Yield Gap explaining factors and solutions to improve yields in a Maize Farm in Portugal

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Resumo Alargado

Ao longo das décadas, tem-se verificado que a intensificação agrícola, que se baseia num uso mais eficiente dos fatores de produção, é substancialmente urgente e necessária, sendo justificada pelo constatado e previsional aumento populacional, e pela impossibilidade de expansão agrícola. Um dos métodos para a consecução deste objetivo é o estudo e investigação das falhas existentes numa produção agrícola, podendo estas advir de condições edafo-climáticas desfavoráveis ou de uma gestão de inputs menos adequada.

Dada a importância socioeconómica da cultura do Milho em Portugal e a necessidade de casos-estudo que exemplifiquem formas de intensificação agrícola, a presente dissertação tem como objetivos a descoberta dos fatores que justifiquem a diferença existente entre a produtividade máxima e atual, conhecida como Yield Gap; bem como a avaliação da sua magnitude, ou seja, quão distante a produtividade real, adquirida pelo produtor, estaria da produtividade máxima, ou potencial.

Existem diversos conceitos integrados na definição de Yield Gap, ou traduzindo, quebra de produtividade. A referida quebra de produtividade destina-se à diferença entre a produtividade real, adquirida pelo produtor, e uma máxima produtividade considerada de referência. Podendo esta produtividade-referência ser:

- Produtividade potencial: definida por fatores ambientais e pela cultivar usada.
- Produtividade atingível: influenciada, não só, pelos parâmetros que definem a produtividade potencial, mas também limitada por parâmetros integrantes à gestão do agricultor como água e nutrientes disponíveis à cultura.

Os métodos existentes para medir as diferenças de produtividade diferem nas escalas (temporal e espacial) e nas complexidades. São sumarizados em:

- Approach 1, a quebra de produtividade é determinada por uma comparação entre o produtividade real e produtividade máxima atingidas em concursos de campos, estações experimentais ou através de produtores da região cujo produtividade é a maior.
- Approach 2 também se baseia numa comparação. De acordo com esta abordagem, a diferença de produtividade é um reflexo de certos factores ambientais que limitam os rendimentos. A comparação é definida entre a produtividade atual e a produtividade máxima estimada através do uso de funções de limite, que são linhas que limitam as tendências das parcelas alcançadas por meio de relações entre fatores climáticos / água / azoto e produtividade.
- Approach 3 é baseado em modelação e fornece parâmetros de referência

viáveis para medir a produtividade potencial (Potential Yield). Esses modelos simulam o rendimento potencial ou limitado por água / azoto.

- Em Approach 4, as estimativas de rendimento das culturas envolvem uma variedade de abordagens de sensoriamento remoto. O sensoriamento remoto é a tecnologia de identificação, observação e medição de um objeto sem contato direto. As abordagens de sensoriamento remoto para estimar o rendimento das culturas podem ser baseadas em (1) produção de biomassa, (2) modelos empíricos relacionados ao índice e rendimento da vegetação espectral e (3) integração de dados detetados remotamente em modelos de crescimento de culturas.

Das abordagens existentes para medir a quebra de produtividade, a mais adequada foi o Approach 1. Dado o contexto do estudo e a região, o ponto de referência para fazer essa comparação foi a produtividade máxima alcançada pelo agricultor, pois especula-se que esta exploração seja a maior e a melhor para comparar na região.

Approach 2 foi excluído por falta de dados. Por sua vez, o mesmo acontece no uso do Approach 3; devido à restrição de dados e consequentes dificuldades na calibração, o uso de modelos de culturas para medir o rendimento potencial seria limitado e incorreto. A situação é ainda semelhante ocorre na Approach 4, onde maioria das ferramentas não se encontrava disponível durante o prazo considerado na análise.

Os dados usados para a descoberta dos fatores responsáveis pelo Yield Gap são referentes a dotações de rega, aplicações de azoto, datas de sementeira, emergencia, floração e maturação, e dados climáticos, recolhidos ao longo de 10 anos e fornecidos pela empresa Milho Amarelo, situada na região de Santarém.

Através destes dados foram calculadas outras variáveis, tais como a acumulação de graus-dia e acumulação térmica média diária, evapotranspiração cultural e a radiação intercetada. Estes dados foram analisados anualmente, de acordo com a totalidade do ciclo e segundo diferentes fases fenológicas (vegetativa e reprodutiva).

Para começar, uma análise bivariada foi usada para estudar não apenas as tendências de produtividade e de manejo (rega, datas de sementeira, aplicações de azoto) mas também o impacto na produtividade real de fatores de integrados na gestão do agricultor, de natureza genotípica e ambiental. De acordo com a natureza desses factores (categórica ou contína) foram utilizados dois métodos estatísticos diferentes: ANOVA e Modelos Lineares.

De forma a complementar a análise bivariada e obter resultados mais consistentes foram ainda usados dois métodos de análise multivariada: as correlações dependentes da escala e modelos lineares de efeito misto. Explicados seguidamente:

Correlações dependentes de escala: Embora os gráficos de dispersão e os testes t de significância nos tenham dado um resultado sobre o impacto de variáveis independentes no rendimento real, essa resposta nem sempre é clara, especialmente ao analisar várias observações ao longo de 10 anos, onde determinadas condições e melhorias tecnológicas mudam.

Em função de um fator determinado, a variabilidade do rendimento pode variar em diferentes escalas. Coisas que parecem estar insignificantemente correlacionadas em grandes escalas espaciais podem se transformar numa resposta de correlação diferente em pequenas escalas.

Portanto, a resposta das produtividades, dependendo das datas de sementeira, foi melhor analisada, executando parcelas em mosaico. Esses gráficos são três parcelas variáveis, significando que o impacto das datas de sementeira nas produtividades foi também analisado sob uma terceira condição, a temperatura.

Para ter uma melhor sensibilidade sobre a variabilidade dos dados, alguns parâmetros, como datas de sementeira e temperaturas, foram divididos em diferentes grupos, de acordo com os valores de faixa determinados.

Modelos lineares de efeito misto: como os modelos de regressão linear não podem lidar com dados desequilibrados ou com problemas de valores ausentes, a abordagem de modelo misto foi escolhida uma vez que era mais adequada à natureza dos dados. Além disso, modelos lineares mistos podem lidar com a irregularidade de medições repetidas e explicar a autocorrelação entre observações provenientes do mesmo lote (condições diferentes para a planta de milho encontradas em diferentes parcelas e anos).

Portanto, este modelo foi necessário para melhorar os resultados obtidos através da análise bivariada.

Para construir este modelo, efeitos aleatórios tiveram que ser determinados. Esse modelo não teve modelos fixos considerados, porque o objetivo de construir esse modelo era perceber quais fatores aleatórios poderiam explicar melhor a variabilidade do rendimento. Efeitos fixos são variáveis que devem impactar diretamente a variável de resposta. Efeitos aleatórios, ou fatores aleatórios, uma vez que são categóricos, são fatores de agrupamento para cada análise que a análise está tentando controlar e considerada o componente de variação do modelo. Neste contexto de estudo, objetivamos analisar o impacto de algumas variáveis (efeitos fixos) na variabilidade do rendimento, entre parcelas e anos (efeitos aleatórios).

O modelo misto, sem considerar modelos fixos, foi submetido a uma função stepAIC, onde se concluiu que a estimativa do modelo misto seria mais adequada a factores aleatórios (1 |

amostra). Isso significa que a causa da variação dos rendimentos é melhor explicada por fatores que diferenciam o caráter e a potencialidade de cada parcela.

A potencialidade das parcelas, posteriormente refletida na produtividade obtida, não foi explicada pelo efeito de azoto ou da irrigação, porque esses fatores não eram limitantes. Dito isto, concluiu-se que a variabilidade da produtividade entre parcelas foi justificada por outros fatores. Cada ano é caracterizado por diferentes condições climáticas. A análise dos dados mostrou que a duração do estado vegetativo, governado pela temperatura, tem um impacto significativo na produtividade. Dependendo das características do ano, refletidas por escalas de temperatura específicas, a duração do período vegetativo será afetada e determinará a magnitude da produtividade. Verificou-se também que esse efeito da temperatura é refletido pelas datas da sementeira. O ano de interação e as datas de semeadura têm um impacto muito importante na produtividade.

Em relação ao efeito de cultivares mais longas ou mais curtas, não foram observados impacto devido a variedades insuficientes com número de FAO menor que 600. Dessa forma, também recomendável testar cultivares com comprimentos diferentes, dependendo das datas de sementeira e condições de temperatura.

De acordo com as produtividades obtidas, estas podem ser classificados como baixa, média e alta, onde os valores baixos são até 16 toneladas por hectare, a média está entre 16 toneladas e 18 toneladas, e os altos rendimentos incluem valores acima de 18 toneladas por hectare.

Dependendo dessa classificação, as diferenças de produtividade variam. Onde para baixas produtividades, a quebra de produtividade variou de 10% a 20%, enquanto nas produtividades médias a altas, as diferenças de produtividade foram inferiores a 10%.

Resumo

Ao longo das décadas, tem-se verificado que a intensificação agrícola, que se baseia num uso mais eficiente dos fatores de produção, é substancialmente urgente e necessária, justificada pelo constatado e previsional aumento populacional, e pela impossibilidade de expansão agrícola. Um dos métodos para a consecução deste objetivo é o estudo e investigação das falhas existentes numa produção agrícola, podendo estas advir de condições edafo-climáticas desfavoráveis ou de uma gestão de inputs menos adequada.

Dada a importância socioeconómica da cultura do Milho em Portugal e a necessidade de casos-estudo que exemplifiquem formas de intensificação agrícola, a presente dissertação tem como objetivos a descoberta dos fatores que justifiquem a diferença existente entre a produtividade máxima e atual, conhecida como *Yield Gap,* analisada internanualmente e entre parcelas, e a magnitude destes desvios.

Através de uma base de dados referente a dotações de rega, aplicações de azoto, datas de sementeira e dados climáticos, recolhida ao longo de 10 anos e fornecida pela empresa Milho Amarelo, situada na região de Santarém, foram calculadas outras variáveis, tais como a acumulação de graus-dia, evapotranspiração cultural e a radiação intercetada. Estes dados foram analisados anualmente, de acordo com a totalidade do ciclo e segundo diferentes fases fenológicas (vegetativa e reprodutiva).

Assim que obtidas e organizadas todas as variáveis, procedeu-se a métodos estatísticos de análise bivariada e multivariada. O cálculo da magnitude da falha de produtividade procedeu-se de acordo com o *Approach 2* indicado pela FAO 41.

Os resultados revelam que a interação das datas de sementeira com as condições climáticas estão na natureza deste desvio, com magnitude oscilando entre os 5 a 20%, dependendo das condições climáticas do ano.

Palavras-chave: Milho; Variabilidade de produtividade; Fatores limitantes; Produtividade potencial; Análise da quebra de produtividade.

Abstract

Over the decades, it has been found that agricultural intensification, that is, the increase in production per hectare, is substantially urgent and necessary, justified by the observed and expected population increase and the impossibility of agricultural expansion. One of the methods for achieving this goal is the study and investigation of yield gaps, which may be explained by unfavorable soil and climate conditions, or less adequate input management.

Given the socio-economic importance of maize crop in Portugal and the need for case studies that exemplify agricultural intensification methods, this dissertation aims to discover which are the reducing factors that justify the gap between the maximum and actual yields, known as yield gaps, which were analyzed between plots and years, and how large was the yield gap over the 10 years.

Through a database of irrigation appropriations, nitrogen applications, sowing dates and climate data, collected over 10 years and provided by Milho Amarelo company, located in the Santarem region, other variables were calculated, such as degree-day accumulation, cultural evapotranspiration and intercepted radiation. These data were analyzed annually according to the whole cycle and according to different phenological phases (vegetative and reproductive).

Once all variables were obtained and organized, statistical methods of bivariate and multivariate analysis were performed. The magnitude of yield gap was calculated according to the Approach 2 indicated by FAO 41.

The results show that interaction of sowing dates with climatic conditions are in the nature of this deviation, with gap's magnitude ranging from 5% to 20%, depending on the climatic conditions of the year.

Keywords: Maize; Yield Variability; Sowing dates; Reducing Factors; Yield Gap Analysis.

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1. Introduction

Population growth has become an extremely important matter and should be discussed and analysed carefully so that urgent preventive measures can be taken.

It is estimated that in 2050 world population will rise towards 9 or 10 billion, which means there will be an increase of food demand of 70% to 100%, as estimated by Godfray et al. (2010). Therefore, it is of extreme importance to increase global food production, and farming community has an essential role for the achievement of this mission. Otherwise, future generations will be facing a dramatic rise in food prices, poverty and hunger (FAO, 2003, 2006; Royal Society of London, 2009; Koning and van Ittersum, 2009; Godfray et al., 2010).

Although in some regions there is opportunity for cropland expansion, by converting lands with potential agriculture conditions, it is generally unlikely and not desirable that the increasing demand for agricultural products will be met by land expansion due to its overall scarcity (Neumann et al., 2010).

Therefore, the goal of many researchers and policy makers focuses on the improvement and better use of resources (Lobell et al., 2009). This is, each hectare of existing cropland will need to produce yields that are substantially greater than current yield levels (van Ittersum & Cassman, 2013).

Increasing the yield of Maize (Zea mays L.), one of the main cultivated species in the world, represents an important step in facing the challenge of an ever-increasing population.

In Portugal, maize is a very important arable crop and one of the best to maximize the efficiency of inputs, such as water and energy. Maize is considered one of the main irrigated crops of the Iberian Peninsula, occupying an area around 650 thousand hectares, with a preponderant role in the establishment of rural populations by creating employment and economic development (Yang et al., 2017).

During the past 50 years, the production of several grains increased (Neumann et al., 2010), thanks to area extension, genetic improvement, intensification of land management and introduction of new technologies (Cassman, 1999; Wood et al., 2000; FAO, 2002a; Foley et al., 2005). However, nowadays and in many regions, the past progress trend in grain yield has been stagnating (Cassman, 1999; Rosegrant and Cline, 2004; Trostle, 2008). There are multiples causes for yield stagnation, among them the inefficient use or management of available agricultural land, soil degradation, pollution and climate change (Lobell et al., 2009).

Yield gap is a concept based on ecological principles and can be estimated as the difference between a benchmark - as “potential” yield - and actual yield, achieved in a farmer’s field (van Ittersum and Cassman, 2013). The quantitative value of the benchmark differs from year to year because it is a function of radiation and temperature (when assuming irrigated crops).

Yield gap analysis is an essential and determinant tool for the required intensification and closure of existing gaps, turning into a possible pathway of meeting grain food demand (Cassman, 1999).

Many studies have examined yield gaps at the scale of the region or agro-climatic zone, using aggregated data on crop yields and explaining factors (Mueller et al., 2012; Neumann et al., 2010). These types of studies are useful to compare different regions in relative terms using harmonized data (van Ittersum et al., 2013). However, in order to further understand yield gaps, more local studies are needed to bring the role of the farm and management characteristics into the picture (Beza et al., 2017).

This research will focus on an irrigated maize farm located in Golegã, Portugal, for which weather, soil and crop data have been recorded over the last ten years. More precisely, the collected and analysed data to this research are varieties, sowing dates, fertilizers, irrigation, and achieved yields.

Given the importance of maize in Portugal and the above-mentioned need of having more cases which can exemplify land intensification by yield gap analysis, the aim of this study concerns on finding an intensification approach, by discovering which factors are limiting yields, to this farm located in the zone of Ribatejo. This way, responsible factors will be identified to explain the existing yield gaps over the last 10 years.

Defining the factors responsible for yield variability is important to realize if maximum actual yields are a reflection of the potential, having only environmental constraints, or if it is still possible to achieve higher current yields, through management changes.

To meet this objective the following research questions should be answered:

Main question 1: Which factors can explain yield variability?

Main question 2: How large was the yield gaps over the last 10 years?

2. Literature

2.1. Maize crop description

2.1.1. Morphology

Maize crop, with a fasciculated root system, has two types of roots: seminal roots and adventitious, or supportive, roots. The root developed by the embryo gives rise to the seminal roots, which in future will develop vertically (Barros and Calado, 2014). On the other hand, supporting roots appear above the soil surface when maize has 5 to 6 leaves, and are responsible for plant support as well as phosphorus absorption (Magalhães et al., 2002). Once fixed, these roots become the most used in the absorption of water and nutrients.

Root depth and growth depend on soil and climate characteristics (Behn, 2012), as well as the absorption and supply of carbohydrates (Magalhães et al., 2002). The root system of maize can usually reach 1 to 2 meters deep (Behn, 2002).

Regarding the stem, it is presented as a unique stem, erect with knots and internodes (OTGR, 2008). Under favorable conditions 16 knots can be developed, accompanied by a gradual tapering to the top of the plant, ending in a panicle where male gametes form. The number of knots and the height is dependent on the varieties as well as the cultural techniques and soil fertility (Castelo, 2009).

The leaves are alternate, long and broad. They are paralelined with a deep rib to the upper half page, developing in the internodes in alternate positions. They are lanceolate, with short ligament and hem. At maturity the plant may have 30 leaves, and the number, appearance and orientation depend on the variety used.

As a monoecious plant it develops flowers grouped in male and female inflorescences. Male inflorescence forms a panicle (flag) at the apex of the stem, producing pollen, and female inflorescence (spike or mace surrounded by bracts / shirts from which long stilts / beards ending with two stigmas), developed in the leaf axils, produces eggs that after fertilization produces grains (Coelho, 2016).

The fruit is distinguished as a caryopsis - characteristic of grasses - composed of pericarp (surrounding part of the seed), endosperm (reserve of substances) and embryo (Magalhães et al., 2002).

Pollination occurs with the transfer of a pollen grain from the male flower to the female flower, most of which occurs through cross-fertilization.

2.1.2. Physiology

The developmental pattern of maize is common to all varieties, however the duration of the phenological phases (Table 1) and cycle depends on different parameters such as edaphoclimatic conditions of the region and selected cultivar.

Table 1 - Duração das fases do ciclo do milho (Paes, 2011)

Fase fenológica	**Duração em dias**
Sementeira – Emergência	5 a 15
Emergência – 8/9 folhas	25 a 45
879 folhas – Floração	10 a 30
Floração – Maturação	30 a 65
Total	70 a 150

The crop cycle presents a vegetative phase, where plant development occurs, and a reproductive phase, in which ear development occurs (Magalhães et al., 2002).

A plant that completes its cycle up to 85 days is considered ultra-early (FAO100), while a plant that completes its cycle over 150 days is considered to be ultra-early (FAO900). Between the utratardium cycle and the early cycle there are other cycles, such as FAO200 (86 to 95 days), FAO300 (96 to 105 days), FAO400 (106 to 115 days), FAO500 (116 125 days), the FAO600 cycle (126 to 135 days), and so on.

The seed germinates at an optimum temperature of 10ºC after 6 to 10 days, depending on the temperature and humidity of the soil. When maize reaches 3 to 4 leaves, plant growth ceases, with greater root development.

Between 4 and 6 leaves the floral organs form, and the apical meristem is on the surface of the soil. When the plant reaches 6 to 8 leaves the installation of the crop is completed, and a water comfort is essential until this stage. Poor insolation and temperatures below 10ºC, considered the vegetative zero, prolong the vegetative phase (Castelo, 2009).

From 6 to 8 leaves up to the R1 phase, the male panicle is developed, and pollination begins. Subsequently, the axillary buds are formed, under which female flowers and silks appear, available to “receive” pollen, fertilized 48 to 72 hours later (Castelo, 2009). In phase R1 too high temperatures (35-38 °) can negatively influence the number of grains per ear (Brito Paes, 2011).

About 15 days later the plant begins to direct nutrients into the reproductive tract. While the number of grains has already been determined, their size will be determined until physiological maturity, or black point (phase at which migrations from grain reserves end), at this time the grain has a moisture content of around the 35%. Harvesting should be done when the grain has a moisture content of 25% (Abendroth, 2011).

A possible appearance of frost before physiological maturation could kill the plant early, which under normal conditions would gradually dry out, reducing grain quality and potential final yield (Abendroth, 2011).

2.1.3. Producing Factors

Proper plant growth and development is achieved when all favorable growth conditions are met. These conditions depend on genetic, environmental, and management parameters:

Genetic factors:

A correct selection of the variety for the specific characteristic conditions of the region indicates the productive potential. Choosing the variety, when done properly, contributes (Plessis, 2003). Maturation time, yield potential, stability and disease resistance are the characteristics to consider when selecting the cultivar (Nafziger, 2009).

Environmental Factors:

Temperature: Maize is a tropical climate plant, developing poorly in areas where the average daily temperature is below 19 ° C or where the average summer day is below 23 ° C. However, the minimum temperature for its germination (vegetative zero) is 10 ° C, being faster and less variable in soils with temperatures from 16 to 18 ° C. The critical temperature affecting yield is approximately 32 ° (Plessis, 2003). Temperatures below 10 ºC, which corresponds to vegetative zero, and the absence of sun prolong the vegetative phase.

The crop needs to accumulate temperature to be able to develop and move on to the following phenological state. The sum of degree days measures the accumulation of temperature since sowing day (Almeida, 1999) and, according to Coelho (2016), this sum in cases of early to medium cycles ranges from 1500 to 1900th day.

Corn is a frost-sensitive crop and can affect its growth in any of the phenological states. The vegetative part is more easily affected, and grain filling can suffer severe damage when frost occurs (Plessis, 2003).

Water: Maize crop is very water demanding and is also one of the most beneficial in dry matter production and water use (Rodrigues et al., 2011).

The quantity and quality produced are closely related to the existence of stress at the most critical stages of its growth (Rodrigues et al., 2011): in the 6-leaf stage expanded on and between 20 days before and after flowering (at this stage the plant consumes about 45% of the total water) (Coelho, 2016). If there is stress in the critical phase, grain yield may be affected (Flores, 2014).

According to Brito Paes (2011) the first watering should not be done before the 3-4 leaves expanded, thus achieving an increase in root capacity (deepening of the roots). However, in the scarcest years, watering before sowing should be done for better germination and emergence.

In the final phase of the cycle, watering appropriations should be gradually reduced until the plant reaches physiological maturity (black spot) (Coimbra, 2017).

Soil: In the case of soil, maize generally adapts well to various types, if the right varieties and appropriate cultivation techniques are used (Flores, 2014). However, the ideal soils for cultivation are those with medium textures, with clay percentages around 30-35% or even clay with good structure. These soils have good drainage as well as a high retention capacity for water and nutrients.

Due to the high development potential of their root system, soils must have high effective depths (greater than 1 meter), since in other cases root development is hindered and there is less capacity to store water (Magalhães and Durães, 2002). . The tolerated pH range is between 5.5 and 7.8, outside these limits generally the availability of certain elements increases or decreases causing toxicity or deficiencies (Flores, 2014).

Management factors

Nitrogen supply: Nitrogen is a crucial nutrient for crop development, as well as for the production of needed assimilates.

Between 10-leaf phase and anthesis, maize is particularly capable of taking advantage of the available nitrogen in the soil because N taken up during this phase is later remobilized to the ear to support kernel formation. Roughly 50-70% of maize grain N at maturity is derived from N remobilization, while N taken up after this period supplies the rest, due to the decrease of the plant's ability to absorb nitrogen, not taking advantage of a high content in the soil (Gallais et al., 2007; Ciampitti and Vyn, 2012; Ning et. al, 2017).

The nitrogen uptake rate varies throughout the corn crop cycle as follows:

- Up to 8-10 leaves, the needs are low (less than 10% of the total absorbed), because the roots are poorly developed and the soil releases little nitrogen (due to the lower temperatures registered in this phase of the cycle that mineralization);
- From the 10 leaves and until denting, the absorption is very intense (60 to 70% of the total absorbed);
- During the filling of the grain, the absorption becomes lower (20 to 30% of the total absorbed)

On the other way around, fertilization in excess increases the risks of water pollution from nitrate leaching, in addition to the increases in production costs and susceptibility to diseases and pests.

Sowing dates: Sowing may take place provided that groundwater and soil temperatures are adequate for good germination. If the minimum air temperature is between 10 and 15 ° C for seven consecutive days then germination will occur normally (Plessis, 2003). Weather permitting, sowing can be done in mid-March / early April (Yellow Corn, 2017).

When the sowing date is earlier, longer cycle varieties should be used. On the other hand, when there is a delay in the sowing date, the varieties used should have shorter cycles (Brito Paes, 2011).

The main causes for emergence sowing losses are due to seed quality, germination conditions, phytosanitary accidents and pests.

2.2. Yield gap concepts

Yield gap is described as the difference between actual yield and a benchmark: potential or attainable yield (Figure 1).

Yield Potential (Y_P) represents the maximum production for a crop, in a given area when submitted to specific weather conditions. It is determined by the crop's response to the temperature and solar radiation regimes during the growing season. Yield Potential is theoretically achieved under ideal management, this is, without water and nutrients restrictions, and biotic stress effectively controlled. According to these criteria, crop growth is determined by solar radiation, temperature, atmospheric CO_2 and cultivar or hybrid maturity, which governs length of growing period and light interception by crop canopy (Lobell et al., 2009). The quantification of potential yield depends on location, explained by climate, but not on soil properties, given that we assume the absence of constraints and a perfect management of water and nutrients (van Ittersum et al., 2013).

Besides Y_P, another benchmark exists to estimate yield gaps – attainable yield, which includes Water limited yield (Y_W) and nutrient limited yield. As suggested, these benchmarks are, respectively, water and nutrient limited

Water-limited yield (Y_W) is also known as Potential water-limited yield. This concept differs from potential yield because water is considered a limiting factor, as in rainfed crops. Under rainfed crop conditions, soil type (e.g. field capacity, wilting point) and plant rooting depth regulate water availability to plants, turning water an important and limiting factor to crop growth.

Actual yield (Y_a) is determined by growth reducing factors, as shown in Figure 1. The occurrence of yield reductions is partly determined by ecological conditions, but the control of weeds, pests and diseases is primarily determined by management measures.

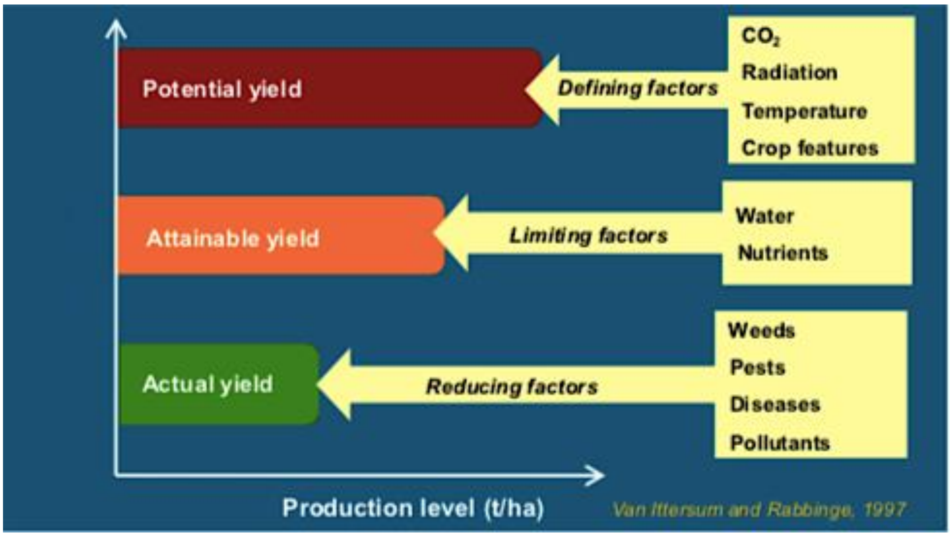


Figure 1 - Production ecological principles of yield levels (Van Ittersum and Rabbinge, 1997)

Although its solid background and referred concepts, there are some responsible reasons for these still existing gaps, such as: the wide range of yield gaps around the world - with average yield varying from 20% to 80% from yield potential – caused by different weather and crop management conditions. Being, this way, impossible to create a unique method to close yield gaps; the non-existence of a global protocol and available data to the public; or the economically unviability of reaching potential yield (van Ittersum & Cassman, 2013).

2.3. Yield Gap measuring approaches

The existing methods for measuring yield gaps differ on scales (both temporal and spatial) and complexities, where there is a wide range of inputs requirements and associated errors. These approaches are summarized from 1 to 4 and explained below (Sadras et al., 2015).

On *Approach 1*, yield gap is determined by a comparison between actual yield and the highest yielding farmers' fields, experimental stations, or growers' contests. Given this, the achieved gap is a difference between actual and the best yield achieved through skillful use of the best available technology (Hall et al. 2013). Consequently, with this method it is not possible to compare results between different regions across the globe, presenting spatial constraints.

Approach 2 is also based on a comparison. According to this approach, yield gap is a reflection of certain environmental factors limiting yields. The comparison is set between actual crop yield and maximum yield estimated through the use of boundary functions. Boundary functions are lines that limit plots' trends achieved through relations between climate/water/nitrogen factors and yield.

Once the boundary functions are only set according to climatic and management factors, there will be a limitation by defining the yield benchmark adapted to a certain cultivar and cannot be generalized to other geographic places due to its specific climatic conditions.

Approach 3 is based on modelling and provides feasible benchmarks for measuring yield potential. These models simulate potential or water/nitrogen-limited yield according to climate, water and nitrogen.

At last, in *Approach 4*, crops yield estimations involve a range of remote sensing approaches. Remote sensing is the technology of identifying, observing and measuring an object without direct contact. Remote sensing approaches to estimate crop yield can be based on (1) biomass production, (2) empirical models relating spectral vegetation index and yield, and (3) integration of remotely sensed data and crop growth models:

(1) Biomass production can be calculated as the product between absorbed photosynthetically active radiation (APAR) and radiation use efficiency.
(2) Empirical models relating spectral vegetation index and yield: linear regression is used in several studies to relate spectral vegetation indices and crop yield. On this method a specific development phase can be selected comparing yield data and a single vegetation index measurement or accumulated vegetation index for crop.
(3) Integration of remotely sensed data and crop growth models: Satellite measurements can be linked with crop simulation models, responsible for simulating potential yield. By comparison of model and satellite-based variables, the model updates its state conditions, remaining more in line with the actual crop growing conditions. This way, production can be estimated on a specific region.

3. Materials and Methods

3.1. Case Study

3.1.1. Maize farm descriptiom

Quinta da Cholda, founded in the 20th century, is a large maize farm located in Golegã, a Portuguese village in Ribatejo, belonging to the district of Santarém, Portugal (39º N, 8º O).

Quinta da Cholda produces grain maize on 560 hectares every year. The farm has 22 fields, ranging in area from 10 to 70 hectares, and consisting only of sandy and clayey soils. As the number of fields, over the last ten years, was not fixed, only those fields were considered in this research for which continuous and long-term data was available. Consequently, the area considered in our analysis comprised 320 hectares, corresponding to 14 parcels.

The fields are located in two different regions, Cholda and Valada, with a distance of 40 km apart, as shown in Figure 2.

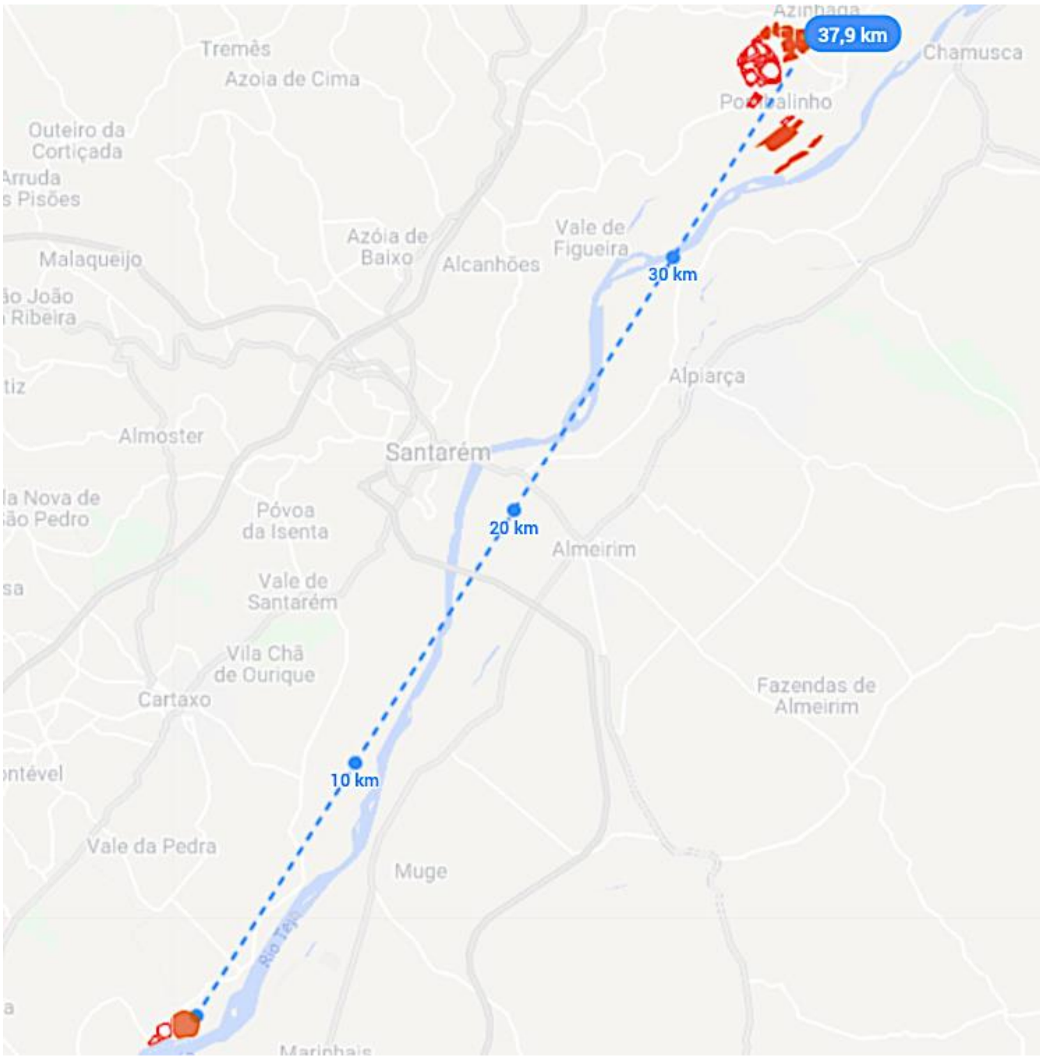


Figure 2 - Distance between Valada and Cholda regions

Marked in orange, Figure 3 illustrates the plots in study, in the regions of Cholda (A) and Valada (B). As shown, these parcels have different shapes, explained by unequal irrigation systems. Circular and rectangular plots are, respectively, watered by pivots and fixed sprinklers.

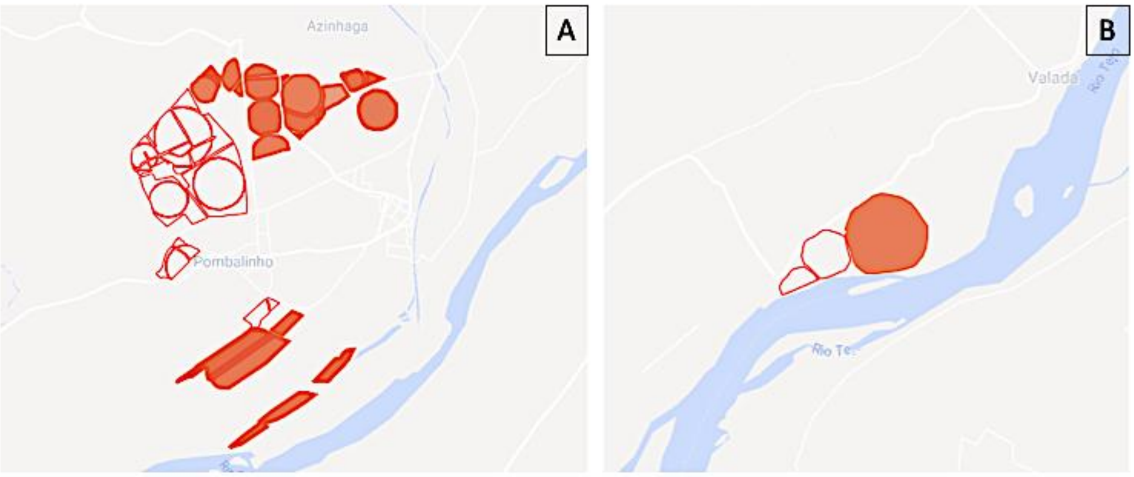


Figure 3 – Parcels in study filled in orange, in Choda (A) and Valada (B) regions

The farmer had always been concerned on adapting his farm to current and fast technological development. A reflection of this can be seen on the methods used to predict irrigation demand. Ten years ago, weekly field inspections were made to predict irrigation supply. Today, the farmer operates according to daily measurements with soil probe and weather forecasts.

The available yield data reveals that there is yield oscillation within and between years, with an average of 16 t ha^{-1} of grain maize, with standard moisture content of 14 %.

3.1.2. Climatic characteristics

De acordo com a classificação climática de Thornthwaite (1948), a zona de estudo insere-se nas regiões que contém o clima sub-húmido seco (mesotérmico B4). Já pela classificação de Köppen (1928), este clima classifica-se como temperado por ser chuvoso e moderadamente quente com chuvas intensas no inverno (tipo Cs), e por apresentar valores de temperatura média do mês mais quente superiores a 22ºC (Figura 4), insere-se no sub-tipo Csa: mesotérmico húmido, com verão quente e seco e um inverno fresco e chuvoso.

The climatic data used for the area where this research was performed was obtained from the Alpiarça weather station, which was more complete within the studied time interval.

According to the climate classification of Thornthwaite (1948), the study area falls within regions containing the dry sub-humid climate (mesothermal B4). According to Köppen (1928) classification, this climate is classified as temperate because it is rainy and moderately warm, with intense winter rains (type Cs), and because it has average values of the warmest month above 22ºC (Figure 4), falls within the sub-type Csa: humid mesothermal, with warm and dry summer and a cool and rainy winter.

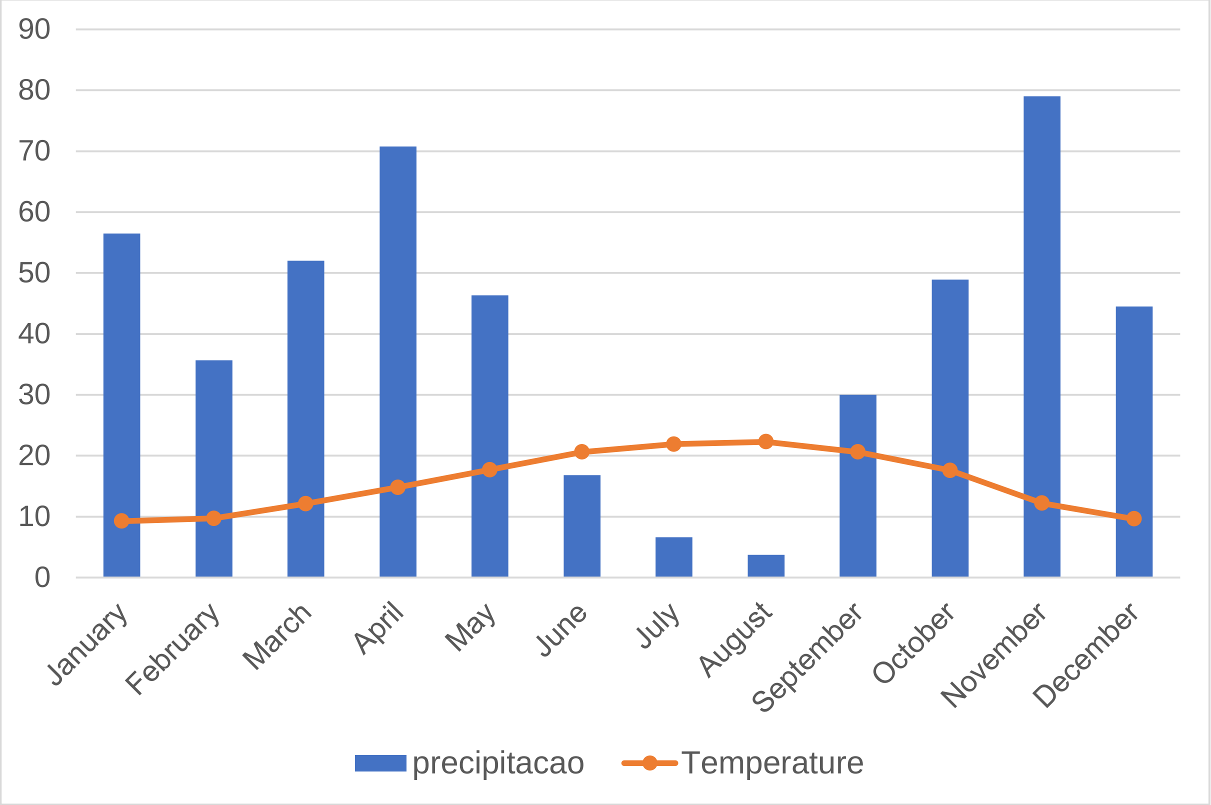


Figure 4 – Gaussen's ombrothermic diagram from 2010 to 2018

Gaussen's ombrothermic diagram is used to define the dry period of a given zone, which corresponds to the spot in where the temperature line is twice of the rainfall line.

As can be seen from figure 4th, the dry season corresponds to the months of July and August. And it starts raining, in average, in September.

3.1.3. Edaphic Characteristics

According to Figueira (1997), the Golegã field is constituted by deep modern alluviosols of light limestone texture or medium limestone texture. They are non-evolved soils, without clearly differentiated genetic horizons, practically reduced to their original material, non-hydromorphic, consisting of stratified alluvial deposits. They are made up of mineral and organic detritic materials carried by river water from gravel and coarse sand to the finest clay particles and their pH is generally neutral.

These alluviosols, according to the FAO classification (IUSS Working Group WRB, 2006) are considered Fluvisols.

3.2. Data description

Over the last 10 years, weather, soil and crop data were recorded, more precisely, the collected data were cultivars, sowing dates, nitrogen and irrigation supply, and actual respective yields, in addition to environmental data, such as maximum, minimum and mean temperatures, relative humidity, solar radiation and precipitation, which was purchased from a neighbored station.

The following chapter describes the parameters used in this research.

3.2.1. Genotype

Within a year the farmer used several cultivars, expanding the genotype*environment interaction over more genotypes, decreasing, consequently, financial risk.

The main cultivars used were from Dekalb and Pioneer. They were hybrids with medium high insertion of the ear, which belong to different FAO groups (500 and 600), have high potential production, are quite resistant to virus, ear diseases and corn fall (consistent stem), and are stay-green varieties. A stay-green variety has delayed senescence, is tolerant to occasional drought, and can have good response when sown in high densities.

FAO-number reflects maturity rating, this is, cultivars with low FAO-number will ripen earlier. This factor is very important for determining the suitability of available varieties for cultivation in a particular area. Only varieties with a FAO-number of 500 and 600 are used because cultivars of FAO-number higher than 600 would need to grow longer to reach maturity than is possible before temperatures fall again in the autumn.

From 2010 most of the varieties were FAO 600 while only, in recent years, few FAO 500 were seeded. Which means that FAO 600 is considerably highly used than FAO 500.

3.2.2. Environment

Weather data was purchased from Alpiarça weather station, a region of Santarém, located between Cholda and Valada, 11km and 28 km apart, respectively.

Cross pollination occurs since there is a mismatch between the maturation of male and female flowers of the same plant in about 3 days. The state of flowering is very sensitive to high temperatures (35-38 ° C), which can lead to drastic reduction in the number of grains per spike as a result of reduced pollination.

Because maize is cold-intolerant and very sensitive to temperatures, the climate parameter taken in account to this analysis was temperatures variation within and between years (Figure 5).

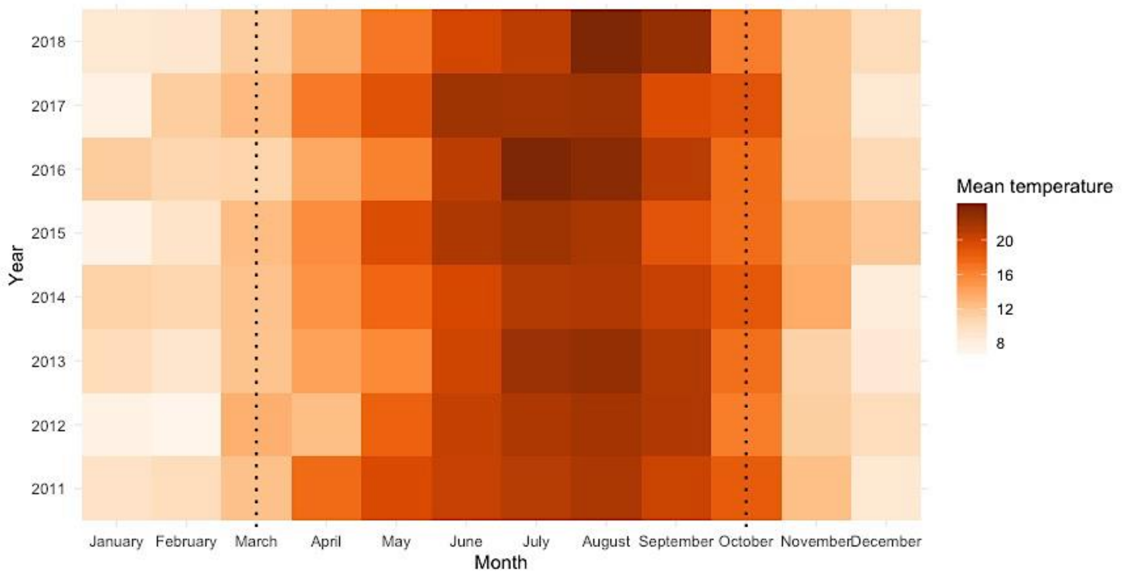


Figure 5 – Mean temperature variability, in degrees, over the years. Dotted lines mark growing maize season

3.2.3. Management

Although yields achieved were available from 2010, some management parameters as irrigation, sowing, emergence, anthesis and maturity dates, could not be analysed for such a long term, due to lack of data.

Nitrogen supply

Given the importance of this parameter, nitrogen supplies, obtained from the records, and available from 2011, were included in this research, to get a better understanding of their impact on actual maize productivity.

Irrigation supply

Maize requires irrigation to reach high yield. Maize is sensitive to water stress from the 10 - leaf stage until denting. Furthermore, if there is not enough water during grain filling, the mean grain weight decreases, as for flowering stage, the number of flowers per spike decreases and its fertilization is affected, giving a lower number of grains per square meter.

Water requirements of maize crops depend on climatic conditions, explaining why the irrigation method has been updated in this farm, has earlier referred.

The records of irrigation, per day, and in total cycle, were then used to explain yield variability.

Sowing, emergence, anthesis and maturity dates

As sowing dates demark the beginning of crop development, this variable is considered an important management parameter, once it is the farmer’s decision to determine on which environmental conditions maize should grow, reaching or not its potential production depending on state variables.

From 2013 these characteristic dates of growing maize season were available. These parameters are very important because through them it is possible calculate the length of critical growing periods, as grain filling, and also verify if the crop is correctly developing according to climatic conditions, once, as it was seen before, it is highly sensitive to temperatures.

3.3. Construction of new variables

In this study the registered data was not enough to achieve an accurate analysis on what factors could explain yield variations. Thus, new variables, were created by extracting features from some of the registered variables to synthetize the interaction between variables and create new non-linear explanatory variables.

These constructed factors demarked different states of the maize growing, cycle length, growing degree days, cultural evapotranspiration and intercepted radiation of each phenological state, were calculated.

Sowing, emergence, anthesis and maturity dates were firstly converted to Julian days so that future analyses, including these parameters, could be restricted to different stages of the growing season.

Another advantage in converting dates to Julian days, is the greater ease in calculating elapsed days between two different events. This way, new variables defining the length of each phenological phase – vegetative and reproductive – were calculated by doing the difference of days from sowing to emergence, from emergence to anthesis, and from anthesis to maturity states, respectively. The sum of these maize development stages resulted on the total length of the cycle.

As the available meteorological data was recorded per day, was also possible to assess mean temperatures on sowing, emergence, anthesis and maturity days. This meteorological data was also important to calculate the growing degree unit, a measure of accumulated temperature per day, which was calculated according to the following equation:

$$\mathrm{GDD} = \frac{\mathrm{Tmax}+\mathrm{Tmin}}{2} - \mathrm{Tbase} \qquad (1)$$

This parameter is calculated according to two conditions:

- If Tbase (considered 10 degrees for grain maize) was lower than the mean temperature, i.e. (Tmax+Tmin)/2<Tbase then the resulted GDD was 0
- If Tmax > 30º, then GDD is calculated with Tmax = 30 º

The average of GDD during vegetative and reproductive stages resulted in the mean growing temperature, or daily average accumulation, during these periods.

One of the parameters provided by the meteorological station is the reference evapotranspiration, ET_0, which is a measure of the “drying power” of the air but does not reflect the water requirement of a specific crop.

For the determination of crop evapotranspiration (ETc), and consequently determination of crop water requirements, the concept of crop coefficient (Kc) is introduced by the following expression:

$$Etc = Et0 \times Kc \tag{2}$$

Where the crop coefficient (Kc) is influenced by different factors, such as:

1) The vegetative state of the crop
    a) The increase of transpiration capacity depends on the increase of the stomatal surface and, therefore, the development of the leaf area
    b) Increased soil cover implies a decrease in soil evaporation

Thus, the value of Kc varies according to the vegetative state of the crop and the crop itself. These values can then be consulted in FAO 56. (G. Allen & al., 1998).

Table 2 - Kc values presented in chapter 5 of FAO paper 56 (G. Allen et al., 1998).

Crop	**$Kc_{initial}$**	**Kc_{middle}**	**Kc_{end}**
Maize (grain)	-	1.2	0.35-0.6

Kc_{end} has a range of 0.35 to 0.6, once the first kc end value is for harvest at high grain moisture. The second kc end value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis). In this context the value to be used is 0.35.

After calculating ETc, in mm per day, the daily values of precipitation were extracted in order to determine the irrigation requirements of the crop.

Other calculated parameter was the intercepted radiation, because it is considered a potential explanatory factor on yield variations, due to its crucial role on photosynthesis. This factor was determined according to the following ordered equations:

$$\mathrm{Ra} = \frac{1440}{\pi} \times \mathrm{Gsc} \times \ \mathrm{dr} \ \times \ (\omega\mathrm{s} \ \times \mathrm{sen}\,\phi \ \times \ \mathrm{sen}\,\delta + \cos\phi \ \times \cos\delta \ \times \ \mathrm{sen}\,\omega\mathrm{s}) \tag{3}$$

$$\mathrm{dr} = 1 + 0{,}033\cos(2\pi \times \mathrm{J}/365) \tag{4}$$

$$\omega\mathrm{s} \ = \ \mathrm{arc}\cos\left(-\tan(\phi) \ + \ \tan(\delta)\right) \tag{5}$$

$$\delta \ = \ 0{,}493\,\mathrm{sen}\left(2\,\pi\,(284 \ + \ \mathrm{J})/365\right) \tag{6}$$

$$\frac{n}{N} = \frac{Rs}{Ra \times b} - \frac{a}{b} \tag{7}$$

$$es(Ta) = 610{,}8 \times \exp(\frac{17{,}28 \times Ta}{T + 237{,}3}) \tag{8}$$

$$ea = es\ (Ta) \times Hr \tag{9}$$

$$Rnl = -\left(0{,}1 + 0{,}9 \times \frac{n}{N}\right) \times \left(0{,}34 - 0{,}14\sqrt{ea}\right) \times 4{,}903 \times 10^{-9} \times \frac{Tx^4 + Tn^4}{2} \tag{10}$$

$$Rn = Rs\ (1 - a) - Rnl \tag{11}$$

On Appendix 1 is presented a description of needed parameters to determine intercepted radiation.

3.4. Bivariate Analysis

To begin with, a bivariate analysis was used to study not only yield and management trends, but also the impact of management, genotype and environmental factors on actual yields, a continuous variable. According to the nature of these factors, categorical or continuous, two different methods, ANOVA and Linear Models were respectively used.

The purpose of analysis of variance (ANOVA) was to test the significance of differences between means. This test was chosen once it was best suited to the nature of our data, where actual yield responses and the number of observations vary within categorical levels.

In this test the null hypothesis is denoted as H_0, and stated as:

H_0: There is no difference between means

This does not imply that sample means are exactly the same, they will always differ. The null hypothesis assumes that the means are not significantly different from one another.

If the test statistic was larger than the critical value, which was considered 0.05, null hypothesis was rejected, accepting, this way, the alternative (H_1):

H_1: At least one of the means is significantly different from the others

To use this method, it is important to confirm some of the assumptions underlying the analysis of variance, such as, random sampling, equal of variances, independence and normal distribution of errors. Fligner–Killeen test and Residual vs Fitted values plot was used to check the homogeneity of variances. Normal Q-Q plot confirmed normal distribution of errors.

Once ANOVA returned a p-value larger than 0.05, meaning that we reject the null hypothesis and accept that at least one of the means was significantly different from the others, a pairwise t-test was performed to identify the differing categorical levels.

Regression analysis was used when the variable explaining *Yield* was also continuous, and with the purpose to test if the fitted regression contributes to explain yield variability. To do so, scatterplots and t-tests, were made.

A t-test is used to conduct hypothesis tests on the regression coefficients obtained in simple linear models. A statistic based on the t distribution is used to study two different hypotheses that the true slope, represented as β_1, equals to some constant. In this context, the constant value was considered of because the aim of this analysis was to ascertain yields variability according to each of the independent and continuous variables presented on appendix 3.

Therefore, the hypotheses are:

$$H_0: \beta_1 = 0$$

$$H_1: \beta 1 \neq 0$$

Null hypothesis (H_0) implies that no linear relationship exists between the independent and dependent variables. If the obtained p-value was lower than the significance level, which was considered of 0,05, the null hypothesis was rejected, and H_1 accepted.

Besides ANOVA and linear regressions, the use of appropriate graphical methods, depending on the nature of the variable was also an important tool to bivariate analysis. The graphs used were, scatterplots, boxplots and tile graphs.

3.5. Multivariate analysis

Scale dependent correlations

Although scatterplots and significance t tests gave us a result about the impact of independent variables on actual yield, this response is not always clear, especially when analyzing multiple observations over 10 years, where determined conditions and technological improvements change.

In function to a determined factor, yield variability can vary across different scales. Things that appear to be insignificantly correlated at large spatial scales may turn into a different correlation response at small scales.

Therefore, the response of yields depending on sowing dates was better analyzed, by running mosaic plots. These graphs are three variable plots, meaning that the impact of sowing dates on yields, was also analyzed under a third condition, which was temperature.

To have a better sensitivity about the variability of data, some parameters, as sowing dates and temperatures, were divided in different groups, according to determined range values.

Linear Mixed Effect Models

As linear regression models cannot deal with unbalanced data, or missing values problems, mixed model approach was chosen once it was best suited for the nature of the data. Furthermore, linear mixed models can handle the unevenness of repeated measurements and account for the autocorrelation between observations coming from the same plot (different conditions for maize plant found in different parcels and years).

Therefore, this model was required to improve the results obtained through bivariate analysis.

To construct this model, random effects had to be determined. This model had no fixed models considered because the aim of constructing this model was to realize which random factors could better explained yield variability. Fixed effects are variables that are expected to have a direct impact on the response variable. Random effects, or random factors, once they are categorical, are grouping factors for each the analysis is trying to control and considered the variance component of the model. In this study context, we aim to analyze the impact of some variables (fixed effects) on yield variability, among parcels and years (random effects).

Therefore, *years* and *parcels* were placed as random effects. For each year there were 14 parcels in study, in some cases, one of these plots could have two different yields, due to two different cultivars sowed. This way, a new object, called *sample* (*Parcel: Year*), was created where parcels are within years, with inexplicit nesting within them. To create this new variable, the following command on R was used:

$$Data \ < -\, within(Data, sample \ < -\, factor(Year{:}\, Parcel))$$

Model selection was made according to Akaike Information Criterion (AIC), where the model with smallest value was chosen. Model selection can be achieved using two existing AIC criteria, the marginal AIC (mAIC) and the conditional AIC (cAIC). The justification of both approaches corresponds therefore to the purpose of the marginal and conditional mixed models' perspective.

Best random effects structure is chosen according to cAIC. To do so, StepAIC function was applied. *StepAIC is a step function that searches space of possible models in a greedy manner*, where the direction of search was specified as "backward", this is the function adds or excludes random effects until cAIC cannot be further improved.

At the end model selection was presented with the following random factor:

$$Yield \sim 1 \ + \ (1 \mid sample)$$

Following the selection of the model, a visual examination of the normal distribution and homoscedasticity of the residuals was performed. Homoscedasticity assumes that the variability of the data is approximately the same across the predicted values.

4. Results

4.1. Yield variability

Management trends

As seen in ANOVA results, appendix 4, management factors present, in a general way, significant differences between means over the years, as p-value was in general lower than 0.05 (Table 3, appendix 4).

Sowing dates present clear significant differences between consecutive years, except for 2014 and 2015, as shown on Figure 6.

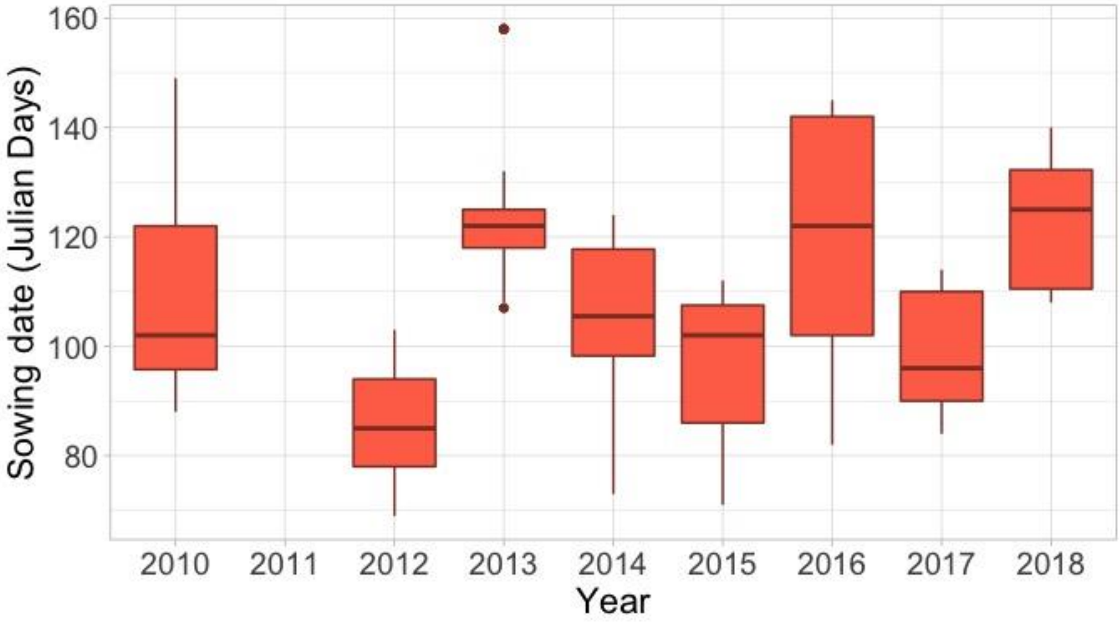


Figure 6 - Variability of sowing dates, presented in Julian Days, over the years. A boxplot summarizes a great deal of information about the distribution of data around the median. Horizontal lines show the median of the response-factor according to the explanatory variable, the bottom and top of the box show the 25th and 75th percentiles, i.e., the location of the middle 50% of the data; the vertical lines are called the "whiskers". The upper and lower whiskers either presents, respectively, the maximum and minimum value, or outliers.

From 2011 to 2014, irrigation supply mean values varied in a visible way, presenting no trend or consistency, and ranging between 300 and 800 mm. Furthermore, 2013 was a year presenting large within-plot variation, but with a low average when compared to other years. On the other hand, in addition to the visible dropping trend over the last four years, was also noticeable a successively lower within years variability on irrigation supply (Figure 7).

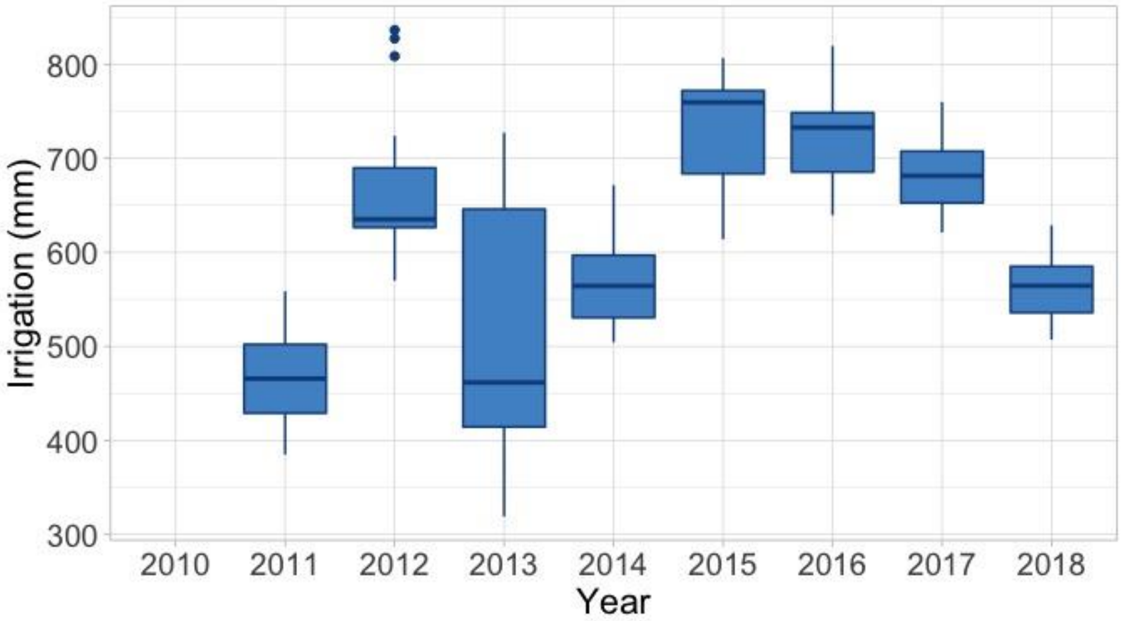


Figure 7 - Oscillation of irrigation supply over the years

Regarding to nitrogen, quantity supplies did not vary much over the years, presenting this way a consistent application. At the same time, average supplies did not oscillate in a significant way within a year, except in 2016, where variability was larger with relatively higher applications (Figure 8).

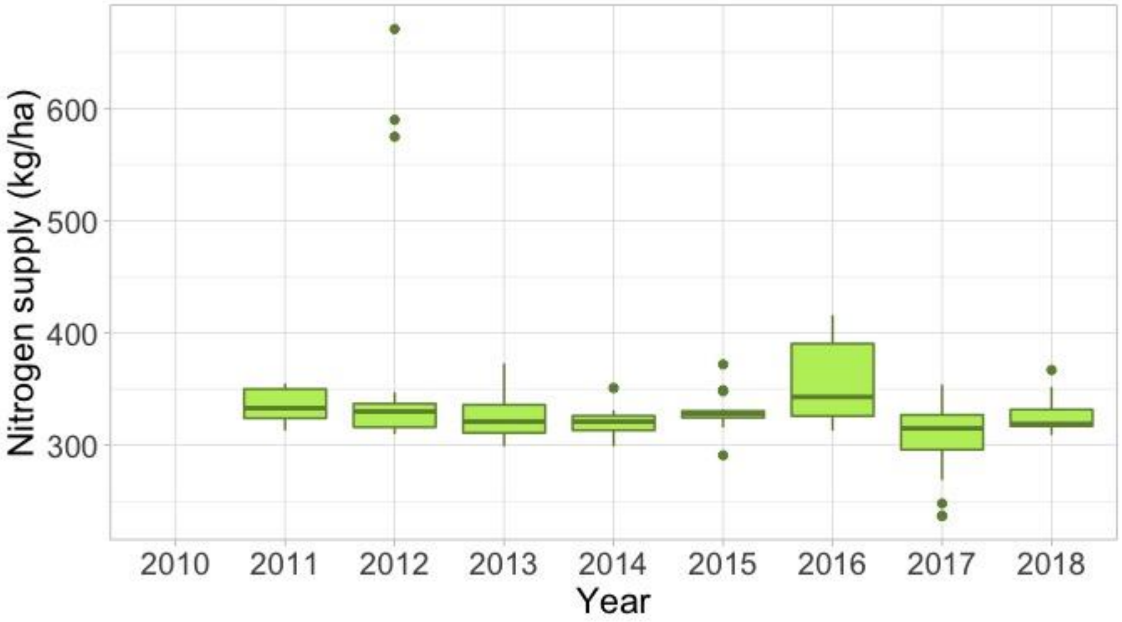


Figure 8 - Oscillation of nitrogen supply over the years

Temporal and intrinsic field variability

ANOVA output results, presented on Table 3, appendix 4, reveal no significant change of yields over the years (*P*>0.05). Moreover, as can be seen through Figure 9, there is a curious and, apparently, doubled parabolic trend from 2010 to 2018.

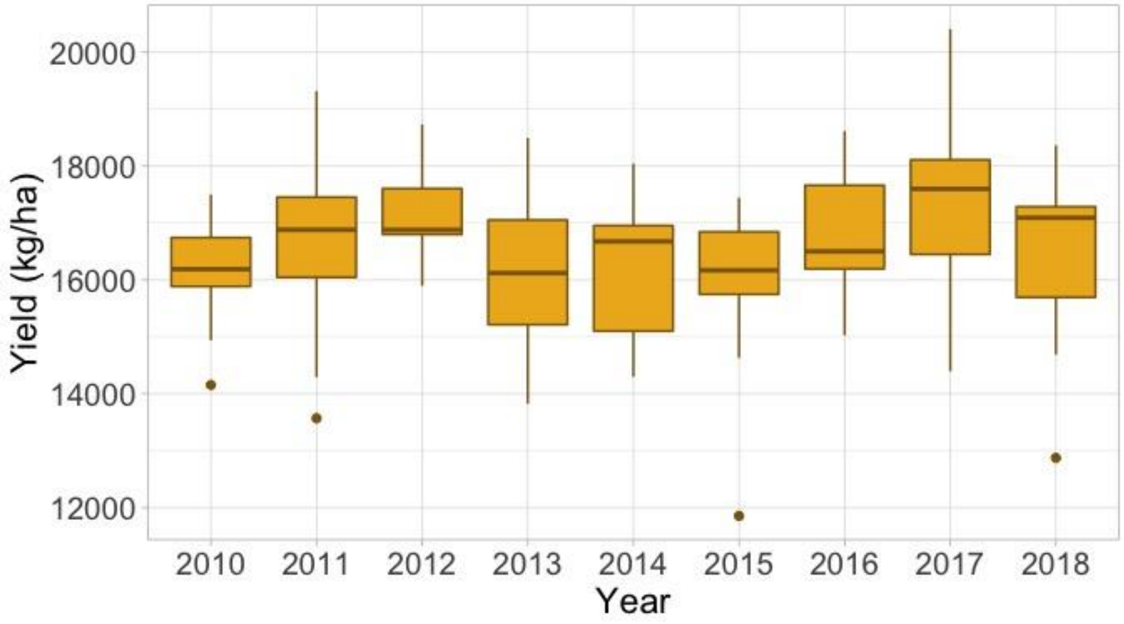


Figure 9 – Yield variability over the years

Contrarily, this farm revealed a significant yield variability between parcels, as it is shown in appendix 4 by ANOVA (P>0.05). This discrepancy among parcels cannot be explained by different soil textures, because analysis of variance has shown that this parameter has no impact on yield oscillation (table 4, appendix 4), as can be confirmed by the boxplot presented on Figure 10, showing an overlap of yield means between the two soil types.

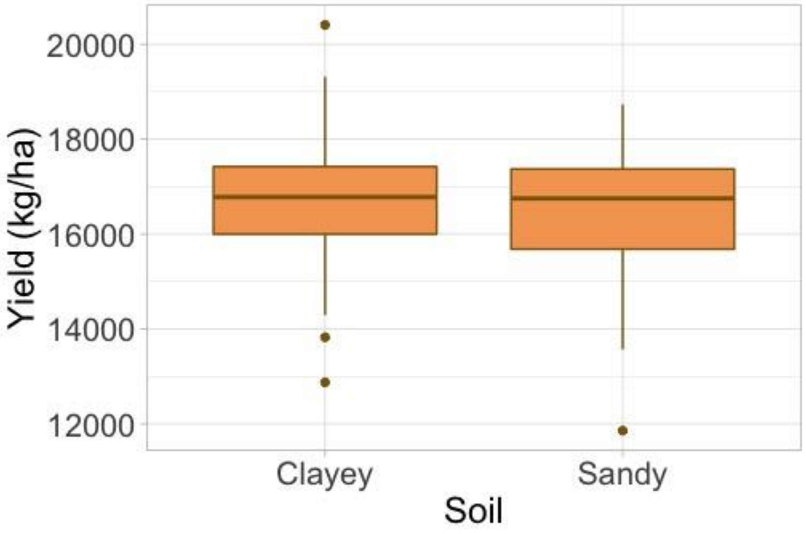


Figure 10 - Yield variability among different soil textures

In contrast to clayey soil parcels, sandy soil plots achieved relatively similar yields, obtaining productivities of 16 to 18 tons per hectare. Even though there are differences within this soil type, Folha Meio and Aviz Areia presented relatively higher results, with yields around 18 tons per hectare. Pessegueiros, in turn, was the sandy parcel with lower productivities.

At the same time, clayey soils parcels' present high variability among them. Laranjeiras, Lameiras Baixo and Cholda, showed observations of 14 to 16 tons per hectare, and Vinha proves to be the field with lower productivity (Figure 11). On the other hand, Mendanha revealed a high productive potential, a bit higher than Folha Meio and Aviz Areia.

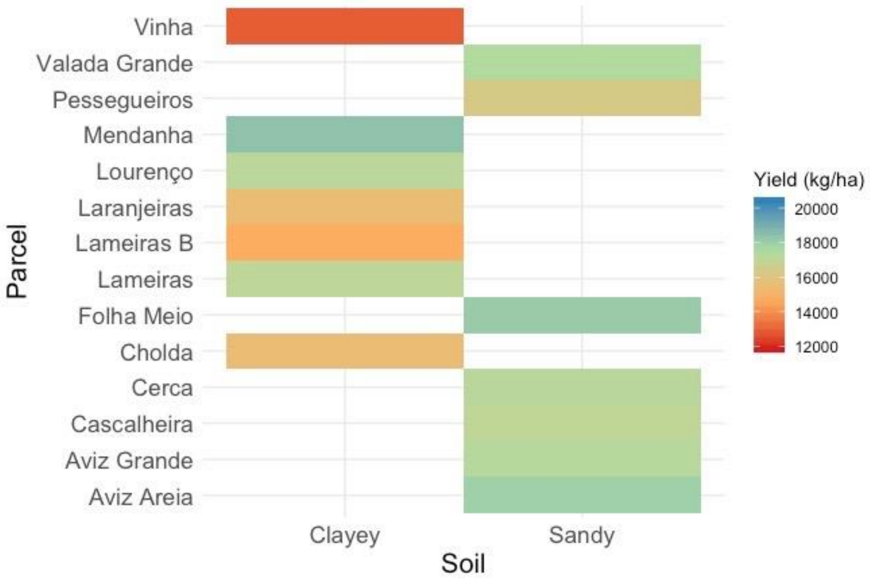


Figure 11 - Representation of yield variability across parcel, and sandy and clayey plots

Effect of irrigation and Nitrogen supply

As seen above, Apart from confirming this last hypothesis, linear model also showed that yield has not been affected by irrigation oscillation (P> 0.05, Table 5, Appendix 5).

The same response explaining yield variability, was seen in nitrogen supply. Meaning that Nitrogen and irrigation supply are not management parameters explaining the oscillation of yields (Table 5, Appendix 5).

Effect of genotype characteristics

Since each plot was sown with different cultivars over the years, the variable *cultivar,* of categorical nature, was also submitted to an ANOVA test, in order to verify its impact on yield variability. According to the result shown in Table 4, appendix 4, the reason of yield oscillation is not interconnected with different seeded varieties (P> 0.05).

Besides cultivars, other parameters related to maize plant characteristics were tested, as the total length of the cycle, and the duration of emergence, vegetative and reproductive periods.

As shown on Table 6, Appendix 5, the total length of the cycle and duration of the period from sowing to emergence period were not significantly correlated to yield.

The total length of the cycle was not significant. Meanwhile, the duration of vegetative and reproductive periods was significant ($P<0.05$), being, respectively, positive and negative correlated with yield (Table 6, appendix 5). In other words, higher yields are achieved through shorter vegetative and longer reproductive stages, as shown on Figure 12, although the weak correlation, as shown is table 6, appendix 5, by the adjusted R^2.

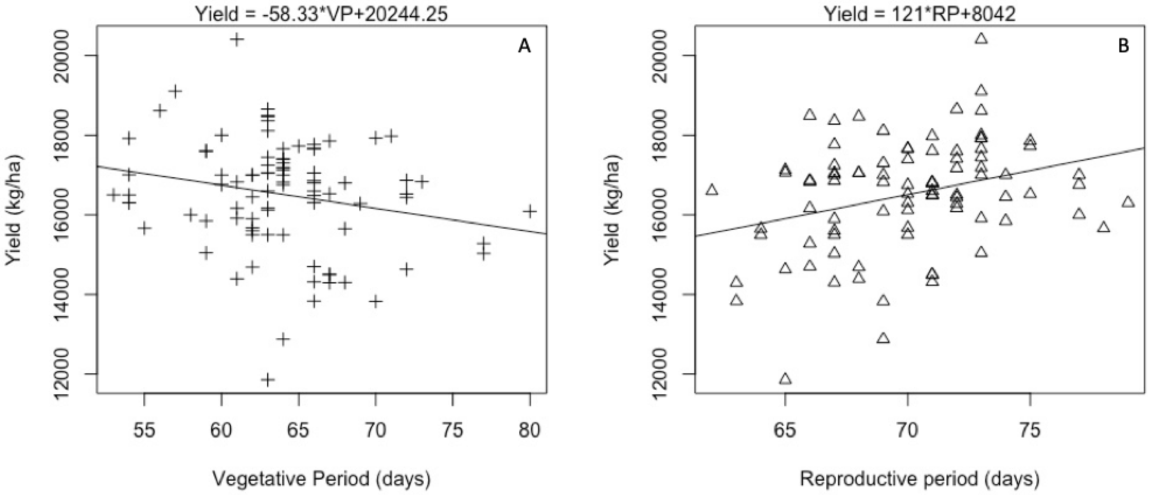


Figure 12 - Influence of vegetative (A) and reproductive (B) periods duration on yield

Effect of environmental parameters

Given the influence of vegetative and reproductive lengths, other meteorological parameters, such as temperatures and intercepted radiation, were also submitted to a significance t-test due to their importance for development and performance of the crop.

According to linear model results presented on Table 7, Appendix 5, intercepted radiation is not significantly correlated with current yield ($P> 0.05$). Mean temperatures on vegetative stage (expressed as *Tday1*), however, is significantly correlated with actual yield variability ($P<0.05$), with positive estimation, meaning higher temperatures during this period are correlated to higher yields.

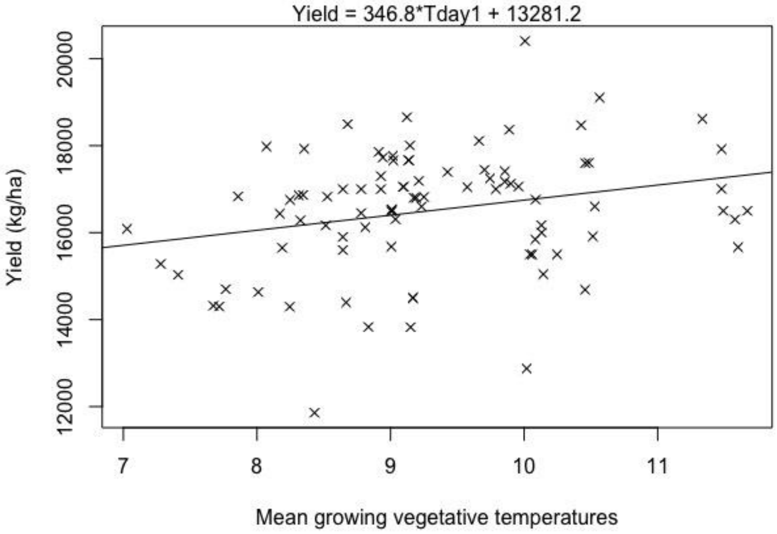


Figure 13 - Effect of mean growing vegetative temperatures on yields

Other temperatures, as temperatures when sowing and at silking stage, which is considered as 63 to 68 days after emerging, and mean temperatures during the reproductive period had no impact on productivity, as shown in appendix 5, Table 7 (P-value>0.05).

The behavior of temperatures on silking stage based on yield, shown in Figure 14, reveals that these parameters cannot be explained with a linear model. Yields increase when mean silking temperatures range around 20 to 27 degrees, remain relatively constant from 27 to 35 degrees, and start to decrease from this point.

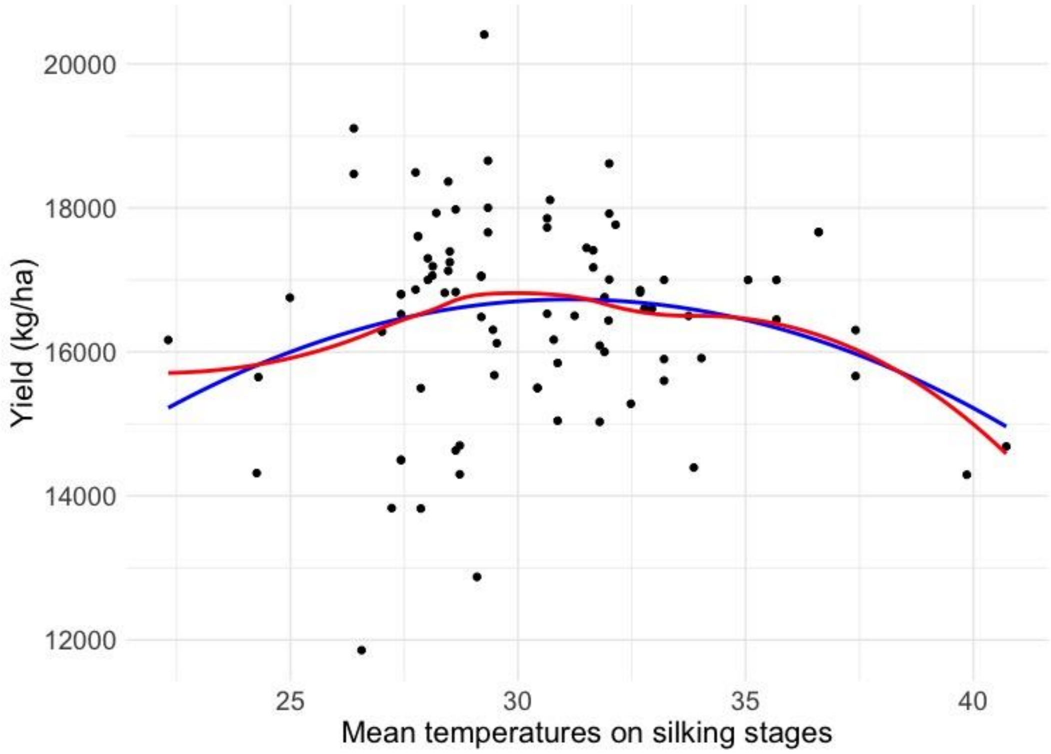


Figure 14 - Yields' oscillation according to silking stage temperatures. Red line presents the fit curve according to data and blue curve presents the parabolical function

Effect of sowing dates

As sowing dates demarcate the beginning of crop development, this variable is considered an important management parameter, because it is the farmer's decision to determine on which environmental conditions maize should grow.

Similarly, to silking stage temperatures, linear model is not the most suitable method to explain this parameter's impact on yield's response, due to its parabolic trend. Consequently, the non-significance ($P>0.05$) of sowing dates on actual yields' variability, as seen through significance t-test presented on appendix 5, was not considered as a result.

Considering that sowing dates depend on present and forecast environmental conditions, the variation of yields according to this variable is not linear, as seen on Figure 15. Among the years, the response of yields to sowing dates has been similar. For each year, the difference between the maximum and the actual sowing date was made, and the response was parabolical. Which means that earlier sowing date is not correlated with higher yields, as suggested by linear models. At the same time, the graph in Figure 15 showed that delayed sowing dates would also be responsible for a decrease in productivity.

Consequently, this linear model method might not be the most suitable to explain the impact of sowing dates.

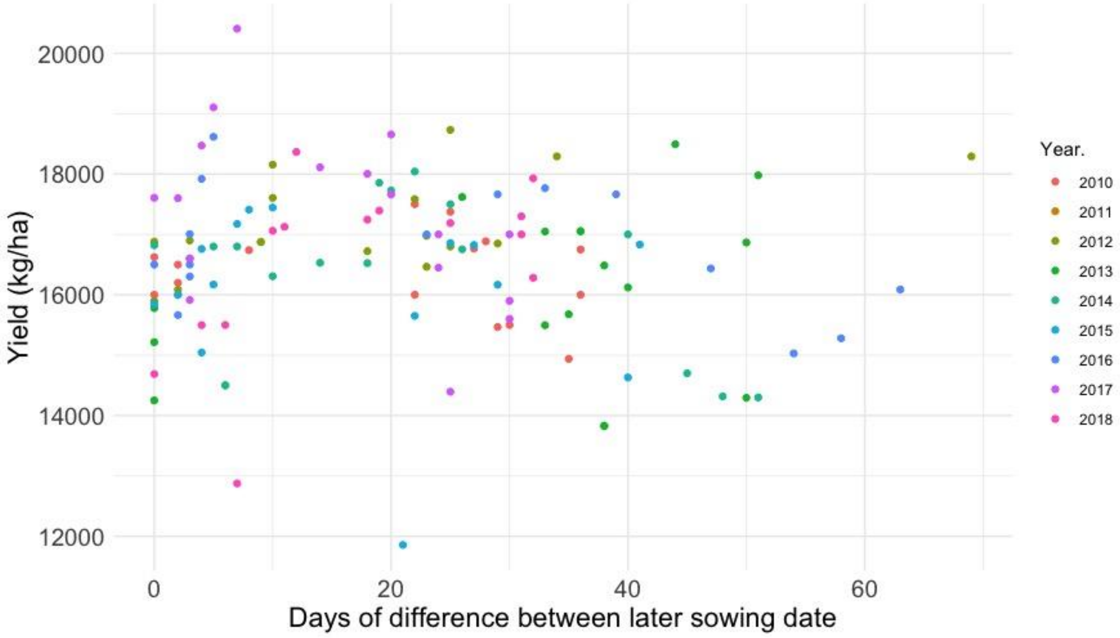


Figure 15 – Yield as a function of sowing date of the year

Thus, the effect of this variable was better analyzed according to within year temperatures, and respective reproductive/vegetative ratio.

Over the last ten years sowing time ranged from middle of March to middle of May. As seen in Figure 16, it is not guaranteed that by sowing at the same time in different years, it is likely to have similar growing conditions, because there are different temperatures during the vegetative stage. As seen above, on Figure 1, chapter 3, years differ from each other not only by averaged temperatures that are reached throughout the year, being, thus, classified as colder or warmer years, but also by the delay of warm temperatures.

Also, by comparing different years, the divergence of *Tday1* along the year is noticeable. Years 2013, 2014, 2016 and 2018 have shown to be cooler until beginning April, with a delayed of high temperatures, while, 2017 was the warmest, reaching higher temperatures earlier, as seen *Tday1* value in SD3. Secondly, 2015, was shown to be a warmer year, reaching high temperatures during vegetative stage when seeded in April.

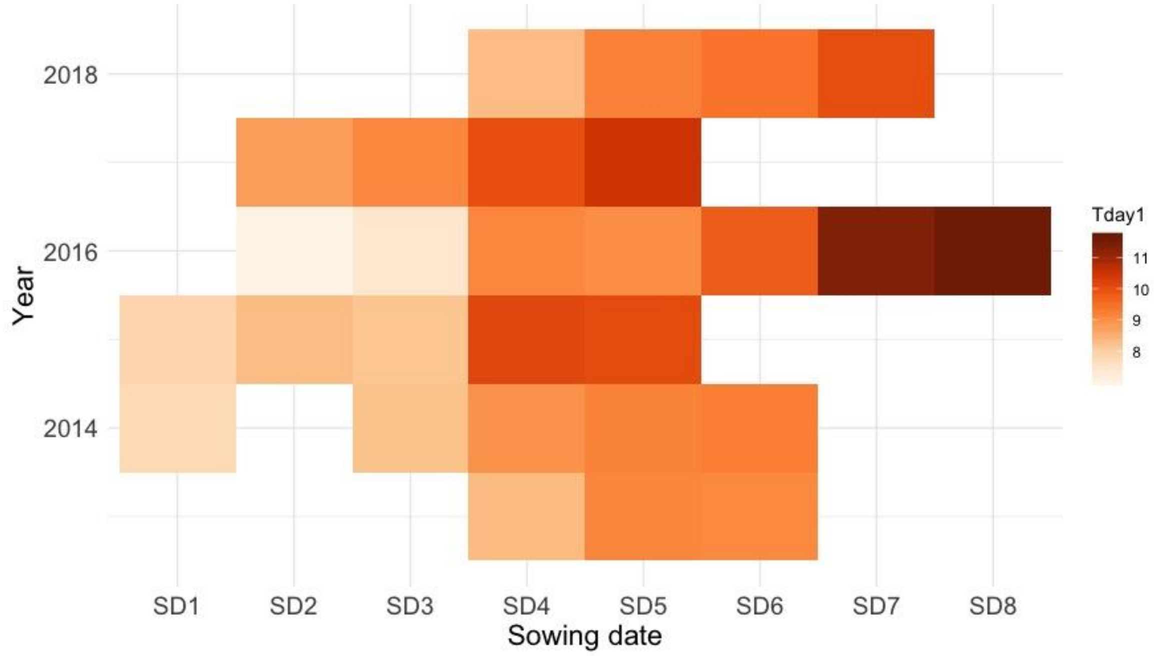


Figure 16 - Relation between sowing dates, years and mean vegetative growing temperatures. SD corresponds from 70 to 150 Julian days, where SD1 to sowing dates from 70 to 80 julian days, SD2 is from 90 to 100 julian days, and so on.

Length Ratio, which correspond, respectively, to the ratio of Reproductive and Vegetative duration periods (RP/VP).

Length ratio has an influence on yield as seen on Figure 17. Ratios lower than 1, meaning the vegetative length is higher than reproductive. A more constant behavior, visibly with slope nearby zero, is showed when ratio is between values around 1.00 and 1.25. From ratio 1.25 a slight decrease on yields can be seen. According to this graph, ratios can be divided in three different classes, A,B,C, as separated on Figure 17.

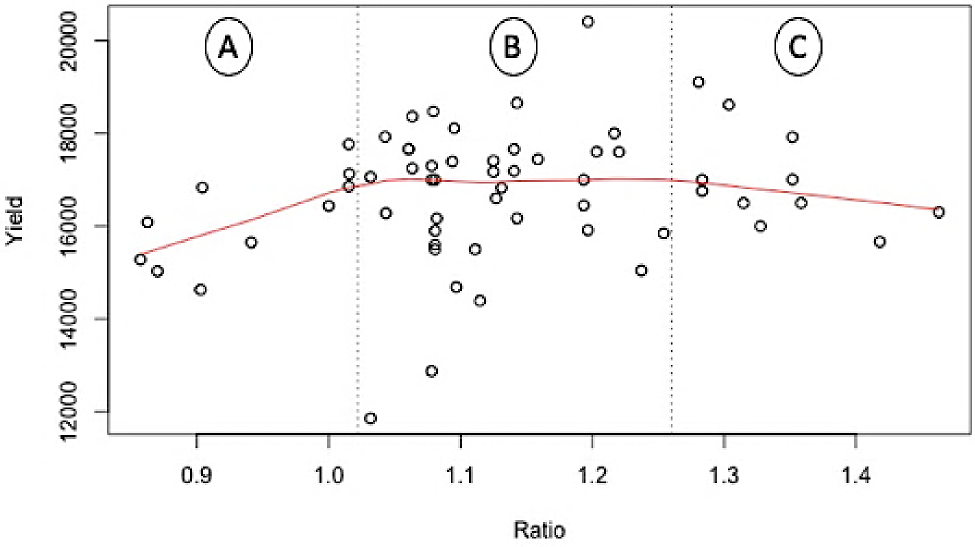


Figure 17 - Yield's response to Length Ratio

When sowed between day 70 and 90, the temperature in the vegetative stage is significantly low. Such high temperature ratios generally correspond to a length ratio of less than 1 (Figure 18).

When sowing dates oscillate around 90 and 130 days, mean temperatures vary between 1.1 and 1.4 (Figure 18), corresponding to the ratio of length B (figure 17).

Seed dates greater than 140 days have caused very low *Tday1*, which means that temperatures during the growing season are higher, resulting in shorter vegetation periods and therefore the length ratio will be higher (Figure 18).

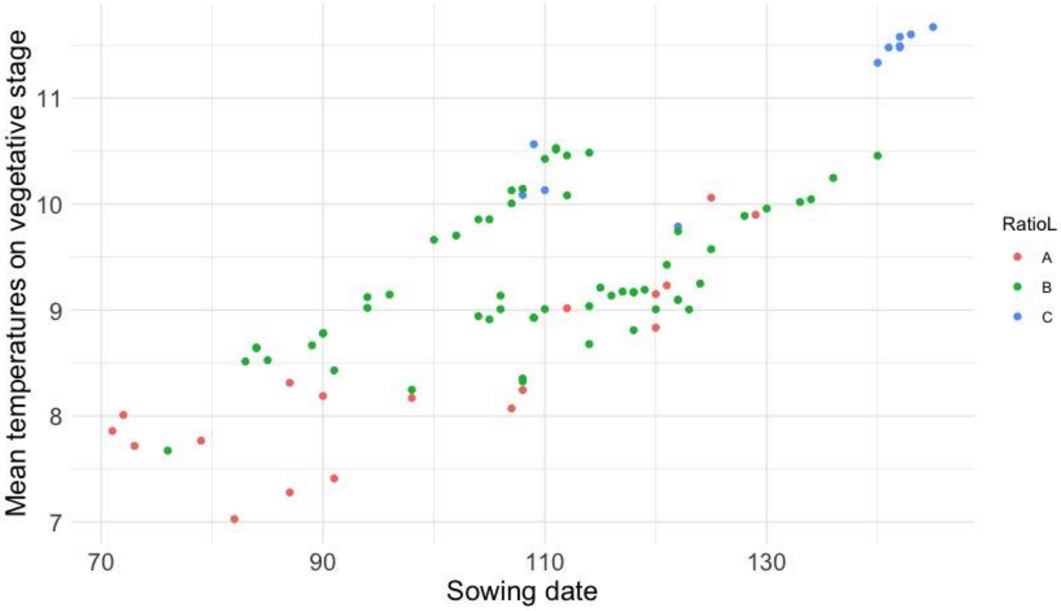


Figure 18 - Mean vegetative temperatures and ratio lengths responses to sowing date

5. Discussion

This research aimed to discover the magnitude of the yield gap and which management, environmental and genotypic factors were related to yield variability and the respective yield gaps in Quinta da Cholda.

Hence, the research questions, as presented on the introduction, “What is the magnitude of the yield gap?” and “Which factors explain yield variability?”, were made and studied according to the methods descripted above.

Which factors explain yield variability?

Yield variability is a complex system affected by several key variables and manifold interactions among them, which explains the requirement of multiple analysis in this research. Nevertheless, both bivariate and multiple variate analyses were needed because neither of them explained completely the reasons behind yield oscillations.

Mixed model, with no fixed models considered, was submitted to a stepAIC function, where it was concluded that mixed model estimating yield would be more suitable with random factors (1 | sample). This means that the cause of variation of yields is better explained by factors that differentiate the character and potentiality of each parcel. Meanwhile, the difference of stepAIC function was not largely different when considering random factors as (1|sample) + (1|year), which means that although yield variability is better explained by differences between parcels, it can also be correlated, although less, with different interannual events.

The potentiality of the plots, later reflected in the yield obtained, was not explained by the effect of nitrogen or irrigation either because these factors were not limiting or because the variability in the inputs was small. That said, it was concluded that yield variability between plots was justified by factors, other than soil textures.

Each year is characterized by different weather conditions. Data analysis showed that the duration of the vegetative stage, governed by temperature, has a significant impact on productivity. Depending on the characteristics of the year, reflected by specific temperature scales, the length of the vegetative period will be affected and will determine the magnitude of productivity. It was also found that this temperature effect is reflected by the sowing dates. The interaction year and sowing dates has a very important impact on productivity.

All these factors are better explained below.

Over the years, nitrogen supply was maintained relatively constant, which method was based on 20 units had to be applied for each tone of extracted productivity. This method revealed efficiency because productivities would not respond differently due to a larger or smaller application.

Irrigation did not contribute to explain yield variability. Which was an expected result considering that, over the years, this parameter was higher than crop water requirements. Also, the results showed a development on the irrigation method, reflected by a larger difference between irrigation and evapotranspiration along the years, which is likely to be explained by an evolution of the method used to decide the amount of water supply, based on the more frequent use of probes and consideration for meteorological changes.

Although the length of the cycle is not relevant to yield variability, the durations of vegetative and reproductive periods of maize crops influence their yield, as also concluded by Sharma (1960).

The growth and vigor are determined by the assimilation and accumulation during vegetative period, while assimilates synthetized and partitioned during the grain filling period determine kernel growth and grain yield. The quantity of assimilates to partition are produced by photosynthesis in the source organs (mainly leaves) and consequently depend on a good dry matter which is determined by a good leaf area index, constructed during vegetative stage (Rani, 2018). Thus, the photosynthate partitioning to the grain (influenced by source/sink organs during reproductive stages) has a great importance on yield (Sharma, Gifford et al., 1984). This is the reason why there is a great importance on having longer reproductive phases to achieve more partitioning of photosynthate to the grain, and therefore higher yields.

Dry matter partitioning is the end result of the flow of assimilates from sources organs via a transport path to the sink organs. The dry matter partitioning among the sinks is primary regulated by the sinks themselves (Marcelis, 1995).

At the same time, length ratio greater than 1.2 (Figure 17), meaning a reproductive period is much higher than the vegetative period, is responsible for a decrease in productivity. In its turn, the vegetative period is related to higher leaf area, which in turn means faster dry matter fixation. Even if the reproductive period is larger, a very small vegetative period can affect yields by the limited to produce biomass and, consequently, assimilates that are later beneficial for grain filling, and for a better crop development performance.

Phenology is driven by accumulated temperatures, more precisely growing temperatures during vegetative period (VP). Higher temperatures on VP are responsible for a shortening of this stage, once plant quickly accumulates the necessary growing degree days to reach flowering. Given that growing mean temperatures on reproductive period did not influence yields, the length of this period is only driven by shorter or longer vegetative period, which in its turn depend on accumulated temperature.

Sowing date is temperature dependent, which explains its oscillations over the years. Earlier sowings have two competing effects on yields. On the one hand, it leads to a lengthened vegetative growth period, because this period occurs at a cooler time of the year when it takes longer to accumulate a given number of GDD, resulting in a higher peak LAI, which builds a bigger engine for photosynthesis during grain filling, increasing this way yields (Sacks & Kucharik, 2011). On the other hand, larger vegetative stages lead to a shortened grainfill period due to an increase, during this vegetative phase, in the number of GDD needed for corn to progress through the reproductive period and reach physiological maturity (Sacks & Kucharik, 2011), decreasing yields. Sowing in the month of March and beginning of April, is generally related with low temperatures, which by its turn will conduct to larger vegetative periods, corresponding also to a length ratio lower than 1.

Vice versa, later sowing dates are related to very high temperatures on vegetative period, and so this period will be very shortened. As referred above, this situation is not profitable to the crop, once it does not have time to produce a beneficial biomass to its performance.

It was observed that there was great amount of variability across the parcels, neither explained by different soil types, larger differences between irrigation and crop water needs, or different cultivars seeded. Furthermore, even in propitious sowing dates and meteorological conditions, the parcel identity has a higher impact on yields.

Accurate collection of dates that determine phenological states may be a limiting factor on obtaining more precise measurements, as these phenological states would not occur in just one day, and so temporal resolution turns to be a limiting factor because it is hard to scout more than once a week every fields. Consequently, the lack of precision of the full phenology of the culture would lead to the calculation of longer or shorter vegetative and reproductive states than in reality. But since the assumed error would be small, varying in just a few days, the conclusions regarding these parameters do not change.

Most of the evaluated factors revealed a relationship with the linear models' method, however other parameters such as silking stage temperatures and sowing dates showed a non-linear but parabolic behavior, thus linear model's method was not the most suitable one.

What is the magnitude of the yield gap?

From the existing approaches to measure yield gap the most suitable was *Approach 1*, based on a comparison between actual yield and high-yielding in farmer's field, experimental stations, or grower's contests, as explained on chapter 2.

Given the context of the study and the region, the benchmark for making this comparison was the maximum yields achieved by the farmer, since it is speculated that these yields' farm is the highest and best to compare in the region.

Approach 2 was excluded because the benchmark to be considered was attainable yield, where the interaction of nitrogen, water and climate would result in a lower yield-standard, than the actual yields. For its turn, due to data restriction and consequent difficulties on calibration, the use of crop models to measure potential yield, as described on *Approach 3*, would be limited and incorrect. The similar situation happens on *Approach 4*, where the method to measure the benchmark would be long and most of the tools were not achievable over the considered term in analysis.

Furthermore, given the description on chapter 2.1, the benchmark to measure yield gap according to *Approach 2*, could almost be considered as *potential* since the factors limiting actual yields are mostly environmental.

According to the obtained yields, these can be classified as low, medium and high, where the low values are up to 16 tons per hectare, the median are between 16 tons and 18 tons, and the high yields include values above 18 tons per hectare.

Depending on this classification, yield gaps vary. Where for low productivities, the yield gaps range from 10 % to 20%, while for median to high productivities, yield gaps are below 10%.

6. Conclusion

Summarizing and answering the research questions asked on the introduction, the factors limiting yield are related to meteorological parameters as temperature, and management, specifically sowing dates, should be adapted to these conditions, that vary between years. Beyond that, determined parcels have naturally low productive potential, that could not be explained for insufficient data.

Yield gaps, measured according to Approach 1, oscillated up to 20%, depending on the class of yields, i.e., low, median or high yields.

7. Recommendations

Sowing dates should be based on weather forecasts, classifying the years as warmer or colder and predicting the anticipation or delay of heat.

In cold years, sowing dates should not be anticipated by mid-March. On the other hand, sowing too late, in May, in warm years should also be avoided. Overall, regardless of the effect of the year, better yields are achieved when sowing dates occur during late March and during the month of April, between 90 and 120 Julian days.

Concerning to the effect of longer or shorter cultivars, no effects could be seen due to insufficient varieties with FAO-number lower than 600. This is way, it is also recommended that cultivars with different lengths are tested, depending on the sowing dates and temperature conditions.

Bibliography

A Foley, J., Defries, R., Asner, G., Barford, C., Bonan, G., Carpenter, S., K Snyder, P. (2005). Global Consequences of Land Use. *Science (New York, N.Y.)*, *309*, 570–574.

Abendroth, L. J., Elmore, R. W., Boyer, M. J., & Marlay, S. R. (2011). *Corn Growth and Development*.

Adelana, B. O., & Milbourn, G. M. (1972). The growth of maize. II. Dry-matter partition in three maize hybrids. *The Journal of Agricultural Science*, *78*(1), 73–78.

Batchelor, W. D., Basso, B., & Paz, J. O. (2002). Examples of strategies to analyze spatial and temporal yield variability using crop models. *European Journal of Agronomy*, *18*(1), 141–158.

Beza, E., Silva, J. V., Kooistra, L., & Reidsma, P. (2017). Review of yield gap explaining factors and opportunities for alternative data collection approaches. *European Journal of Agronomy*, *82*, 206–222.

Butler, E. E., & Huybers, P. (2015). Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environmental Research Letters*, *10*(3), 034009.

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences*, *96*(11), 5952–5959.

Corn Growth Stages. Retrieved 22 August 2019, from Odell's World website: https://odells.typepad.com/blog/corn-growth-stages.html

de Bruyn, L. P., & de Jager, J. M. (1978). A meteorological approach to the identification of drought sensitive periods in field crops. *Agricultural Meteorology*, *19*(1), 35–40.

FAO (Ed.). (2006). *Food aid for food security?* Rome: FAO.

FAO - C 2003/REPORT. (n.d.). Retrieved 23 August 2019, from http://www.fao.org/3/J1262e/J1262e00.htm

G. Allen, R., S.Pereira, L., Raes, D., & Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. Retrieved

FAO_Irrigation_and_drainage_paper_56

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, *327*(5967), 812–818.

Grassini, P., Thorburn, J., Burr, C., & Cassman, K. G. (2011). High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research*, *120*(1), 142–150.

Hengsdijk, H., & Langeveld, H. *Yield trends and yield gap analysis of major crops in the world*. 62.

Hunter, R. B., Tollenaar, M., & Breuer, C. M. (1977). EFFECTS OF PHOTOPERIOD AND TEMPERATURE ON VEGETATIVE AND REPRODUCTIVE GROWTH OF A MAIZE (ZEA MAYS) HYBRID. *Canadian Journal of Plant Science*, *57*(4), 1127–1133.

Iglesias, A., & Podestá, F. (2005). *28 Photosynthate Formation and Partitioning in Crop Plants*.

Koning, N., & van Ittersum, M. K. (2009). Will the world have enough to eat? *Current Opinion in Environmental Sustainability*, 77–82.

Lizaso, J. I., Ruiz-Ramos, M., Rodríguez, L., Gabaldon-Leal, C., Oliveira, J. A., Lorite, I. J., … Rodríguez, A. (2018). Impact of high temperatures in maize: Phenology and yield components. *Field Crops Research*, *216*, 129–140.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources*, *34*(1), 179–204.

Long, N. V., Assefa, Y., Schwalbert, R., & Ciampitti, I. A. (2017). Maize Yield and Planting Date Relationship: A Synthesis-Analysis for US High-Yielding Contest-Winner and Field Research Data. *Frontiers in Plant Science*, *8*.

Marcelis, L. F. M. (n.d.). *Sink strength as a determinant of dry matter partitioning in the whole plant*. 12.

Marton, C., Kálmán, L., Árendás, T., Bónis, P., & Szieberth, D. (2007). Comparison of some methods for estimating vegetation periods in maize. *Acta Agronomica Hungarica*, *55*(1), 1–5.

Marton, L. C., Szieberth, D., & Csuros, M. (2004). New method to determine FAO number of maize, Zea mays L. *Genetika*, *36*

Muchow, R. C. (1988). Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment I. Leaf growth and leaf nitrogen. *Field Crops Research*, *18*(1), 1–16.

Muchow, R. C. (1994). Effect of nitrogen on yield determination in irrigated maize in tropical and subtropical environments. *Field Crops Research*, *38*(1), 1–13.

Mueller, N., Gerber, J., Johnston, M., Ray, D., Ramankutty, N., & A Foley, J. (2012). Closing yield gaps through nutrient and water management. *Nature*, *490*, 254–257.

Nasielski, J., Earl, H., & Deen, B. (2019). Luxury Vegetative Nitrogen Uptake in Maize Buffers Grain Yield Under Post-silking Water and Nitrogen Stress: A Mechanistic Understanding. *Frontiers in Plant Science*, *10*.

Neild, R. E., & Newman, J. E. (1990). *Growing season characteristics and requirements in the Corn Belt*. Purdue University.

Neumann, K., Verburg, P. H., Stehfest, E., & Müller, C. (2010). The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, *103*(5), 316–326.

(PDF) Effect of Sowing Dates and Maize Cultivars in Growth and Yield of Maize along with their Agro-Climatic Indices in Nawalparasi, Nepal. (n.d.). Retrieved 21 August 2019, from https://www.researchgate.net/publication/299749221_Effect_of_Sowing_Dates_and_Maize_Cultivars_in_Growth_and_Yield_of_Maize_along_with_their_Agro-Climatic_Indices_in_Nawalparasi_Nepal

Rani, P. (2018). *Dry matter partitioning and grain yield potential of maize (Zea mays L.) as influenced by dates of sowing and nitrogen application*.

Reidsma, P., Ewert, F., Boogaard, H., & Diepen, K. van. (2009). Regional crop modelling in Europe: The impact of climatic conditions and farm characteristics on maize yields. *Agricultural Systems*, *100*(1), 51–60. https://doi.org/10.1016/j.agsy.2008.12.009

Sadras, V., KGG, C., P, G., AJ, H., Bastiaanssen, W. G. M., Laborte, A., … P, S. (2015). *Yield gap analysis of field crops: Methods and case studies*.

Säfken, B., Rügamer, D., Kneib, T., & Greven, S. (2018). Conditional Model Selection in Mixed-Effects Models with cAIC4. *ArXiv:1803.05664 [Stat]*. Retrieved from

Shaw, R. H., & Thom, H. C. S. (1951). On the Phenology of Field Corn, Silking to Maturity 1. *Agronomy Journal*, *43*(11), 541–546.

Srivastava, R. K., Panda, R. K., Chakraborty, A., & Halder, D. (2018). Enhancing grain yield, biomass and nitrogen use efficiency of maize by varying sowing dates and nitrogen rate under rainfed and irrigated conditions. *Field Crops Research*, *221*, 339–349.

Stewart, D. W., Dwyer, L. M., & Carrigan, L. L. (1998). Phenological Temperature Response of Maize. *Agronomy Journal*, *90*(1), 73–79.

Suwa, R., Hakata, H., Hara, H., El-Shemy, H., Adu-Gyamfi, J., Nt, N., … Fujita, K. (2010). High temperature effects on photosynthate partitioning and sugar metabolism during ear expansion in maize (Zea mays L.) genotypes. *Plant Physiology and Biochemistry: PPB / Société Française de Physiologie Végétale*, *48*, 124–130.

Tollenaar, M., & Dwyer, L. M. (1999). Physiology of Maize. In D. L. Smith & C. Hamel (Eds.), *Crop Yield: Physiology and Processes* (pp. 169–204).

Trostle, R. Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices. Retrieved 23 August 2019, from http://www.ers.usda.gov/publications/pub-details/?pubid=40464

van Ittersum, M. K., & Cassman, K. G. (2013a). Yield gap analysis—Rationale, methods and applications—Introduction to the Special Issue. *Field Crops Research*, *143*, 1–3.

van Ittersum, M. K., & Cassman, K. G. (2013b). Yield gap analysis—Rationale, methods and applications—Introduction to the Special Issue. *Field Crops Research*, *143*, 1–3.

van Ittersum, M. K., & Rabbinge, R. (2012). *Concepts in production ecology for analysis and quantification of agricultural input-output combinations.* Retrieved from https://www.wur.nl/en/Publication-details.htm?publicationId=publication-way-3337383432

W Rosegrant, M., & Cline, S. (2004). Global Food Security: Challenges and Policies. *Science (New York, N.Y.)*, *302*, 1917–1919.

Wallach, D., Makowski, D., Jones, J., & Brun, F. (2019). *Working with Dynamic Crop Models—3rd Edition* (3rd ed.). Retrieved from https://www.elsevier.com/books/working-with-dynamic-crop-models/wallach/978-0-12-811756-9

Wolf, J. (2003, April). *Calibration of WOFOST crop growth simulation model for use within CGMS*. Wageningen University & Research Centre.

Wood, S., Rosen, C., Billings, H., Powell, M., Sebastian, K., Scherr, S., Winograd, M. (2001). *Pilot Analysis of Global Ecosystems: Agroecosystems*.

Yang, C., Fraga, H., Ieperen, W. V., & Santos, J. A. (2017). Assessment of irrigated maize yield response to climate change scenarios in Portugal. *Agricultural Water Management*, *184*, 178–190.

Yang, H. S., Dobermann, A., Lindquist, J. L., Walters, D. T., Arkebauer, T. J., & Cassman, K. G. (2004). Hybrid-maize—A maize simulation model that combines two crop modeling approaches. *Field Crops Research*, *87*(2), 131–154.

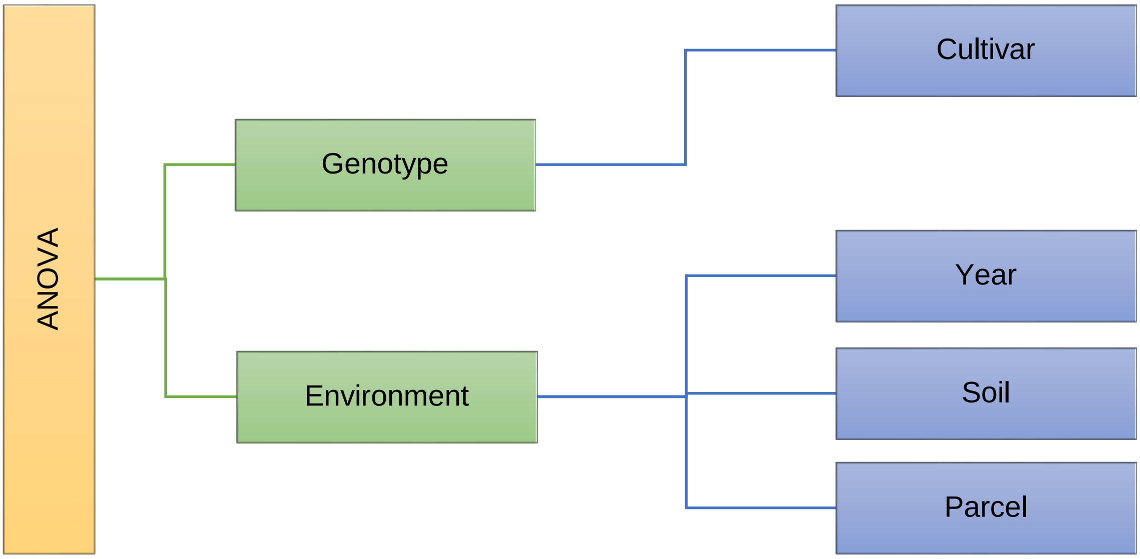
Appendices

Appendix 1: Intercepted radiation parameters

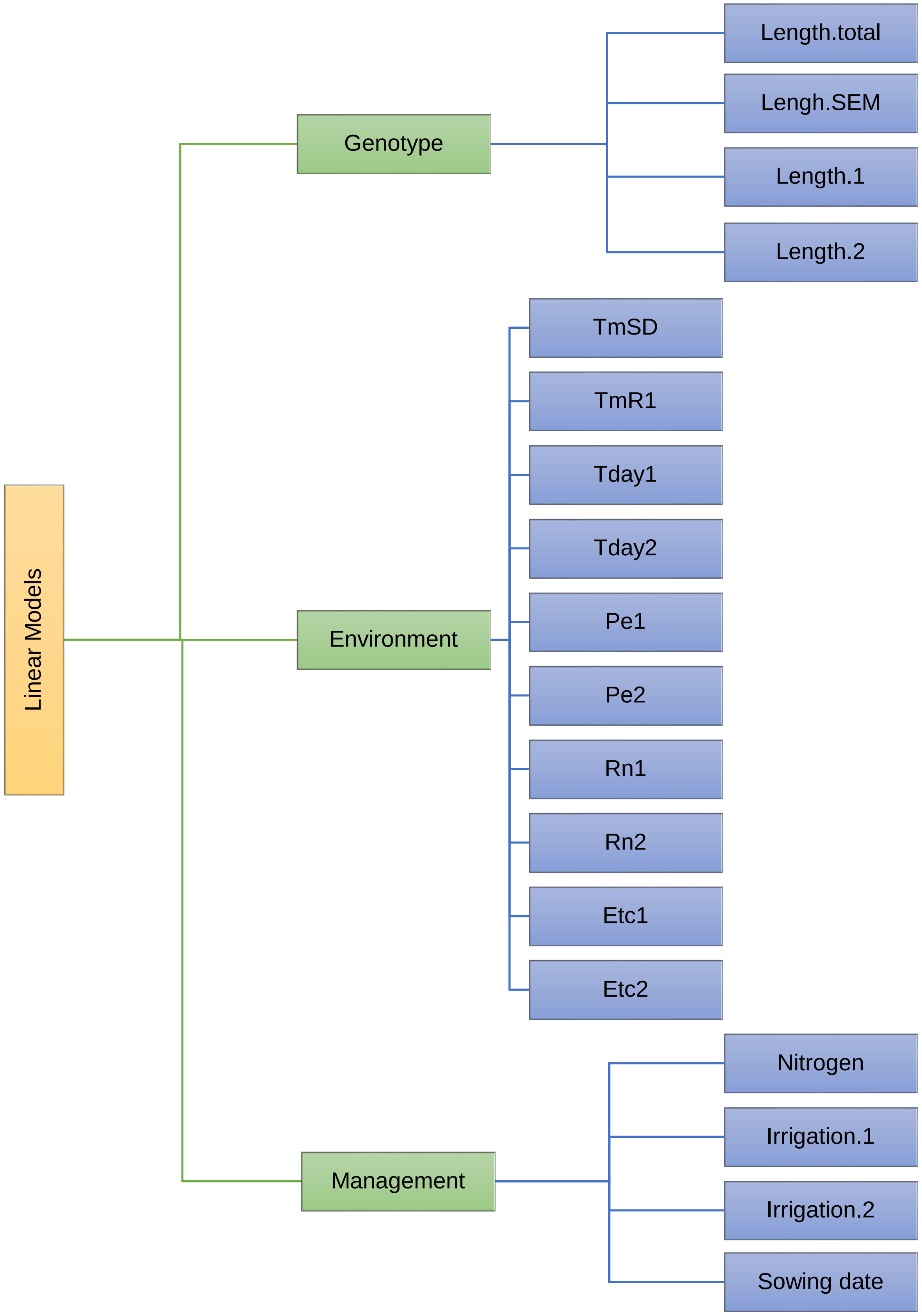
Table 3 – Summarized description of parameters needed to determine intercepted radiation (Rn)

Equation	**Parameter**	**Description**	**Constant value**	**Unit**
(3) (7)	Ra	Solar radiation at the top of the atmosphere		MJ m^{-2} d^{-1}
(3)	G_{sc}	Solar constant	0,0820	MJ m^{-2} min^{-1}
(3) (4)	d_r	Relative distance from the land to the sun		
(3) (5)	ω_s	Angle of the sunset		Radians
(3) (5) (6)	δ	Solar declination		Radians
(3) (5)	ϕ	Latitude of the place in study		Radians
(4) (6)	J	Day of the year in Julian days		
(7)	a	Ängstron coefficient	0,25	
(7)	b	Ängstron coefficient	0,5	
(7)	n/N	Insolation		
(7)	n	Daily number of sun hours of the place of study		
(7)	N	Maximum daily sunshine duration for latitude and day of the place in study		
(7) (11)	Rs	Solar radiation		MJ.m^{-2} dia^{-1}
(8)	$es(Ta)$	Water vapor saturation pressure to air temperature		Kpa
(10) (11)	Rnl	Long-wave radiation to the surface		MJ.m^{-2} dia^{-1}
(10)	$Tmax$	Maximum daily temperature		Kelvin
(10)	$Tmin$	Minimum daily temperature		Kelvin
(9) (10)	e_a	Absolute water vapor pressure		Kpa
(11)	a	Albedo – reflection coefficient	0,23	
(11)	Rn	Intercepted radiation		MJ.m^{-2} dia^{-1}

Appendix 2 : Independent variables submitted to ANOVA significance tests



Appendix 3 : Variables submitted to linear model significance tests



Appendix 4 : ANOVA output analysis

Table 4 – ANOVA results for interaction between management factors and Years

Variable	**Df**	**Sum sq**	**Mean sq**	**F value**	**Pr(>F)**
Nitrogen supply	7	59507	8501.0	3.778	0.0009758 ***
Residual	120	270065	2250.2		
Irrigation supply	7	1123444	160492	31.831	< 2.2e-16 ***
Residual	119	600009	5042		
Sowing date	7	22578	3225.4	13.247	1.356e-12 ***
Residual	121	29462	243.5		
Yield	7	2482120	2482120	1.4545	0.2298
Residual	144	245731817	1706471		
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1					

Table 5 – Yield variability according to parcel, scale, soil texture, irrigation method and cultivar.

Variable	**Df**	**Sum sq**	**Mean sq**	**F value**	**Pr(>F)**
Parcel	13	90440187	6956937	5.82	2.13e-08 ***
Scale	2	9519763	4759882	2.852	0.061
Irrigation type	1	3158139	3158139	1.856	0.175
Soil	1	2334181	2334181	1.367	0.244
Cultivar	14	24966567	1783326	0.977	0.482

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Appendix 5 : Linear model output

Table 6 - Yield's response to management factors

	Dependent variable:	
	Irrigation supply (mm) (1)	Nitrogen Supply (2)
Yield	1.759	1.166
Constant	15542.150***	16221.494***.
Observations	126	127
R^2	0.024	0.002
Adjusted R^2	0.016	-0.006
Residual Std. Error	1332 (df = 124)	51.279 (df = 125)
F Statistic	2.992 (df = 1; 124)	0.240 (df = 1; 125)
P-value	0.08616	0.6249

Table 7 - Yield's response to several stages' duration

	Dependent variable:			
	Reproductive Period (1)	Vegetative Period (2)	Sowing-Eme. (3)	Total cycle (4)
Yield	117.07**	-58.33*	-75.37	-20.24
Constant	8329.14**	20244.25***	17378.70***	19454.83
Observations	90	89	89	89
R^2	0.089	0.043	0.031	0.007
Adjusted R^2	0.079	0.033	0.020	-0.004
Residual Std. Error	1343 (df = 88)	1380 (df = 87)	1389 (df = 87)	1405 (df = 87)
F Statistic	8.590** (df = 1; 88)	3.956* (df = 1;87)	2.751 (df = 1; 87)	0.654 (df = 1; 87)
P-value	0.004306	0.04984	0.1008	0.4211
Note:				*p<0.05; **p<0.01; ***p<0.001

Table 8 - Yields' response to environmental factors

			Dependent variable:			
	`Rn 1`	`Rn 2`	Tmedsd	TmedR1	Tday1	Tday2
	(1)	(2)	(3)	(4)	(5)	(6)
Yield	-1.235	1.166	78.37	5.176	346.8*	92.38
Constant	17781.916***	16221.494***	15393.89***	16333.424***	13281.2***.	15442.88**
Observations	89	92	113	95	89	90
R^2	0.014	0.001	0.029	0.0002	0.065	0.0005
Adjusted R^2	0.003	-0.010	0.020	-0.011	0.054	-0.011
F-Value	1400. (df = 1;87)	0.2403 (df=1;125)	3.343 (df=1;111)	0.01436 (df = 1;93).	6.07 (df =1;87)	0.04063 (df =1;88)
P-value	0.2611.	0.6249	0.0702	0.9049	0.0157	0.8407
Note:						*p<0.05; **p<0.01; ***p<0.001