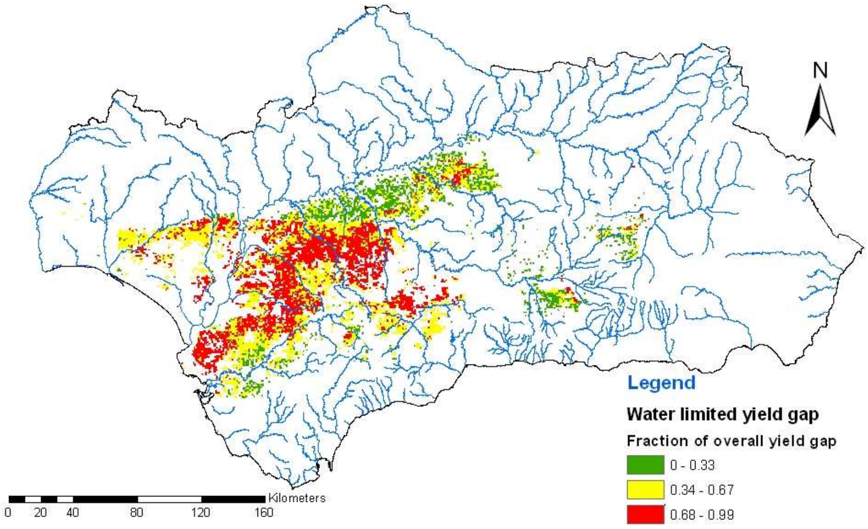


Figure 47: Map of fraction of water limited yield gap to overall yield gap for sunflower, year 2005

Figure 45 shows that in 2001, water limited yield gap contributed high fraction to the overall yield gap of sunflower. In most area, the water limited yield gap was taking place from 71 to almost 100% of overall yield gap.

In 2002, figure 46 shows that 60 to 100% of overall yield gap was caused by water shortage for in most area of sunflower cultivation in Andalucia. Meanwhile (in figure 47) the water limited yield gap contributed 68 to 99% to overall yield gap in more than half of sunflower cultivation area in Andalucia in 2005.

From the fraction maps of 3 years, it is possible to state that the fraction of water limited yield gap to overall yield gap was variable from site to site, and from year to year. At the same time, the water shortage is a main limited factor causing yield gap for sunflower in Andalucia over the years.

5. Conclusions and Recommendations

5.1. Conclusions

- The Production Situation Model can be used to identify the variability of potential yield of sunflower in Andalucia during five years (2001 – 2005). The lowest potential yield of sunflower was 2167 kg/ha in 2001 with average potential yield for five years was 3389 kg/ha. For water limited yield during five years, the lowest yield was in 2005 with 263 kg/ha and the average yield was 1630 kg/ha.
- The 8 daily product of Gross Primary Productivity (GPP) which cover the space and time of sunflower growth can be used to extrapolate the potential yield of sunflower from point data to raster with the resolution of 1 km^2 a pixel. The regression analysis shows that there was a strong correlation of potential yield and GPP values calculated in the time the sunflower grew. However, this correlation was different from year to year.
- The Water Sufficiency Coefficient (cfH2O) aggregated for 8-day period can be used to calculate the 8-day basic water limited yield from potential yield instead of using daily data. The results of 2 calculation methods are not much different from each other. Meanwhile the monthly aggregated data of cfH2O is not significant for calculating the monthly water limited yield. This result also shows that, for sunflower, the impact of water stress (drought) on its daily productivity is not much different from 8-daily productivity but this impact is very significant between each month period.
- During 5 years, 68.99% of sunflower areas in Andalucia had the yield reduction by water shortage from 1,500 to 2,500 kg/ha. There was only 5.07% of the areas that had the yield reduction less than 1,500 kg/ha and 25.94% of the area where the yield reduction was in the range of 2,500 to 4,815 kg/ha. The objective of this research has been achieved by having the final maps of water limited yield gap which have quantified the patterns of water limited yield reduction in space (the variability of yield gap from plot to plot) and in time (the variability of this gap during 5 years).
- The water shortage (drought) was a main limiting factor causing yield gap of sunflower in Andalucia. This factor contributed more than 60% to the overall yield gap in most area of sunflower cultivation in Andalucia for every year. It is a significant result of this research to consider the intervention for narrowing the yield gap of sunflower in Andalucia by irrigation supply. It is also proves that the weather based estimation data from Production Situation Model together with remote sensing data can be used to quantify a component of yield gap of sunflower (water limited yield gap). By this result, the alternative hypothesis of this research has been accepted.
- Beside the water shortage, there are other factors causing yield gap for sunflower in Andalucia. These factors also would be variable in space and time. However, in most area, they contributed less than 40% of overall yield gap of sunflower in Andalucia.

5.2. Recommendations

- The water shortage situation (drought) in Andalucia contributed more than 60% to the overall gap of sunflower (in most area). Another gap component (30 to 40%) could come from other constraints or limiting factors like soil or land management. Supplying enough water for sunflower cultivation should be taken into account in order to improve the productivity of this crop in Andalucia.
- The maps of quantified patterns of water limited yield gap and overall yield gap of sunflower could be a reference for farmers or decision makers in implementing intervention or making plan to improve the agricultural production in the area.
- Other studies should be conduct to identify the constraints or other factors that caused the second yield gap of sunflower. Soil and management factors should be taken into account for further researches to quantify the influence of these factors on the variability of sunflower yield gap.

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Appendices

Appendix 1: Interview and observation format

Interview and Observation Sheet

Date:………………………….

Interview No: Sample No:

Framer's name:

Coordinates: X: Y:

I. Land and spatial factors:

Size of farm: ha

Soil fertility: ☐ Good ☐ Moderate ☐ Poor ☐ Bad

Depth of cultivating layer: cm

PH: From To

Stone rate: %

Slope:

Groundwater level:☐ Low ☐ Medium ☐ High

Weather factors:

Rainfall: ☐ Low ☐ Medium ☐ High

Temperature: ☐ Low ☐ Medium ☐ High

II. Management factors:

Land use purpose: ☐ Subsidized by EU ☐ Good market ☐ Suitability of soil

Ploughing: First ploughing: Y/N Date:

If not, why: Method:

Second ploughing: Y/N Date:

If not, why: Method

Seedbed preparation:

Planting: Seeding date: Why (selected this date)?

Seed rate (kg/ha) Source: Why?

Method: ☐ People ☐ Machine

Depth of planting (cm):

Planting Density (seed/ha):

Variety selection: Name: Why?

Weed control: First weeding: Y/N Week after planting: week(s)

If not: why? Method: ☐ Hand ☐ Machine ☐ Chemical

Second weeding: Y/N Week after planting: week(s)

If not: why? Method: ☐ Hand ☐ Machine ☐ Chemical

Fertilizer application: Do you apply fertilizer? Y/N; if no: why?

If yes: type of fertilizer:

NPK: rate: kg/ha; Timing (after planting date): days/weeks

Urea ($(NH_2)_2CO$): rate: kg/ha; Timing:

Other applied: rate: kg/ha; Timing:

Lime applied? Y/N; if yes; rate: kg/ha; Timing

Organic matter application:

Animal manure(s): rate: ton/ha; Timing

Non-applied: Reason (why):

Diseases:

Jopo:

Other(s):

Insects: Y/N; if yes, specify:

Harvesting date:

Situation of harvested seeds: ☐ Dry ☐ Not dry enough

III. Other factors:

Market

Subsidy situation:

Extension services:

Infrastructure:

Sunflower yield:

Original target yield aimed at:	kg/ha
Actual yield obtained:	kg/ha

Estimated yield losses:

Loss factor	Estimated loss in % of original target yield

- Drought:
- Flood:
- Erosion:
- Pests and diseases:
- Insufficient fertilizers:
- Birds and animals
- Others(specify)

Remarks:

Appendix 2: Potential yield and water limited yield calculated by PSn model for 40 points

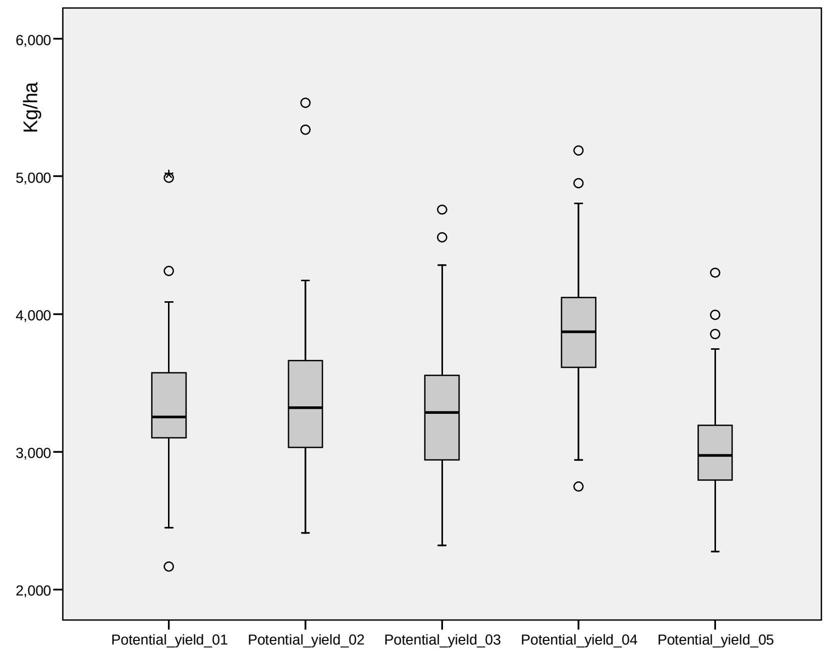

Figure 48: Potential yield calculated by PS1 model for 5 years

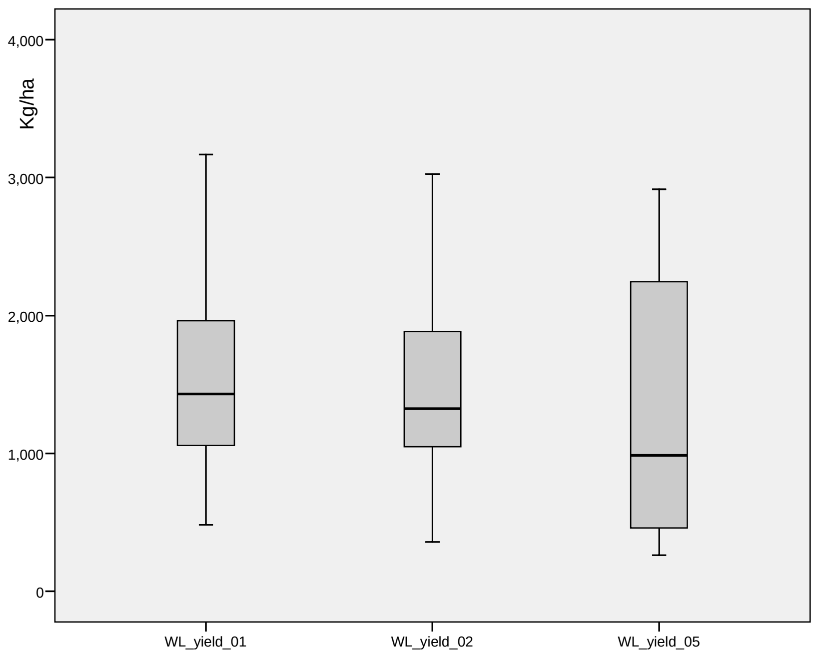

Figure 49: Water limited yield calculated by PS2 model for 3 years

Appendix 3: Statistic results for the correlation between Potential yield and GPP; and correlation between Water limited yield and NPP

Table 11: The regression results showing the correlation of potential yields of sunflower and GPP values for years of 2002 to 2005

Model Summary

Year	R	R Square(a)	Adjusted R Square	Std. Error of the Estimate
2002	.970(c)	.941	.938	876.35565
2003	.946(c)	.895	.888	1123.01691
2004	.969(c)	.940	.936	996.27830
2005	.923(c)	.851	.842	1200.52487

ANOVA

Year		Sum of Squares	df	Mean Square	F	Sig.
2002	Regression	441901487.076	2	220950743.538	287.697	.000(c)
	Residual	27647971.924	36	767999.220		
	Total	469549459.000(b)	38			
2003	Regression	301924542.479	2	150962271.239	119.700	.000(c)
	Residual	35312675.521	28	1261166.983		
	Total	337237218.000(b)	30			
2004	Regression	556854003.779	2	278427001.890	280.511	.000(c)
	Residual	35732536.221	36	992570.451		
	Total	592586540.000(b)	38			
2005	Regression	263621334.063	2	131810667.032	91.455	.000(c)
	Residual	46120318.937	32	1441259.967		
	Total	309741653.000(b)	34			

Coefficients

Year		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
2002	GPP113	18.187	1.502	.694	12.111	.000
	GPP177	7.855	1.302	.346	6.032	.000
2003	GPP129	13.190	1.845	.638	7.148	.000
	GPP169	12.490	2.984	.374	4.185	.000
2004	GPP97	12.393	1.719	.536	7.208	.000
	GPP177	66.103	10.316	.476	6.408	.000
2005	GPP89	17.692	2.268	.681	7.802	.000
	GPP169	58.544	15.529	.329	3.770	.001

Table 12: Results of regression analysis showing the correlation between water limited yields and NPP values for the years of 2002 and 2005

Model Summary

Year	R	R Square(a)	Adjusted R Square	Std. Error of the Estimate
2002	.880(c)	.775	.759	811.00548
2005	.802(c)	.644	.619	956.37388

ANOVA

Year		Sum of Squares	df	Mean Square	F	Sig.
2002	Regression	63387875.020	2	31693937.510	48.187	.000(c)
	Residual	18416436.980	28	657729.892		
	Total	81804312.000(b)	30			
2005	Regression	47947829.881	2	23973914.941	26.211	.000(c)
	Residual	26524879.119	29	914651.004		
	Total	74472709.000(b)	31			

Coefficients

Year		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
2002	NPP129	15.169	2.220	.664	6.833	.000
	NPP185	10.283	2.656	.376	3.871	.001
2005	NPP137	98.028	27.038	.545	3.626	.001
	NPP65	13.569	6.254	.326	2.170	.038

Appendix 4: Raster map of classified potential yield and water limited yield of sunflower for year 2001

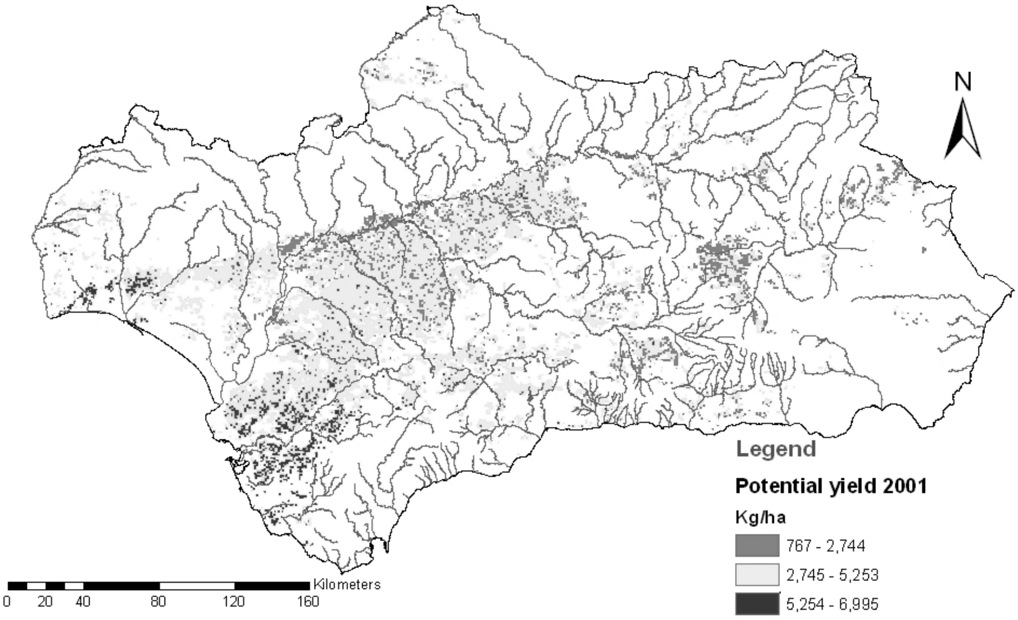

Figure 50: Map of classified potential yield of sunflower year 2001 in Andalucia

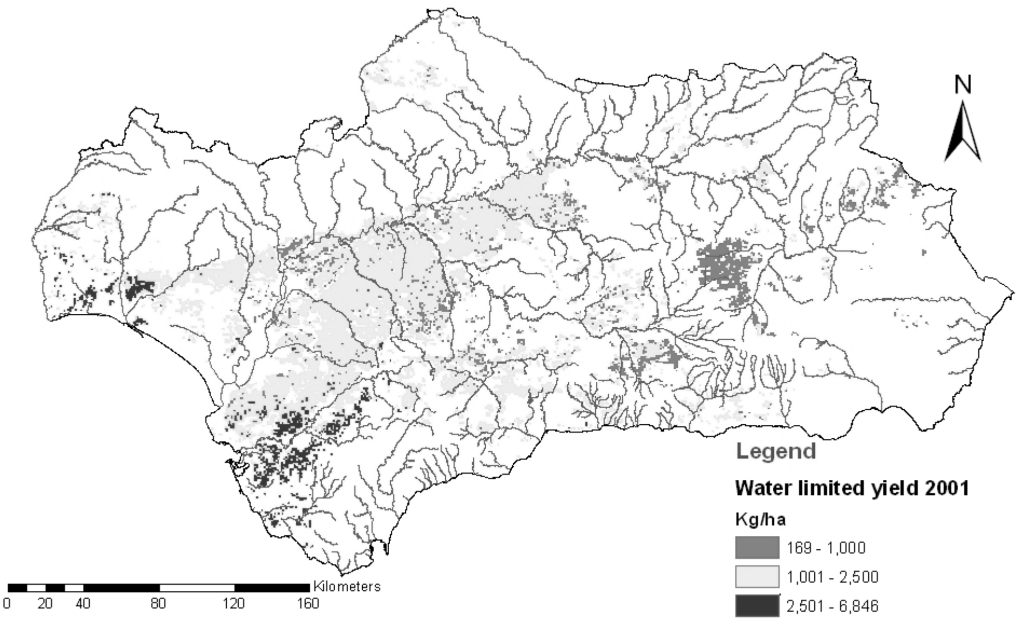

Figure 51: Map of classified water limited yield of sunflower year 2001 in Andalucia