Universidade de Trás – os – Montes e Alto Douro

IRRIGATION ON CHESTNUT ORCHARDS:

UNDERSTANDING THE SOIL AND PLANT WATER RELATIONS TO OPTIMIZE THE WATER MANAGEMENT

- **Final version -**

Doctoral thesis in Agronomical Sciences and Forestry

MARIA MARGARIDA DE OLIVEIRA MOTA

Supervisors:

Prof. Doctor José Carlos Esteves Gomes-Laranjo, Associate Professor at Universidade de Trás-os-Montes e Alto Douro;

Prof. Doctor Fernando Pedro Falcão Raimundo, Assistant Professor ar Universidade de Trás-os-Montes e Alto Douro;

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VILA REAL, 2018

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to Núria

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LIST OF CONTENTS

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RESUMO

Em Portugal as maiores manchas de castanheiro (*Castanea sativa* Mill) situam-se nas regiões de Trás-os-Montes e Alto-Douro, Beira Alta e Minho. O castanheiro é tradicionalmente cultivado em condições de sequeiro, tipicamente em zonas montanhosas, em diferentes condições edáficas e climáticas, mas que transversalmente possuem verões quentes e secos e invernos húmidos e frios. Nos últimos anos, devido a uma série de fatores de natureza económica (competitividade dos mercados internacionais e forte incremento na procura de castanha em quantidade e qualidade) e climática (verões cada vez mais quentes, secos e prolongados) têm obrigado a uma adequação do modelo de cultura, nomeadamente a introdução da rega no castanheiro, de forma a promover uma maior regularidade da produção e o aumento da produtividade do souto. No entanto, há uma série de questões que se levantam à volta deste tema, tão inexplorado no sector: qual o custo/benefício da rega no castanheiro? Qual o efeito na produção? Qual o sistema de rega mais adequado? Como fazer a gestão da rega por forma a usar conscientemente os recursos hídricos? Foi no sentido de dar resposta a estas questões que traçaram-se os objetivos gerais deste trabalho: caracterizar o potencial produtivo do castanheiro regado e encontrar a melhor forma de gerir a água de rega.

O estudo realizou-se durante quatro anos (2013 a 2016) num souto plantado em 1993, no concelho de Bragança, com as variedades 'Longal' e 'Judia' enxertadas em porta-enxerto seminal de *C. sativa*., nas condições edafo-climáticas da região da Terra Fria em Trás-os-Montes. Inicialmente, 2013 e 2014, instalou-se no campo experimental um sistema de rega por micro-aspersão com o objetivo primário de avaliar a produtividade fotossintética do castanheiro sob diferentes regimes hídricos por forma a definir um valor de potencial hídrico que refletisse as melhores condições produtivas do castanheiro. Para isso, foram delineados três tratamentos: NI- sequeiro (não foi aplicada qualquer rega ao longo do ciclo), DI - rega deficitária (a rega foi ativada sempre que o potencial hídrico às 9 h da manhã fosse inferior a -0.8 MPa) e FI - rega máxima (a rega foi ativada sempre que o potencial hídrico às 9 h da manhã fosse inferior a -0.6 MPa). Mais tarde, em 2015 e 2016 instalou-se uma parcela experimental no mesmo souto com dois tipos diferentes de sistemas de rega. Os tratamentos aplicados foram NI-sequeiro (não foi aplicada qualquer rega ao longo do ciclo), TI - rega gota-a-gota (a rega foi

ativada cada vez que o potencial hídrico de ramo do meio-dia fosse inferior a -1.2 MPa) e SI – rega micro-aspersão suspenso (a rega foi ativada sempre que o potencial hídrico de ramo do meio-dia fosse inferior a -1.2 MPa). Nesta fase, pretendeu-se avaliar a resposta fisiológica do castanheiro, a sua produção e a qualidade da castanha; fazer um balanço económico sobre custo/benefício da rega nos soutos; e por fim, estabelecer guias orientadoras para a gestão da rega no castanheiro com base em parâmetros da planta e do solo. Foram avaliados diversos parâmetros às plantas (potencial hídrico, temperatura foliar, pigmentos foliares fotossintéticos, fluorescência da clorofila, análises minerais e trocas gasosas), ao solo (conteúdo da água no perfil do solo, potencial mátrico do solo e análises minerais), à castanha (produção, curva de crescimento do fruto, calibre, análise química e sensorial) e clima (precipitação, soma das temperaturas, temperatura do ar, humidade relativa e evapotranspiração de referência).

O ano de 2014 foi um verão excecionalmente húmido e as regas não foram ativadas. Não obstante, este facto reflete a otimização do uso da água quando a rega é baseada no potencial hídrico da planta. Em 2013, as regas realizadas (num total de 1490 m^3 ha^{-1} em FI e 600 m^3 ha^{-1} em DI) foram suficientes para se observarem diferenças nomeadamente nas medições feitas ao meio-dia. As árvores regadas apresentaram potenciais hídricos mais altos, maiores taxas fotossintéticas e maiores níveis de transpiração que, por sua vez, tiveram um efeito termorregulador na temperatura foliar e, no final, produziram mais 72% de castanha. Nas condições deste ensaio, verificou-se que as árvores de todos os tratamentos, incluindo as não regadas, apresentavam ao início da manhã valores elevados de potencial hídrico, provavelmente devido à absorção de água, existente nas camadas mais profundas do solo e cuja presença não é tão facilmente influenciada por condições de rega. No entanto a presença ou não de níveis hídricos adequados nas camadas mais superficiais, que permitam processos de absorção mais rápidos, induziram diferenças significativas no potencial hídrico ao meio-dia sugerindo o interesse deste parâmetro na gestão da rega. Uma vez que as maiores taxas fotossintéticas foram observadas quando os potenciais hídricos ao meio-dia se situavam entre -1.0 e -1.2 MPa, este último foi o valor definido para se ativar a rega no ensaio de 2015 e 2016.

O ano de 2016 revelou-se mais quente e mais seco do que o de 2015 e registaram-se frequentemente potenciais hídricos abaixo de -1.2 MPa, implicando maior aporte de água em 2016 (870 m^3 ha^{-1} em TI e 979 m^3 ha^{-1} em SI) do que em 2015 (460 m^3 ha^{-1} TI e 480 m^3 ha^{-1} em SI). No que diz respeito à produção, esta foi sempre superior nas árvores regadas embora a produção decrescesse dum ano para o outro (de 52 para 44 kg $árvore^{-1}$ em SI; de 54 para 43 kg $árvore^{-1}$ em TI e de 44 para 33 kg $árvore^{-1}$ em NI de 2015 para 2016, respetivamente). O tamanho da castanha também decresceu de um ano para o outro, embora tenha sido sempre maior nos tratamentos regados (de 65 para 122 frutos kg^{-1} em NI; de 62 para 89 frutos kg^{-1} em TI e de 63 para 79 frutos kg^{-1} em SI de 2015 para 2016, respetivamente). Não foram encontradas diferenças significativas entre os tratamentos quanto à composição química e sensorial da castanha. Estes resultados são importantes pois revelaram que a rega acrescentou valor comercial à castanha, não só porque aumentou a produção e melhorou o seu tamanho, mas sobretudo porque estas vantagens não interferiram negativamente na qualidade nutricional e sensorial da castanha. A nível fisiológico, os potenciais hídricos, as taxas fotossintética e de transpiração foram mais altos nas árvores regadas. A fluorescência da clorofila revelou-se um método pertinente na avaliação da performance fotossintética do castanheiro. O estudo económico revelou que os custos anuais foram maiores em SI (4.654 € ha^{-1}) e TI (4.549 € ha^{-1}) do que em NI (1.530 € ha^{-1}), tendo a maior receita (22.126 € ha^{-1} em TI, 21.984 € ha^{-1} em SI e 16.174 € ha^{-1}em NI) compensado o investimento. O sistema de gota-a-gota tem um investimento menor do que o de micro-aspersão suspenso e, para resultados semelhantes, consome menos água. No entanto, o sistema de micro-aspersão apresenta vantagem pela facilidade de limpeza de infestantes na linha e, tendo maior área regada, pode aumentar o potencial de produção de cogumelos não obstante poder ser limitativo se potenciar a dispersão de doenças, como o cancro. No final, as correlações positivas obtidas entre o potencial hídrico do castanheiro, a taxa fotossintética, conteúdo de água no solo e do potencial mátrico do solo permitiram indicar um modelo de gestão da água no castanheiro baseado em parâmetros do solo que, por sua vez, podem ser monitorizados à distância num lógica de “rega inteligente”.

Este estudo contribuiu para aprofundar o conhecimento sobre as relações hídricas entre solo e planta, definir valores de referência para a gestão da água no castanheiro e avaliar os benefícios da rega no castanheiro. No entanto, e como seria de esperar de um tema tão recente no sector da “castanhicultura”, ainda é muito escassa a informação que existe e demasiadas as interrogações que se colocam. Futuramente, devem ser conduzidos estudos com vista a testar e aperfeiçoar outras formas de gestão da água de rega, introduzir e avaliar outros tipos de sistema de rega que não só sejam mais eficientes como também se coadunem com as práticas culturais do souto, e estudar o efeito da rega em soutos com diferentes sistemas de condução, com outras variedades e noutros tipos de solo.

ABSTRACT

The largest chestnut tree (*Castanea sativa* Mill) areas in Portugal are situated in the Trás-os-Montes, Alto-Douro, Beira Alta and Minho regions. The Chestnut tree is typically cultivated in mountainous places with different types of soil and climatic conditions that, however, usually have dry and warm summers and cold and wet winters. Due to a series of economic (for example; competition of foreign markets and the increased demand for quality chestnuts) and climatic factors (longer, drier and hotter summers) the introduction of irrigation on the chestnut orchards has become a standard practice in order to achieve production increase and regularity. There are however a few questions that arise around this unexplored theme; what is the cost/benefit of the irrigation for Chestnut trees? What is the most adequate system? How to manage irrigation in order to save precious hydrological resources? Answering these questions was the driver behind the objectives of this work: characterizing the productive response of the chestnut tree after the introduction of irrigation and finding the best way to manage the available water.

The study was conducted during four consecutive years (2013 to 2016), with the soil and climatic conditions of Trás-os-Montes, on a 20-year-old orchard with ‘Longal’ and ‘Judia’ varieties, and the trees were 5 meters apart on the row and 10 meter on the inter row. The study evolved from an experimental trial in 2013 and 2014 on which a micro-sprinkler system was installed. Evaluating the photosynthetic productivity of the chestnut tree under different hydrological regimes was the main objective of this study in order to define a water potential value that better reflects the best productive conditions of the chestnut tree. And so, three treatments were done: NI – non-irrigated (no irrigation was applied during the cycle), DI – deficiently irrigated (irrigation was activated every time the water potential was below -0.8 MPa) and FI – fully irrigated (irrigation was activated every time the dawn water potential was below -0.6 MPa). Later, in 2015 and 2016 a trial was set up on the same orchard with two types of irrigation systems. The applied treatments were NI (no irrigation was applied during the cycle), TI – drip irrigation (it was activated every time the midday stem water potential was below -1.2 MPa) and SI – micro-sprinkler irrigation (it was activated each time the midday stem water potential was below -1.2 MPa). This trial’s main objective was to evaluate the chestnut tree’s physiological response, production and nut quality; to make

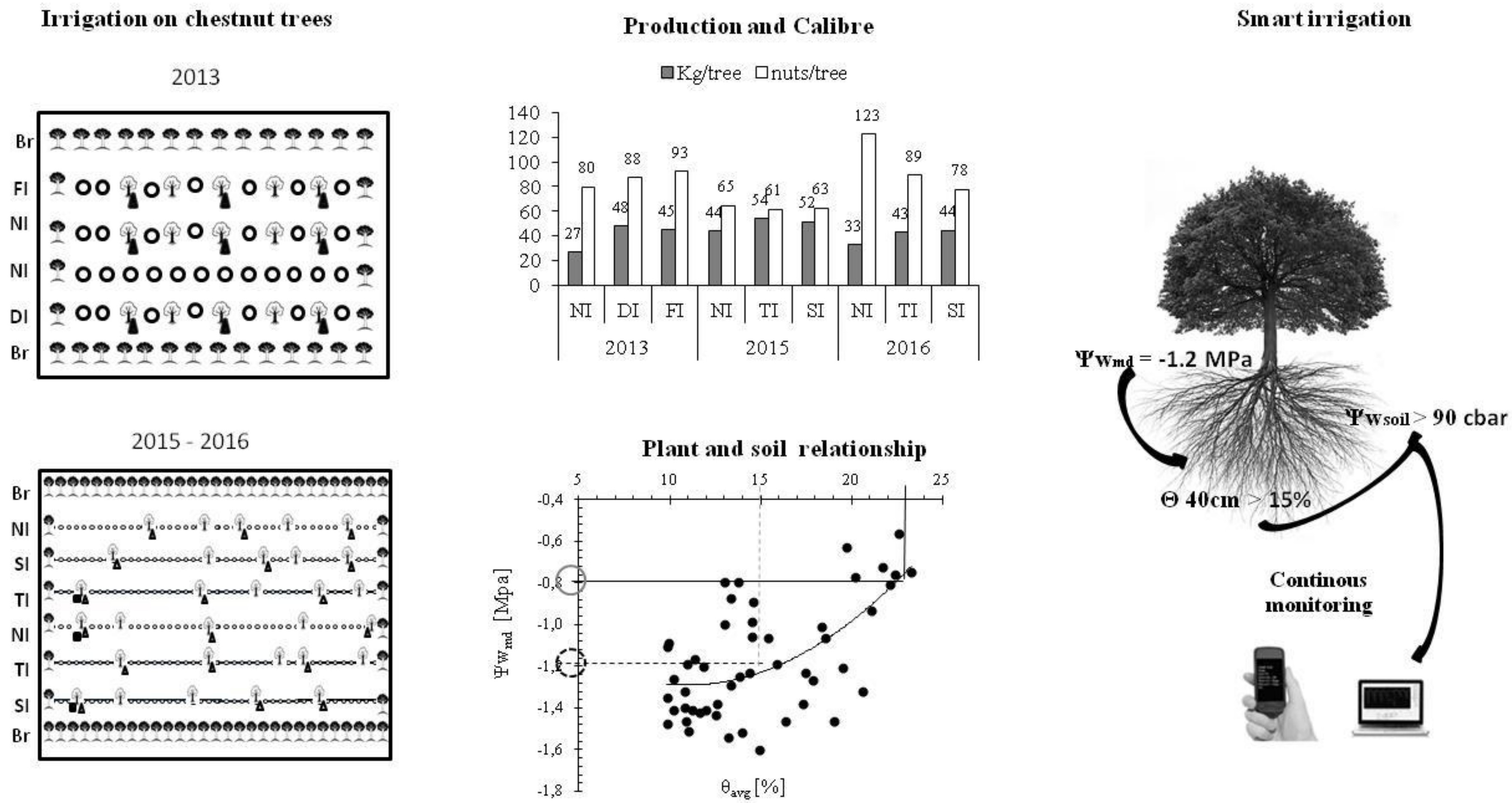
an economical assessment about the cost/benefit of the irrigation and on the absence of it and, at last, to establish guidelines for the management of irrigation of the chestnut trees based on soil and plant parameters. Several data points from the plants were gathered (water potential, foliar temperature, foliar photosynthetic pigments, chlorophyll fluorescence, mineral analysis and gaseous exchanges), from the soil (water content, water potential and mineral analysis), from the chestnuts (production per tree, fruit growth, calibre and a sensorial and chemical analysis) and from the climate (precipitation, temperature sums, air temperature, relative humidity and reference evapo-transpiration).

2014 was an exceptionally humid summer and since every plant's water potential was above the limits set to initiate irrigation no treatment was applied. Regardless, this fact reflects the optimization of water use for irrigation whenever this is triggered/ managed by the water potential. For 2013 the applied irrigation (a total of 1490 m^3ha^{-1} for FI and 600 m^3ha^{-1} for DI) wetted the soil's superficial layers and it was enough to make a difference on the midday measurements. The irrigated trees produced more chestnuts, presented a higher water potential, higher photosynthetic rates and higher transpiration levels that, in turn, had a thermoregulatory effect on the foliar temperature. Every tree recovered their hydric comfort during the night, independently of the irrigation, most likely because of the water absorption by the deeper roots. Therefore, for irrigation management look more interesting to use the readings of the water potential at midday. Since the highest photosynthetic rates were found when the midday water potential was between -1.0 and -1.2 MPa this last one was the chosen value to trigger irrigation on the 2015 and 2016 trials.

2016's summer was warmer and drier than 2015 and, consequently, the midday stem water potential values was several times below -1.2 MPa. As consequence, it was necessary to use more water in this year (870 m^3ha^{-1} in TI and 979 m^3ha^{-1} for SI) than in 2015 (460 m^3ha^{-1} in TI and 480 m^3ha^{-1} for SI). The chestnut production was always higher on the watered trees although it decreased from one year to the next (52 to 44 kg $tree^{-1}$ in SI; 54 to 43 kg $tree^{-1}$ in TI and 44 to 33 kg $tree^{-1}$ in 2015 and 2016, respectively) and this happened to the nut size as well although it was always bigger in the watered treatments (65 to 122 fruits kg^{-1} for NI; 62 to 89 fruits kg^{-1} for TI and 63 to 79 fruits kg^{-1} for SI in 2015 and 2016, respectively). No significant differences between the chestnut's sensorial and chemical compositions were found. Thus, it can be said that the irrigation added commercial value to the chestnut because it not only increased the production as it increased fruit size and did not interfere with the chemical and sensorial compositions of the fruit. At a physiological level, the stem water potential, the photosynthetic and transpiration rates were higher for irrigated trees and the chlorophyll fluorescence has proved to be a relevant method when evaluating the chestnut tree's photosynthetic performance. The economic study revealed that the annual costs were higher for SI (4.654 € ha^{-1}) and TI (4.549 € ha^{-1}) than for NI (1.530 € ha^{-1}) but a higher revenue (21.984 € $ha^{-1}$for SI, 22.126 € ha^{-1} for TI and 16.174 € ha^{-1} for NI) made up for the investment. The drip system required a smaller investment than that of the suspended micro-sprinkler system and, for similar results, it consumes less water. The micro-sprinkler system has the advantage to be easier to clean the line weeds and also the larger wet area may promote larger mushroom growth's area; however, it can also promote disease spread. In the end, the positive correlations between the plant's water potential, photosynthetic rate, soil water content and soil water potential allow the formation of a water management model based on soil parameters that, in turn, can be monitored remotely and help to the decision to irrigate.

This study has contributed to build knowledge on hydric relations between soil and plant, to define reference values for chestnut tree water management and to evaluate the benefits of the introduction of irrigation in this culture. As expected however, there are too many questions to answer and information is still scarce on this new sector of the chestnut production. Future studies should test and perfect other types of irrigation water management, introduce and evaluate other types of irrigation systems, to determine the water needs of the chestnut tree based on evapo-transpiration values of trees with different ages and of other varieties and in different types of soil and different training systems.

GRAPHICAL ABSTRACT



LIST OF FIGURES

LIST OF SUPPLEMENTARY FIGURES

LIST OF TABLES

LIST OF ABREVIATIONS

Chestnut chemical composition

DM - Dry matter (g 100 g^{-1} FW);

SS - Soluble sugars (g 100 g^{-1} DW);

CF – Crude fat (g 100 g^{-1} DW);

CP – Crude protein (g 100 g^{-1} DW);

Meteorological parameters

GDD - Annual growing degree day (°D);

VPD – Air vapour deficit;

T_{leaf} or **T_{folha}** – Leaf's temperature (°C);

T_{med} - Mean monthly temperature (°C);

$T_{média\ d}$ – Temperatura média diária (°C);

T_{max} – Mean maximal monthly temperature (°C);

$T_{max\ d}$ Temperatura máxima diária (°C);

T_{min} – Mean minimal monthly temperature (°C);

PP – Total monthly precipitation (mm);

ET_0 – Evapotranspiration of reference (mm)

Etc – Crop evapotranspiration (mm);

Chlorophyll fluorescence parameters

ABS/RC - Absorbed energy flux per reaction centre (RC);

TR_0/RC - Trapped energy flux;

ET_0/RC - Electron transport flux;

DI_0/RC - Dissipated energy flux;

TR_0/CS - Trapped energy flux per CS;

ET_0/CS - Electron transport flux per CS;

DI_0/CS - Dissipated energy flux per CS;

PI_{ABS} - Performance index on an absorption basis;

F_0 - Chlorophyll fluorescence intensity measured when all PSII reaction centres are assumed to be open, however, the measured value may be affected by several other parameters (at t=0);

F_J - Fluorescence intensity at the J-step during fluorescence induction (at 2 ms);

F_I - Fluorescence intensity at the I-step during fluorescence induction (at 30 ms);

F_M - Maximal chlorophyll fluorescence intensity measured when all PSII reaction centres are closed;

T_{FM} - Time needed to reach F_M; F_V/F_0 - a value that is proportional to the activity of the water-splitting complex on the donor side of the PSII; Area - the area above the chlorophyll fluorescence curve between F_0 and F_m (reflecting the size of the plastoquinone pool);

S_M - (Area)/(F_m −F_o), Representing energy necessary for the closure of all reaction centres;

N - The number indicating how many times Q_A is reduced while fluorescence reaches its maximal value; V_J - relative variable fluorescence at time J;

$jp_o/(1- jp_o)$ - A ‘conformation’ term for primary photochemistry;

$Y_0/(1- Y_0)$ - Conformation’ term for thermal reactions (nonlight dependent reactions);

M_o - Density of reaction centres per PSII antenna chlorophyll;

SFi_{ABS} - An indicator of PSII 'structure and functioning', calculated as (RC/ABS)×jp_o;

F_v/F_m - Maximum quantum yield of primary photochemistry (at t = 0).

Gas exchange parameters

A or ***P_N*** - Photosynthetic rate (µmol CO_2 m^{-2} s^{-1});

A_{md} or ***P_{Nmd}***– Photosynthetic rate at 12:00 h (µmol CO_2 m^{-2} s^{-1});

A_d or ***P_{Nd}*** – Photosynthetic rate at 09:00 h (µmol CO_2 m^{-2} s^{-1});

E – Transpiration rate (mmol H_2O m^{-2} s^{-1});

E_{md} or **E_{12h}**– Transpiration rate at 12:00 h (mmol H_2O m^{-2} s^{-1});

E_d or **$E9_h$** – Transpiration rate at 09:00 h (mmol H_2O m^{-2} s^{-1});

gs - Stomatal conductance (mmol m^{-2} s^{-1});

A/ci – carboxylic efficiency (µmol CO_2 μbar^{-1})

Photosynthetic pigments

Car_{tot} – Total carotenoids (mg cm^{-2});

Chl_{tot} – Total chlorophyll (mg cm^{-2});

Chla/Chlb– Ratio of chlorophyll a and chlorophyll b;

Chl/Car– Ratio of chlorophyll and carotenoids;

Soil parameters

θ_{soil} or **θ_{solo}** – Soil water content (cm^{-3} H_2O 100cm^{-3}soil);

θ_{WP} - Soil water content at wilting point (m^3 m^{-3});

θ_{FC} - Soil water content at field capacity (m^3 m^{-3});

θ_{avg} **-** Mean soil water content on the first 0-40 cm;

Z_r - Rooting depth (m);

$\Psi w_{m\ soil}$ – Soil water matric potential (MPa);

Plant water parameters

Ψw_d or **Ψw_m** - Dawn water potential measured at 09:00 h (MPa);

Ψw_{pd} or **Ψw_{base}** - Predawn water potential measured before sunrise (MPa);

Ψw_{md} or **Ψw_{ramo}**– Midday stem water potential (MPa);

Ψw_l or **$\Psi w_{w\ folha}$**– Leaf water potential measured at daylight (MPa)

Ψw_s - Stem water potential (MPa)

RWC – Relative leaf water content (%);

T_{leaf} or T_{folha} – leaf temperature (°C);

Treatments

NI – Trees were not irrigated during the whole chestnut's vegetative cycle.

DI – Trees were deficiently irrigated – micro-sprinkler irrigation started when dawn water potential was below -0.8 MPa

FI – Trees were full irrigated – micro-sprinkler irrigation started when dawn water potential was bellow -0.6 MPa

SI – Trees were irrigated with a hanging micro-sprinkler when midday stem water potential was below -1.2 MPa

TI - Trees were irrigated with a double line drip system when midday stem water potential was below -1.2 MPa

RR – Árvores regadas por micro-aspersão e gota-a-gota sempre que potencial hídrico de ramo ao meio dia era inferior a -1.2 MPa

NR – Árvores não regadas durante o ciclo vegetativo

THESIS STRUCTURE

This manuscript was written based on four years of field work where two experimental trials were performed. The database from the field work was gathered according to specific objectives approached in different scientific articles which, by their turn, aim to answer the main objective of this project. The scientific articles are shown in the original language in what they were published. So, the thesis structure is composed by the following chapters:

CHAPTER I – GENERAL INTRODUCTION explains the background of this project in terms of its conception and the entities evolved. It is made a brief statement of the irrigation problem on chestnut tree and the objectives are defined.

CHAPTER II- LITERATURE REVIEW makes a general characterization of the European and in particular the Portuguese chestnut sector context. The chapter deals with the challenges that the chestnut sector will have in the near future which makes the bridge for the existence of this study. Because the main problematic is about water management, it is made an overview of this theme in other fruit crops that underpin the methodology used in this study.

CHAPTER III - STUDY AREA gives an overview of the study area; its location, soil features and climatic condition as well as it describes the experimental trials.

CHAPTER IV – PHOTOSYNTHETIC TRAITS OF THE CHESTNUT TREE UNDER IRRIGATION is about various physiological features evaluated on the chestnut trees and soil behaviour under different water regimes. It is composed by two scientific articles with data mainly from 2013, and by a third scientific article with data from 2015 and 2016.

CHAPTER V – THE EFFECT OF IRRIGATION ON THE CHESTNUT'S CHEMICAL COMPOSITION, FRUIT SIZE AND SENSORIAL ATTRIBUTES is composed by one scientific article and it approaches the effect of irrigation on the chestnut fruit quality which concerns its biochemistry composition and sensorial parameters; results are from the years 2015 and 2016.

CHAPTER VI - UNDERSTANDING THE SOIL AND PLANT WATER RELATIONS ON CHESTNUT TREES TO IMPROVE WATER MANAGEMENT is composed by two scientific articles which essentially reflect upon the soil and plant water relationship and gives primary directions about managing water in the chestnut orchards.

CHAPTER VII - ECONOMICAL ANALISYS OF THE CHESTNUT TREE IN IRRIGATED OR NON-IRRIGATED ORCHARDS is composed by one scientific article which deals with the study on yield of the chestnut orchard when in rainfed or under two irrigation systems types and the database is from 2015 and 2016.

CHAPTER VIII - CONCLUSION finally, there is a general discussion about all the works presented in this study and a general reflection on the objectives achievement.

CHAPTER VIII – REFERENCES where the references used to support this work can be found and includes the articles published during the project.

I. GENERAL INTRODUCTION

A. The project background: a partnership to strengthen the chestnut sector

In Europe, chestnut production fruit (*Castanea sativa* Mill) are mainly from the Mediterranean countries and from traditionally rainfed orchards. In a context of climate change there is a prediction that summers will be longer, hotter and drier than in the past thus affecting healthy trees and inducing strong variations in fruit production. The chestnut is specie with considerable water needs during its vegetative cycle, especially during August and September. The introduction of irrigation with high water use efficiency by the trees might be the option for the future due to the increasing water restrictions in the Mediterranean countries.

The necessity to increase knowledge and innovation to face the upcoming challenges for this crop were on the basis of the present partnership between different entities over the last four years; GEOSIL – Empreendimentos Agrosilvícolas SA, a chestnut producing company and the owner of the orchard where the study was conducted; the specialized private company in irrigation systems, management and plant nutrition, Hubel Verde SA – Engenharia Agronómica; and the public scientific research entity with great experience in chestnut research, CITAB-UTAD – Trás-os-Montes e Alto Douro University. The collaboration of the Portuguese Association on Chestnut – Refcast was also very important.

The present thesis is the first study about chestnut irrigation and intends to answer many basic questions in order to give primordial information about a smart irrigation for chestnut trees and hopefully being useful for further studies.

B. Objectives

The starting point for this study is based on the certainty that water restriction influences the production of a chestnut orchard. Therefore, the main objective of this research work is to evaluate the contribution of irrigation on the increasing productivity and stabilizing annual production through a water management based on soil and plant water relations.

The following specific objectives were defined:

- To evaluate the influence of irrigation on the chestnuts' quality (production, calibre, chemical composition and sensorial attributes).
- To deepen knowledge on the chestnut tree's nutrition for further use in fertigation.
- To identify, select and define values of plant parameters that are able to be used in water management;
- To relate the plant with soil parameters to optimize the irrigation scheduling based on communicable soil devices;
- To compare two irrigation systems: the hanging micro-sprinkler and the drip system;
- To evaluate the economic feasibility of two types of irrigation systems on the chestnut orchard;

II. LITERATURE REVIEW

C. Taxonomy, botany and ecology of the sweet chestnut tree

The latin name of the European sweet chestnut specie is *Castanea sativa* Mill.. According to Cronquist (1968), the European chestnut presents the following taxonomic classification:

Kingdom:	Plantae
Sub-Kingdom:	Embryophyta (Cornophyta)
Division:	Spermatophyta (Anthophyta)
Sub-Division:	Angiospermae (Magnoliophytina)
Class:	Dicotyledonae (Magnoliopsida)
Sub-Class:	Hamamelidae
Order:	Fagales
Family:	Fagaceae
Sub-Family:	Castaneoideae
Genus:	*Castanea*
Specie:	*Castanea sativa*

The *Castanea sativa* is a deciduous plant, with simple and alternate leaves, with oblong-lanceolate limbus, acute or acuminate apex, and crenate-serrated or serrated marginal cut (Fig. C-1, A). The root system is deep and steep, with most roots on the first 50 cm of soil (Fig. C-1, B) but the root's depth naturally depends on the soil's thickness and mobilization before plantation (Portela *et al*, 2007).

The chestnut tree is a monoecious tree with male and female flowers on the same plant. The male flowers are called catkins and can be unisexual (Fig. C-1, A) or androgynous with female inflorescences at the base of the catkin (Fig. C-1, C). Chestnut flowers are not self-compatible, so the pollination of the chestnut tree is mainly crossed. In general, and depending on climatic factors, the bloom happens from June to July, and it starts as soon as the sum of temperatures is at least 3,200 ºC (Fenaroli, 1945) and after the completed vegetative growth of the new branches where the catkins showed up (Guerreiro, 1957).

The fruit is a voluminous, reddish-brown achene that is protected by a dome (urchin) formed from the receptacle and covered by thorny bracts (Fig. C-1, D). The urchin is normally dehiscent and two to three fruits are released. The fruit maturation takes about 75 to 120 days since the pollination and it needs a sum temperature of about 2,100 to 2,500ºC after flowering (Gomes-Laranjo *et al*, 2007). In natural conditions, generally the first yield occurs in 15 year-old trees but in grafted-chestnuts the first yield can happen after only 5 years.

The chestnut tree is widely dispersed in Europe between the 37°N to 53°N latitudes. In Portugal, it occupies soils from sea level on the sea cost (Madeira Island, Azores Island and Minho Region) up to 1000 m a.s.l. in the inner regions (Trás-os-Montes region) where annual mean maximal air temperature ranges from 27°C up to 31°C, respectively (Gomes-Laranjo *et al*, 2007). The annual mean precipitation must range between 600 and 2000 mm year^{-1} and solar radiation between 1,600 to 2,600 hours (Gomes-Laranjo *et al*, 2007). The sweet chestnut tree grows on a wide variety of soils but preferably in deep, moderately fertile and acid soils with pH values around 6.0 (Portela *et al*, 2007; Dengiz *et al*, 2011).

Fig. C-1 *Castanea sativa* detailed photos of: A) **serrate leaves and unisexual catkins in bloom; B) deep roots; C) androgynous catkins with the female flower at the base; D) bur with three sweet chestnuts.**

D. Past, present and future of the Portuguese chestnut sector

Chestnut trees have a millenary presence in Portugal witnessed by trace fossils from different ages (Abreu, 2007). Most probably, the European chestnut tree has its origin in the Chinese chestnut (*Castanea molissima* Bl.) and its European dispersion began in the mountain regions of Anatolia in Turkey (Villani *et al.*, 1999). The ancient Greeks played a fundamental role in developing the cultivation of chestnut especially in the Italian Greek colonies and later it was spread throughout the empire by the Romans without no evidence of systematic tree planting (Conedera *et al.*, 2007). The chestnut tree assumed an important role in certain historical periods for the survival of the mountain people of most Mediterranean and southern parts of Central Europe either as a food source or timber production (Conedera *et al.*, 2007). Nowadays it is still mainly dispersed throughout Mediterranean countries and Central Europe as shown in Fig. D-1.

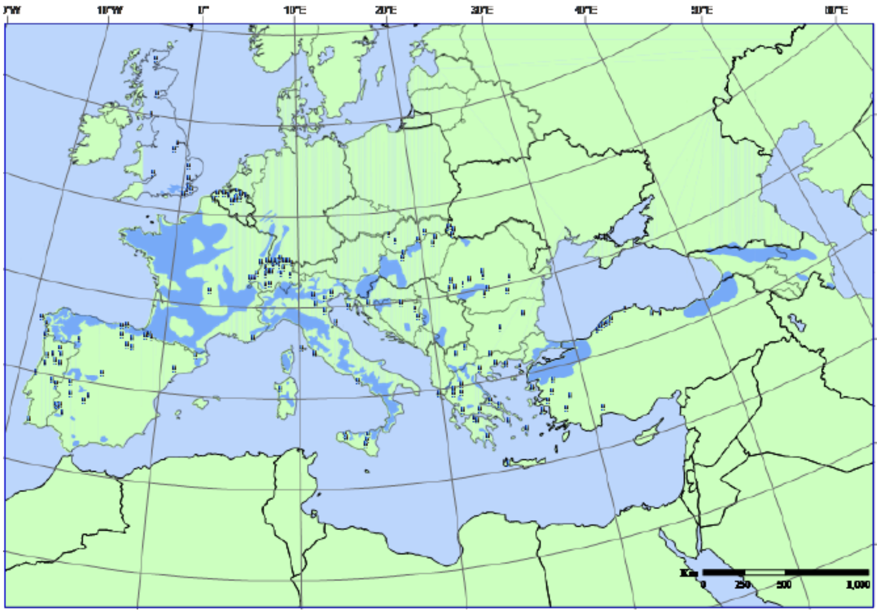


Fig. D-1 - *Castanea sativa* dispersion map (source: EUFORGEN, 2016).

The "golden age" of the chestnut started in the Renaissance period and lasted until the XIX century (Abreu, 2007) but the decline of the traditional European chestnut culture took place in different countries at different times, including Portugal, from common driving factors (Ferreira-Cardoso, 2007) such as: the introduction and spread of the soil-born plant pathogen *Phytophthora* spp. (ink disease) and the wound-parasite *Cryphonectria parasitica* (chestnut blight); the introduction of new crops with a proper and efficient logistic such as potatoes or maize that allowed a greater production of calories with shorter rotation cycle, causing the progressive substitution of the chestnuts as a staple food; the industrial revolution had changed the social and economical system in rural areas because it led to urban migration with consequent rural depopulation and population aging in rural areas; the inconsequent and systematic cut of chestnut groves for tannin production from the wood without re-plantation of chestnut trees; and finally the forest fires that systematically occur in Portugal that burn the chestnut trees.

The above factors explained the decrease of the chestnut area in Portugal from an estimated 70.000 hectares in the fifties of 20th Century, to 30,048 hectares in 2014 (INE, 2016). The last available data revealed that Portugal had increased its chestnut area up to 35,595 ha and most of it is located in the northern region (31,346 ha) (INE, 2016). This increment in area is attributed to several financial incentives given by National and European programmes but, even so, the mean productivity is far from other chestnut producing countries (Tab. D-1). Portugal has the lowest productivity values (0.7 t ha^{-1}), with the exception of Alentejo (3 t ha^{-1}). However, these values may be erroneous because it considers the unproductive new plantations, the unproductive area due to illness and mortality plus the parallel market or auto-consumption that is not contemplated. Many studies refer an average tree production ranging between 40 and 60 kg of chestnut (Martins *et al*., 2011) which represents a yield of 4 to 6 t ha^{-1} (with 100 trees ha^{-1}). So, it is acceptable to say that a healthy adult chestnut orchard in Portugal produces more than 4 t ha^{-1}. Nevertheless, during the time of this study (2013 to 2016), the National chestnut production varied from 24,739 t in 2013 to 18,465 t in 2014, being this decay mainly justified by unfavourable climatic conditions and disease development in 2014 (INE, 2015). In 2015, the production was about 27,628 t and in 2016, Portugal produced 26,780 t (INE, 2017) being the third biggest European producer of chestnuts (Tab. D-1). The producer's price increased from 2013 to 2014 (171.60 € to 212.37 € per 100 kg, respectively) but decreased in 2015 to 149.94 € 100 kg^{-1} (INE, 2016), increasing again in 2016 (179.09 € 100 kg^{-1}) (INE, 2017). Concerning exportations, in 2016, Portugal sold 19,783 t of chestnuts which represented about 51 million Euros of gains to the Portuguese economy and merely imported 1,292 t (INE, 2017).

Tab. D-1 - Total area (ha), production (t) and calculated yield (t ha^{-1}) of chestnut trees for the main producing countries and for the Portuguese regions.

Main countries/region	Total Area	Total production	Calculated yield
China*	305,000	1,650,000	5.4
Republic of Korea*	36,500	70,000	1.9
Turkey*	38,780	59,789	1.5
Italy*	25,000	52,000	2.1
Japan*	21,000	20,900	1.0
Portugal**	35,718	26,780	0.7
North region	31,439	22,136	0.7
Centre region	3,582	2,819	0.8
Lisbon region	5	6	1.2
Alentejo region	522	1,562	3.0
Algarve region	16	15	0.9
Spain*	7,000	10,000	1.4
France*	7,165	8,581	1.2
Greece *	6,900	8700	1.3

* Last available data from FAO, 2012.

** Last available data from INE, 2017.

The Portuguese chestnut production system has some features we can highlight such as:

- The chestnut trees are mainly located in mountainous regions that are sparsely inhabited and market isolated populations (Gomes-Laranjo *et al*., 2016);
- The majority of the chestnut trees are seedlings from *C. sativa* grafted with autochthonous varieties; recently, autochthonous varieties have been grafted on ink resistant rootstock (Ca90; COLUTAD) (Gomes-Laranjo *et al*., 2016);
- Some new plantations use hybrid varieties (usually French developed varieties such as Marigoule or Bouche Betizac) (Gomes-Laranjo *et al*., 2016);
- The majority of the orchards are old and most of them are affected by ink or blight (Gomes-Laranjo *et al*., 2016);
- Traditional tree spacing was usually of 12 x 12 m or 10 x 10 m. Nowadays, when used hybrid rootstocks the space has been adjusted to 9 x 9 m or eventually 8 x 8 m (Gomes-Laranjo *et al*., 2016);
- Soil mobilization is commonly done in spite of warnings about its prejudicial effects (Martins *et al*. 2010, Raimundo *et al*. 2007);

- Very few producers incorporate manure or fertilizers to the soil as well as liming for soil's pH correction according soil analysis (Gomes-Laranjo *et al*., 2016);
- Sanitary cuttings and initial formation pruning are frequently done (Gomes-Laranjo *et al*., 2016);
- The majority of chestnut trees do not have an irrigation system (Gomes-Laranjo *et al*., 2016);
- The ink and cancer diseases are still in expansion (Martins *et al.*, 2016);
- The *Dryocosmus kuriphilus* Yasumatsu was installed in Portugal since 2014, being in expansion (DRAPN, 2016);
- The high Asiatic chestnut production influences the market price (Bertoncello, 2016);
- The chestnut groves are located in regions with dry a hot summers (Gomes-Laranjo *et al*., 2007).

The 21st century brings new challenges to the world and this is transversal to the chestnut sector. FAO (2011) describes a few challenges for food security in the 21st century many of which the chestnut sector must be aware of in order to inspire itself to guide its own future. The primary concerns/challenges exposed by FAO (2011) are related with **a)** the rapidly growing and urbanizing population which is expected to be of about 9.2 billion people in 2050; **b)** the availability of quality land and water resources to assure food security based on the intensification of their use but at same time aiming to mitigate the environmental impact; **c)** the climate change which is manifested in more frequent extreme weather episodes and shifts in seasons that affect food production in many areas of the world and finally **d)** globalization which is spurred by market liberalization, growth of international trade, increased international financial transactions and capital flows, advances in information and communication technologies and logistics systems.

Meeting the considerations made by Conedera *et al*. (2007) about the European chestnut tree, the Portuguese chestnut sector must embrace the new opportunities that arise from the changing needs of a society that has moved from being rural to industrial and urban-oriented and whose people are more and more sensitive to the new services and goods related with ecological source of food and environmentally friendly products, especially those from marginal and mountainous areas. The new derived fruit products such as frozen chestnut, beer, flour or pasta, increase the chestnut demand as raw material on human feeding or even on high gastronomy. The co-products are also being investigated, such as the fruit peel and wood due to their high content on tannins. The antioxidant properties have been studied to incorporate them on cheese and wine production (Barreira *et al*., 2008). People start to understand the chestnut tree as a multifunctional landscape element contributing for the biodiversity, multidisciplinary input to the producer, land and biodiversity conservation varieties. In the end, the European chestnut chain must be more and more innovative, cohesive and competitive on the production, industrial and market levels in order to have its own place in this globalized world.

At the crop level, there is a long way for the improvement of the modern agronomic techniques related both tree and soil management, such the soil cover with bio diverse pasture, soil chemical analysis, tree pruning, control of plagues and diseases, installation of irrigation systems, grafting with selected varieties. In spite of the fact that, traditionally, the chestnut tree is part of a multifunctional agro-system production it can also be faced as an intensive fruit crop with a huge market potential. This is especially true if we consider the changing of climatic conditions over the last decades. According to the Köppen-Geiger Climate Classification for the Iberian Peninsula and the Balearic Islands, Bragança council is located in an area classified as Csb (temperate with dry or temperate summer) (AEM and IMP, 2011).

Fig. D-2 shows the total annual precipitation and annual mean temperature of the last few decades (1980 to 2016) registered by the Portuguese government's official meteorological station located in Bragança which data can be accessed through the Portuguese Institute of the Sea and Atmosphere (IPMA) website. The high inter annual variation of both total precipitation and mean air temperature is quite clear. The average of annual air temperature of these decades is 15.7°C and the average annual precipitation of 827 mm. The linear tendency of the air's temperature increases along the last decades and the precipitation decreases slightly. This situation is expected to be more accentuated as predicted by Miranda *et al.* (2002) which refers increasing of air temperature and drier during the summer in Portugal. At the end, the present work arose taking into consideration this climatic prediction and the effect that it has in the chestnut production. The temperature effect on the chestnut tree have been studied (Gomes-Laranjo *et al.* 2006, Almeida *et al*. 2007, Dinis *et al*. 2011) and revealed morphological and physiological adaptive features of the chestnut tree related to the highest air's temperature but with undesirable reflects on the chestnut production, especially fruit calibre. In many years, the combination of hot and dry summer's time lead to the decreasing of the chestnut production and quality. Therefore, this study was developed thinking that irrigation might positively affect the chestnut production, increasing the productivity and buffering the production over the years. Thus it could be a tool to mitigate these stresses induced by climatic changes.

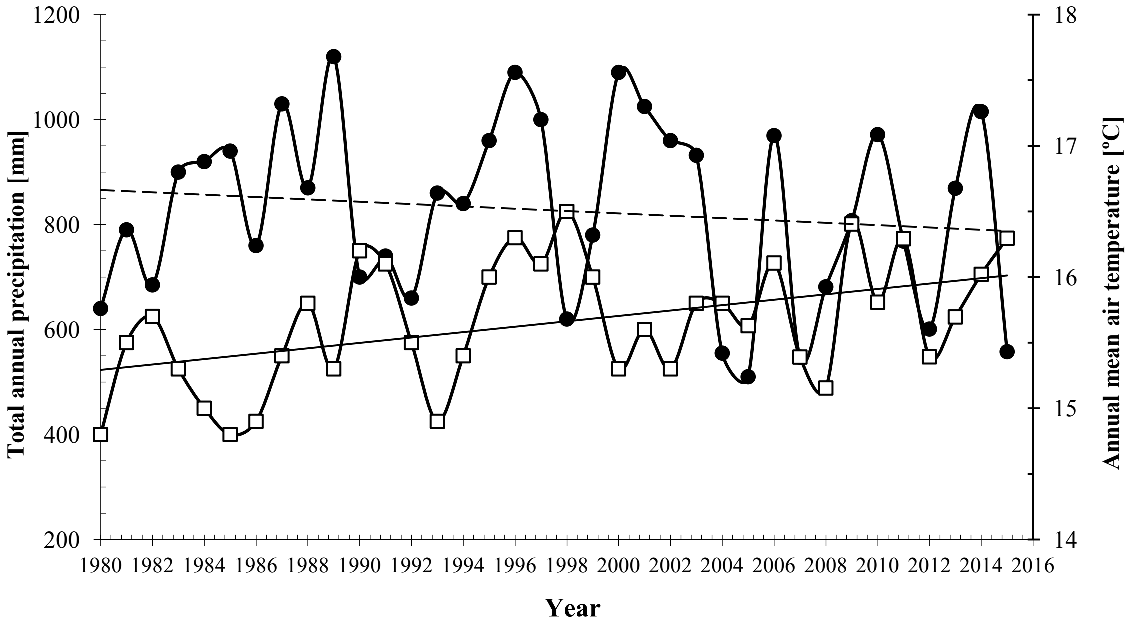


Fig. D-2 - Total annual precipitation (mm, ●) and annual mean air temperature (□), with respective tendency line, over the last few decades on the Bragança Region. Source: IPMA, 2018.

However, irrigation by itself is not interesting if the water is not correctly managed leading to waste of water and economical resources. For that reason, it is important to know about the proper way to irrigate chestnut trees which depends on the orchard's features, soil's type, irrigation system and irrigation scheduling. This is particularly challenging if we consider that other irrigated crops such as vineyards, nut trees or olive trees did not immediately transited from a forestry tree to an agricultural crop. However, the water management on the mentioned crops must be as the starting point for irrigation on chestnut trees due to their common features such as to be Mediterranean plants with deep root system.

E. Irrigation management on fruit trees

In spite of Breisch (1995) had concluded that watering the chestnut tree assures to the farmer a regular income and the correct water supply influences fruit load, mostly of the Portuguese chestnut growers do not irrigate them, even the new orchards. Contrarily, in France, mainly in the south-east region, where new plantations with hybrid varieties are common, irrigation is assumed as almost mandatory. Chestnut irrigation on old trees (more than 50 years) may be dispensable because of their ability to absorb water from deeper soil layers which allows them to refill their water levels during the night (Martins *et al.*, 2010). This last feature depends on the root depth which is highly related with the existence of compact soil layers. So, irrigation may also be useful if the orchards are installed on soil with a low effective thickness or if the soil has compact layers which induces the water deficit during the summer (Portela *et al*., 2007). The future must answer several questions about water management such as *how to* irrigate it, *how much* and *how many*?

Water management is a continuous decision-making endeavour about when to irrigate and how much water to give each time. Along this process, it is necessary to meet the water needs of the crop and to know its effectiveness, attending to the specific constraints of the irrigation method adopted, the availability of water resources and the financial and economic implications of the practice of irrigation (Pereira, 2007). When the understanding and management of these components is appropriated there is a more efficient use of water, saving of resources and reduction of costs while obtaining good yields.

Irrigation systems in fruit trees – how to irrigate?

There are numerous types of irrigation such as sprinklers, micro-sprinklers, drip tapes, bubblers, sprayers, micro-jets, pulsators or porous pipes (Phocaides, 2007). The irrigation system must be chosen depending on the water availability and its purity, soil permeability and its water storage capacity, topography, value of production, labour costs, energy costs, capital and technology requirement (Brower *et al.* 2003, Pereira 2007).

In the past the surface irrigation was the most common method used in orchards but this method often requires a much higher labour input - for construction, operation and maintenance - than sprinkler or drip irrigation. Surface irrigation requires accurate land levelling, regular maintenance and a high level of farmers' organization to operate the system (Brower *et al.,* 2003). Nowadays, fruit trees are commonly irrigated by drip systems or micro-sprinkler systems or even by both. For instance, in some of the kiwifruit orchards there are daily drip-irrigated conjugated with micro-sprinklers to increase air humidity and decrease air temperature around the canopy (Monastra *et al*., 1997). In the chestnut orchards the common irrigation type is the micro-sprinkler or the drip system (Valderrama, 2016).

In general, drip irrigation system has been preferentially used on fruit orchards because it is easily adapted to automation and allows a great economy of water and nutrients. It involves dripping water onto the soil at very low rate (2-20 L h^{-1}) from a system of small diameter plastic pipes fitted with outlets called emitters or drippers. Water is applied close to plants so that only part of the soil in which the roots grow is wetted reducing weeds growing and reducing evaporation (Brower *et al.,* 2003). It is adaptable to any farmable slope, to most of the soils, to trees and row crops and to saline water (Brower *et al.*, 2003). However, it requires a high capital investment, a proper filtration system to clean water up from sediments to avoid drippers' blockage and a high level of 'know-how' has to be available for equipment maintenance (Brower *et al.* 2003, Pereira 2007). Several drip systems can be found in fruit orchards: in single or double line, with a sub lateral loops or a single line suspended from the soil (Fig. E-1).

Fig. E-1 - Examples of A) drip line with sublateral loop (retrieved from FAO, 2018); and drip system with single (B) or double (C) line (retrieved from Amnon, 2018)

By its turn the micro-sprinkler system has a larger area of coverage, lower susceptibility to clogging due to larger orifice sizes, operates under low pressure (typically 1.4 – 2.4 bar), with wetting patterns of 3 to 10 meters, and a variety of discharge flows from 35 to

300 L h^{-1} to more closely match soil infiltration rates, orchard size, tree maturity and spacing and the depth of the rooting system and can be used for frost control (Godin and Broner, 2013). However, the micro-sprinkler system, has a higher potential for evaporation and wind drift issues when compared to drip, waters both crops and weeds, cannot be used on crops susceptible to foliar diseases and has a higher potential for soil rusting, water runoff and erosion compared to drip (Godin and Broner, 2013) (

Fig. **E-2**).

Fig. E-2 – The hanging micro-sprinkler irrigation (A, photos retrieved from Amnon, 2018) and micro-sprinkler irrigation (B, photos retrieved from Amnon, 2018).

Another alternative are the sub-surface drip systems. The benefits are related with savings of energy and water due to low evaporation; the farm equipment can enter the farm even during irrigation events, limits crusting of the soil surface, reduces the potential of weeds germination and can be an alternative for disposing wastewaters with an unpleasant smell (Payero *et al*., 2005). However, it requires a great initial investment and a well pre-designed project since after installation it no longer can be changed; several types of particles can clog the dripers if the system does not have a good filtration system, a flushing system, air/vacuum release valves or proper use of chemicals (acids, chlorines or herbicides); the rodents are also a huge problem in this systems (Benham and Payero 2001, Payero *et al.* 2005). For the chestnut tree this system would be preferable installed simultaneously with the plantation, since after it the opening of rows for the pipes can damage the roots and increase the potential development of ink disease (Fig. E-3).

Fig. E-3 - Double surface drip line in olive trees (A, photo retrieved from Hydrotech, 2018) and simple subsurface drip line in vineyards (B, photo retrieved from Extension, 2018).

Whichever the irrigation type chosen, its performance must be evaluated through its distribution uniformity (*DU*) and application efficiency (*AE*) (Burt *et al.* 1997, Pereira 2007). The *DU* measures the system's ability to apply water uniformly throughout the plot in order to avoid lost production due to a deficit or excess of water in the soil. *AE* measures the ability of the person to manage the system to apply more accurately the needs of water which implies knowledge about the features and constraints of the irrigation system as well as the water requirements of the crop (Pereira, 2007). The equation that translate these irrigation performance indicators are:

$$\text{(Eq.1) } DU = 100(Zlq \div Zavg)$$

Where: *DU* is the distribution uniformity (%) of the irrigation system; Z_{lq} is the mean of the lowest quartile of water infiltrated in the irrigated area (mm) and Z_{avg} is the average amount of water infiltrated on the plot (mm).

$$\text{(Eq. 2) } AE = 100 \times (Zr, lq \div D)$$

Where: *AE* is the application efficiency (%) of the irrigation system; $Z_{r,lq}$ is the average amount of water added to storage in the root zone in the lower quartile (mm) and *D* is the total allocation applied (mm).

Low values of *DU* translate conditions of excess or infiltration deficit into parts of the plot (Burt *et al.*, 1997) causing production losses due to both deficit and excess water in the soil, and losses of water and fertilizers where water infiltrated in excess percolates beyond the root zone. On its turn, low values of *AE* indicate that some of the water applied is not used for production and can actually be lost if added to groundwater or degraded surface water. The *DU* depends essentially on the variables that characterize the irrigation system and that are usually involved in the simulation and design models. In a micro-irrigation system, the variables are the emitters' pressure, pressure variation within the system, coefficient variation of the emitters' debit, emitters' flow regime and filtration features (Pereira *et al.*, 2007). On the other hand, the application efficiency depends on the same project variables related to *DU* plus the variables of water management such as the soil's water at the moment of irrigation, duration of the irrigation and irrigations' frequency (Pereira, 2007).

Irrigation scheduling: when to irrigate and how much?

Before the explanation of the different methods that are used to plan irrigation some soil's features definition must be known in order to do proper irrigation. Thus, it is necessary to know the total soil water availability (*TAW*) that refers to the capacity of a soil to retain water available to plants on a certain soil depth and is given by the difference between field capacity (*FC*) and the wilting point (*WP*). The *FC* is the amount of water that a well-drained soil should hold against gravitational forces or the amount of water remaining when downward drainage has markedly decreased while the *WP* is the soil water content at which plants will permanently wilt because the crop can no longer extract the remaining water. The *TAW* is given by the following equation (Allen *et al.* 1998):

$$\text{(Eq.3)}\ TAW = 1000(\theta FC - \theta WP)Zr$$

Where: *TAW* is the total available soil water in the root zone (mm), θ_{FC} is the water content at field capacity ($m^3\ m^{-3}$), θ_{WP} is the water content at wilting point ($m^3\ m^{-3}$) and Zr the rooting depth (m). Typical ranges of *FC* and *WP* for different soils and effective rooting depth can be consulted in Allen *et al.* (1998).

Although the water is theoretically available until the wilting point, the crop water uptake is strongly reduced well before wilting point is reached. So the fraction of *TAW* that a crop can extract from the root zone without suffering water stress is the readily available soil water (*RAW*) given by the equation:

$$(\text{Eq.4}) \quad RAW = p \times TAW$$

Where: p is the average fraction of *TAW* that can be depleted from the root zone before moisture stress and normally varies from 0.30 for shallow rooted plants at high rates of ETc (> 8 mm d^{-1}) to 0.70 for deep rooted plants at low rates of ETc (< 3 mm d^{-1}). A value of 0.50 for p is commonly used for many tree crops (Allen *et al.* 1998).

Additionally, there is another term, the Management Allowed Depletion (*MAD*), which is influenced by management and economic factors in addition to the eco-physiological factors influencing p. When irrigation is scheduled in absence of crop water stress, the *MAD* parameter can be assumed equal to the p coefficient. When irrigation is managed under water deficit conditions the *MAD* parameter is higher than p. This last circumstance is typical of the arid Mediterranean environments (Rallo *et al*., 2010).

Finally, there are several options to plan the irrigation but they can generally be divided into i) **evapotranspiration-based methods**; ii) **soil-based methods** and by iii) **plant-based methods**.

The **evapotranspiration-based methods** are underlined that the crop water requirements are equal to the crop evapotranspiration (ET_c). The evapotranspiration reflects the water loss by the crop's transpiration plus the water loss from the surface soil either by soil's evaporation or herbaceous' transpiration (Allen *et al.* 1998). Basically, the evapotranspiration-based methods approach starts the irrigation season with a soil profile at maximum water holding capacity and replaces the water used by ET_c, at each irrigation (Fallahi *et al.* 2010, Godin and Broner 2013). The irrigation intervals depend on the *RAW* or *MAD*; when it is a sandy soil the intervals are shorter (daily) and when it is a clay soil the irrigation intervals are longer (days).

To know the ET_c it can be used the hydrological or the micrometeorological methods or by conjugation of the sap flow measurements to determine the crop's transpiration with soil's evaporation measurements (Silva, 2010). The micrometeorological methods quantify the water flow to the atmosphere using meteorological variables observed at one or two levels above the evaporating surface and using equations describing the water vapour flow in the atmosphere. Thus three type of information can be found: energy balance method, aerodynamic methods and the method of instantaneous fluctuations (eddy covariance, EC) (Silva, 2010). In spite of it reliability the micrometeorological methods require the installation of towers to carry out the measurements, homogeneous plots with large dimensions and relatively flat and expensive instruments for routine application (Silva, 2010).

The hydrological method is based on the soil water balance. The soil water balance consists of assessing the incoming and outgoing water flux into the crop root zone over a period of time (Allen *et al.* 1998) as represented in Fig. E-4.

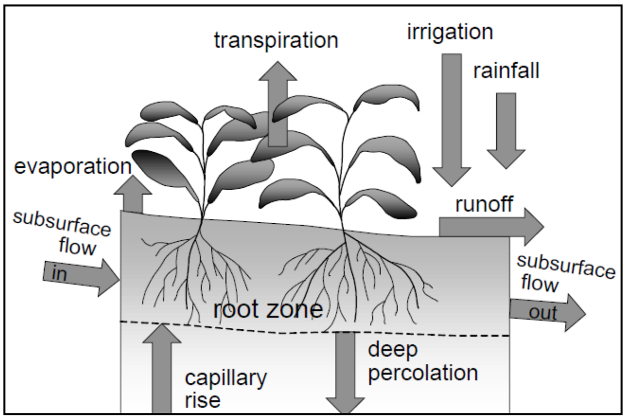


Fig. E-4 - Representation of the incoming and outgoing water flux into the crop root zone, the soil water balance (adapted from Allen *et al.*, 1998).

The soil water balance can be accessed by lysimeters. This is an expensive method, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel (Allen *et al.*, 1998). Then, the following equation can be used to determined ET_c:

$$\text{(Eq.5)} \quad ETc = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW$$

Where: irrigation (*I*) and rainfall (*P*) add water to the root zone. Part of this water might be lost by surface runoff (*RO*) and by deep percolation (*DP*). Water might also be transported upward by capillary rise (*CR*) from a shallow water table towards the root zone or even transferred horizontally by subsurface flow in (SF_{in}) or out of (SF_{out}) the root zone. In many situations, SF_{in} and SF_{out} are minor and can be ignored. Soil evaporation and crop transpiration (ET_c) deplete water from the root zone. If all fluxes other than ET_c can be assessed, then this last can be deduced from the change in soil water content (ΔSW). However, the hydrological method on fruit crops faces some constraints such as the characterization of the total soil volume explored by the deeper roots, the heterogeneity of the distribution of the root system in this volume and the low resolution associated to the method plus the difficulties and uncertainties in the determination of some terms of the water balance (Silva, 2010).

An easier and practical way to estimate the ET_c is using the so-called FAO Penman-Monteith method in where the ET_c is determined from the following simplified equation (Allen *et al*., 1998):

$$\text{(Eq.6) } ETc = ET0 \times Kc$$

Where: ET_0 is the reference evapotranspiration of a crop with an assumed height of 0.12 m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered and the Kc is the crop coefficient and serves as an aggregation of the physical and physiological differences between crops and also considers the crop size and vegetative stage. Various Kc can be consulted in Allen *et al.* (1998) under different climatic, ground, irrigation conditions and cultural practices but so far no information is given for the chestnut tree. The ET_0 may be available from a governmental meteorological station or it can be calculated following the equations of (Allen *et al*., 1998)

In the end, these mentioned methods are inappropriate for routine measurements and they do not allow continuous monitoring of what is occurring at the moment, so the irrigation decision is not made at the right time. So far, in Portugal an irrigation scheduling simulation based on the soil-water balance was developed under the model ISAREG and constitutes a useful tool for the farmers (Pereira *et al*., 2003).

The **soil-based methods** intend to measure, directly or indirectly, the soil moisture in order to decide about irrigation. The direct way to determine it is using the weight difference between before and after drying a soil sample, either by the gravimetric method (water content as weight of water over weight of dry soil) or by the volumetric method (volume of water related to the volume of an oven-dried undisturbed sample) (Munoz-Carpena, 2015). Although, these direct methods are accurate and inexpensive, they are destructive, slow, time-consuming and do not allow for repetitions in the same location. Alternatively, many indirect methods are available for monitoring soil moisture, in continuum or momentary, and the suitability of each method depends on several issues like cost, accuracy, response time, installation, management and durability (Oliveira 2003, Enciso *et al.* 2007, Munoz-Carpena 2015). Soil water status can be accessed by time-domain reflectometer *(TDR)* probes, by frequency- domain reflectometry *(FDR)* probes and by neutron probes to determine volumetric soil water content; or by tensiometer and by granular matrix sensors to determine the soil water matric potential (Munoz-Carpena, 2015). The matric potential is one of the components of the total soil water potential that also includes gravitational, osmotic, gas pressure and other overburden components (Munoz-Carpena, 2015).

The *TDR* probes are based on the dielectric constant of the soil which is higher if the soil is wetted and, to access it, an electromagnetic wave with high frequency is applied and the velocity of propagation is measured – the lower the velocity the higher the dielectric constant and the higher the soil humidity (Górriz, 2010). The *FDR* probes access the soil water volumetric content through capacitance sensors that create an electric field on a specific volume of soil and the electric frequency is different depending of the water and air content (Górriz, 2010).The neutron probes measure the energy lost on the soil by fast neutrons of high energy emitted from a decaying radioactive source – when the neutrons collide with the atomic nucleus of the soil and water they lose energy and become slow (Oliveira, 2003); this loss of energy depends on the presence of hydrogen and water which is the main source of hydrogen in most soils (Munoz-Carpena, 2015). The tensiometer instruments have a porous porcelain terminal in contact with the soil through which water can move and in the other extremity it has a pressure gauge that measures the pressure variation (Boteta *et al*., 2003). Thereby, water is drawn out of the porous medium in a dry soil and goes into it when the soil is wetted. The higher pressure read by the manometer means the soil is drier. The ‘Watermark’ sensor is a granular matrix sensor that measures the electric resistance between two electrodes soaked in a porous material – the soil water flows in the porous material until the matric potential is equal in the soil and in the sensor. The higher the electric resistance the drier is the soil (Lopes *et al*., 2003). All the referred soil-based methods are more or less automatic and can even be connected to the irrigation controller which eases the decision of irrigation. Nevertheless, when using soil-based methods other soil features such as soil texture, depth, field capacity, wilting point and groundwater level should be known to better use the water and the equipment. The major disadvantages of the use of soil-based methods in perennial plants, like the chestnut tree, are due to their deep and irregular root system that generally occupies a large volume of soil unevenly, exceeding the volume of irrigated soil, and in general, it is recommended to identify the average (representative) conditions in terms of soil type, depth, plant distribution, sources of water and place the instruments in each representative zone (Munoz-Carpena, 2015) and the number of instruments may be such that it becomes economically unfeasible.

According to Girona *et al.* (2006) the use of plant-based indicators to trigger irrigation provides more site-specific information and can thus account for spatial variations. The **plant-based methods** imply the selection of one or more physiological parameters that translate the plant water status. These parameters are monitored and, according to predefined threshold values, the irrigation can be decided. Because the plant's physiological behaviour is the final answer to the complex interaction between plant's morphology, soil features and climatic conditions normally the monitoring of these factors are in parallel to understand the plant response under known conditions and thus to give robustness to the reference physiological values. Within the plant water status indicators it can be mentioned the sap flow variation (Huguet *et al.* 1992, Silva 2010, Marsal *et al*. 2002) where is assumed an equivalence between sap flow in the trunk and transpiration being valid on a daily scale. There are several methods to determine the sap flow variation (heat impulse method, constant heating method or by heat balance method) and such methods can be automated, robust and relatively reliable for operation in field conditions for long periods of time (Fernández *et al*., 2008). Additionally, the root sap flow (Nadezhdina *et al.* 2008, David *et al.* 2013) helps to understand the water redistribution at root level and the passive hydraulic redistribution of water in the soil from areas with higher humidity to areas with lower water availability, and may play an important role in the redistribution of the vertical water profile (Nadezhdina *et al.* 2008). The trunk diameter fluctuation can be based on the maximum daily trunk shrinkage (*MDS*) or the trunk growth rate (*TGR*) (Livellara *et al*., 2011). The *MDS* is the difference between the maximum value of trunk diameter just before sunrise and the minimal value of the trunk diameter sometime in the afternoon and it is associated with the combined effects of soil water supply and evapotranspiration demand (Goldhamer and Fereres, 2001). The trunk diameter fluctuations are highly sensitive to changing soil moisture availability and it is related to plant water potential (Naor and Cohen, 2003) but there is a lack of reference values which would allow taking irrigation decisions. For any given environmental conditions, the leaf temperature is directly related to the rate of transpiration from the canopy surface. Therefore, infrared sensing of the canopy temperature can be used to monitor stomatal conductance or to estimate the transpiration rate of plants but the measurements of leaf temperature alone are not enough to allow estimates of the transpiration rate or the stomatal conductance (Leinonen and Jones, 2004) and because leaves' temperature depends on air temperature, relative humidity, solar radiation, leaf resistance, and boundary layer resistance it is important to know and integrate all parameters (Udompetaikul *et al*., 2011) which gives complexity to this methodology. All the previous methods require sophisticated implementation, a high degree of technical support and special calibration requirements for each species and edapho-climatic conditions (Livellara *et al*., 2011) and few have actually been used by producers due to their complexity and high cost. For deeper details of plant-based methods it can be consulted the review of Jones (2004).

The measurement of the plant water potential by a pressure chamber is one of the commonest procedures to infer about plant water status for irrigation purpose. Although, the water potential readings are a non-continuous and non-automatic measurement, the lower variability, lower cost and greater amount of data in the literature make it more practical for commercial uses. In addition, it has been served to validate other plant parameters automation methodologies such as sap flow or trunk diameter fluctuations (Goldhamer and Fereres 2001, Cohen *et al*. 2012) or leaf temperature (Leinonen and Jones, 2004). The plant water potential can be read before sunrise (predawn water potential, Ψw_{pd}), under sunlight in transpiring leaves (leaf water potential, Ψw_l) or in shaded and non-transpiring leaves (stem water potential, Ψw_s), during daylight or specifically at midday (Ψw_{md}).

The Ψw_{pd} measures plant water status in non-transpiring leaves at practically zero plant water flux and provides information on the root's zone soil water potential because it is considered to be in equilibrium with the soil water status (Choné *et al*., 2001). However, under certain conditions of soil moisture's heterogeneity through the soil profile (Ameglio *et al*., 1997), soil water content, and in high trees with appreciable capacity to storage water internally (Donovan *et al*., 2001) the balance between the plant and the soil may not be achieved during the night. On the same way, the air vapour pressure deficit (VPD) origins some nocturnal transpiration (by cuticular way) and then the null water flux may not be verified. The predawn water potential also integrates the water potential gradient needed to keep the water flux during the night (Donovan *et al.* 2001, 2003). In the particular situations where exists hydraulic lift from roots to the soil there were observed unbalance between the predawn and the soil water status (Donovan *et al*., 2003). When used in orchards with drip or micro-sprinkler irrigation, the Ψw_{pd} may be less sensitive to gradual soil moisture depletion compared with techniques that incorporate the added stress of midday water movement in the tree. In spite of these particularities together with the inconvenient of the time of the reading and the low visibility at pre-dawn, the Ψw_{pd} may be preferred because it minimizes variations due to light exposure and temperature issues associated with daytime readings (Fulton *et al.*, 2014).

According to Shackel *et al.* (1997) the midday stem water potential (Ψw_{md}) has been indicated as the most sensitive and reasonable in the detection of water status of perennial crops such as almond, walnut and plum tree than the leaf water potential. It has shown to be very well correlated with soil water content and vapour pressure deficit. Similar findings are reported for the olive tree (Moriana *et al.* 2012, Gomez-del-Campo 2013) and for vineyards (Choné *et al.* 2001, Mirás-Avalos *et al.* 2014, 2016). The Ψw_{md} is currently considered a better indicator of the plant water status than the Ψw_l because the variability among the samples is smaller than the observed with Ψw_l and it is more sensitive to situations of lower water stress (Choné *et al.* 2001, Naor 2006). The Ψw_l uses an uncovered leaf when plant tension is greatest and there is a high variation among leaves from the same stem because each leaf experiences different light exposure and temperature. Garnier and Berger (1985) reported that bare leaves desiccate more rapidly when they are excised from the tree. On the procedure of the Ψw_{md} measurement, a leaf close to a main branch is selected and placed inside a foil bag to reduce photosynthesis and avoid transpiration so the leaf xylem sieve reaches equilibrium with that on stem of the adjacent branches and trunk (McCutchan and

Shackel 1992, Fulton *et al.* 2001). However, the measurements may show variability among the samplings depending on the variation rate of the pressure chamber (Naor and Peres, 2001) and on procedure's inconsistencies on the leave's isolation and advance in the reading (Fulton *et al.,* 2001). Unlike Ψw_{pd}, the readings of Ψw_{md} are done under full sunlight and the frame time for readings is larger compared with readings of midday leaf water potential (Fulton *et al.* 2014, Gómez-del-Campo 2013).

However, the Ψw_{md} is also affected by meteorological conditions, even if the irrigation management and soil moisture are stable. Researchers from the Fruit and Nut Research and Information Centre of the UC Davis' developed a refinement model of the use of the stem water potential for water management in prunes, almonds and walnuts, called SWP-baseline concept (Shackel 2011, Fulton *et al*. 2014). In summary, baseline values of the stem water potential were derived from mathematical models validated in field experiments such as in the McCutchan and Shackel (1992). Therefore, for a given air temperature and air relative humidity a predefined midday stem water potential value is expected when the crop has abundant soil moisture and without limiting transpiration. In practice the producers can evaluate the water status of their crop by comparing their stem water potential measurements with the baseline value given by the Fruit and Nut Research and Information Centre of the UC Davis' website after they have selected the nearest weather station to their farm. In addition, this platform provides referential values of stem water potential to use in regulated deficit irrigation (Fulton and Buchner, 2003).

Deficit Irrigation Concepts

Traditionally, the purpose of the crop irrigation management was to maintain the plants in full water comfort throughout the entire vegetative cycle but the benefit of controlling vegetative development in some crops resulting in less pruning, less incidence of disease, and improvement of fruit quality and value while saving water and economical resources took to the development of the deficit irrigation. Generally, there are two approaches to the deficit irrigation: the regulated deficit irrigation (*RDI*) and the partial root-zone irrigation (*PRI*).

The management mode with *PRI* requires a dual irrigation system that allows two separate soil volumes to be dampened (operated by the root system) and irrigation is performed alternately in each of the volumes with control of the water status of the plant. For deepen knowledge of this strategy it can be consulted studies on vineyards or apple tree (Santos *et al.* 2005, Fallahi *et al.* 2010) or the review Sepaskhah and Ahmadi (2010).

The *RDI* is based on the imposition of water restrictions at certain developmental periods when fruit growth is less sensitive to soil water deficit while full tree water requirements are applied during the rest of the season. The evaluation of the opportunity to apply water stress may be conducted using information from the evapotranspiration based-methods, from the soil-based methods or from plant-based methods. For instance, with *RDI*, the water furnished through irrigation can be such that only restore 50% of the ET_0 through the entire vegetative cycle or, alternatively, it restores 50% ET_0 during specific phenological stages and furnishing 100% ET_0 during other vegetative stages (see studies on olive tree, Fernández *et al*. 2013; in vineyards, Intrigliolo and Castel 2011; or in citrus, Ballester *et al.* 2013). The *RDI* using the stem water potential as irrigation based- decision allows the decreasing of the Ψw_{md} water comfort value during specific stages. For instance, in almonds, it is acceptable that irrigation can be such that keeps the Ψw_{md} between -0.6 to -1.0 MPa during the shoot growth but it is recommended to decrease to moderate levels of stress (-1.4 to -1.8 MPa) during hull split for the control of hull rot (Teviotdale *et al.*, 2011). For deepen knowledge of this strategy it can be consulted (Shackel *et al.* 2000, Buchner *et al.* 2005, Moriana *et al.* 2012, Mirás-Avalos *et al*. 2014).

The use of stem water potential for water management is based on the concept of soil-plant-air continuum (*SPAC*) theory. In Fulton *et al.* (2014) a simple explanation of this theory is detailed as we describe: the water moves from the soil into fine root tips, up through the vascular system, and out into atmosphere (Fig. E-5). Water flows through the tree from high potential in the soil (about -0.1 bar) to low potential in the atmosphere (- 40 bar). Low potential is created at leaf surface through the stomata that open and close to regulate gas exchange. Simultaneously, water held in the soil enters root tissue and begins its journey to the leaves. This creates a vacuum or tension within the water-conducting system of the tree. The amount of water depends on the balance between available soil moisture and the rate at which water is transpired from leaves. Innumerous computational models of irrigation management can be developed over this theory and various parameters of the plant's physiology, soil and climate have to be continuously monitored and integrated.

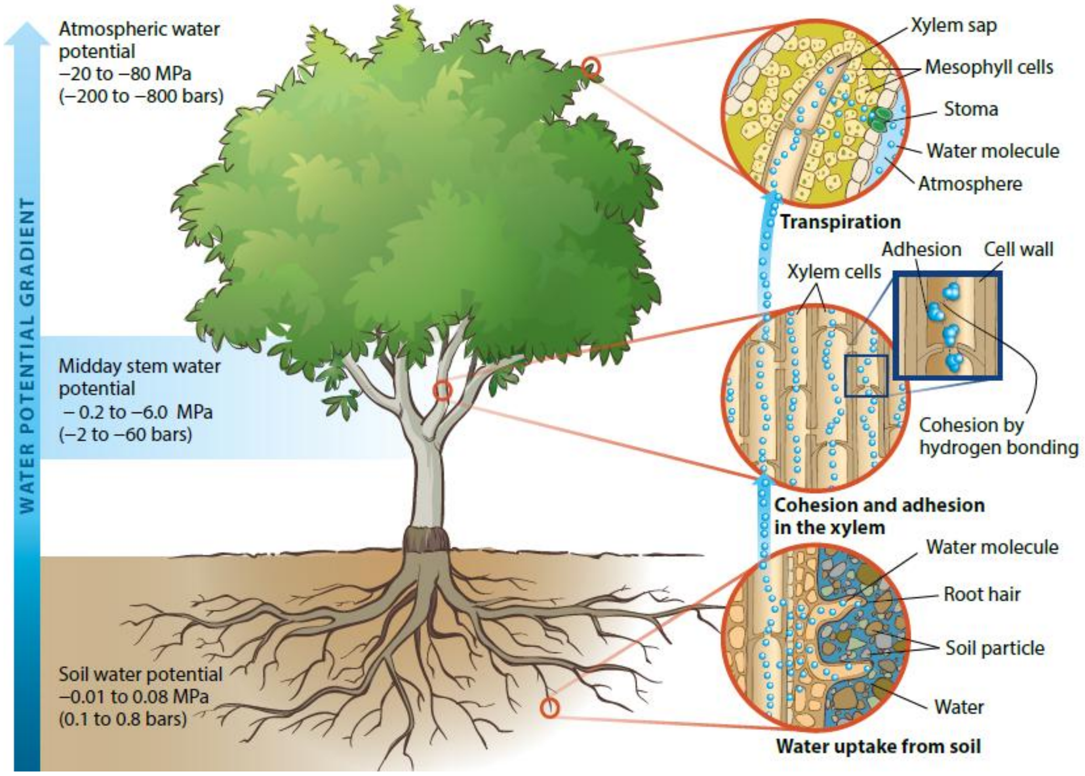


Fig. E-5- Soil-Plant-Atmosphere Continuum representation (adapted from: Fulton *et al*., 2014).

III. STUDY AREA

F. Site location and orchard characterization

The selection of the orchard was determined by its regional location and climatic conditions, by the variety used and by other factors such as field labour support, existence of electrical power and water availability. Thus, the study carry out in Sortes, a small town belonging to Bragança Council, located in the northeast of Portugal (41°39'28.16"N; 6°50'37.09"W) at 862 m above sea level (Fig. F-1) commonly named "Terra Fria Transmontana".

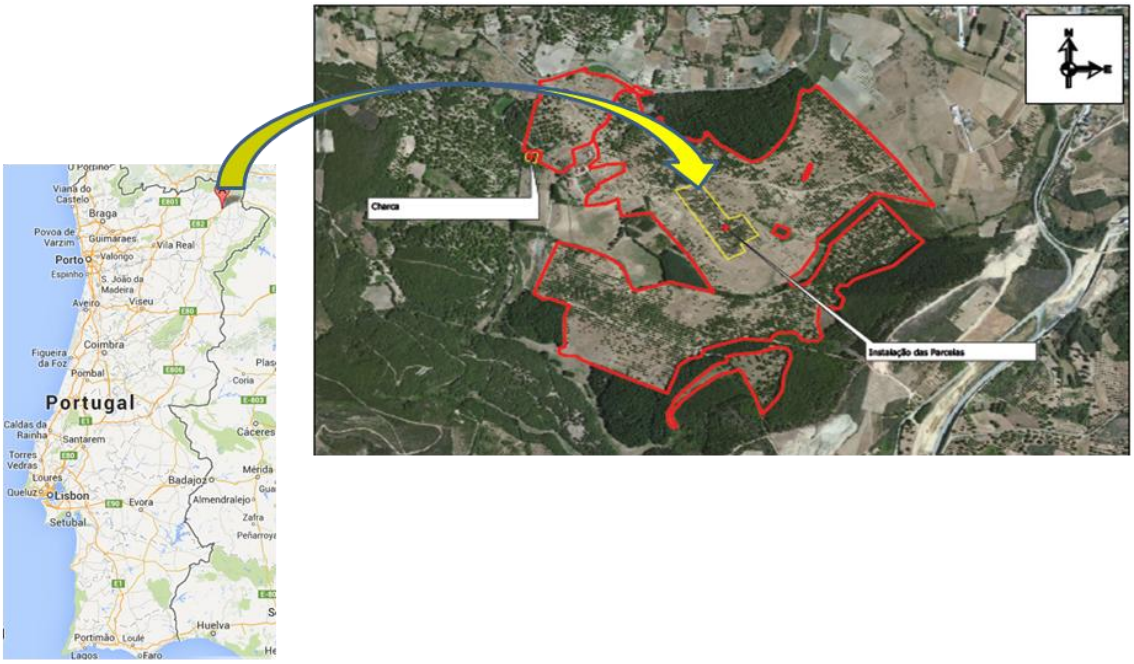


Fig. F-1 – Location of the study area - Sortes small town, Bragança Council, Northeast of Portugal. The red line defined the farm borderers and the yellow line the trial area. Adapted from GoogleEarth with updated photos in 2013.

The trial was done in a 20-year-old rainfed commercial chestnut orchard with 5 x 10 m tree spacing. The rootstocks were seedlings from *Castanea sativa* M. and grafted at the 2 m mark with 'Longal' and 'Judia' variety. The average of chestnut trees perimeter at breast height is of 0.87 ± 0.04 m, the crown projection area is of about 47.08 ± 3.98 m^2 and the canopy height begins at 1.9 ± 0.1 m from the soil.

The total study area had about 15.000 m^2 and the crop practices as fertilization, pasture management and pruning were made according to the grower decision. Since the first years of plantation, the soil is kept with seeded bio diverse pasture composed by

Trifolium repens, *Trifolium incarnatum*, *Trifolium subterraneum*, and grass-plot (annual and perennial) that are cut in middle of June. The pasture is fed by a flock of sheep and several types of mushrooms (eatable or not) appear at the autumn period (Fig. F-2)

Fig. F-2 - Landscape of the farm and study area: A - pasture with seeded legumes and grass-pot growing under the chestnut trees; B - chestnut trees; C - flock of sheep's pasturing after chestnut's harvesting; D- ***Amanita muscaria*** **mushroom not eatable.**

G. Meteorological characteristics

Meteorological data along the four years was obtained from the agro bulletins of the Portuguese Institute of Sea and Atmosphere's weather station, located in Bragança city. This weather station was 20 km far away from the study place and it was at lower altitude (670 m). These four years had similar features to what climatic conditions are concerned (

Fig. G-1), exception to 2014 which had a very wet summer (total precipitation, PP, of 37.5 mm in July and August). The July and August were the hottest and drier months (PP = 9.6, 7.9 and 10.6 mm in 2013, 2015 and 2016, respectively). The total annual precipitation in 2013, 2014, 2015 and 2016 was of 823, 747, 593 and 971 mm. The annual mean air temperature and relative humidity was of 12.7°C and 69.3% (2013), 13.1°C and 76.0% (2014), 13.4 °C and 74.5% (2015) and 13.2°C and 75.74% (2016), respectively. In what concerns the mean annual evapotranspiration of reference (ET_0) it was of 95.2 mm (2013), 92.0 mm (2014), 93.3 mm (2015) and 99.0 mm (2016). The growing degree days between May to October was of 2301 °D, 2206°D, 2348°D and 2504 °D for 2013, 2014, 2015 and 2016, respectively, considering a basal temperature of 6°C (Gomes-Laranjo *et al.*, 2008).

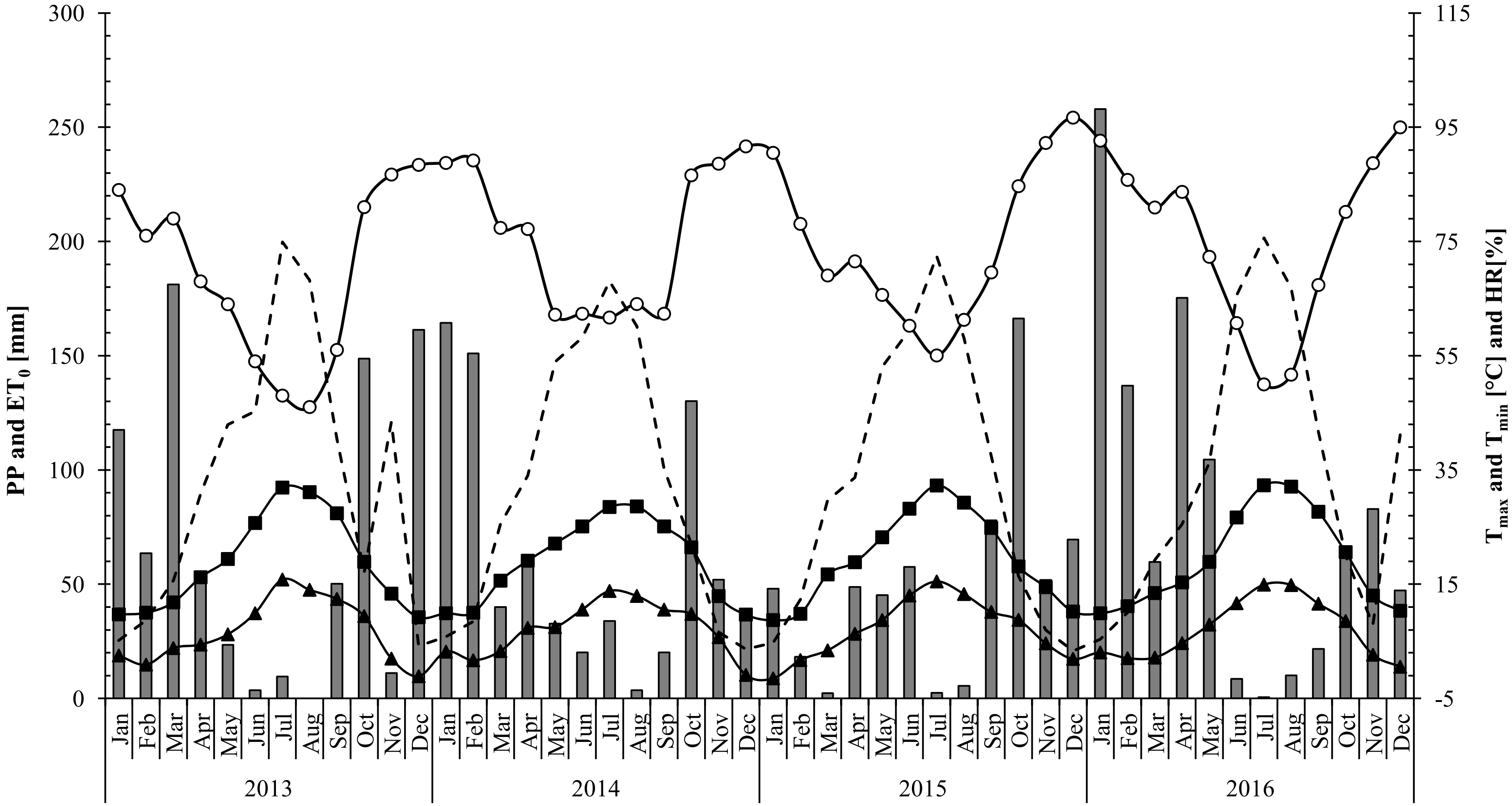


Fig. G-1- Meteorological features over the study years: monthly total precipitation, PP (mm, columns), monthly mean evapotranspiration of reference, ET_0 (mm, dash line), monthly mean air relative humidity, HR (%, ○), monthly mean maximal air temperature, T_{max} (°C, ■) and monthly mean minimal air temperature, T_{min} (°C,▲). Source: IPMA, 2013, 2014, 2015, 2016.

H. Soil physical and chemical characteristics

According Trás-os-Montes Map Soils (Agroconsultores and COBA, 1991) the area where the trial was implanted presents as dominant soil units the orthi-dystric Leptosols and the cambi-dystric leptosols, derived from schists and similar rock. The subdominant soil units are the chromi-dystric cambisols and the dystric regosols, derived from schists and similar rock. Three soil profiles were opened, in the inter row of the trees, according to the slope of the study area in order to do a soil detailed characterization (Fig. H-1). According to this procedure, the soils were classified as hapli-dystric cambissol (FAO, 2014) derived from schists (Tab. H-1).

Tab. H-1 - Morphological description of the soil profile of the hapli-dystric cambissol of the trial.

Ap₁	**0-15 cm** Yellowish brown (10 YR 5/6) (dry); dark yellowish brown (10 YR 3/6) (moist); loam with some gravel; blocky subangular medium structure, moderate; low compactness in moist; many pores; many fine roots of herbaceous; friable in moist; clear transition to
Ap₂	**15-29 cm** Yellowish brown (10 YR 5/6) (dry); dark yellowish brown (10 YR 3/6) (moist); loam with some gravel; blocky subangular medium structure, moderate; medium to high compactness in moist; few porosity; some fine and medium roots of chestnut tree; friable in moist; clear transition to
B	**29-57 cm** Brownish yellow (10 YR 6/6) (dry); yellowish brown (10 YR 5/6) (moist); loam with some gravel; blocky subangular medium structure, moderate; medium compactness in moist; many pores; many fine and medium roots of chestnut tree; friable in moist; clear transition to; diffuse and wavy transition to
C	**57-110 cm** Soft disintegrated schist, predominates the gravel and cobbles, as well as some fine earth; evidences of deep ripping up to 80 cm; the rocks' fragments have a light yellowish brown colour (2.5 Y 6/4) (moist) with brownish yellow spots (10 YR 6/6) (moist); diffuse and undulating transition to
R	**>110 cm** Compact schist with oblique cleavage.

In the experimental area the soils are moderately evolved (cambisols), with an average thickness of 100 cm, with the C horizon showing many coarse gravel and cobbles due to the deep ripping. Soils present a medium texture class (loam). According to INIAP

(2006) the organic matter content had a medium level in the superficial layer, presenting values close to 30 g kg^{-1}. The extractable P_2O_5 values are low and the extractable K_2O presented medium to high values. The values of the effective cation exchange capacity are very low to low and the degree of base saturation high in A horizon and low in B horizon. The water pH values are acid in A horizon and very acid in B horizon (Tab. H-2, Tab. H-3).

Tab. H-2 - Concentration of coarse elements (EC), coarse sand (SC), fine sand (FS), silt (S), clay (C), organic matter content (OM) and pH values for different soil depth.

Soil Depth	Horiz.	EC*	SC#	FS#	S#	C#	OM	pH	
(cm)		------------------------- g kg^{-1} -------------------------						(H_2O)	(KCl)
0-15	Ap1	255.5	290.8	303.2	253.3	152.7	3.2	5.0	4.2
15-29	Ap2	238.9	301.2	297.0	239.0	162.7	2.5	4.8	4.1
29-57	B	242.4	223.7	271.1	297.2	208.0	0.7	4.3	3.9

* - in relation to total earth; # - in relation to fine earth

Tab. H-3 - Exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+, Exchange acidity (EA), effective cation exchange capacity (ECEC), degree of base saturation (DBS) and extractable P_2O_5 and K_2O from different soil depth.

Soil Depth	Horiz.	Cations				EA	ECEC	DBS*	Extractable	
		Ca	Mg	K	Na				P_2O_5	K_2O
(cm)		---------------------- cmol$_c$ kg^{-1} ----------------						(%)	----- mg kg^{-1} -----	
0-15	Ap1	3.25	0.61	0.30	0.11	1.16	5.4	73.1	39.8	128.0
15-29	Ap2	1.97	0.26	0.22	0.08	1.76	4.3	53.3	26.0	120.0
29-57	B	1.60	0.16	0.16	0.08	3.19	5.2	39.7	11.1	96.0

* - in relation to ECEC

In each soil profile three soil samplings at different soil depth were collected to evaluate the soil field capacity and the wilting point (Tab. H-4). The moisture contents at field capacity and wilting point were determined with a pressure plate apparatus at -10 and -1500 kPa, respectively. In this method, undisturbed soil sample is placed on a porous ceramic plate in a chamber and saturated with water. A pressure of 10 or 1500 kPa is applied until equilibrium in water content between the plate and the soil sample is reached at which time soil water content is determined (Silva *et al*., 1975).

Tab. H-4 - Volumetric soil water content (cm^3 H_2O 100 cm^{-3}soil) at field capacity (pF = 2.0), wilting point (pF = 4.2) and Bulk density for different soil depth. The 'nd' means not determined.

Profile No.	Soil Depth cm	Bulk density (g cm^{-3})	Water at different pF's pF 2	pF 2.5	pF 4.2
1	0-15	1.4	29.9	25.0	11.0
	15-30	1.4	30.1	24.1	12.3
	30-60	nd	Nd	nd	nd
	60-80	1.4	Nd	nd	nd
2	0-15	1.5	28.8	25.5	11.2
	15-30	1.4	31.1	28.4	13.4
	30-60	1.4	30.8	28.5	15.7
	60-80	1.4	33.1	29.7	16.4
3	0-15	1.4	31.0	25.9	12.2
	15-30	1.4	33.7	28.6	13.5
	30-60	1.4	30.0	27.0	16.1
	60-80	1.4	32.9	29.6	15.9
Average	0-15	1.4	29.9	25.5	11.4
	15-30	1.4	31.6	27.1	13.0
	30-60	1.4	34.3	30.5	15.9
	60-80	1.4	33.0	29.6	16.1

Fig. H-1- Photos of the soil profile for detailed soil characterization.

I. Experimental trial

Border trees were kept around the study area and between each tree sample.

In 2013 and 2014, a micro sprinkler irrigation system was installed in twenty four trees. In half of them, the irrigation started when stem water potential measured at 09:00 h fall below -0.6 MPa (full irrigated treatment, FI) and, on the other half, irrigation started when stem water potential at 9:00 h fall below -0.8 MPa (deficit irrigated treatment, DI). Each sprinkler had a debit of 40 L h^{-1}, placed 1.5 m away from the trunk and at 0.9 m above soil, with a wetting area of 13 m^2. In each watering, on both irrigated treatments, it was furnish a mean of 7.5 mm of water. Twelve non irrigated trees (NI) were kept for control. Five sample trees per treatment were selected (Fig. I-1).

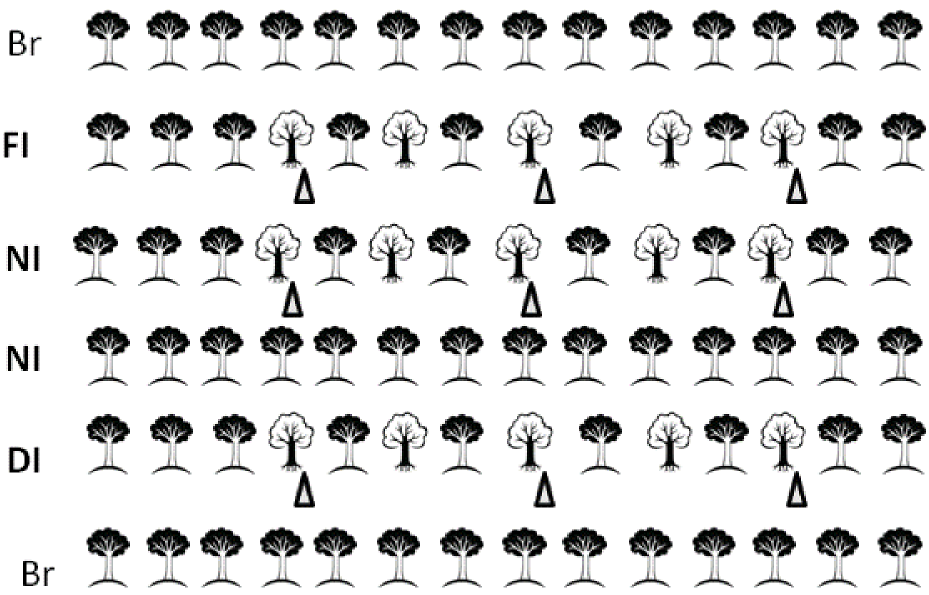


Fig. I-1- Experimental plot of 2013 and 2014 with micro-sprinkler system (FI and DI), non irrigated trees (NI). The triangles (Δ) represent the location of the access tubes of Diviner 2000. Sampled trees are represented by white trees ( ) and guard trees by black trees ( ).

In 2015 and 2016, two types of irrigation systems were installed, each one in forty trees, as follow: TI – drip irrigation – two pipes per row, emitters spaced 1 m with debit of 3.6 L h^{-1}; SI – sprinkler irrigation – one hanging pipe with emitters every 5 meters and a debit of 50 L h^{-1}. In each watering, on both irrigated treatments, it was furnish a mean of 5 mm of water. Forty non irrigated trees (NI) were kept for control. Ten sample trees per treatment were selected (Fig. I-2).

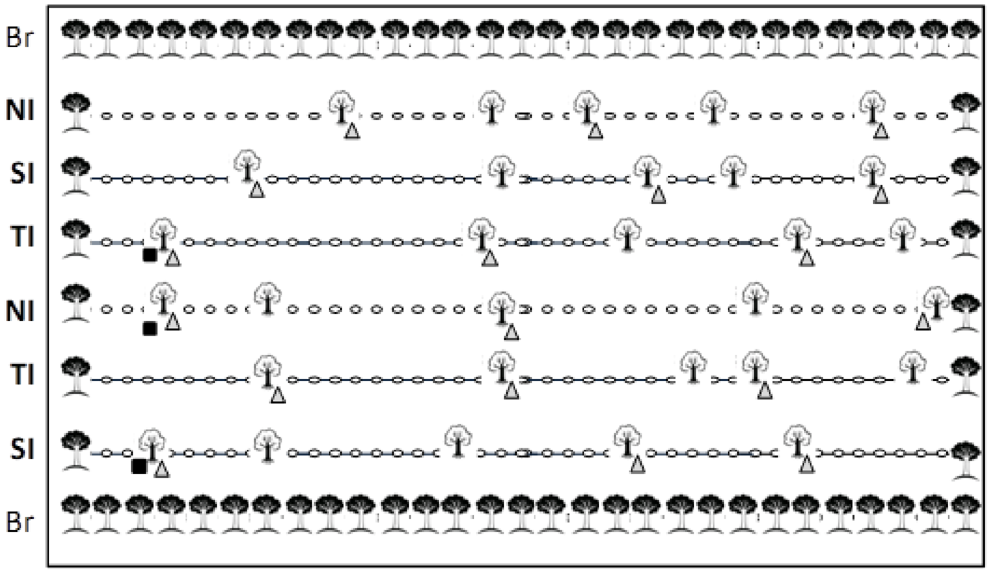


Fig. I-2- Experimental plot of 2015 and 2016 with micro-sprinkler system (SI), drip system (TI), non irrigated trees (NI) and border trees (Br). The triangles (∆) represent the location of the access tubes of Diviner 2000, the squares (■) represents the location of the logger onto where three 'Watermark' sensors were connected. Sampled trees are represented by white trees ( ), others by circles (○) and border trees by black trees ( ).

IV. PHOTOSYNTHETIC TRAITS OF THE CHESTNUT TREE UNDER IRRIGATION

J. Efeitos da rega na produtividade fotossintética do castanheiro

Actas Portuguesas de Horticultura
23 (2014) 166-173

Resumo

Os longos períodos de elevadas temperaturas e pouca precipitação durante o Verão, podem ser problemáticos na produção da castanha pois é neste período que o castanheiro tem maiores necessidades hídricas. Este estudo teve como objetivo avaliar o efeito da rega na produtividade fotossintética do castanheiro e aprofundar as relações solo-planta. O ensaio situa-se em Bragança num souto com 20 anos espaçado 10*5m. Foram aplicados três tratamentos, um por linha com 12 castanheiros: não regado (NI), rega deficitária (DI) e rega completa (FI). Foram utilizados microaspersores elevados a 0,9 m altura. Os dados foram recolhidos semanalmente entre Junho a Outubro de 2013 em cinco árvores por tratamento, duas folhas por árvore. Foram registados os valores do potencial hídrico foliar de base (Ψw_{base}) e do meio-dia (Ψw_l). Foi também medida a taxa fotossintética (“A”) e taxa de transpiração (“E”). A humidade do solo foi medida a cada 10cm até 80 cm de profundidade. Os dados foram objeto de análise de variância efetuado no programa Statview 4.0., tendo-se usado o teste Fisher ($p < 0.05$). A infiltração da água de rega fez-se sentir até aos 40 cm de profundidade. O Ψw_{base} médio variou significativamente entre -0,3 ± 0,06 MPa, para FI e DI, e -0.4 ±0,12 MPa em NI. O Ψw_l foi sempre significativamente maior em FI (-1,2 ± 0,15 a -1,7±0,12MPa) do que em NI (-1,7 ± 0,21 a -2,0 ± 0,17 MPa). Todas as árvores estão dentro de conforto hídrico pelo que se induz que as raízes profundas foram cruciais para as árvores recuperarem durante a noite as perdas de água. A média dos valores de “A” ao meio dia foi significativamente maior em FI (11,2 ± 1,9 µmol CO_2 m^{-2} s^{-1}) em comparação com NI (7,5 ± 1,2 µmol CO_2 m^{-2} s^{-1}). O “E” ao meio-dia foi significativamente maior em FI (2,7 ± 0,5 mmol H_2O m^{-2} s^{-1}) em comparação com DI (2,4 ± 0,6 mmol H_2O m^{-2} s^{-1}) e NI (1,9 ± 0,5 mmol H_2O m^{-2} s^{-1}). O melhor desempenho fotossintético durante o dia pode dever-se ao benefício da rega nas raízes superficiais. Já a produção da castanha foi de 27

kg árv.$^{-1}$ em NI e para FI de 45 kg árv.$^{-1}$, mas este último com menor tamanho do fruto sem prejuízo em termos de valorização no mercado.

Palavras-chave: *Castanea sativa*, irrigação, humidade do solo, potencial hídrico foliar, taxa fotossintética.

Abstract

Water needs of chestnut trees are higher during the summer period and the production can be affected by high temperature and low precipitation. This study aims to understand the effect of irrigation on photosynthetic productivity of chestnut trees. The trial is located in Bragança on a Chestnut orchard of 20 years old, spaced 10*5m. Three treatments were applied per line of twelve trees: non irrigated (NI), deficit irrigated (DI) and full irrigated (FI). On irrigated treatments were used elevated micro sprinkler. Measurements were weekly made from June to October 2013. Five trees per treatment and two leaves from each were sampled. Predawn water potential (Ψw_{base}) and midday water potential (Ψw_l) were measured as well as photosynthetic rate ("A") and transpiration rate ("E"). Soil moisture was measured every 10cm until 80cm depth. Analysis of variance (ANOVA) was carried out with StatView 4.0 software, and comparisons were made with Fisher test ($p<0.05$). Irrigation affected soil moisture until the 40 cm deep. The Ψw_{base} varied from -0.3 ± 0.06 MPa, for FI e DI, to -0.4 ± 0.12 MPa at NI. The Ψw_l was always significantly higher at FI (-1.2 ± 0.15 to -1.7 ± 0.12MPa) than NI (-1.7 ± 0.21 to -2 ± 0.17 MPa). By morning, all trees were within a comfortable water status which may be related with water absorption during the night by deep roots. The mean of "*A*" at midday was significantly higher at FI (11.2 ± 1.9 µmol CO_2 m^{-2} s^{-1}) than at NI (7.5 ± 1.2 µmol CO_2 m^{-2} s^{-1}). The mean of "*E*" at midday was significantly higher at FI (2.7 ± 0.5 mmol H_2O m^{-2} s^{-1}) than at DI (2.4 ± 0.6 mmol H_2O m^{-2} s^{-1}) or at NI (1.9 ± 0.5 mmol H_2O m^{-2} s^{-1}). This higher photosynthetic performance during the day may be related with water absorption from superficial roots. The chestnut production was 27 kg tree^{-1} at NI and 45 kg tree^{-1} for FI, the first with large fruit size.

Keywords: *Castanea sativa*, irrigation, soil moisture, water potential, photosynthetic rate.

Introdução

O setor de castanha portuguesa tem grande importância económica e social, mas precisa produzir mais e com maior qualidade para atender às necessidades do mercado (Ferreira-Cardoso, 2007). É importante haver uma maior eficiência no uso de fatores de produção assim como fazer uso sustentável dos recursos, nomeadamente da água (Miranda *et al.*, 2002). A introdução de rega em soutos permite uma produção mais regular e maior ao longo dos anos (Breisch, 1995) e satisfazer as necessidades de água do castanheiro nos anos mais secos, que se preveem ser mais frequentes (Miranda *et al.*, 2002). A produtividade do castanheiro depende do fornecimento adequado de água uma vez que o stress hídrico reduz o crescimento vegetativo e diminui a produção de frutos (Breisch, 1995). Alguns produtores portugueses têm vindo a introduzir a rega nos seus soutos, ainda que de forma empírica e sem qualquer avaliação do efeito sobre as relações solo-planta e produtividade (Martins *et al.,* 2010). É importante conhecerem-se melhor as relações hídricas entre o solo e o castanheiro através do recurso a diferentes tecnologias e métodos já existentes, como por exemplo através da leitura do potencial hídrico foliar, pelas variações do fluxo de seiva ou pelo recurso a diferentes tipos de sondas de leitura da humidade do solo (Silva, 2010). É importante conhecer a influência que determinadas condições hídricas têm ao nível fisiológico e consequentemente no crescimento e produtividade do castanheiro.

Em Portugal, o projeto Regcast iniciou estudos experimentais que visam dar orientações aos produtores para a gestão da água de rega no castanheiro. No âmbito deste projeto, o presente estudo tem como objetivo compreender o efeito da rega na produtividade fotossintética do castanheiro e aprofundar as relações solo planta.

Material e Métodos

O ensaio foi instalado em Santa Comba de Rossas, Bragança, a 862 m de altitude, num souto com 20 anos de idade da variedade 'Longal', espaçadas 5 m linha e 10 m na entrelinha. A precipitação média anual ronda os 822 mm, sendo os valores médios entre Junho e Setembro de 115.9 mm. A temperatura média anual é de 12,3 °C sendo o seu somatório entre Maio a Outubro (1981-2010) de 2194,4 ºD (segundo os relatórios do Instituto Português do Mar e Atmosfera). O solo é de textura média, com pH (H_2O) próximo de 5 e teor de matéria orgânica de 1,5%. O sob coberto é mantido com pastagem semeada de sequeiro, realizando-se um corte por ano em Junho e não se fazendo mobilizações no solo.

Três tratamentos foram aplicados por linha de doze árvores: não irrigado (NI), onde as árvores não foram regadas durante todo o ciclo vegetativo; rega deficitária (DI), rega iniciada quando o potencial hídrico às 9h da manhã (Ψw_m) inferior – 0,8 MPa; e irrigação plena (FI), rega iniciada quando Ψw_m inferior a -0,6 MPa. Foram instalados microaspersores com débito de 40 l h^{-1} espaçados 1,5 metros do tronco (dois microaspersores por árvore) e elevados a 0,9 m do solo. O tempo de rega foi de quatro horas, equivalendo a dotações de 30 mm. As medições foram feitas em cinco árvores por tratamento e os valores foram registrados semanalmente de Junho a Setembro de 2013. A amostragem proveio de duas folhas retiradas dos ramos de frutificação do ano, do lado norte exterior da copa.

O estado hídrico na planta foi avaliado através do potencial hídrico foliar com recurso a uma câmara de pressão tipo Scholander (PMS 1000, PMS Instrument® Corvallis, Oregon, EUA). Foi medido o potencial hídrico de base (Ψw_{base}), o potencial hídrico às 9h da manhã (Ψw_m) e ao meio-dia (Ψw_l). A taxa fotossintética ("*A*"), taxa de transpiração ("*E*"), condutância estomática (*gs*) e a eficiência de assimilação do carbono (A/ci) foram obtidas através do IRGA (mod. LCpro +, Desenvolvimento Analítico Co®, Hoddesdon, UK) às 9 h da manhã e, a partir de 30 de Agosto também ao meio-dia. A temperatura da folha (T_{folha}) foi registrada com um termómetro de infravermelhos às 9h e ao meio-dia. Dados meteorológicos foram obtidos através da estação meteorológica da Direção Regional de Agricultura e Pescas do Norte, situada em Bragança (20 km do ensaio).

A humidade do solo foi medida através de uma sonda Diviner 2000 (Sentek Technologies) até aos 80 cm de profundidade. Colocaram-se três tubos de acesso a meio da copa da árvore em três árvores por tratamento.

Os dados foram objeto de análise de variância recorrendo-se ao programa StatView 4,0 (Abacus Concepts, Inc.). As comparações foram feitas com recurso ao teste de Fisher, com nível de significância de 0,05.

Resultados e Discussão

Segundo os dados meteorológicos obtidos, entre Janeiro e Março, os valores da precipitação foram de 362 mm, e entre Abril e Setembro a precipitação foi de 140 mm, com ausência ou quase ausência no trimestre Junho a Agosto. Julho e Agosto foram os meses mais quentes com temperatura média das máximas de 31°C e Setembro com 27,4 °C.

O potencial hídrico foliar foi monitorizado a fim de se decidir sobre o início da primeira rega. A partir de meados de Agosto, o potencial hídrico foliar de base ($\Psi w_{base)}$ variou entre -0,3 ± 0,1 MPa, em FI e DI, e -0.4±0,1 MPa em NI (Fig. J-1), sendo na maioria das datas de leitura significativamente diferentes entre tratamentos regados e não regado. Os valores de Ψw_{base} são semelhantes aos encontrados por Martins *et al.* (2010), num estudo efetuado entre 2003 e 2006 na mesma região (Macedo de Cavaleiros) com *C. sativa* var. 'Longal', idade do souto 40 anos, espaçados 12 $_X$ 12 m, cujos Ψw_{base} variaram entre -0,4 e -0,6 Mpa no início de Julho e entre os -0,5 e -1,0 MPa no final do Verão, sendo o valor mínimo correspondente ao ano de 2005, caracterizado por ser extremamente seco (Martins *et al.*, 2010). No mesmo estudo não existiram diferenças significativas a nível do Ψw_{base} entre o tratamento com pastagem semeada regada e o tratamento com pastagem semeada não regada, nos anos menos secos (2003 e 2004). No presente estudo, os valores do Ψw_l, a partir de meados de Agosto, foram muito mais baixos, variando entre -1,2 ± 0,2 a -1,7 ± 0,1 MPa (FI), -1,3 ± 0,2 a -1,9 ± 0,1 MPa (DI) e -1,7 ± 0,2 a -2±0,2 MPa (NI). Assim, a rega iniciou-se em FI a 28 de Agosto, ao final da tarde. Quarenta e oito horas após a irrigação novas medições foram feitas e os resultados mostraram que o Ψw_l em FI aumentou de -1,7 para -1,3 ± 0,1 MPa, sendo que os valores de Ψw_l para DI (-1,5 ± 0,2 MPa) e NI (-1,7 ± 0,3 MPa) se mantiveram semelhantes aos obtidos anteriormente a 28 de Agosto. No entanto, seis dias após a primeira rega em FI, a 03 de Setembro, os valores diminuíram drasticamente para -1,9 ± 0,1 MPa, -1,7 ± 0,1 MPa e -2,0 ± 0,2 MPa para DI, FI e NI, respetivamente. Foram então reintroduzidas regas em FI (6, 16 e 23 de Setembro) e uma rega a 4 de Setembro em DI. Nas medições realizadas a 9 e 17 de Setembro, três e um dia após a irrigação em FI, o valor de Ψw_l foi próximo de -1,2 MPa enquanto a 23 de Setembro, seis dias após a última irrigação, Ψw_l era de -1,6 ± 0,2 Mpa. Quanto ao tratamento DI, os valores de Ψwl foram de -1.3 ± 0,1 MPa a 9 de Setembro (cinco dias após a irrigação), diminuindo para -1,6 ± 0,1 MPa a 17 de Setembro (13 dias após a irrigação) e -1,8 ± 0,1 MPa a 23 de Setembro (19 dias após a irrigação). Não se regou novamente em DI, numa lógica de poupança de água, devido a previsão de chuva para início de Outubro. Relativamente a NI, os valores de Ψw_l oscilaram entre -1,7 ± 0,1 MPa e -2,0 ± 0,2 MPa a partir do final de Agosto. No estudo efetuado por Martins *et al.* (2010), o Ψw_l oscilou entre -1,5 e -2,0 MPa, nos anos menos secos (2003 e 2004), e entre -1,6 e -2,7 MPa no ano mais seco de 2005, apresentando o tratamento com pastagem semeada regada valores significativamente superiores que o tratamento com pastagem semeada não regada. No presente estudo, não se atingiram valores de Ψw_l abaixo de -2 MPa em NI, mas no entanto foram sempre significativamente mais baixos em NI do que FI, relevando algum efeito da rega no estado hídrico da planta ao meio dia. Os valores de DI ao meio dia mostram um meio-termo equilibrado entre FI e DI.

Comparou-se os teores de humidade de solo com os valores obtidos em laboratório segundo o método da placa de pressão de amostras não perturbadas do solo tiradas a 20 e 80 cm de profundidade no ano de 2007 (Afonso Martins, comunicação pessoal) e submetidas à pressão de -1,5 MPa, geralmente aceite como o coeficiente de emurchecimento para a maioria das plantas (Kramer 1969, FAO1979, Marshall and Holmes 1988 and White 2006 cited in Martins *et al.*, 2010) (Fig. J-2). O conteúdo de água no solo (θ_{solo}) nestas condições é de 8,0 % (cm^3 H_2O 100 cm^{-3}solo) aos 20cm e de 14,9% aos 80 cm. A infiltração da água de rega foi evidente até aos 40 cm de profundidade, a partir da qual não se verificaram oscilações na humidade do solo devido a rega. Para todos os tratamentos, o θ_{solo} entre os 60 cm e 80 cm de profundidade foi diminuindo a partir de 23 de Julho (18,0 ± 3,0 e 19,9 ± 2,9%, aos 60 e 80 cm, respetivamente) até atingir o valor mínimo a 23 de Setembro (15,0 ± 3,1 e 15,5 ± 3,6 %, aos 60 e 80 cm, respetivamente),antes das chuvas (valores próximos do coeficiente de emurchecimento aos 80 cm). Esta diminuição da humidade do solo vem indicar a capacidade que o castanheiro tem de extrair água de camadas mais profundas corroborando com a literatura (Garnier and Berger 1985, David *et al.* 2007, Martins *et al.* 2010). Antes da rega, o θ_{solo} a 20 cm foi de 9,1 ± 0.7 e de 9,0 ± 0,4 % para FI e DI, respetivamente. Estes valores representam já um deficit hídrico elevado, estando muito próximos do coeficiente de emurchecimento dessa camada (8 %). Após a rega, θ_{solo} a 20 cm aumentou para 11,7 ± 2,8 e 12,2 ± 2,3 % para FI e DI, respetivamente. Após a rega o θ_{solo} entre os 10 e 20 cm foi significativamente maior em FI e DI do que NI, cujo θ_{solo} variou entre 4,7 ± 0,2 e os 9,4 ± 2,1 % a 10 e 20 cm, respetivamente.

Relativamente a taxa respiração às 9h,"E_{9h}", aumentou até fins de Julho, (1,9 ± 0,4 mmol H_2O m^2 s^{-1}) correspondente ao período mais quente (T_{media} 24°C), a partir do qual diminuiu até Setembro (1,6 ± 0,5 mmol H_2O m^2 s^{-1}; 19,9°C), sendo a variação essencialmente justificada pelos dados (18,3%) e sua interação com o tratamento (30,4%) (Tab. J-1). Relativamente a "E_{12h}", 45% da variação observada entre 30 de Agosto ($T_{max\ d}$ = 31,1° C) e 23 de Setembro ($T_{max\ d}$ = 27,4 ° C) foi devida aos tratamentos. Assim, a "E_{12h}" em FI foi de 2,7 ± 0,7 mmol H_2O m^2 s^{-1}, DI com 2,3 ± 0,6 mmol H_2O m^2 s^{-1} e NI de 1,9 ± 0,6 mmol H_2O m^2 s^{-1}, que representa uma diminuição de cerca de 30% relativamente a FI. Além disso, entre as 9 h da manhã e o meio-dia a variação de "*E*" foi de 0,54 mmol H_2O m^2 s^{-1} (NI), 1,22 mmol H_2O m^2 s^{-1} (DI) e 1,45 mmol H_2O m^2 s^{-1} (FI) (Tab. J-1) correspondendo este valor a uma aumento de três vezes em relação NI, sugerindo o benefício da irrigação. Este aspeto é positivo, pois a transpiração tem um papel importante na termorregulação (Gomes-Laranjo *et al.*, 2007a). Em relação à taxa fotossintética, "*A*", às 9h da manhã os valores mais elevados foram observados a 23 de Julho 7,7 ± 1,7 µmol CO_2 m^{-2} s^{-1} (T_{folha} 19°C, $T_{média\ d}$ = 24°C), não apresentando qualquer variação padrão consistente entre os tratamentos durante todo o estudo, embora se verifique um aumento global de 20% de NI para FI. Por outro lado, no período de rega (30 Agosto-23 Setembro) a média de "A_{12}" foi significativamente maior em FI (11,2 ± 2,4 µmol CO_2 m^{-2} s^{-1}), comparando com o NI (7,5 ± 1,3 µmol CO_2 m^{-2} s^{-1}) e DI (8,0 ± 1,7 µmol CO_2 m^{-2} s^{-1}). Estes índices foram medidos com uma $T_{média}$ de cerca de 27 °C. Em relação à variação de "*A*" das 9 h ao 12 h houve um aumento, 30%, 44% e 63%, de NI, DI e FI, respetivamente, enfatizando a importância de um nível hídrico foliar adequado. A partir de 30 de Agosto, a condutância estomática (*gs*) de FI (132,3 ± 46,0 mmol m^{-2} s^{-1}), foi significativamente maior do que NI (90,4 ± 31,5 mmol m^{-2} s^{-1}), ao meio-dia (Tab. J-1). No entanto, às 9 h para o mesmo período, *gs* foi significativamente mais elevado em NI (81,9 ± 79,6 mmol m^{-2} s^{-1}) do que em FI (63,5 ± 23,9 mmol m^{-2} s^{-1}). Isto pode reforçar a influência das camadas superficiais regadas nos processos fisiológicos, ao meio-dia. Quanto à razão entre a fotossíntese e taxa interna de CO_2 (A/ci) às 9 h da manhã, isto é, sem restrições a nível da condutância estomática, não se verificaram diferenças significativas entre os tratamentos, apesar dos valores de FI e NI serem 0,04 ± 0,02 e 0,03 ± 0,01 mmol CO_2 μbar^{-1}, respetivamente, indicando que alguma influência, mas não significativa, pode ser atribuída à condição hídrica foliar.

No que diz respeito à produção de castanha por árvore, esta foi 66% maior em FI (45 kg) que em NI (27 kg) (Tab. J-2). Os frutos maiores foram encontrados em NI (79,7 frutos kg^{-1}), comparando com os tratamentos irrigados (87,5 frutos kg^{-1} em DI e 92,5 frutos kg^{-1} em FI). Estes calibres estão dentro dos valores encontrados em literatura (Almeida *et al*., 2007), que variam entre os 86 e os 161 frutos kg^{-1} dependendo da região e condições edafoclimáticas. Tendo em conta a semelhança do estado fisiológico das árvores nos três tratamentos na altura da polinização, espera-se que o número de flores femininas polinizadas seja semelhante (Portela *et al*., 2014). Acresce ainda que o número de castanhas viáveis em cada ouriço era semelhante em cada um dos tratamentos. Deste modo, os resultados sugerem que possa ter havido uma queda precoce de ouriços em função das piores condições hídricas a que as plantas do tratamento NI estavam sujeitas. Os frutos de maiores tamanhos encontrados em NI podem ser justificados pelo menor número de frutos (Portela *et al*., 2014). Não obstante o tamanho da castanha ser mais pequeno em FI do que em NI, com consequente menor valorização no mercado, a diferença de produção poderá compensar em termos absolutos.

Conclusões

Os resultados apresentados mostram que uma dotação de cerca de 30 mm de água de rega foi capaz de aumentar a humidade do solo até cerca de 40 cm, a partir da qual o valor de humidade medido era semelhante ao tratamento não regado. Esta diferença permitiu que houvesse um aumento do desempenho fotossintético e do potencial hídrico foliar dos castanheiros regados, nas horas de maior calor, relevando a importância da absorção de água pelas raízes nas camadas mais superficiais do solo. Por outro lado, verificou-se também que durante a noite todas as árvores (regadas e não regadas) conseguiam recuperação hídrica semelhante, sugerindo que esta tenha sido suportada pela absorção radicular da água existente nas camadas mais profundas, permitindo um desempenho fotossintético semelhante durante as primeiras horas do dia. Em consequência, verifica-se um impacto positivo de 72% na produção.

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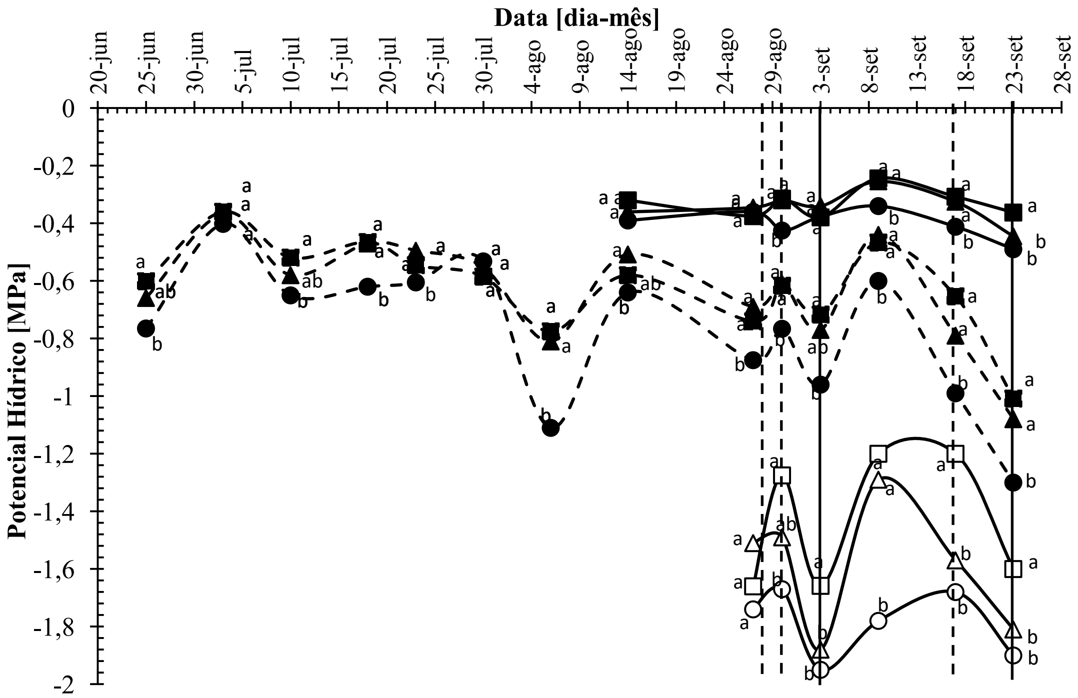

Fig. J-1- Potencial hídrico (MPa) em 2013. Potencial hídrico foliar de base (Ψw_{base}, linha contínua com símbolos fechados), potencial hídrico foliar às 9h (Ψw_{m}, linha tracejada) e potencial hídrico foliar ao meio-dia (Ψw_{l}, linha contínua com símbolos abertos) no tratamento não irrigado (NI, círculos), Rega deficitária (DI, triângulos) e Rega plena (FI, quadrados). A linha tracejada indica a data de irrigação para a FI e a linha contínua indica a data de rega para DI e FI. Valores com letras diferentes são significativamente diferente de acordo com o Fisher teste (p <0,05).

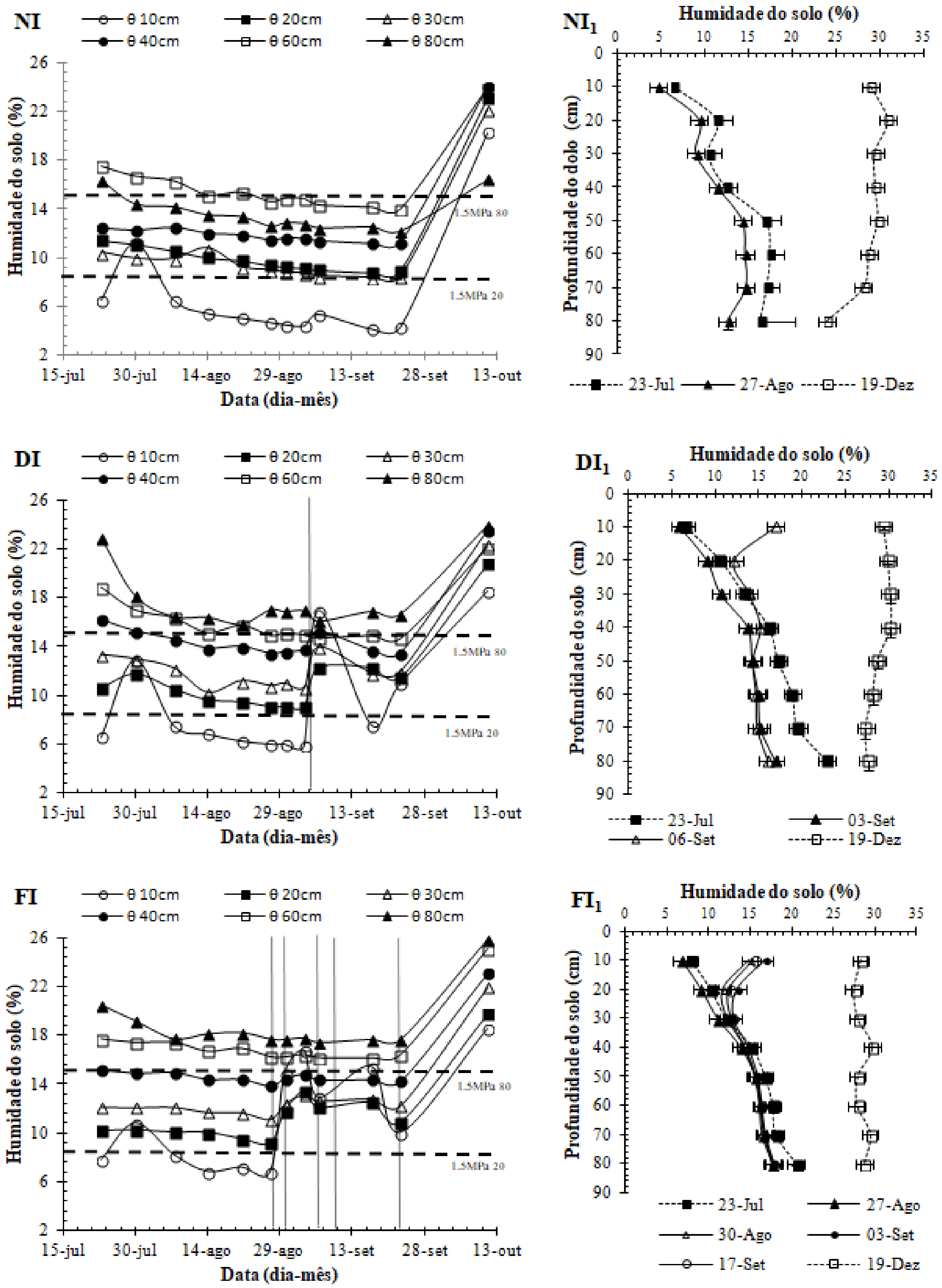

Fig. J-2- Conteúdo de água no solo (%) no tratamento não irrigado (NI), na rega deficitária (DI) e em rega plena (FI) para 10, 20, 30, 40, 60 e 80 centímetros de profundidade em 2013. As linhas tracejadas verticais indicam as datas de rega para os tratamentos: 28 e 30 de Agosto (FI); 3 de Setembro (DI), 17 e 23 de Setembro (FI). As linhas tracejadas horizontais indicam o conteúdo água no solo no coeficiente de emurchecimento a 80cm (-1,5 MPa 80) e 20 cm (-1,5 MPa 20).

Tab. J-1- Transpiração, *E* (mmol H_2O m^{-2} s^{-1}), Fotossíntese, *A* (µmol CO_2 m^{-2} s^{-1}), condutância estomática, *gs* (mmol m^{-2} s^{-1}), eficiência carboxílica, A/ci (µmol CO_2 µbar^{-1}) e Temperatura da folha, T_{folha}. As letras minúsculas representam a diferença estatística (teste de Fisher para um nível de significância de 0,05) entre os tratamentos dentro da mesma data. Letras maiúsculas representam a diferença estatística (teste de Fisher para um nível de significância de 0,05) para cada tratamento através de datas diferentes

Data	E		A		gs		A/ci	T_{folha}	
	9h	12h	9h	12h	9h	12h	9h	9AM	12AM
25/Jun	**1.3 ± 0.3**		**5.9 ± 1.3**		**56.0 ± 17.1**		**0.04 ± 0.01**		
NI	1.0 ± 0.2 c		5.2 ± 0.9 b		42.5 ± 11.2 c		0.04 ± 0.01 b		
DI	1.3 ± 0.4 b		5.3 ± 1.4 b		56.0 ± 20.6 b		0.03 ± 0.01 c		
FI	1.6 ± 0.4 a		7.4 ± 1.7 a		69.5 ± 19.6 a		0.05 ± 0.01 a		
3/Jul	**1.0 ± 0.5**		**4.4 ± 1.7**		**56.9 ± 37.2**		**0.02 ± 0.01**	**17.2 ± 0.6**	
NI	1.4 ± 0.5 a		5.6 ± 1.9 a		79.5 ± 33.6 a		0.03 ± 0.01 a	17.1 ± 0.5 a	
DI	1.0 ± 0.7 b		4.2 ± 1.6 b		57.0 ± 51.8 ab		0.02 ± 0.01 a	17.1 ± 0.5 a	
FI	0.7 ± 0.4 b		3.4 ± 1.5 b		34.3 ± 26.2 b		0.02 ± 0.01 a	17.3 ± 0.7 a	
10/Jul	**1.4 ± 0.4**		**5.4 ± 1.6**		**73.5 ± 24.4**		**0.03 ± 0.02**	**21.3 ± 1.0**	
NI	1.9 ± 0.5 a		7.0 ± 2.2 a		110.5 ± 34.4 a		0.03 ± 0.01 a	21.0 ± 0.8 a	
DI	1.1 ± 0.3 b		5.0 ± 1.6 b		54.5 ± 19.1 b		0.03 ± 0.04 a	21.9 ± 0.9 a	
FI	1.1 ± 0.3 b		4.4 ± 1.1 b		55.5 ± 19.9 b		0.02 ± 0.01 a	21.0 ± 1.3 a	
18/Jul	**1.5 ± 0.4**		**7.1 ± 1.7**		**83.2 ± 28.1**		**0.04 ± 0.01**	**17.5 ± 0.9**	
NI	1.5 ± 0.5 ab		6.8 ± 1.8 a		87.0 ± 32.0 a		0.03 ± 0.01 b	18.1 ± 1.1 a	
DI	1.3 ± 0.2 b		6.6 ± 1.2 a		72.0 ± 16.4 a		0.04 ± 0.01 ab	17.7 ± 0.5 ab	
FI	1.6 ± 0.5 a		7.7 ± 2.2 a		90.5 ± 35.9 a		0.04 ± 0.02 a	16.7 ± 1.0 b	
23/Jul	**1.5 ± 0.4**		**7.7 ± 1.7**		**93.0 ± 27.3**		**0.04 ± 0.01**	**19.2 ± 0.5**	
NI	1.6 ± 0.4 a		7.9 ± 1.5 a		100.8 ± 28.9 a		0.04 ± 0.01 a	19.3 ± 0.5 a	
DI	1.4 ± 0.4 b		7.5 ± 2.4 a		83.8 ± 27.0 a		0.04 ± 0.02 a	18.9 ± 0.6 a	
FI	1.6 ± 0.3 ab		7.9 ± 1.3 a		94.5 ± 26.0 a		0.04 ± 0.01 a	19.3 ± 0.5 a	
30/Jul	**1.9 ± 0.4**		**7.5 ± 1.4**		**111.6 ± 34.5**		**0.03 ± 0.01**	**17.3 ± 0.8**	
NI	1.6 ± 0.4 b		7.5 ± 1.5 a		91.5 ± 28.7 b		0.04 ± 0.01 a	17.9 ± 0.5 a	
DI	2.0 ± 0.6 a		7.6 ± 1.3 a		120.0 ± 45.5 a		0.03 ± 0.01 ab	17.2 ± 0.9 a	
FI	2.1 ± 0.3 a		7.2 ± 1.4 a		123.3 ± 29.4 a		0.03 ± 0.01 b	16.9 ± 1.1 a	
21/Ago	**1.8 ± 0.4**		**4.6 ± 1.5**		**82.4 ± 27.3**		**0.02 ± 0.01**	**17.0 ± 0.6**	
NI	1.2 ± 0.4 b		4.9 ± 1.7 a		61.4 ± 25.0 b		0.02 ± 0.01 a	18.5 ± 0.8 a	
DI	1.3 ± 0.5 b		4.3 ± 1.3 a		56.2 ± 26.7 b		0.02 ± 0.01 ab	16.0 ± 0.3 b	
FI	2.7 ± 0.4 a		4.7 ± 1.4 a		129.5 ± 30.3 a		0.02 ± 0.01 b	16.5 ± 0.6 ab	
27/Ago	**1.1 ± 0.7**		**5.4 ± 1.1**		**49.2 ± 21.2**		**0.05 ± 0.03**	**13.7 ± 1.0**	
NI	0.5 ± 0.2 b		5.1 ± 0.7 b		28.5 ± 7.5 b		0.08 ± 0.07 a	14.0 ± 1.1 a	
DI	0.8 ± 0.4 b		4.6 ± 1.5 b		42.4 ± 24.3 b		0.03 ± 0.02 b	13.3 ± 1.2 a	
FI	1.8 ± 1.6 a		6.3 ± 1.1 a		76.7 ± 31.8 a		0.03 ± 0.00 b	13.9 ± 0.6 a	
30/Ago	**1.2 ± 0.4**	**2.3 ± 0.6**	**5.2 ± 1.1**	**8.3 ± 1.4**	**61.3 ± 27.9**	**121.9 ± 43.5**	**0.03 ± 0.03**	**19.0 ± 1.9**	
NI	0.9 ± 0.4 b	2.0 ± 0.5 bAB	4.3 ± 0.6 b	7.6 ± 1.1 bB	50.0 ± 26.7 a	106.4 ± 43.4 bA	0.02 ± 0.01 a	20.2 ± 0.8 a	
DI	1.2 ± 0.5 ab	2.2 ± 0.7 bB	5.3 ± 1.6 a	7.2 ± 1.2 bCD	66.0 ± 37.2 a	110.7 ± 48.9 bB	0.05 ± 0.07 a	19.1 ± 0.4 a	
FI	1.3 ± 0.3 a	2.8 ± 0.5 aAB	5.9 ± 1.1 a	10.2 ± 1.7 aB	68.0 ± 19.7 a	148.6 ± 38.2 aA	0.03 ± 0.01 a	17.7 ± 4.7 a	
3/Set	**1.0 ± 0.2**	**2.6 ± 0.7**	**5.6 ± 2.2**	**8.4 ± 1.3**	**46.5 ± 13.3**	**112.4 ± 35.0**	**0.04 ± 0.02**	**19.4 ± 0.8**	**23.2 ± 1.51**
NI	0.9 ± 0.1 b	2.1 ± 0.5 bA	6.0 ± 4.7 a	7.5 ± 1.0 bB	42.7 ± 10.3 b	94.0 ± 20.6 bA	0.03 ± 0.01 b	19.9 ± 0.6 a	24.5 ± 1.58 a
DI 4 Set	0.8 ± 0.3 b	2.3 ± 0.7 bB	4.4 ± 0.6 a	6.5 ± 1.4 cD	37.5 ± 12.2 b	95.3 ± 38.3 bB	0.04 ± 0.03 ab	19.0 ± 1.2 a	22.6 ± 1.15 a
FI	1.3 ± 0.3 a	3.3 ± 0.8 aA	6.5 ± 1.5 a	11.1 ± 1.4 aB	59.4 ± 17.3 a	148.0 ± 46.0 aA	0.05 ± 0.02 a	19.3 ± 0.7 a	22.5 ± 1.80 a
6/Set	**1.7 ± 0.7**	**2.5 ± 0.5**	**6.5 ± 1.0**	**10.5 ± 1.4**	**115.6 ± 72.8**	**130.5 ± 35.7**	**0.03 ± 0.05**	**14.1 ± 0.6**	**19.8 ± 1.37**
NI	2.6 ± 1.0 a	2.2 ± 0.5 bA	6.7 ± 1.3 a	8.7 ± 1.2 bA	188.0 ± 112.8 a	105.3 ± 29.5 bA	0.03 ± 0.01 b	14.4 ± 0.9 a	21.8 ± 2.41 a
DI	1.5 ± 0.9 b	2.8 ± 0.4 aA	6.4 ± 0.8 a	8.6 ± 1.4 bA	98.0 ± 91.1 b	148.6 ± 33.2 aA	0.04 ± 0.02 a	14.0 ± 0.8 c	20.0 ± 1.13 ab
FI	1.1 ± 0.2 b	2.6 ± 0.6 abBC	6.5 ± 0.9 a	14.1 ± 1.7 aA	60.7 ± 14.4 b	137.6 ± 44.4 aA	0.04 ± 0.12 a	13.9 ± 0.2 b	17.5 ± 0.58 b
17/Set	**0.8 ± 0.3**	**2.0 ± 0.5**	**6.1 ± 3.1**	**8.3 ± 1.3**	**42.2 ± 19.3**	**100.4 ± 29.3**	**0.04 ± 0.02**	**14.3 ± 1.0**	**17.9 ± 1.00**
NI	0.7 ± 0.2 a	1.3 ± 0.5 cC	4.8 ± 0.9 b	6.5 ± 0.8 cC	36.7 ± 12.9 a	66.0 ± 22.6 cB	0.04 ± 0.02 a	15.2 ± 1.6 a	19.7 ± 1.15 a
DI	0.7 ± 0.4 a	2.0 ± 0.4 bBC	5.6 ± 1.6 ab	8.0 ± 0.9 bBC	40.0 ± 20.0 a	94.7 ± 27.7 bB	0.05 ± 0.02 a	14.2 ± 0.5 a	17.4 ± 0.97 ab
FI	0.9 ± 0.4 a	2.7 ± 0.5 aB	8.0 ± 7.0 a	10.4 ± 2.2 aB	50.0 ± 25.1 a	140.6 ± 37.7 aA	0.04 ± 0.02 a	13.5 ± 1.0 a	16.5 ± 0.89 b
23/Set	**1.6 ± 0.5**	**2.2 ± 0.5**	**6.8 ± 1.7**	**9.0 ± 1.8**	**76.7 ± 32.7**	**90.7 ± 25.7**	**0.04 ± 0.02**	**19.0 ± 0.7**	**23.4 ± 0.83**
NI	1.7 ± 0.6 ab	1.8 ± 0.4 bcB	7.1 ± 2.1 ab	6.9 ± 1.2 bBC	92.0 ± 51.3 a	80.0 ± 17.5 bB	0.04 ± 0.02 ab	19.2 ± 0.9 a	25.0 ± 0.98 a
DI	1.4 ± 0.3 b	2.5 ± 0.4 aAB	6.0 ± 0.9 b	9.5 ± 1.7 aA	58.8 ± 15.4 b	105.3 ± 23.6 aB	0.03 ± 0.01 b	18.7 ± 0.9 a	23.4 ± 0.94 b
FI	1.8 ± 0.5 a	2.2 ± 0.7 abC	7.4 ± 2.1 a	10.4 ± 2.6 aB	79.3 ± 31.3 ab	86.9 ± 35.9 abB	0.05 ± 0.02 a	18.0 ± 0.2 a	21.8 ± 0.58 c
30/Ago-23/Set	**1.2 ± 0.6**	**2.3 ± 0.6**	**6.1 ± 2.5**	**8.9 ± 1.8**	**68.5 ± 51.3**	**111.2 ± 38.0**	**0.04 ± 0.14**	**17.1 ± 0.7**	**21.1 ± 2.70**
NI	1.4 ± 0.9 a	1.9 ± 0.6 c	5.8 ± 2.6 b	7.5 ± 1.3 b	81.9 ± 79.6 a	90.4 ± 31.5 c	0.03 ± 0.01 a	17.8 ± 0.8 a	22.8 ± 2.66 a
DI	1.1 ± 0.6 a	2.3 ± 0.6 b	5.5 ± 1.4 b	8.0 ± 1.7 b	60.1 ± 50.3 b	110.9 ± 36.7 b	0.04 ± 0.39 a	17.0 ± 0.5 b	20.9 ± 2.57 b
FI	1.3 ± 0.4 a	2.7 ± 0.7 a	6.9 ± 3.4 a	11.2 ± 2.4 a	63.5 ± 23.9 b	132.3 ± 46.0 a	0.04 ± 0.02 a	16.5 ± 0.7 b	19.6 ± 2.87 b
Análise variância									
Tratamento	3.7	40.2	9.4	65.8	5.24	30.07	1.43	31.95	12.03
Data	18.3	4.0	2.4	4.7	13.85	5.81	0.59	51.99	75.12
Data*Trat.	30.4	12.1	3.4	9.0	25.18	11.35	2.12	0.17	1.35
Residual	47.6	43.7	84.7	20.5	55.73	52.77	95.85	15.89	11.50
Total	100.0	100.0	100.0	100.0	100.00	100.00	100.00	100.00	100.00

Tab. J-2- Produção (kg árv^{-1}), calibre (n.º castanha kg^{-1}), n.º frutos viáveis por ouriço e n.º ouriços por árvore em 2013.

Tratamento	Produção (kg árv^{-1})	Produção (%)	Calibre (nº frutos kg^{-1})		Frutos viáveis (n.º ouriço^{-1})		Ouriços (n.ºárvore^{-1})
NI	26,9	100	79,7	b	2,36	a	1464
DI	47,9	178,1	87,5	a	2,36	a	2840
FI	44,6	165,8	92,5	a	2,47	a	3010

K. Understanding the photosynthetic productivity and stem water potential relationship in *Castanea sativa* to support irrigation decision

Photosynthetica
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Resumo

O estudo avalia a possibilidade de utilização do potencial hídrico de ramo como indicador de rega baseando-se na sua relação com a produtividade fotossintética. O ensaio ocorreu no nordeste de Portugal, com árvores adultas, em 2013. Foram testados dois regimes hídricos, utilizando-se o potencial hídrico às 9 h da manhã para activar as regas sempre que estivesse abaixo de -0,8 MPa (DI) e abaixo de -0,6 MPa (FI); árvores de controlo foram mantidas sem rega (NI). Os resultados mostraram a capacidade das árvores, tanto as regadas quanto as não regadas, de manterem o seu estado hídrico durante a madrugada e parcialmente durante a manhã cedo, enquanto ao meio-dia foram identificadas diferenças: as árvores regadas apresentaram maior potencial hídrico, taxa fotossintética e taxa de transpiração do que árvores controlo. Nenhuma diferença significativa foi observada entre FI e DI, indicando que a programação da rega nos castanheiros pode ser baseado no potencial hídrico às 9h da manhã, -0,8 MPa, ou no potencial hídrico de ramo ao meio-dia, devendo o valor limite ser em torno de – 1 MPa.

Palavras-chave: castanha, fluorescência da clorofila, trocas gasosas, produção.

Abstract

The study evaluates the possibility of using the stem water potential to regulate irrigation on chestnut trees based on its relationship with photosynthetic productivity. The trial occurred in the northeast of Portugal, with adult trees, in 2013. Two water regimes were tested, using the dawn water potential as threshold values, below -0.8 MPa (DI) and below -0.6 MPa (FI) to schedule the irrigation; control trees were kept without irrigation (NI). Results showed the capacity of trees, both irrigated and not, to buffer the water status on the predawn and partially on dawn time, while at midday differences were ascribed: irrigated trees showed higher stem water potential, photosynthetic rate and transpiration rate than control trees. No significant difference was observed between FI and DI indicating that irrigation scheduling on the chestnut trees can be based on dawn stem water potential, -0.8 MPa, or on the midday stem water potential, threshold value should be around – 1MPa.

Additional keywords: chestnut, chlorophyll fluorescence, gas exchange, production.

Abbreviations

P_{Nd} – Photosynthetic rate at 12:00h; P_{Nd} – Photosynthetic rate at 09:00; Car_{tot} – total carotenoids; Chl_{tot} – total chlorophyll; E_{md} – transpiration rate at 12:00; E_d – transpiration rate at 09:00h; GDD - annual growing degree day; *gs* - stomatal conductance; RWC – relative water content; T_{leaf} - leaf temperature; T_{med} - mean monthly temperature; T_{medd} – daily mean air temperature; Ψw_d - dawn water potential; Ψw_{pd} - predawn water potential; Ψw_{md} – midday water potential; ABS/RC absorbed energy flux per reaction centre (RC); TR_0/RC -trapped energy flux; ET_0/RC - electron transport flux ; DI_0/RC dissipated energy flux; TR_0/CS trapped energy flux per CS; ET_0/CS - electron transport flux per CS; DI_0/CS - dissipated energy flux per CS; PI_{ABS} - performance index on an absorption basis; F_0 - chlorophyll fluorescence intensity measured when all PSII reaction centres are assumed to be open, however, the measured value may be affected by several other parameters (at t=0); F_J - fluorescence intensity at the J-step during fluorescence induction (at 2 ms; F_I - fluorescence intensity at the I-step during fluorescence induction (at 30 ms); F_M - maximal chlorophyll fluorescence intensity measured when all PSII reaction centres are closed; T_{FM} - time needed to reach F_M; F_V/F_0 - a value that is proportional to the activity of the water-splitting complex on the donor side of the PSII; Area - the area above the chlorophyll fluorescence curve between F_0 and F_m (reflecting the size of the plastoquinone pool); S_M - (Area)/(F_m −F_o), representing energy necessary for the closure of all reaction centres; N - the number indicating how many times Q_A is reduced while fluorescence reaches its maximal value; V_J - relative variable fluorescence at time J; $jp_o/(1-jp_o)$ - a 'conformation' term for primary photochemistry; $Y_0/(1-Y_0)$ - conformation' term for thermal reactions (nonlight dependent reactions, M_o - density of reaction centres per PSII antenna chlorophyll; SFi_{ABS} - an indicator of PSII 'structure and functioning', calculated as (RC/ABS)×jp_o; F_v/F_m - maximum quantum yield of primary photochemistry (at t = 0).

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Introduction

Irrigation on chestnut trees increases chestnut yield and promotes production regularity over the years (Breisch 1995) but little is known about water relations and its impact on the photosynthetic productivity. So, the understanding of the chestnut tree physiological response to the water supply is crucial for further irrigation programmes based on plant parameters. Therefore, plant water status can be inferred from different methods like the determination of the relative leaf water content, RWC, (Smart and Bingham 1974, Brown *et al.* 2014) to the determination of the plant water potential through a pressure chamber (Scholander *et al.* 1965). This last method allows measuring both the leaf or the stem water potential and some studies have been done on the chestnut tree (Rosas 1998, Almeida *et al.* 2007, Gomes-Laranjo *et al.* 2008, Gomes-Laranjo *et al.* 2008a, Martins *et al.* 2010). The theory under the use of the leaf or stem water potential is that the water must be under tension to be transported through the plant's xylem from the roots to the leaves and that depends on soil water potential close to the root system, on the canopy size, on the air water potential and on the climatic conditions (Choné *et al.* 2001). The use of plant-based indicators to trigger irrigation provides more site-specific information and can thus account for spatial variations (Girona *et al,*. 2006). Additionally, the tree water status may best provide thresholds for irrigation scheduling because it responds to the interaction of soil moisture availability, atmospheric demand and canopy conductance (Naor, 2006). The predawn water potential (Ψw_{pd}) measures plant water status at practically zero plant water flux and provides information on the root's soil zone water potential because it is considered to be in equilibrium with soil water status (Choné *et al.* 2001). It has the inconvenience that it must be measured before any sunshine. On its turn, the midday stem water potential (Ψw_{md}) is measured on a non-transpiring leaf indicating the capacity of the plant to conduct water from the soil to the atmosphere and the soil/root water conductivity and it has been used successfully as a water stress indicator on vine, peach, apple, olive tree and many other crops (Kenneth *et al.* 1997, Shackel *et al.* 2000, Naor 2006, Girona *et al.* 2006). Although the use of the pressure chamber is a destructive method, time consuming and it is not amenable to automatic data acquisition (Naor, 2006) so far, the stem water potential is the most used and affordable plant water stress indicator to manage irrigation on commercial orchards. A similar reading at morning time would be interesting in the point of view of the producer's daily agenda. Naturally, recent non-destructive and automatic methods are already in use but mostly at a research level such as the sap flow variation (Silva, 2010), root sap flow (Fernández *et al.* 2007, David *et al.* 2013), trunk diameter fluctuation (Huguet *et al.* 1992, Marsal *et al.* 2002), leaf temperature (Testi *et al.* 2008), leaf gas exchange analysis (Tamayo *et al.*, 2001) and chlorophyll fluorescence (Maxwell and Johnson 2000, Christen *et al.* 2007). How some of these physiological parameters are correlated with the stem water potential allows us to bring to the field more accuracy on its values' interpretation for irrigation-decision purpose.

As far as our knowledge goes, there are no studies about the dawn water potential of the chestnut trees and no reference values to support irrigation-decision. So, the definition of this threshold took into consideration Martins *et al.* (2010) and Brown *et al.* (2014) that refers a hydric comfort level when the predawn water potential is within -0.4 and -0.6 MPa. Thus, we admitted a slight decrease of these values at dawn time. In that way, this study aims to evaluate the sensitivity of the dawn water potential as a reliable parameter to support smart irrigation based on the photosynthetic productivity parameters for two water regimes (-0.6 and -0.8MPa). Additionally the chestnut production was evaluated.

Material and methods

Site location: The trial was conducted during June to September of 2013, in Bragança Council, northeast of Portugal (41°39'28.16"N; 6°50'37.09"W) at 862 m above sea level.

Orchard characterization: The trial was done in a 20 year old rainfed commercial chestnut orchard with 5 x 10 m tree spacing. The rootstocks were seedlings from *Castanea sativa* M. and grafted at the 2 m mark with 'Longal' variety. The soil is kept with annual reseeding and perennial legumes and grass-plot that are cut to straw-bale in June. The soil, at a 30 cm depth, has a medium texture, pH of 5.5, 3.1% of organic matter, 39 mg P_2O_5 kg^{-1} and 101 mg K_2O kg^{-1} by Egnér-Riehm method.

Treatments: Two irrigation treatments where tested based on dawn water potential (Ψw_d) measured at 9:00h: full irrigation (FI) – irrigation was triggered when Ψw_d < -0.6 MPa; deficit irrigation (DI) – triggered when Ψw_d < -0.8 MPa and control (NI) – where trees were not irrigated during the whole season. There were border trees around the study area and each modality was composed by twelve trees per row, one row per treatment. Five of those twelve trees were selected to make de measurements. The irrigation was done by a micro sprinkler system, with emitters placed 1.5 m away from each side of the trunk, a debit of 40 L h^{-1} and covering a wetted area of 12.6 m^2. Water volume allocated for each irrigation was of 300 m^3 ha^{-1}.

The following measurements were taken weekly from the leaves of the year's fruiting branches on the external north side of the canopy in five trees per treatment:

Water Relations: Tree water status was assessed by measuring stem water potential with a Schoelander-type pressure chamber (PMS 1000, PMS Instrument® Corvallis). Ten leaves per treatment were used and they were previously covered with aluminium foil into a plastic bag at least one hour before measurement to avoid transpiration and to allow the leaves to be in equilibrium with the stem and to be less dependent on occasional climatic conditions. Measurements were taken between 6:00 and 7:00 h (Ψw_{pd}), between 9:00 and 10:00 h (Ψw_d) and between 12:00 and 13:30 h (Ψw_{md}). The Ψw_d was measured between June to September. The Ψw_{pd} and Ψw_{md} were measured from August to September.

Relative Water Content: at 9:00 h, 10 leaves per treatment had been weighted (fresh mass, FM) and after it they were soaked in distilled water for 3 days to further determine the turgid mass (TM). Then, they were dried (60 ºC, two days) and weighted (dry mass, DM). It was calculated according to Turner (1981): the relative water content:

$$RWC = \left[\frac{FM - DM}{TM - DM}\right] \times 100.$$

Gas exchanges: Fifteen leaves per treatment were taken to determined the photosynthetic rate (P_N), transpiration rate (E) and stomatal conductance (gs) using an Infrared Gas Analyser (IRGA, mod. LC*pro*+, Analytical Development Co®, Hoddesdon) setted up at temperature 25°C and PPFD at 1600 µmol m^{-2} s^{-1}. Readings were taken at dawn from June to September 2013 and at midday from August 30th until the end of September 2013.

Leaf temperature: Leaf temperature (T_{leaf}) was taken with an infrared thermometer (Telatemp Corporation, Model DT1100, California) by pointed it at the leaves at 20 cm distance and performing a circular motion. This was done to five trees per treatment at dawn and midday on the shaded and sunny faces of the canopy.

Leaf photosynthetic pigment: Ten leaves per treatment were sampled to measure photosynthetic. From each leaf, six 8 mm's disc were punched. Two of them were dried during 48 h at 60 ºC to determine dry weight. The other six discs were immersed in 2 mL of 80% (w/v) acetone for 48 h until complete discoloration was achieved. The absorbency of extract was measured in a spectrophotometer UV-VIS (Spectronic® 20 Genesys™) at 663.6, 645 and 470 nm. Chlorophyll a (*C*hl*a*) and b (*C*hl*b*) and Carotenoids (Car) were quantified according to the Lichtenthaler (1987) equations. Additionally, on July 23rd and September 3rd the leaves' protein, starch and soluble sugars were determined. Proteins were quantified according to the Bradford (1976) methodology with minor modifications. For that, one disc of 8 mm in diameter was crushed with liquid nitrogen. Later, 700 µL of the extraction solution were added (40 mL phosphate buffer pH 7.5 with EDTA, 40 µL de PMSF (proteases inhibitor) and 0.8 g de PVP (Merck). The liquid was centrifuged at 15,000 rpm for 30 minutes at 4 °C. Later, 100 µL of supernatant were mixed with 1 mL of Comassie Blue g 250. Absorbance was read at 595 nm. Soluble sugars were quantified according to the Irigoyen *et al.* (1992) methodology. To extract the soluble sugars, 10 mL of ethanol (80%) was added on to a disc of 8 mm in diameter and taken to 80 °C for one hour. After this, 200 µL of liquid was used and added to it 3 mL of anthron. The mix was put in a hot bath at 100 °C for 10 minutes. After cooling the absorbance was determined at 625 nm. Starch was quantified according to the adapted Osaki *et al.* (1991) methodology. To the same disc previously used to measure soluble sugars was added 5 mL of perchloric acid. It was warmed in hot water to 60 °C for one hour. After, 300 µL were used and added 3 mL of anthron. Again, the solution was warmed in a water bath at 100 °C for 10 minutes. After cooling absorbance was determined at 625 nm.

Chlorophyll Fluorescence: The chlorophyll fluorescence was measured once at the end of the cycle (September 23rd) at 9:00 h and at 12:00 h with an OS-30p Chlorophyll fluorometer (Opti-Sciences, Inc., Hudson) using the O-J-I-P test protocol. This measurement took place in two leafs per tree, in five trees per treatment, after adapting to the darkness for thirty minutes.

Meteorological data: Meteorological data was obtained from the agro bulletins of the Portuguese Institute of Sea and Atmosphere's weather station, located 20 km's from the trial and data was compared with the 1980-2010 climatic averages given by the former official entity.

Chestnut production: The harvesting occurred from the middle to the late October and five parameters were evaluated: chestnut production per canopy area (kg m^{-2}) and per tree (kg $tree^{-1}$), the chestnut calibre (fruits kg^{-1}) as well as the starch, soluble sugars content and crude protein. The starch was determined by enzymatic hydrolysis (Salomonsson *et al.* 1984) and the soluble sugars were determined by the colorimetric method of anthrone after extraction with ethanol, as described by Irrigoyen *et al.* (1992). The crude protein was calculated from nitrogen, determined by micro-Kjeldahl method with a selenium catalyst, by the use of factor N x 5.3 as recommended by McCarthy and Meredith (1988).

Statistical analysis: Statistical analysis was carried out using Microsoft Excel and StatView 4.0 software (Abacus Concepts, Inc.). Comparisons were made with Fisher test, using a significance level of 0.05 and results are shown with standard error (± SE).

Results

The first irrigation was introduced on FI in the evening of August 28th and repeated on August 30th. Three more irrigations in FI were needed to keep the Ψw_d above -0.6 MPa. On DI treatment, the first irrigation happened on September 3rd. Only two irrigations were needed to accomplish the irrigation scheduling in DI. The last irrigation was made in September 23rd on FI and DI since after that it rained for a few days (Fig. K-1). The total water furnished on FI in August was of 59 mm and represented 32% of the cumulative monthly evapotranspiration of reference (ET_0 = 183 mm) (Supplementary Fig. K-1). In September, the balance between ET_0 (114 mm), precipitation (50.2 mm) and irrigation on FI (89 mm) was positive. In DI the total water furnished was of 59 mm in September.

Climatic conditions: The annual mean temperature (1980-2010) of Bragança is 12.6ºC, with T_{med} (May-September) of 20.1ºC and growing degree days, GDD, (January-December) of 2,500 ºD using 6ºC as the base-temperature (Gomes-Laranjo *et al.*, 2008a). In 2013 these values were of 12.7 ºC, 21.0 ºC and 2,549 ºD, respectively. The July 2013

(T_{med} = 24 °C) was 2.3 °C higher than that of last decades and the total annual precipitation was 823 mm and only 10% felt between May – September. Comparatively, the decades 1980-2010 had a mean annual precipitation of 783 mm and 23% of that occurred between May and September. In 2013, as a consequence, the air water potential (Ψw_{air}) decayed below -80 MPa in June, July and September with a minimum of -103 MPa in August (Supplementary Fig. K-1).

Water Relations: In general, the mean Ψw_d of all treatments, decreased from -0.4 ± 0.02 to -0.7 ± 0.04 MPa (Fig. K-1). Differences on Ψw_d were observed between the NI trees during July (3rd, 10th and 23rd) and on August 14th before starting the treatments and after irrigation these differences became more evident and values were consistently lower in NI. The Ψw_d of NI on August 27th was -0.8 MPa and fell to -1.3 MPa on September 23rd. During the irrigated period, the NI Ψw_d was in average 0.23 MPa lower than in FI (mean of -0.69 ± 0.02 MPa) and 0.19 MPa lower than in DI (mean of -0.74 ± 0.04MPa).

The Ψw_{pd} between August 27th and September 23rd varied between -0.25 MPa and -0.45 MPa for all treatments (Fig. K-2). The difference of the Ψw_{pd} between treatments was also slight: between NI - DI it was around 0.06 MPa and between NI - FI it was around 0.07 MPa and it was significantly higher for FI and DI on September 18th and for FI at September 23rd. In what concerns the Ψw_{md} it varied within the range of -0.80 ± 0.05 MPa to -1.55 ± 0.05 MPa, depending on the treatment (Fig. K-2). On August 27th, immediately before irrigation, the values were not significantly different between treatments, -1.11 ± 0.08 MPa for DI, -1.26 ± 0.09 MPa for FI and -1.34 ± 0.13 MPa for NI modality. Nevertheless, after irrigation, the measurements taken on the following day showed a significant increase on the Ψw_{md} of FI trees contrarily to the DI and NI trees. After that, the Ψw_{md} of FI had constantly the highest values. In DI trees there was only 0.2 MPa difference when comparing with NI, with a maximum of 0.5 MPa on September 9th. The variation between the predawn water potential and the midday water potential ($\Delta\Psi_w$) diminished when trees were irrigated. Before the first irrigation on FI, the $\Delta\Psi_w$ was of 0.89, 0.77 and 0.98 MPa for FI, DI and NI respectively and after it the $\Delta\Psi_w$ was of 0.56 in FI, contrarily to the other ones with $\Delta\Psi_w$ of 0.77 and 0.85 MPa for DI and NI trees, respectively. The same pattern was observed in DI: before first the irrigation the $\Delta\Psi_w$ was of 1.14 MPa and after it decreased to 0.64 MPa.

Relative Water content: In what concerns to RWC there was a non-significant difference between treatments neither before nor after irrigation being the variation less than 6% between them (Fig. K-3). However, irrigation helped trees to preserve their RWC at around 83% whilst on none-irrigated ones the decrease was clear from June (88.9 ± 2.52 %) until September (72.58 ± 3.42 %) as observed by the tendency line (Fig. K-3). In general, FI and DI leave in irrigated trees showed higher hydration level than NI leaves. The results showed a synchronization of RWC with the chestnut vegetative cycle and the irrigation helped to keep better leaves' hydration during morning time.

Gas exchange: Gas exchange measurements were taken thirteen times between mid-June and the end of September. On such days, daily maximal air temperature at midday varied between 25ºC (July 30th, August 30th and September 6th) to a maximum of 36.5ºC (July 10th). The second fortnight of July was a very important period, corresponding also to the flowering period and the photosynthetic rate at 9:00 h registered the highest values. Statistical differences on the photosynthetic and transpiration rate and on the stomatal conductance happened punctually across the time before irrigation period suggesting some plot to plot fluctuation (Fig. K-4). In general, both dawn stomatal conductance (gs_d), E_d and P_{Nd} increased from June to July when maximal rates were measured with exception for August 21st where the maximal value of E_d and gs_d was registered in FI (2.7 mmol H_2O m^{-2} s^{-1} and 130 mmol m^{-2} s^{-1}, for *Ed* and gs_d respectively) and on the day September 6th were a maximal value of E_d and gs_d was registered in NI (2.6 mmol H_2O m^{-2} s^{-1} and 188 mmol m^{-2} $s^{-}1$, for E_d and gs_d respectively) (Fig. K-4, *B, C*). It is noteworthy that on the mentioned days the P_{Nd} had similar values between treatments without statistical difference (4.6 and 6.2 µmol CO_2 m^{-2} s^{-1} for August 21st and September 6th) (Fig. K-4, *A*). After July, all the gas exchange rates decayed until a minimum value by the end of August. The E_d had an overall rate on July 30th (T_{medd} = 18°C) of 1.93 mmol H_2O m^{-2} s^{-1} and, after it, the E_d decreased reaching the lowest value on August 27th (0.78 mmol H_2O m^{-2} s^{-1}, T_{medd} = 19.5°C) (Fig. K-4, *B*). In what concerns to P_{Nd}, the overall maximum rate was registered on July 23rd (T_{medd} = 22.3°C) with 7.8 µmol CO_2 m^{-2} s^{-1} (Fig. K-4, *A*) and the minimum P_{Nd} was then registered on August 21st (4.6 µmol CO_2 m^{-2} s^{-1}; T_{medd} = 26°C). By the end of August the irrigation starts and from here until the end of September, depending on the water regime, the rate of P_{Nd}, E_d and gs_d is partially recovered. After irrigation, the P_{Nd} of FI had consistently the highest rates (mean of 6.6 µmol CO_2 m^{-2} s^{-1}) representing 13% and 21% higher than in DI and NI, respectively.

After the introduction of irrigation, the midday stomatal conductance (gs_{md}), transpiration rate (E_{md}) and photosynthetic rate (P_{Nmd}) were also measured in order to evaluate their daily course (Fig. K-5, *A, B*). Significant differences in all of these parameters were observed between irrigated and non irrigated trees and values were consistently higher in FI. The introduction of irrigation increased tree water status on FI and DI above -0.6 MPa and -0.8 MPa, respectively, and the mean of gs_{md} was of 110.4 mmol m^{-2} s^{-1} in DI and 131.8 mmol m^{-2} s^{-1} in FI, which represents 22% and 46% more than in NI (90.3 mmol m^{-2} s^{-1}) (Fig. K-5, *C*). The overall value of E_{md}, was 2.72 mmol H_2O .m^{-2} s^{-1} on FI, decreasing around 14% in DI and 30% in NI. Higher values of P_{Nmd} were also measured on FI (mean of 14.1 µmol CO_2 m^{-2} s^{-1}), diminishing 29% in DI and 34% in NI trees.

A regression between P_N and E was plotted at dawn and midday (Fig. K-6) as well as the regression between E and the water potential (Fig. K-7, *A,B*) and P_N and the water potential (Fig. K-7, *C,D*). At dawn, the E_d was correlated with P_{Nd} (R^2 = 0.42; Fig. K-6, left) but at midday the correlation was lower, R^2 = 0.21 (Fig. K-6, right). Nevertheless, neither E_d nor P_{Nd} had a great correlation with Ψw_d when it ranged from -0.3 to -1.2 MPa (Fig. K-7, *A, C*). Conversely, at midday, the Ψw_{md} was better correlated with P_{Nmd} (R^2= 0.40; Fig. K-7, *D*) and the highest photosynthetic rate (14.1 µmol CO_2 m^{-2} s^{-1}) was achieved when the Ψw_{md} was around -0.8 MPa. In what concerns the E_{md} it presented a low correlation with $\Psi w_{md,}$ r^2=0.24 (Fig. K-7, *C*).

Leaf temperature: Daily mean air temperature (T_{medd}) is correlated with the shadowy T_{leaf} both at midday (R^2=0.72) and at dawn (R^2=0.43) and differences between treatments were punctually found before and after irrigated period (Supplementary Fig. K-2). Nevertheless, at midday, the T_{leaf} of the shady leaves was always higher in NI (mean of 22.8 ± 1.5 °C) than FI (19.6 ± 1.0 °C) or DI (20.9 ± 1.1 °C) suggesting some irrigation effect.

*Chlorophyll fluorescenc*e: In what concerns chlorophyll fluorescence measured in September, at dawn, both levels of irrigation (DI and FI) did not influence most of the parameters characterizing PSII photochemical with exception of T_{FM} and DI_0/RC

(Supplementary Fig. K-3). The T_{FM} was higher in both irrigated treatments, with more visibility on DI (20%). In relation to DI_0/RC it was 20% higher in irrigated plots than in non-irrigated ones. The Fv/Fm ratio found at dawn and midday was of 0.83 in all treatments. However, pronounced changes were observed at midday: the DI_0/RC was 40% (FI) and 20% (DI) higher than on NI. The other parameters influenced by irrigation were S_M (10% less), M_o (10% more), ABS/RC (10-15% more), TR_0/RC (10-15% more), ET_0/RC (10-15% more) and TR_0/CS_m (both, 10% more), DI_0/CS (10-15% more) and PI_{ABS} (10-20% less). The overall results showed that irrigated leaves had more light absorbed per reaction centre, more light trapped per reaction centre and, in spite of slightly more electrons transferred in the chain per reaction centre, showed a strong dissipation of energy flux which became reflected in the lower $PI_{ABS.}$ This apparent contradiction needs to be pursued with further studies, since it was expected that irrigation would favour the density of RC per chlorophyll antenna, and the PSII structure and functioning (Kalaji *et al.* 2011). According Björkman and Demming (1987), normal efficiency of PSII in higher plants (F_v/F_m) is close to 0.83 which is similar to the results from irrigated and non-irrigated chestnuts either at dawn or midday.

Leaf biochemistry: The differences on tree water level observed did not influence the leaf photosynthetic pigment content. Chl_{tot} increased from June (40.6 mg.cm^{-2}) to the end of August when it reached the highest value (54.3 mg cm^{-2}) (Supplementary Fig. K-4, *A*). The irrigation started just when the maximal content of chlorophyll was measured. For all treatments, the Car_{tot} increased from June (8.9 mg cm^{-2}) to October (10.9 mg cm^{-2}) and the Chl_a/Chl_b ratio changed from 3.1 to 4.2 (Supplementary Fig. K-4, *B, D*). The Chl/Car ratio consistently decreased since the beginning of September (Supplementary Fig. K-4, *C*). The leaf photosynthetic pigments analysis brings deeper knowledge about chestnut leaves' across the vegetative cycle but no consistence difference between irrigated and non-irrigated trees was detected.

Chestnut production: Irrigated treatments had significantly higher production than non-irrigated trees. Based on the projected canopy area, FI produced on average 0.95 kg m^{-2}, DI 1.02 kg m^{-2} and NI 0.57 kg m^{-2} (Tab. K-1). In what concerns the production per tree it was also higher in DI, followed by FI and NI (48, 45 and 27 kg tree^{-1}, respectively). However, nut calibre was lower in NI (79.7 nuts kg^{-1}) than in DI (87.5 nuts kg^{-1}) and FI

(92.5 nuts kg^{-1}) which means that big nuts were in NI. Concerning chestnut biochemical content, nuts from non-irrigated trees had 15% less content of ashes than FI (3.16 ± 0.2 g $100g^{-1}$DM), but they have 60 % more fats and 15% more protein than FI which had 1.61 g $100g^{-1}$DM and 6.05 g $100g^{-1}$DM , for crude fat and crude protein respectively (Tab. K-1).

Discussion

The irrigation scheduling presented here was based on the dawn water potential and the predefined values to trigger irrigation (-0.6 and -0.8 MPa) were chosen with the belief that they did not reflect an extreme water stress for the chestnut trees. Because of this scheduling, the irrigation events started in the late summer despite the higher temperatures occurred in July. For one hand it highlights the high needs of water in end of the summer which is in accordance with other authors (Pimentel-Pereira *et al.* 2007, Breisch 1995) who enhanced the importance of no water restrictions one month before harvesting the chestnuts. On the other hand, the need for watering only in the end of August indicates that until that moment the soil water storage was enough to accomplish the chestnut tree water needs. According with Bounous and Beccaro (2002) the adequate annual rainfall for *Castanea sativa* must be between 800 and 900 mm $year^{-1}$ and this range is within the values of our study although the precipitation was not so regularly distributed during the vegetative cycle which resulted in a very dry summer. The rain that fell during the winter was very important to replenish soil water content and, apparently, it helped trees to better buffer their water content during the dry season (expressed through the predawn water potential) most probably due to their deeper roots, as reported by other authors for Mediterranean trees (Martins *et al.* 2010, David *et al.* 2013). The monitoring of the soil water content at different depths, especially at the ones deeper than one meter, would be useful to understand the soil's water dynamics across the year and the xylem and root sap flow could help us to understand the water redistribution on the plant as studied by Fernández *et al.* (2007) and David *et al.* (2013).

We can say that our study trees, in all of the plots, were not under very critical water limitation since, even in the late summer, the predawn water potential was higher than -0.45 MPa which, according to Martins *et al.* (2010) and Brown *et al.* (2014), is within the hydric comfort interval for the chestnut tree (-0.4 to -0.6 MPa). The RWC analysis revealed no differences between treatments, even after irrigation, which may be due to the fact that leaves were collected at early morning and, as previously indicated by the predawn leaf water potential, all trees seemed to recover their water status during the night. The O-J-I-P test done one month after the beginning of irrigation also suggests that during the morning, the mechanism of the photosynthetic apparatus was not affected by treatments. Additionally, it was noteworthy that irrigated trees revealed a quite smaller variation between predawn to the midday water potential which suggests that irrigation helped the plant buffer the water potential during the morning. The variation pattern on water potential during daylight in non-irrigated chestnut trees is already reported on Gomes-Laranjo *et al.* (2008) and a similar pattern were observed in the present study with lower water potential at midday.

Before irrigation, at dawn, several days revealed differences among treatments in what concerns the water potential, the photosynthetic rate, transpiration rate and the stomatal conductance which may reflect tree-to-tree variations and their different responses to soil water refurbished during the morning (Fig. K-1, Fig. K-4). After irrigation, the dawn water potential revealed consistently higher values in the irrigated treatments (Fig. K-1, Fig. K-2) and its use as a tool for irrigation scheduling can be considered. Nevertheless, at morning time the trees still benefit from the soil's water absorbed during the night and the correlation between the dawn water potential and the photosynthetic rate were not strong (Fig. K-7, *C*). On the contrary, the correlation between photosynthetic rate and water potential at midday was high (Fig. K-7, *D*) and also; Lampinen *et al.* (2004) found a linear correlation between stem water potential and the maximal photosynthetic rate in French prunes. So our results too suggested that the midday stem water potential may be a good indicator of plant water status as reported by other authors in several fruit trees, vines and olive trees (McCutchan and Shackel 1992, Choné *et al.* 2001, Girona *et al.* 2006, Mirás‐Avalos *et al.* 2016).

So, in what concerns the midday, the highest value of the photosynthetic rate was found in the irrigated treatments, which had higher transpiration rates and lower leaves temperature. The T_{leaf} was influenced by the daily mean air temperature (Supplementary Fig. K-2) which is in agreement with the literature (Udompetaikul *et al.* 2011) and it also revealed to be very sensitive to a breeze or occasional clouds making it difficult to be measured without these occasional variants' influence. The lower value observed in the irrigated trees suggests some thermoregulation effect due to the high levels of transpiration at midday (Fig. K-5, *B*) which is in line with Gomes-Laranjo *et al* (2007). The mean transpiration (E_{md} = 2.3 mmol $H_2Om^{-2}s^{-1}$) found in this study is lower than those reported by Gomes-Laranjo *et al.* (2006), which is of about 4.1 to 2.6 mmol H_2O m^{-2} s^{-1} at mean temperatures of 26 and 18 °C, respectively. In general, the photosynthetic rate found in our study is closer to that reported by Martins *et al.* (2010) (9 µmol CO_2 m^{-2} $s^{-}1$, with air temperature ranging from 21 to 25°C) and by Gomes-Laranjo *et al.* (2006) which, for non-irrigated trees, found that the highest P_N (6.7 µmol CO_2 m^{-2} s^{-1}) occurred in September when the mean air temperature was of 26 ºC. According to Almeida *et al.* (2007) and Gomes- Laranjo *et al.* (2008), the general optimal growth temperature for the European chestnut is about 24°C where the maximal photosynthesis rate is of 10 µmol $CO_2.m^{-2}.s^{-1}$ and corresponds to a leaf water potential close to -1.0 MPa. In the present study, the maximal photosynthetic rates were found during the irrigated period on FI trees (P_{Nmd} = 11.2 µmol CO_2 m^{-2} s^{-1}) under mean daily air temperature of 21°C and with a mean Ψw_{md} of -0.99 ± 0.06 MPa. At September 6th it was registered the highest photosynthetic rate (14.1 µmol CO_2 m^{-2} s^{-1}) corresponding to a midday water potential of -0.8 MPa (Fig. K-47, *D*) and daily air temperature of 18°C (Supplementary Fig. K-2, *B*). Therefore, in spite of the midday stem water potential reflects the performance of the photosynthetic rate it is important to evaluate it considering the air temperature at the moment. Thus, in deficit irrigation strategies, where it can be admissible decays of 10% in the maximal photosynthetic rate the water management should be such that at midday the stem water potential should not decrease too much below -1.0 MPa, under mean air temperature of 21°C (Fig. K-4, *D*).

In our study, the fruit size was bigger in the non-irrigated modality despite the lower production. Also Jayne (2005) found bigger fruits but lower production in the non-irrigated trees. So, irrigation on FI and DI trees helped them to have more production but the water availability due to the late rain one month prior the harvest contributed to an increase in fruit size for NI. This is in line with Breisch (1995) and Pimentel-Pereira *et al.* (2007) who report the importance of water availability in later stages of the nut development. The lower fruit load in non-irrigated trees allows large fruit growth due to lower assimilates competition. The DM, crude protein, crude fat and ashes are close to the values reported by Ferreira-Cardoso (2007) for 'Longal' variety in different climatic regions of Portugal which are, respectively, 43%, 6.2 g $100g^{-1}$ DM, 1.2 g $100g^{-1}$ DM and 2.4 g $100g^{-1}$ DM. The presence of low ashes content in NI trees reflects low transpiration rates and, consequently, low mineral translocation from soil to trees. The almost double crude fat content in NI's nuts reflects hard conditions and, in spite of its high level of crude protein, this one could come from the high content of free amino acids that actually did not constitute protein due to adverse conditions (Ferreira-Cardoso, 2007). The irrigation on the chestnut trees assumes a very big importance for good production levels in long summers and drier autumns.

Conclusion

The irrigation scheduling on the chestnut trees based on the dawn water potential is reliable but our results suggests that at dawn and under such edaphoclimatic conditions the water potential is supported not only by the current root water absorption, but also by the night water refurbished into the canopy due to the root's pressure and this could buffer the variations on dawn water potential between irrigated and non-irrigated plants. Nevertheless, at midday, the accuracy of the water potential increased because it was mainly dependent of the current root water absorption besides the temperature's effect. Results also demonstrate the benefit of irrigation under the studied water regimes (threshold dawn water potential of -0.6 or -0.8 MPa) when compared to non-irrigated plants, both at the level of gas exchanges and chestnut production. However, since only slight differences were observed between the two water regimes, we suggest the use of the threshold dawn water potential of -0.8 MPa to save water resources or, on the contrary, it can be more accurate to use the midday water potential using the threshold of -1MPa. Further works need to be done in order to confirm these thresholds of stem water potential for irrigation purpose, as well as to deepen knowledge on the soil-plant water relations in different soil textures, climatic conditions, chestnut varieties, different rootstocks and orchard age.

Tables and Figures

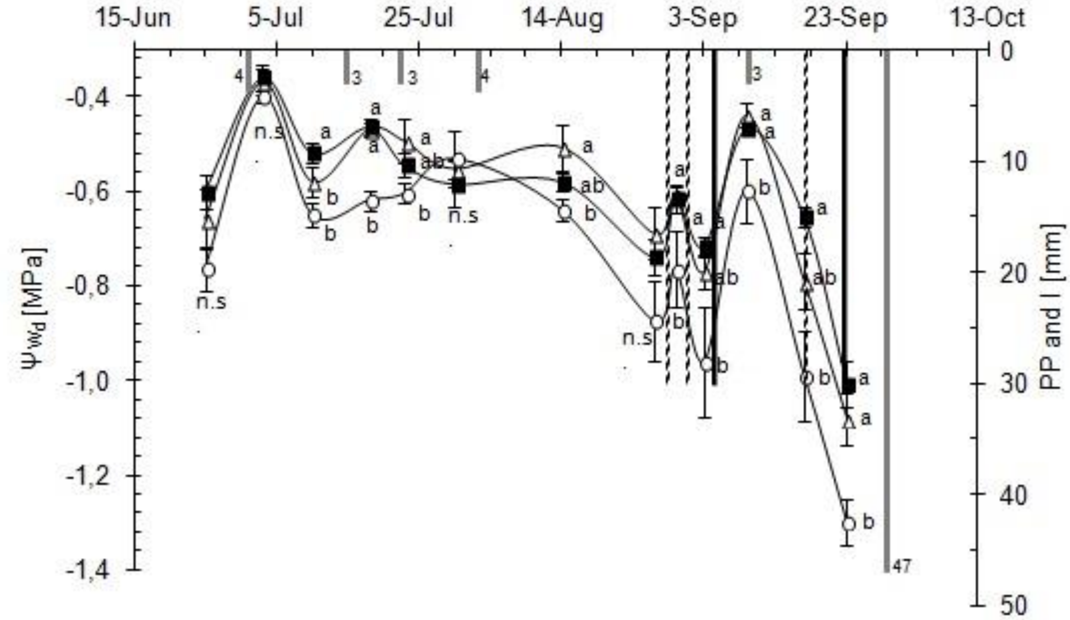


Fig. K-1 - Time course of dawn water potential (Ψw_d, MPa) for non-irrigated treatment (NI, ○), deficiently irrigated (DI, ∆) and fully irrigated (FI, ■) system, in 2013, with respective standard error bars. Values with different letters are statically different between treatments at same day according to Fisher test ($p<0.05$). Precipitation (PP, mm) is represented by grey columns and irrigation (I, mm) is represented by dashed columns for FI (August 28th, August 30th, and September 17th) and by full black columns for DI and FI (September 3rd and September 23rd) in 2013.

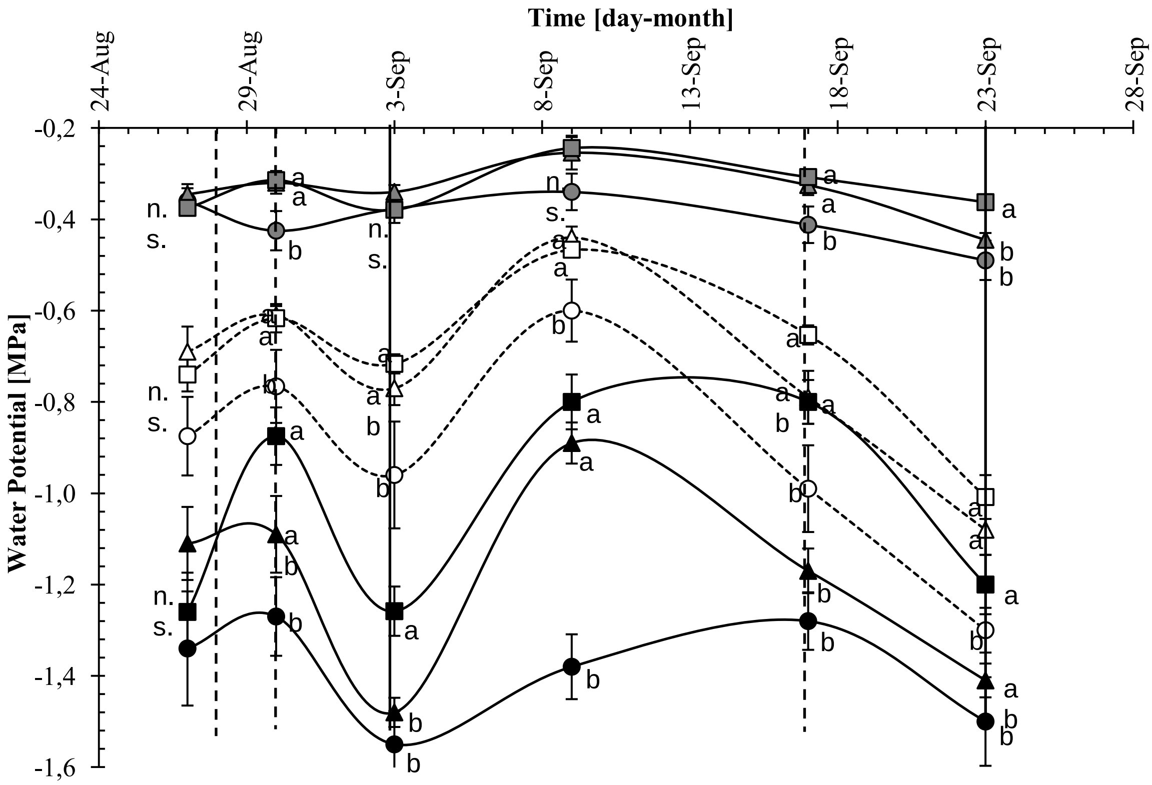


Fig. K-2 - Time course of water potential (MPa) at predawn (grey symbols), dawn (open symbols) and midday (black symbols) for non-irrigated treatment (NI, circles), deficiently irrigated (DI, triangles) and fully irrigated (FI, squares) systems with respective error bars according to Fisher test (p<0.05). Values with different letters are significantly different between treatments for the same day and time. Vertical dashed line refers to FI irrigation date (August 28th, August 30th, and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd) in 2013.

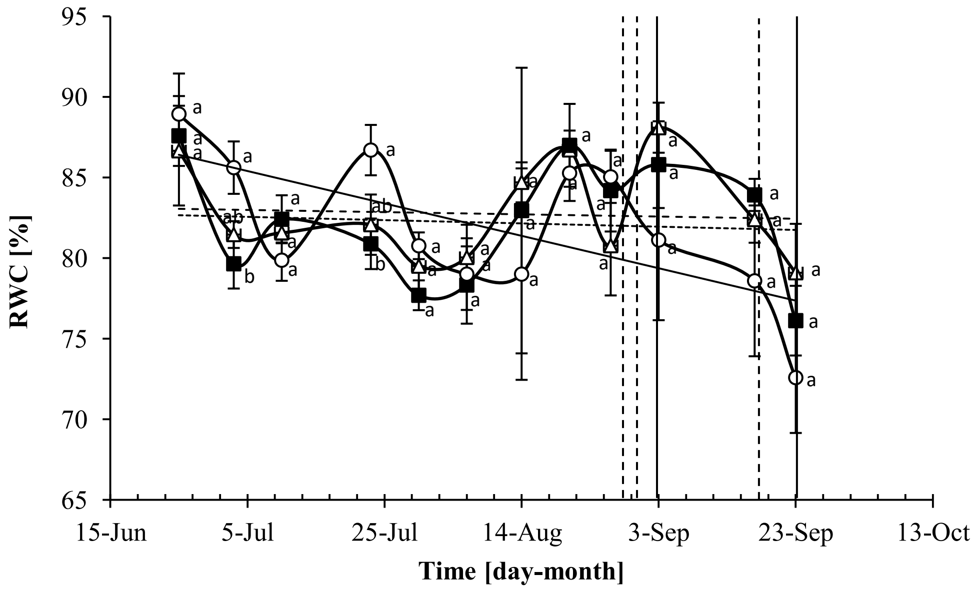


Fig. K-3 - Time course of relative water content (RWC, %) of non-irrigated treatment (NI, ○), deficiently irrigated system (DI, Δ) and fully irrigated system (FI, ■) in 2013, with respective error bars according to Fisher test ($p<0.05$). Values with different letters are significantly different. Vertical dashed line refers to FI irrigation date (August 28th, August 30th, and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd) in 2013.

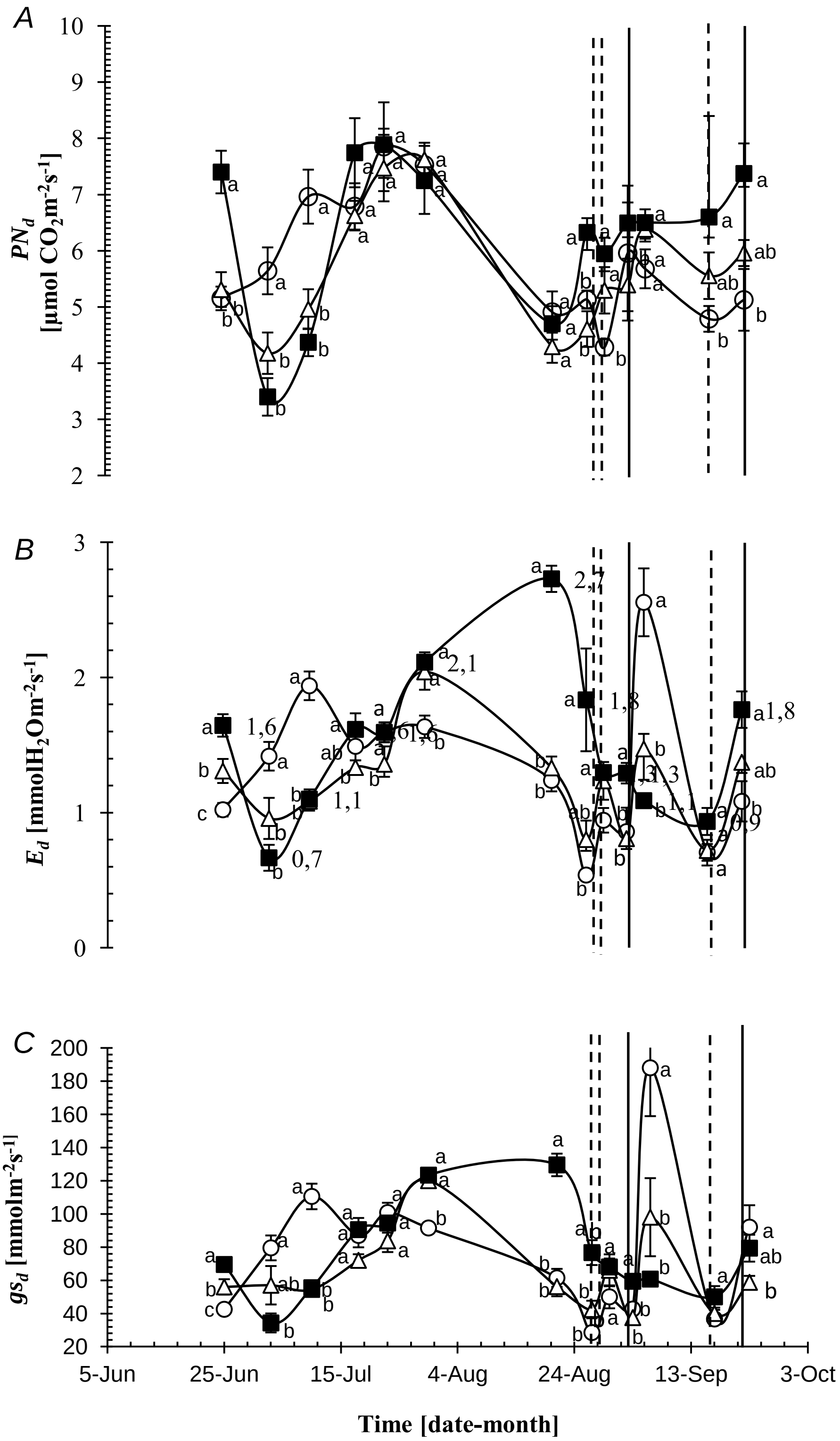


Fig. K-4 - Gas exchanges during dawn period respectively for A) photosynthetic rate P_{Nd} [µmol CO_2 m^{-2} s^{-1}], B) transpiration rate E_d [mmol H_2O m^{-2} s^{-1}] and C) stomatal conductance gs_d [mmol m^{-2} s^{-1}] for non irrigated (NI, ○), full irrigated (FI, ■) and deficit irrigated (DI, Δ) systems with respective error bars according to Fisher test (p<0.05). Values with different letters are significantly different. Vertical dashed line refers to FI irrigation date (August 28th, August 30th, and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd) in 2013.

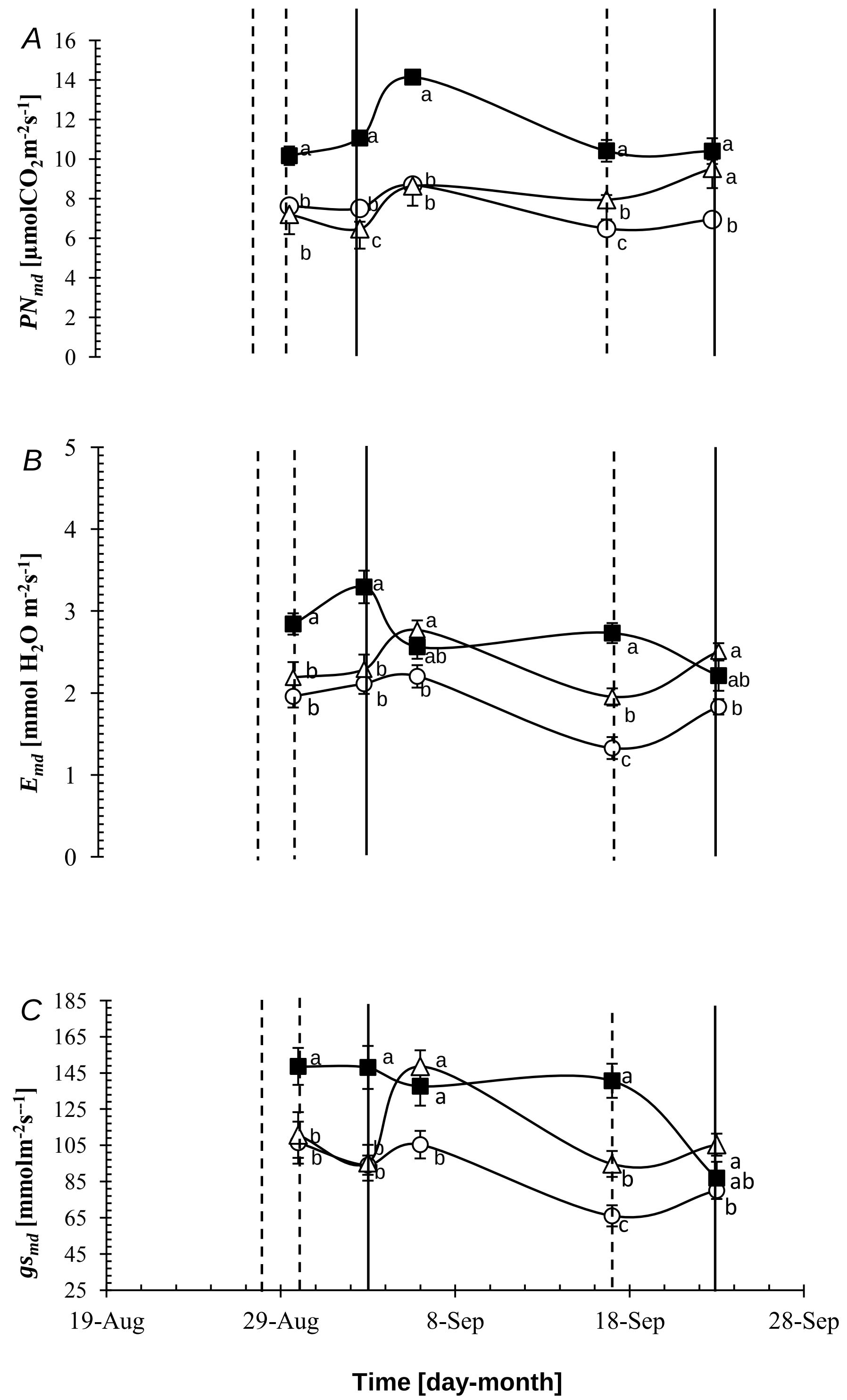


Fig. K-5 - Gas exchanges during midday period respectively for A) photosynthetic rate $P_{N\text{md}}$ [µmol CO_2 m^{-2} s^{-1}], B) transpiration rate E_{md} [mmol H_2O m^{-2} s^{-1}] and C) stomatal conductance gs_{md} [mmol m^{-2} s^{-1}] for non irrigated (NI, ○), full irrigated (FI,■) and deficit irrigated (DI, Δ) systems with respective error bars according to Fisher test ($p<0.05$). Values with different letters are significantly different. Vertical dashed line refers to FI irrigation date (August 28th, August 30th, and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd) in 2013.

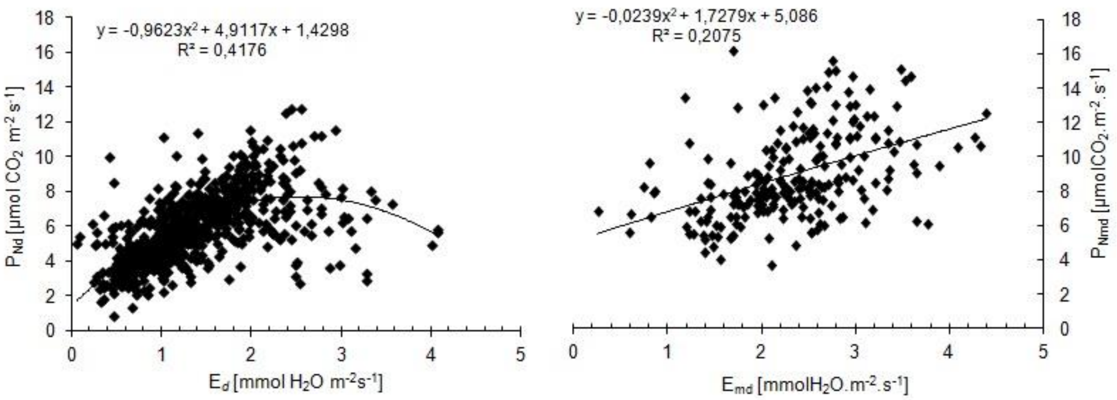


Fig. K-6 - Relationship between photosynthetic rate P_N [µmol CO_2 m^{-2} s^{-1}] and transpiration rate E_d [mmol H_2O m^{-2} s^{-1}] at the dawn time (left) and midday time (right).

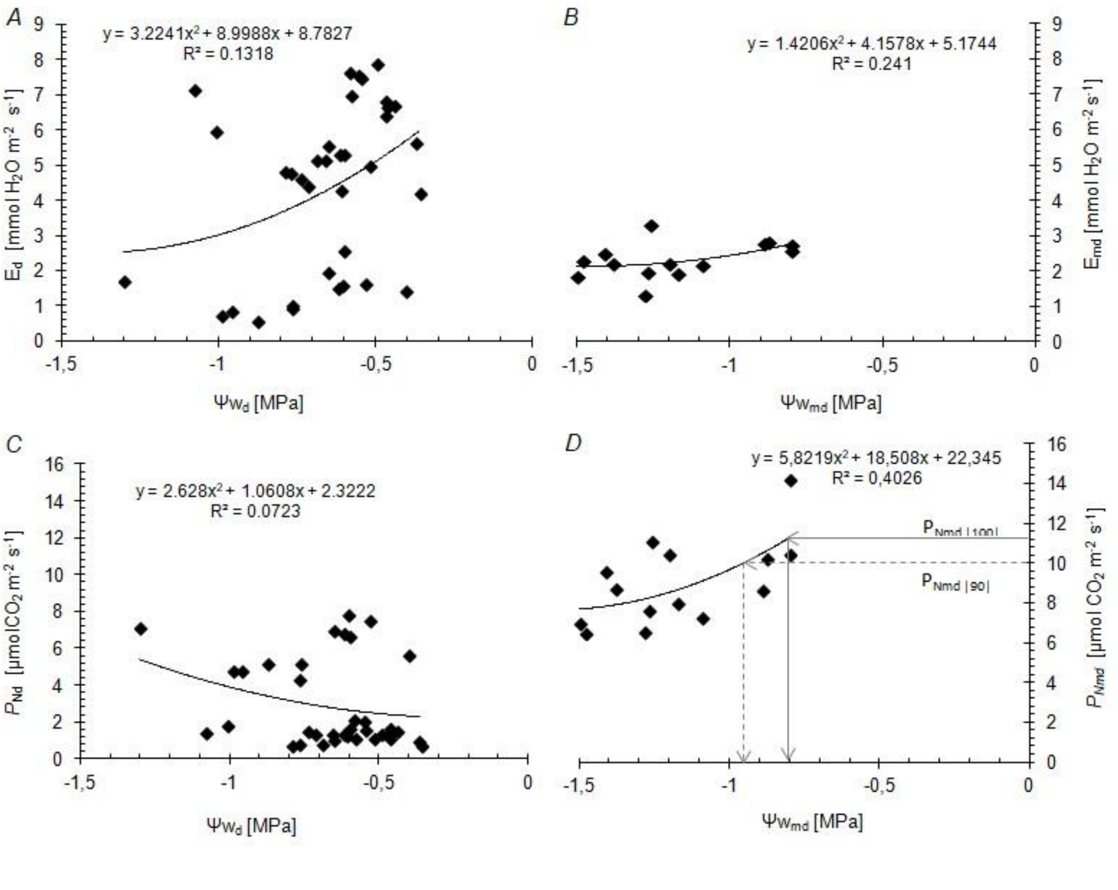
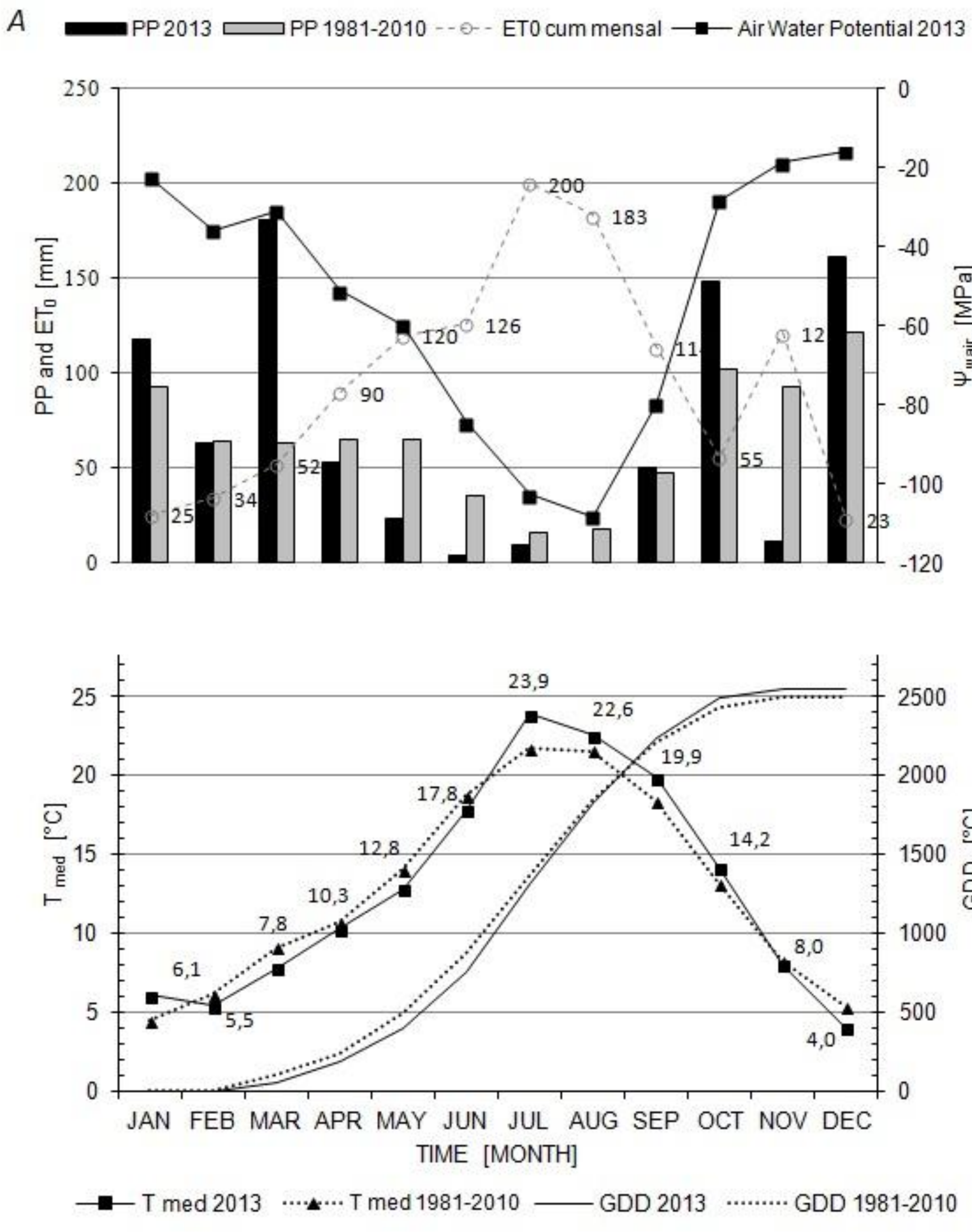


Fig. K-7 - Relationship between transpiration rate *E* [mmol H_2O m^{-2} s^{-1}] and water potential Ψw [MPa] at dawn (*A*) and midday (*B*) time, and relationship between photosynthetic rate P_N [µmol CO_2 m^{-2} s^{-1}] and water potential Ψw [MPa] at dawn (*C*) and midday (*D*) time. $A_{|100|}$ is the maximal photosynthetic rate found with the regression and $A_{|90|}$ is the admissible decay from the maximal photosynthetic rate (-10%).

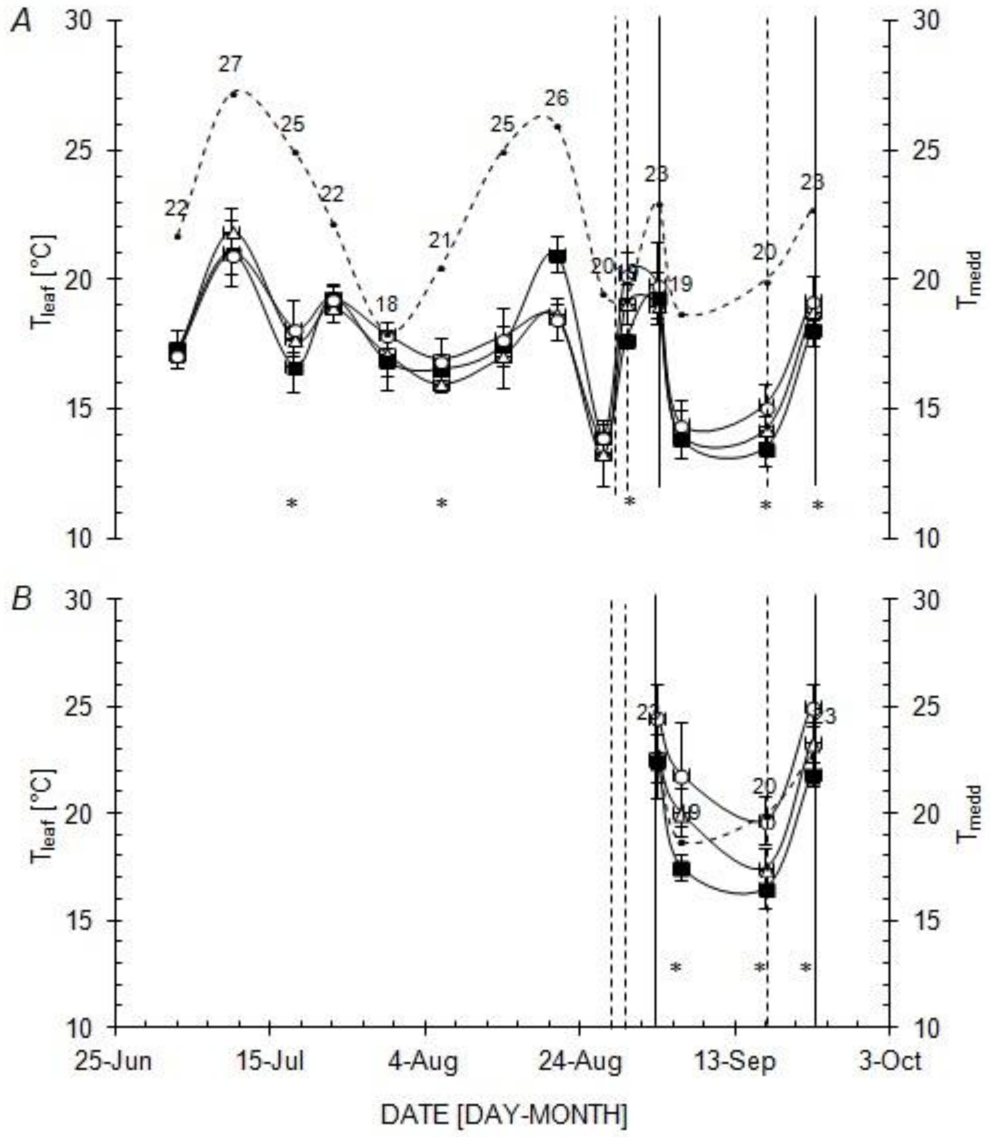
Tab. K-1 - Average chestnuts' production per canopy area P [kg m^{-2}], chestnut's calibre [nuts $tree^{-1}$], fruit setting (%), chestnuts' density [g Ml^{-1}], dry matter DM [g $100g^{-1}$fresh weight], ashes [g $100g^{-1}$DM], crude fat CF [g $100g^{-1}$DM] and crude protein CP [g $100g^{-1}$DM] (±se) for non-irrigated (NI), deficit (DI) and fully (FI) irrigated treatment. Values with different letters are significantly different (p<0.05) by Fisher test on the vertical reading.

Treat	P	Calibre	Fruit setting	Density	DM	Ashes	CF	CP
NI	0.57^{b}	$79.7±5.1^{b}$	$85.9±3.9^{a}$	$1.04±0.1^{a}$	$45.4± 3.8^{a}$	$2.66± 0,4^{b}$	$1.61± 0.3^{a}$	$6.05± 1.1^{a}$
DI	1.02^{a}	$87.5±3.3^{a}$	$85.6±3.5^{a}$	$1.07± 0.2^{a}$	$42.5± 2.4^{b}$	$3.07± 0.3^{a}$	$0.86± 0.4^{b}$	$5.51± 6.5^{b}$
FI	0.95^{a}	$92.5±2.5^{a}$	$83.0±3.2^{a}$	$1.06± 0.1^{a}$	$42.2± 1.6^{b}$	$3.16± 0.2^{a}$	$0.99± 0.3^{b}$	$5.21± 0.3^{b}$

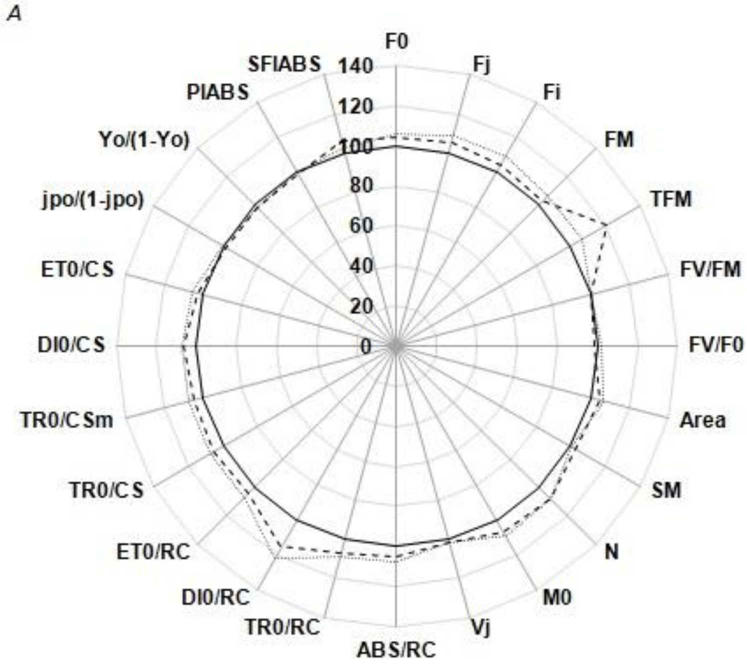
Supplementary Figures

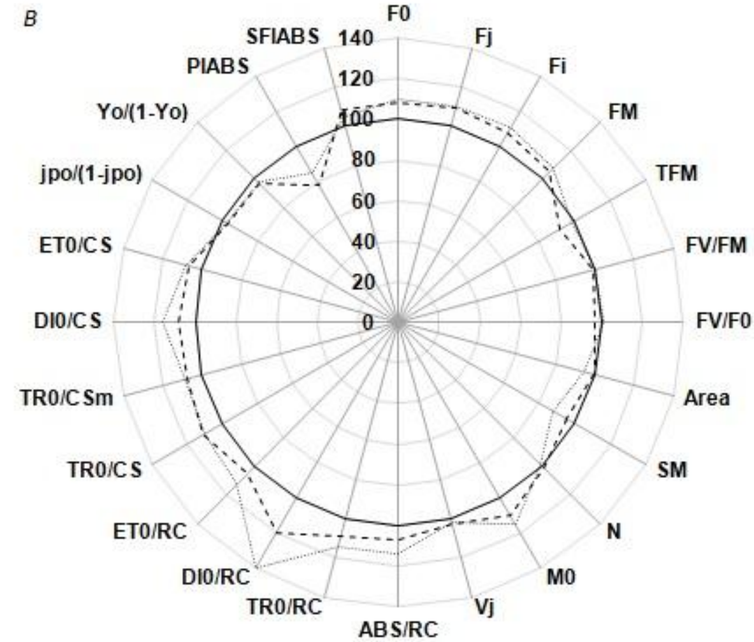


Supplementary Fig. K-1 - *A*: Mean monthly temperature (T_{med}, °C), growing degree days (GDD, °C) in 2013 (full line) and on the decade 1981-2010 (dashed line) for Bragança region. *B*: Monthly precipitation on the decade 1981-2010 ($PP_{1981-2010}$, grey columns, mm); monthly precipitation in 2013 (PP_{2013}, black columns, mm), cumulative monthly evapotranspiration of reference (ET_0, dashed grey line, mm), air water potential (Ψw_{air}, full black line, MPa) in 2013. Source: IPMA, 2013.

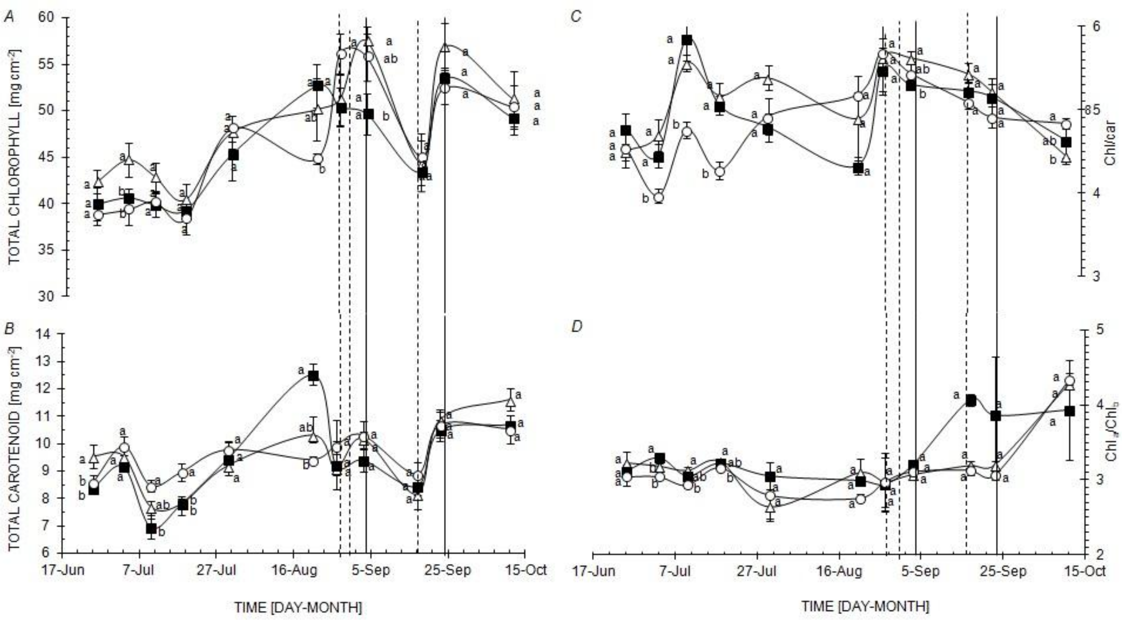


Supplementary Fig. K-2 - Time course mean daily air temperature (T_{medd}, °C) and leaf temperature (T_{leaf}, °C) on the shadowy canopy at dawn time (*A*) and at midday (*B*) for non-irrigated treatment (NI, ○), deficiently (DI, ∆) and full (FI,■) irrigated system, with respective errors bars according to Fisher test ($p<0.05$). The asterisks show significant difference according to Fisher test ($p<0.05$). Vertical dashed line refers to FI irrigation date (August 28th, August 30th and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd).





Supplementary Fig. K-3 - A 'spider plot' of O-J-I-P test parameters of chestnut leaves from non-irrigated (NI, full line), deficiently (DI, grey dash line) and full (FI, black dashed line) irrigated treatments measured on dawn time (*A*) and midday (*B*) time. All values are shown as percent of control plants (NI plants = 100). See the List of abbreviations for the meaning of the symbols and the parameters.



Supplementary Fig. K-4 - Time course for total chlorophyll [mg cm^{-2}] (*A*), total carotenoids [mg cm^{-2}] (*B*), chlorophyll/carotenoids ratio (*C*) and Chlorophyll a/b ratio (*D*) for non irrigated (NI, o), full (FI, ■) and deficit irrigated (DI, ∆) treatment with respective error bars according to Fisher test (5%). Values with different letters are significantly different. Vertical dashed line refers to FI irrigation date (August 28th, August 30th and September 17th) and vertical full line refers to DI and FI irrigation date (September 3rd and September 23rd). Values with different letters are significantly different by Fisher test (p<0.05).

L. The effect of irrigation on chestnuts' physiology and production (*Castanea sativa*)

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Resumo

Este estudo tem como objetivo avaliar a influência da rega na fisiologia do castanheiro, no calibre e na produção da castanha. O estudo ocorreu durante 2015 e 2016, num souto em Bragança com variedade 'Judia'. Foram instalados dois sistemas de rega: gota-a-gota (TI) e micro-aspersão (SI) e avaliadas 10 árvores em cada modalidade. A rega foi iniciada sempre que o potencial hídrico de ramo era inferior a -1,2 MPa. Outras dez árvores foram mantidas em condições de sequeiro (NI). De junho a outubro, foram medidos o potencial hídrico de ramo, a fluorescência da clorofila, as taxas fotossintética e de transpiração e a produção por árvore. A quantidade média total de água fornecida foi de 470 e 925 m^3 ha^{-1} em 2015 e 2016, respetivamente. Nos dois anos, a fotossíntese e transpiração foram maiores nas árvores regadas (8,6 µmol CO_2 $m^{-2}s^{-1}$ e 1,9 mmol H_2O m^{-2} s^{-1}) que nas não regadas (7,6 µmol CO_2 $m^{-2}s^{-1}$ e 1,8 mmol de H_2O m^{-2} s^{-1}). A produção de castanha foi 26% maior nas modalidades com rega (em média 48 kg por árvore). A castanha das árvores não regadas foi mais pequena (93 castanha kg^{-1}) do que nas regadas (75 castanha kg^{-1}). Apesar das diferenças entre tratamentos, as condições climáticas de 2016, afetaram a produção e o tamanho dos frutos. De 2015 a 2016, a produção diminuiu 16%, 27% e 33% para SI, TI e NI, respetivamente. O tamanho dos frutos também diminuiu 90%, 45% e 24% para NI, TI e SI, respetivamente, quando a soma das temperaturas (maio a outubro) variou de 2348 para 2504 ° D. A rega permitiu suavizar a queda da produção e do tamanho da castanha, mas a temperatura desempenha um papel importante na fisiologia e produção das árvores.

Palavras-chave: *Castanea sativa*, programação de irrigação, relação planta-solo.

Abstract

This study aims to evaluate the influence of irrigation on the chestnut's physiology, nut calibre and yield. The study was carried out during 2015 and 2016, in a chestnut orchard of the 'Judia' variety located in Bragança on the northeast of Portugal. Two irrigation systems were installed in ten trees each: drip (TI) and micro-sprinkler (SI). Irrigation was triggered when stem water potential fell below -1.2 MPa. Other ten sample trees were kept in rainfed conditions (NI). From June to October the stem water potential, chlorophyll fluorescence, photosynthetic and transpiration rates were monitored and production per tree was weighted. The total mean amount of water furnished was of 470 and 925 m^3 ha^{-1} in 2015 and 2016, respectively. On both years the photosynthetic and transpiration rates were higher for irrigated trees (8.6 µmolCO_2 m^{-2} s^{-1} and 1.9 mmol H_2O m^{-2} s^{-1}) than for none irrigated ones (7.6 µmol CO_2 m^{-2} s^{-1} and 1.8 mmol H_2O m^{-2} s^{-1}). Chestnut production was 26% higher for irrigated trees with 48.2 kg/tree and nut size was smaller in non irrigated trees (93 nuts kg^{-1}) than for the irrigated ones (75 nuts kg^{-1}). Despite of these differences the climatic conditions, particularly the hotter temperatures in 2016, affected production and nut size. From 2015 to 2016 production decreased 16%, 27% and 33% for SI, TI and NI respectively. Nut size also decreased 90%, 45% and 24% for NI, TI and SI, respectively when the temperature sum (May-October) varied from 2348 to 2504°D. The introduction of irrigation in the chestnut orchard is beneficial but air temperature plays an important role in the tree physiology and production.

Keywords: Water potential, irrigation scheduling, plant-soil relationships, photosynthetic traits, nut's growth

Introduction

The high market demand for the chestnuts and the international market pressure especially by the Asian countries (Bertoncello, 2016), coupled with the high pressure of plagues over the European chestnut (Ferracini, 2016) started to change the way producers look at their traditionally rainfed chestnut trees. More and more it is important to invest in new agricultural practices to get high and more regular chestnut production in where it fits irrigation (Breisch, 1995). Water availability is by far one of the most important factors in the success of the crops, being determinant on the crop's production and physiological processes. According to Ferrini and Nicense (2000), in a climatic context with a total annual precipitation varying from 600 to 1600 mm, the European chestnut needs at least about 33 mm of water in the summer months to avoid nut production loss.

According to Mota *et al*. (2014) it was suggested that the midday water potential of the 20-years old trees was sensitive to the effect of irrigation made on the top soil layers and irrigated trees revealed higher water potentials and photosynthetic rates comparing with the non-irrigated ones. Martins *et al.* (2010) also found higher photosynthetic rate in the irrigated trees but without significance in the hotter years which may reflect the importance of temperature in the chestnut's physiological behaviour. The same author referred that irrigation may not be advantageous when comparing with other rainfed modalities studied due to the very deep roots of the 40 years-old chestnut trees. On the other hand, Jayne (2005) in an experimental trial with young chestnut trees (12 years-old) observed the increasing of nut production with irrigation. However, this study did not approach the physiological behaviour of the trees neither the soil-plant water relations which is fundamental to the performance of the irrigation in order to avoid water's waste and to get more production with less water.

Besides the water potential and gas exchange techniques to approach the water status of the tree, the chlorophyll fluorescence is another technique that can be used as a proxy of plant stress because environmental stresses can reduce the ability of a plant to metabolize normally (Maxwell and Johnson, 2000). Among the various approaches to the analysis of chlorophyll *a* fluorescence signals, the so-called 'OJIP-test' give us information about the structure and function of the photosynthetic apparatus (mostly related to PSII) and offers simple equations expressing the equilibrium between the inflow and outflow of the entire energy flux within PSII (Kalaji *et al.*, 2011). Within the wide range of parameters calculated using the 'JIP-test', the 'performance index' (PI_{ABS}) has shown to be sensitive to the effect of water deficit on plant vitality (Živčák *et al*., 2008; Van Heerden *et al*., 2007).

The present study aims to understand the physiological behavior (tree water potential, gas exchange and chlorophyll fluorescence) of the chestnut tree under two different irrigation modalities and under none irrigation and, additionally, also intends to evaluate nut growth and production.

Material and methods

Site description The experiment was conducted during 2015 and 2016 in the northeast of Portugal at 862 m a.s.l. on a commercial rainfed chestnut orchard planted in 1993. The rootstocks were of *Castanea sativa* Mill grafted with 'Judia' cultivar. Tree density is of 200 plants/ha with an average trunk diameter at breast height, crown projection area and canopy high of 0.87 ± 0.04 m, 47.08 ± 3.98 m^2 and 1.9 ± 0.1, respectively. Soil is kept with seeded legumes and grass-plot for sheep pasture and straw-bale in June. The soil is kept with seeded pasture since plantation. The soils are Cambisols, with 100 cm of thickness and C horizon shows many coarse gravel and cobbles. Soils are loam and, on the shallowest 10 to 60 cm organic matter is of about 3% and has 26 and 115 mg kg^{-1} of extractable P_2O_5 and K_2O (Egnér-Rihem method) respectively and a pH (H_2O) of 4.7.

Treatments Three treatments were applied: non-irrigated (NI), trees were not irrigated during the whole season; drip irrigation (TI) and micro-sprinkler irrigation (SI). The drip system was installed with two pipes per tree line with emitters spaced every meter with a debit of 3.6 l h^{-1}. The micro-sprinkler pipe was installed hanging in trees' trunk and it had emitters with debit of 50 l h^{-1} spaced every 5 meters. Each treatment (replicated twice) was installed along the row of trees. Each row had forty trees and five sample trees were chosen (ten trees per treatment). Border trees were around the study area and between each sampled tree on the row. In both TI and SI modality, the irrigation was triggered every time the midday stem water potential (Ψw_{md}) was equal or bellows -1.2 MPa.

Data Collection From June to October the midday stem water potential was monitored every 7-10 days on the ten trees per treatment in one leaf per tree (n = 30). Readings were taken between 12:00 h and 13:30 h with a pressure chamber (Model "pump-up" PMS Instruments®) according to the methodology recommended and adapted by Fulton *et al.* (2014). Briefly, the sample leaf was covered with an aluminium foil and plastic bag for at least 40 minutes before excision. After the excision the leaf was immediately putted into the chamber pressure.

The photosynthetic (A_{md}) and transpiration rates (E_{md}) were determined in July and August with an Infrared Gas Analyser (IRGA, mod. LC*pro*+, Analytical Development Co®), twice a month in 2015 and once a month in 2016. The measurements were taken at

12:00 h in one leaf per tree in ten trees per treatment (n=30) and leaves were from the shadowy external side of the canopy.

The chlorophyll fluorescence was measured between 12:00 and 13:30 h every 7-10 days with an OS-30p Chlorophyll fluorometer (Opti-Sciences, Inc.) using the OJIP test protocol. The following parameters were subsequently calculated: 'PI_{ABS}' (performance index), 'Area' (the area above the chlorophyll fluorescence curve between F_0 and Fm, reflecting the size of the plastoquinone pool), 'T_{FM}' (maximal chlorophyll fluorescence intensity measured when all PSII reaction centres are closed), 'F_v/F_m' (maximal quantum efficiency of PS II photochemistry) and 'F_v/F_0' (value that is proportional to the activity of the water-splitting complex on the donor side of the PSII) (see details in Kalaji *et al.*, 2011). The measurements took place in one leaf per tree, ten trees per treatment, after thirty minutes of darkness adaptation. Leaves were taken from the shadowy external side of the canopy.

The meteorological data was obtained from the monthly agro-meteorological bulletin provided by the website of the Portuguese Institute of Sea and Atmosphere. It refers to the monthly precipitation (PP), mean air temperature (T_{med}), mean air humidity (HR) and evapotranspiration of reference (ET_0). The temperature sum was calculated according to Dinis *et al.* (2011).

For chestnut production an area of harvest beneath the canopy of each tree was delimited using a tape measure. The chestnuts that dropped within the delimited area were caught and weighted on the field with a manual scale. The nut production is expressed by kilograms per trees and by kilograms per square meter of the canopy's area. Healthy chestnuts (n = 185 in 2015; n = 211 in 2016) were used to determine the calibre (nuts per kilogram). In 2016 from August 24^{th} to November 10^{th} ten chestnuts per treatment (n=30) were collected weekly and weighted in a digital scale to accompany their growth curve.

Statistical analysis. Results were analysed with the StatView 4.0 software (Abacus, concepts, Inc.). Comparisons were made with Fisher test, using a significance level of 0.05. Data are shown with standard error (± se).

Results

The temperature sum (May – Oct.) was of 2348°D and 2504°D and the total precipitation (May – Oct.) was of 355 and 213 mm in 2015 and 2016 respectively (Fig. L-1). 2016 was drier from June to October than 2015 as well as the air temperature was higher in September and October of 2016 during nut ripening.

Because the irrigation was triggered every time the Ψw_{md} <-1.2 MPa the number of events was higher in 2016 (Fig. L-2) and the total water volume furnished in TI was of 461 and 871 m^3 ha^{-1} and in SI was of 479 and 979 m^3 ha^{-1} for 2015 and 2016 respectively. During the irrigation period trees from NI had lower water potential than TI or SI. In 2015, the values were of -1.19 ± 0.09 MPa, -1.13 ± 0.06 MPa and 1.10 ± 0.07 MPa for NI, TI and SI respectively and in 2016; -1.51 ± 0.09 MPa, -1.29 ± 0.08 and -1.30 ± 0.06 in NI, TI and SI respectively. In spite of the differences given by irrigation the Ψw_{md} varied with air temperature and tree-to-tree variation was also observed.

TI modality had higher 'V_j', 'RC/ABS', 'ABS/RC', 'TR_0/RC' and 'DI_0/CS' than the control in September 2015 but it was lower in September 2016 (Fig. L-3). For the same parameters SI had a similar behaviour as TI in 2015 but kept slightly higher than NI in 2016. According to Tab. L-1, in 2016, the PI_{ABS} was significantly higher in TI and SI after irrigation however just before it, at July 20th, the PI_{ABS} was significantly lower in TI (8.6 ± 1.1) compared with SI (11.6 ± 0.5) and NI (12.9 ± 1.4). By the end of September, the irrigated trees had PI_{ABS} of 7.0 ± 0.4 and 5.1 ± 0.5 (TI and SI, respectively) while NI had PI_{ABS} = 2.8 ± 0.6. The T_{FM} was higher in irrigated trees but not significantly, as well as the 'F_v/F_m', 'F_v/F_0' and 'Area' (Tab. L-1).

In August, the A_{md} was significantly lower in NI (7.1 and 5.6 µmol CO_2 m^{-2} s^{-1}, for 2015 and 2016 respectively) than in TI (9.6 and 7.4 µmol $CO_2.m^{-2}.s^{-1}$, for 2015 and 2016 respectively) or in SI (9.9 and 7.3 µmol $CO_2.m^{-2}.s^{-1}$, for 2015 and 2016 respectively). The transpiration rate was also lower in the non-irrigated trees on August but without significance (1.5, 1.7 and 1.9 mmol H_2O m^{-2} s^{-1} for NI, TI and SI respectively in 2015; and 1.8, 2.1 and 2.0 mmol H_2O m^{-2} s^{-1} for NI, TI and SI respectively in 2016) (Fig. L-4).

The chestnut's harvest started in the last week of October in both years. From 2015 to 2016 the chestnut production lowered without a significant difference within treatments: from 0.98± 0.2 to 0.75 ± 0.1 kg m^{-2} in NI, from 1.11 ± 0.1 to 0.92 ± 0.2 kg m^{-2} in TI and from 1.5 ± 0.1 to 1.05 ± 0.3 kg m^{-2} in SI which was equivalent to 44 to 33 kg $tree^{-1}$ in NI, from 54 to 43 kg $tree^{-1}$ in TI and from 52 to 44 kg $tree^{-1}$ in SI.

In 2015 nut size was bigger in irrigated treatments without significance (64.5 ± 4.2, 61.4 ± 2.1 and 62.7 ± 3.8 nuts kg^{-1} in NI, TI and SI, respectively) but was significantly different in 2016 (122.7 ± 8.5, 89.0 ± 5.1 and 77.7 ± 8.5 nuts kg^{-1} in NI, TI and SI respectively).

The fruit growth curve revealed differences in early September between irrigated and non-irrigated trees and the final weight per nut was of 9.0 g in NI, 12.3 in TI and 12.9 g in SI (Fig. L-5).

Discussion

Compared to 2015, the drier and hotter conditions of 2016 were determinant to the decreasing of tree water potential, photosynthesis rate, transpiration rate, nut yield and nut size. The irrigation, however, both by drip or micro-sprinkler system influenced nut production giving more and bigger nuts as well as it helped trees to have a higher photosynthetic rate and stem water potential when compared with the non-irrigated ones. In fact, after irrigation, the stem water potential of the TI and SI trees was higher than the NI trees (Fig. L-2). In 2016, this difference was statistically significant in August and September revealing that under hotter conditions the higher soil moisture is fundamental to keeping higher stem water potentials. The effect of temperature in the photosynthesis and water potential is well studied in the chestnut tree (Gomes-Laranjo *et al*. 2008, Gomes-Laranjo *et al*. 2007). Also, Dinis *et al*. (2011) found differences in nut calibre depending on the temperature sum. Thus, according to this author, in a study about the morphological and chemical diversity of chestnut trees under different temperature sums, the best calibres (40-60 nuts kg^{-1}) were reached when the temperature sum (May – Oct.) ranged between 2000 to 2200 °D. Outside this range the author observed decay up to 50% in nut size. In our study the decay of nut size was of 90%, 45% and 24% for NI, TI and SI respectively, when temperature sum (May-Oct.) was of 2348 °D to 2504°D.

In what concerns nut growth, the chestnut has a smooth sigmoid curve typical of other nuts (Ezura and Hiwasa-Tanase, 2010) which is notorious in September. Other authors report the importance of watering the chestnut during nut development and the importance of rain by the end of the summer (Breisch 1995, Bounous 2014, Gomes-Laranjo *et al*. 2007) and, in this study, the nut size was effectively determined by irrigation. The autumn in Portugal has been tendentiously drier and hotter in the last years and the introduction of irrigation may be more and more useful in the rainfed chestnut trees to guarantee nut quality, market appreciation and to reduce producer climatic dependency. No clear differences were found between the two irrigation systems although the bigger nuts were found in micro-sprinkler system under hotter conditions probably due to the little more water furnished, or it may suggest some kind of influence in air temperature decrease around the trees due to soil evaporation.

The PI_{ABS} reflects the functionality of both PSI and PSII giving quantitative information on the current state of plant performance under stress conditions (Strasser *et al.,* 2004). The increase of PI_{ABS} after irrigation on TI and SI systems (Tab. L-1) reflects the better conditions that irrigated trees were by the end of the summer 2016 and, thus, the PI_{ABS} could be an interesting parameter to analyse the chestnut's overall photosynthetic performance under water stress as found by other authors (Živčák *et al.*, 2008). However, on the late September 2015 (Fig. L-3), the PI_{ABS} was not clearly detached from the irrigated trees to the non irrigated trees as it was in 2016. This may reveal less stress in non-irrigated trees in 2015 and that PI_{ABS} is more dependent of the air temperature than water soil conditions. The F_V/F_M was almost unaffected by irrigation (Tab. L-1) which is in accordance with the findings of Genty *et al.* (1987) and Christen *et al.* (2007) that consider the F_V/F_M parameter was not really affected by early changes of plant photosynthesis due to water stress. According to Bjorkman and Demmig (1987), in higher plants, the F_v/F_m is close to 0.83 which was near the values found in our study. The overall analysis indicates that climatic conditions influence the chlorophyll fluorescence behaviour of irrigated trees and those under micro-sprinkler systems were less affected by it.

In which concerns the photosynthetic rate, the values found in our study are within the ones found in literature (Gomes-Laranjo *et al.* 2007, Gomes-Laranjo *et al*. 2008, Martins *et al.* 2010) which varied from 7 to 13 $\mu molCO_2.m^{-2}.s^{-1}$ depending on air temperature, soil water conditions and water potential. The overall mean transpiration (E_{md} = 1.8 mmol $H_2Om^{-2}s^{-1}$) found in this study was lower than those reported by Gomes-Laranjo *et al.* (2006), which is of about 4.1 to 2.6 mmol $H_2Om^{-2}s^{-1}$ at the mean temperature of 26 and 18 °C, respectively, and this can reflect an adaptive response of the Judia's cultivar population under study.

Conclusion

The present study shows that irrigation on adult chestnut trees induces differences on the tree water potential, on the photosynthetic productivity and nut production. In which respects nut production, watering the chestnut tree about two months prior to the harvest conducts to higher calibres, independently of the irrigation system used. Nut calibre also depends on the air temperature. Irrigated trees had higher photosynthetic and transpiration rates as well as higher midday stem water level than the non-irrigated ones but air temperature plays an important role in all those parameters.

Acknowledgements

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Tables and Figures

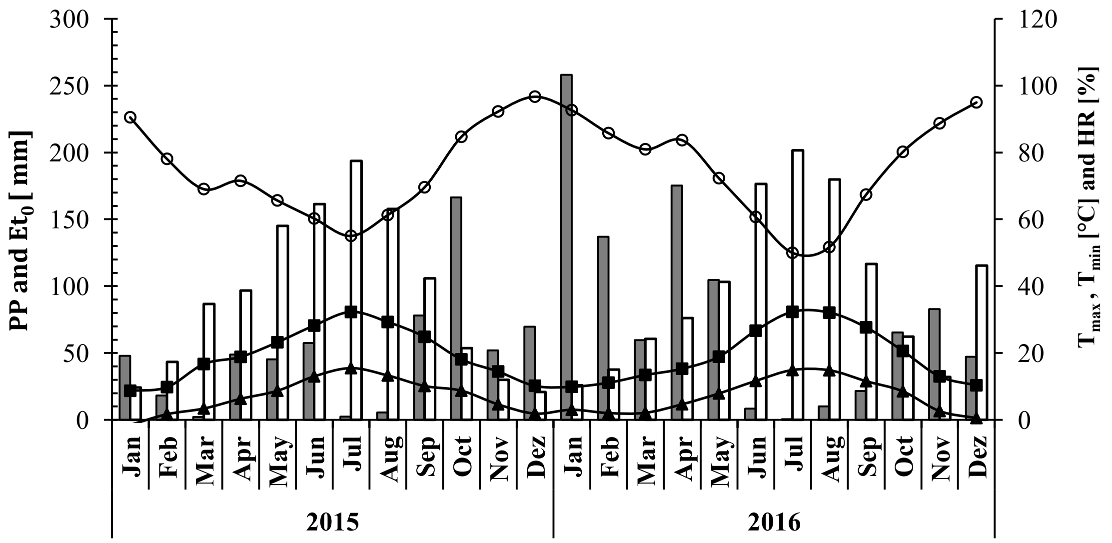

Fig. L-1 - Monthly total precipitation (PP, mm, grey columns) and evapotranspiration of reference (ET_0, mm, white columns), monthly minimal (T_{min}, ▲) and maximal (T_{max},■) air's temperature (°C) and air relative humidity (HR, in %) during 2015 and 2016 in Bragança region (source: IPMA 2015, 2016).

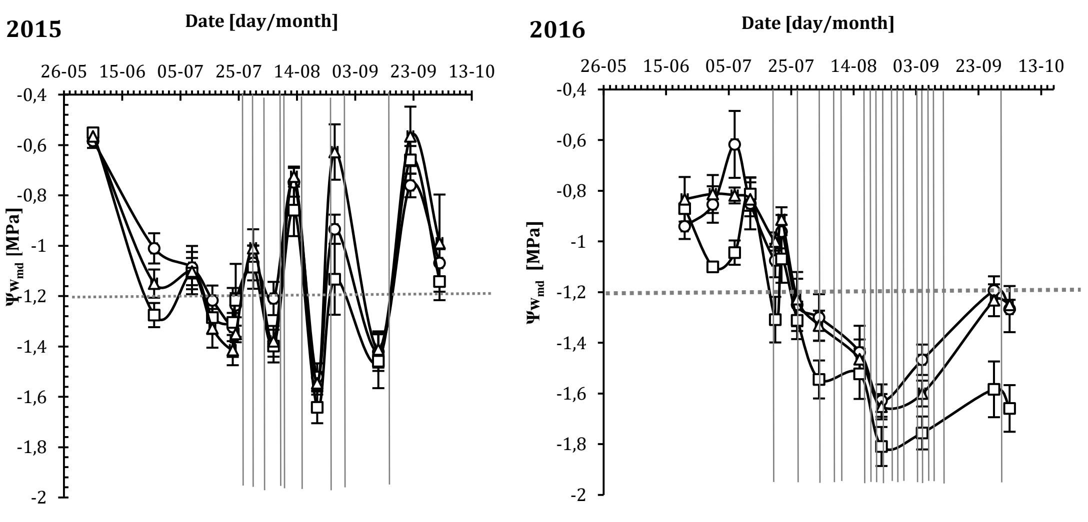

Fig. L-2 - Time course of midday stem water potential (Ψw_{md}, MPa) in 2015 (left) and 2016 (right) for non irrigated (□), drip irrigated (Δ) and micro sprinkler irrigated (○) trees. Vertical bars are the standard error according to Fisher test (5%). Grey bars represents the irrigation events.

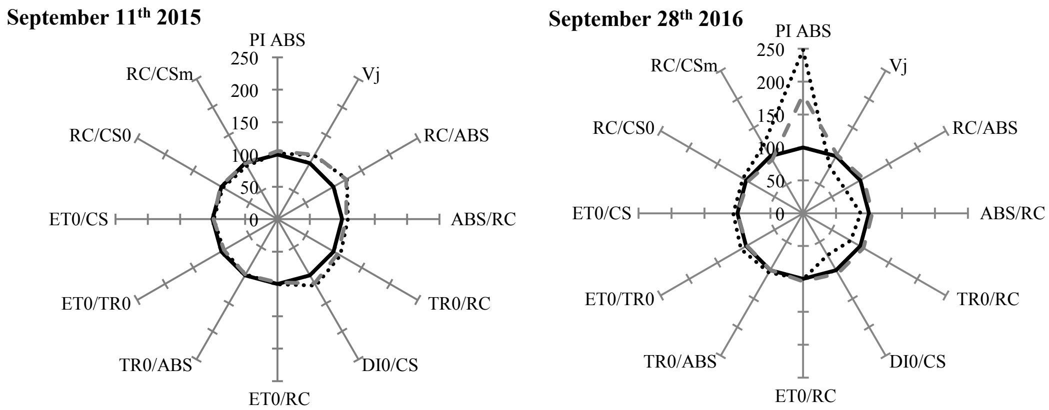

Fig. L-3 - A 'spider plot' of selected parameters characterizing the behaviour of Photosystem II in non-irrigated (full black line), drip irrigated (dash black line) and micro-sprinkler irrigated (dashed grey line) trees, in September 11th 2015 (left) and at September 28th 2016 (right). All values are shown as percent of control (control plants = 100).

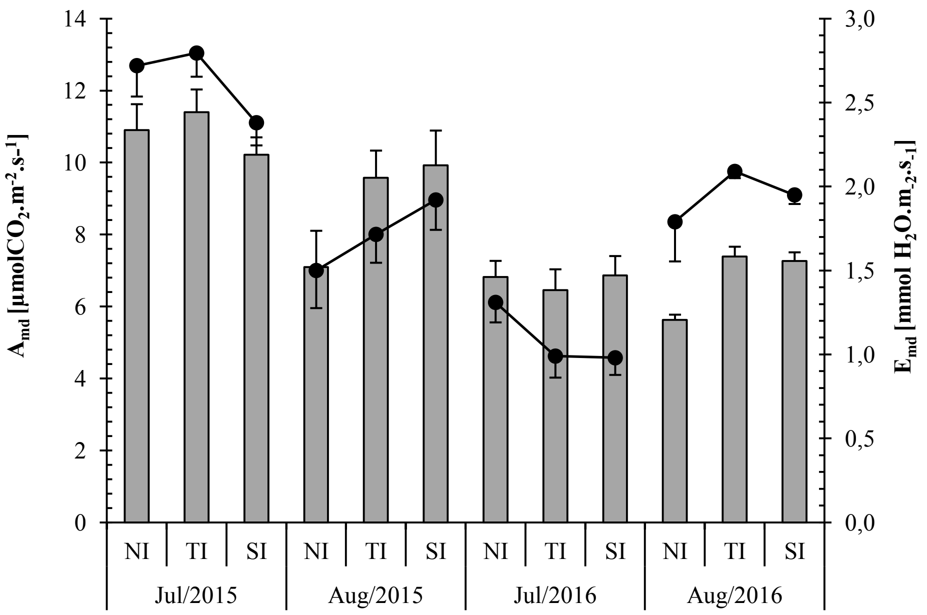

Fig. L-4 - Photosynthetic rate (A_{md}, µmolCO$_2$.m^{-2}.s^{-1}, columns) and transpiration rate (E_{md}, mmol H$_2$O.m^{-2}.s^{-1}, lines) measured at midday in non irrigated (NI), drip irrigated (TI) and micro-sprinkler irrigated (SI) trees in 2015 and 2016. Vertical bars are the standard error according to Fisher test (5%).

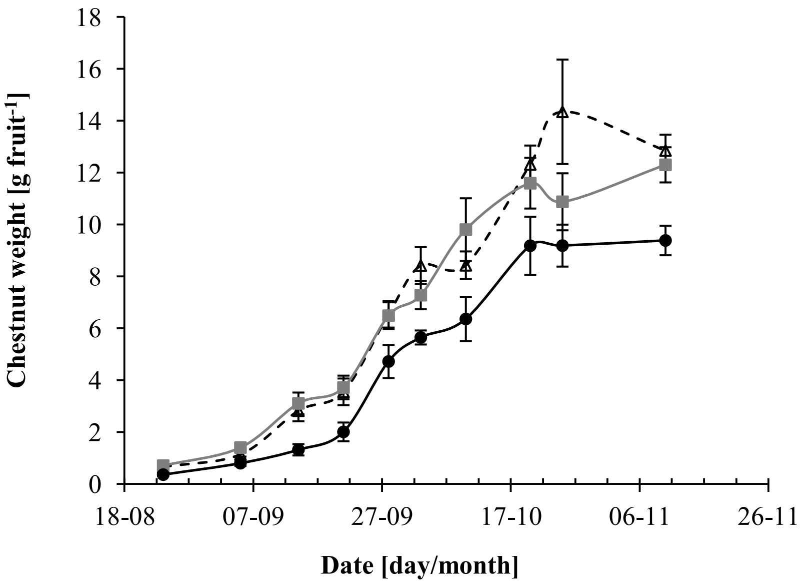

Fig. L-5 - Curve of the chestnut growth given in fresh weight per individual fruit (g/fruit) for none irrigated (●), drip irrigated (■) and micro-sprinkler irrigated (Δ) trees, in 2016. Bars represent standard error according to Fisher test (5%)

Tab. L-1 - Chlorophyll *a* fluorescence parameters of non irrigated (NI), drip irrigated (TI) and micro-sprinkler irrigated (SI) in chestnut trees of 'Judia', in 2016, before irrigation (June 30th and July 20th) and after irrigation (August 23rd and September 28th) where: 'Area' is the area above the chlorophyll fluorescence curve between F_0 and F_m reflecting the size of the plastoquinone pool, 'T_{FM}' is the maximal chlorophyll fluorescence intensity measured when all PSII reaction centres are closed, 'F_v/F_m' is the maximal quantum efficiency of PS II photochemistry and 'F_v/F_0' is the value that is proportional to the activity of the water-splitting complex on the donor side of the PSII and 'PI_{ABS}' is the performance index (more details in Kalaji *et al.*, 2011). Values with '*' are significant different according to Fisher test (5%) within the same date, between treatments. Numbers are given as relative units and as percentage of control trees (non- irrigated).

Date	Area			T_{FM}			F_v/F_m			F_v/F_0			PI_{ABS}		
	TI	NI	SI	TI	NI	SI	TI	NI	SI	TI	NI	SI	TI	NI	SI
30/Jun	31876.80	18991.38	24226.08	730.00	276.25	575.00	0.81	0.80	0.81	4.41	4.10	4.27	9.79	7.29	8.59
20/Jul	29818.70	20536.00	23604.00	589.00	272.50	367.27	0.79	0.81	0.82	4.06	4.32	4.65	8.62*	12.90	11.62
23/Aug	11981.38	13205.25	18721.30	238.75	233.75	291.00	0.74	0.74	0.76	2.97	2.97	3.20	5.06	1.57*	4.55
28/Sep	20807.13	17385.50	17744.33	311.25	245.00	463.33	0.81	0.77	0.77	4.19	3.59	3.48*	7.05	2.84**	5.10*
Mean	**24423.97**	**17529.53**	**21363.55**	**488.61**	**256.88**	**429.05**	**0.79**	**0.78**	**0.79**	**3.94**	**3.74**	**3.95**	**7.81**	**6.15**	**7.68**
Date		%			%			%			%			%	
30/Jun	168	100	128	264	100	208	101	100	100	108	100	104	134	100	118
20/Jul	145	100	115	216	100	135	98	100	102	94	100	108	67	100	90
23/Aug	91	100	142	102	100	124	100	100	103	100	100	108	323	100	291
28/Sep	120	100	102	127	100	189	104	100	100	117	100	97	248	100	180
Total	139	100	122	190	100	167	101	100	101	105	100	105	127	100	125

V. THE EFFECT OF IRRIGATION ON CHESTNUT'S QUALITY

M. Irrigation positively affects the chestnut's quality: the chemical composition, fruit size and sensory attributes

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Resumo

Na região do Nordeste, maior zona produtora de castanha em Portugal, começam-se a instalar sistemas de rega em soutos muito embora pouco se saiba sobre a influência da da rega na qualidade da castanha. Este estudo teve como objetivo avaliar o efeito da rega na qualidade das castanhas da variedade 'Judia' no que diz respeito à sua composição química, ao calibre e ao aspeto sensorial da castanha. Três tratamentos foram aplicados durante 2015 e 2016: o sistema de gota-a-gota, o sistema de micro-aspersão e um tratamento controlo, sem rega. Nos dois anos, os tratamentos regados apresentaram as castanhas maiores e produções mais altas. Em 2015, foram encontradas diferenças significativas entre os tratamentos no que diz respeito às cinzas, amido, açúcares solúveis e teor de proteína bruta mas, em 2016 não foram encontradas estas diferenças. Apesar, das castanhas provenientes do controlo foram as mais doces mas apresentaram sempre tamanhos pequenos. As castanhas provenientes da micro-aspersão eram as mais firmes e eram tão doces quanto as castanhas da modalidade gota-a-gota. Os resultados sugerem que a rega, nomeadamente com sistema de micro-aspersão, valoriza as castanhas uma vez que aumenta o seu tamanho e mantem o seu valor nutricional bem como a sua qualidade sensorial.

Palavra-chave: C*astanea sativa,* humidade do solo, nutrição, calibre, valor mercado.

Abstract

In the northeast of Portugal there is a tendency to introduce irrigation system on the chestnut orchards but the effect of irrigation on the chestnut's quality has not been studied yet. This study aims to evaluate the effect of irrigation on the 'Judia' cultivar chestnuts quality concerning its chemical composition, fruit size and tastiness. Three treatments were applied during 2015 and 2016: the drip system, the micro-sprinkler system and a non-irrigated treatment. In both years the bigger chestnuts and production were always present in irrigated treatments. Significant differences among treatments were found in ashes, starch, soluble sugars, and crude protein contents in 2015, but in 2016 no significant differences were found. Moreover, the non-irrigated chestnuts were the sweetest but with smaller calibre. The chestnuts from micro-sprinkler were the firmest and they were as sweet as the drip's chestnuts. Results suggest that irrigation, namely with sprinkler system, valorise the chestnuts by increasing its size and keeping its nutritional value and its sensory quality.

Keywords: *Castanea sativa*; soil moisture; nutrition; chestnut calibre; market value.

Introduction

The nutritional value of the chestnut, which is a consequence of its chemical composition, reflects the interaction between the binomial genotype and climate conditions and its related to the mineral composition of the soil where the chestnut trees are cultivated (Ferreira-Cardoso 2007, Pereira-Lorenzo *et al*. 2006). The 'Judia' cultivar mostly grows in the northeast region of Portugal, where are produced more than 22.000 t of chestnuts (INE, 2017). The use of irrigation on the Portuguese chestnut trees is still incipient but, according to PRODER (2014), from the new 835 ha planted within 2007-2013, about 23% included an irrigation system. According to Breisch (1995) and Mota *et al*. (2017, 2014) the irrigation increases chestnut yield as it happens in other dry fruits (Garrot and Kilby 1993, Goldhamer and Beede 2004). Also Dengiz and Sarioglu (2011) report the need of irrigation for good vigour of the chestnut orchard. Currently, we are witnessing the evidence that the lack of rain in the end of the summer or in the autumn (IPMA, 2017) in not-irrigated orchards constraints the chestnut development and consequently their productivity and brings losses to the income in the chestnut sector (Vida Rural, 2017).

Some studies have focused on the effect of irrigation on the chestnut's size index, fruit weight or production per tree (Martins *et al.* 2010, Martins *et al.* 2011) but, as far as our knowledge goes, the effect of watering on the chestnut's chemical composition has not yet been studied. However, it is known from the other fresh crops the interest of irrigation into the final fruit composition. For instance, in grapes, different water regimes influence the fruit weight, phenols and anthocyanins' levels but not the total soluble sugars (Intrigliolo and Castel 2011, Santos *et al.* 2005). For apples (Mills *et al.*,

1996) and citrus (Ballester *et al*., 2013) the sugars level was higher in deficit irrigated trees with better shelf life. Carbonell-Barrachina *et al.* (2014) found that in pistachio the regulated deficit irrigation had no significant influence on production yield, weight, size, colour and on the mineral composition but it had influence in the lipids composition. From these studies, become clear the existence of a benefit due to irrigation on fruit quality but is highlighted the importance of a good water management to meet the desired final product. According to Mota *et al.* (2017) a minimal irrigation, based on tree water potential, was enough to increase the chestnut production per tree but chestnut composition was not evaluated. The irrigation system also brings the possibility for developing fertigation programmes which naturally will enhance plant nutritional status and the chestnut quality as well.

The chestnut is a great source of starch, with low fat and cholesterol free, low in sodium, rich in dietary fibre, and rich in potassium and in proteins with high biological value and thus, its integration in the human diet is highly recommended (Ferreira-Cardoso 2007, Ferreira-Cardoso and De Vasconcelos 2009, De Vasconcelos *et al.* 2010). Additionally, it can be a healthy alternative to specific human groups as the diabetics (chestnuts have low glycaemia index) or celiac patients since the chestnut is gluten free (Mujić *et al*., 2010). Besides the chestnut's health benefits, the consumer appreciates it mostly due to its sweetness (Pereira-Lorenzo *et al*., 2006) and the chestnut market tends to valorise its size (Breisch 1993, Martins *et al.* 2011)

This study aims to understand the effect of watering through different irrigation systems on the chestnut's quality namely fruit size, chemical composition and sensory attributes. Additionally, the plant nutritional status is addressed in a general way because it is related to the soil fertility and moisture and affects the fruit quality.

Material and methods

Site location and treatments The experiment was performed in a commercial chestnut orchard during 2015 and 2016, located in the northeast of Portugal at 862 m of altitude. Trees were planted in 1993, spaced 10 by 5 m, and were traditionally rain-fed. The rootstocks are seedlings from *C. sativa* and they are grafted at 2 m height with 'Judia' cultivar. Two types of irrigation system were installed, each one in about forty trees, as follow: TI – drip irrigation – two pipes per tree row, emitters spaced 1 m, 3.6 L h^{-1}; SI –

sprinkler irrigation – one handing pipe, emitters spaced 5 m, 50 L h^{-1}. Border trees were kept around the study area and between each tree sample (ten trees per treatment). Non-irrigated trees (NI) were kept for control (Fig. M-1).

Irrigation on TI and SI systems was triggered every time the midday stem water potential (Ψw_{md}) was lower than -1.2 MPa. The decision to start the irrigation at this midday stem water potential was based on preliminary data taken in 2013 on the same orchard which indicated that the good photosynthetic rate can be achieved when the midday stem water potential (Ψw_{md}) was around -1 MPa. Plus we decided to define a value below it in an attempt to create a deficit irrigation condition that on one hand saves water and on the other did not harm too much the photosynthetic rate. The Ψw_{md} was measured weekly from July to October with a Scholander-type pressure chamber (model "pump-up", PMS Instrument® Corvallis, Oregon, USA). The leaves used to measure the Ψw_{md} were from the north fruit branch of the sample trees and were covered by a plastic and aluminium foil at least 40 minutes before readings, according to Fulton *et al.* (2014). Tab. M-1 resumes the irrigation events. The mean water volume of the both treatments given in July, August and September was, respectively, 8.8 mm, 32.3 mm and 5.9 mm in 2015; and 6.7 mm, 49.1 mm and 36.8 mm in 2016.

Edapho-climatic conditions General meteorological data (total monthly precipitation, PP; mean monthly air temperature, T_{med}; total monthly evapotranspiration of reference, ET_0 and air relative humidity, HR) were gathered from the agro-meteorological bulletins given by the Portuguese Institute of the Sea and Atmosphere (IPMA, 2015, 2016) which by its turn retrieved the data from a meteorological station located at 20 km away from the study site. The growing degree-days (GDD, ºD) was calculated according to Cesaraccio *et al.* (2001) using the following equation (1):

$$^{0}D = (Tx - t0)\, n$$

Where "$\varkappa$" is the average temperature of each month, "$t0$" the base temperature, which was considered 6ºC (Gomes-Laranjo *et al*., 2006) and "n" the total of days of each month. Three soil profiles were opened, in the inter row of the trees, according to the slope of the study area in order to do a soil profile classification according to FAO (2014).

The soil water content was estimated with a capacitance probe (Diviner 2000, Sentek Technologies) and six access tubes were installed per treatment, one single tube per tree. The access tubes were located 1.5 m away from the chestnut tree's trunk, below the canopy. Readings were registered weekly from 10 cm up to 80 cm in depth. The soil water content is expressed in % (cm^3 H_2O $100cm^{-3}$soil).

Soil and leaves mineral analysis In 2016, a soil mineral analysis was made. The laboratory procedures for extractable phosphorous (P_2O_5) and potassium (K_2O), exchangeable bases (Ca, Mg, K and Na), pH (in H_2O) and organic matter (OM) are described elsewhere in Dinis *et al.* (2011).

From each treatment, twenty leaves completely expanded from the north fruit branches were sampled in the beginning of July (flowering), August (post-flowering), September (fruit development) and October (previous harvesting). In the laboratory, the leaves were dried at 60 ºC during one week and ground to pass through a 1 mm screen. They were digested as described by Schouwenburg and Walinga (1978). The Ca, Mg, Fe, Cu, Zn and Mn were determined by atomic absorption spectrophotometer and the K by flame photometry. For N and P analysis, the digestion was done with sulphuric acid (Novozamsky *et al.*, 1983) and their concentration were determined on an auto analyser. Boron was measured spectrophotometrically by the azomethine H method (Wolf, 1971).

Chestnut production, calibre and density Thirty urchins were collected from each treatment in 2015 and in 2016 and their healthy chestnuts (185 in 2015 and 211 in 2016) were used to determine the calibre (fruits kg^{-1}). To determine its density ($g\ mL^{-1}$) the chestnuts were weighted and placed inside a graduated test tube to read the volumetric difference.

An area of harvest beneath the canopy of each sampled tree was delimited using stripe tape. The chestnuts that dropped within the delimited area were caught and weighted on the field with a manual scale. Chestnut production is given in fresh weight per meters squared of the tree's canopy area (kg FW m^{-2}). It was measured the diameter North-South ($\theta_{N\text{-}S}$) and the diameter West-East ($\theta_{W\text{-}E}$) of the shadow projected at 12:00 h by the canopy to determine the tree's canopy area (m^2) as the following equation (2):

$$A = \pi \times (\frac{\theta N - S + \theta W - E}{4})^2$$

Chestnut's basic chemical composition In each year (2015 and 2016), the chestnut's dry matter (DM) was determined from 35 healthy chestnuts from each treatment according to AOAC (1990). For the following determinations the pre-dried chestnuts were previously crushed until reaching a fine powder and were analysed in triplicate. Organic matter (OM) and total ashes content were determined according to AOAC (1990). Starch was determined by enzymatic hydrolysis (Salomonsson *et al*., 1984), and the soluble sugars (SS) by the colorimetric method of anthrone after extraction with ethanol, as described by Irigoyen *et al.* (1992). Crude fat (CF) was determined by extraction with petroleum ether in a Soxhlet apparatus according to AOAC (1990). Crude protein (CP) was calculated from total nitrogen, determined by micro-Kjeldahl method with a selenium catalyst, by the use of factor N_{total} x 5.3 as recommended by McCarthy and Meredith (1988).

Chestnut's sensory evaluation At November 25th of 2016, twenty chestnuts were randomly collected from each treatment and stored in perforated plastic bags in the refrigerator. The cooked chestnut samples were evaluated by a trained panel of twelve judges (three men and nine women, ranging from 45 to 60 years of age) from the University of Trás-os-Montes and Alto Douro (ECVA/DeBA-UTAD) tasting panel. The tests took place from 14:00 to 17:00 h in a laboratory equipped for sensory analysis according to the ISO 8589 (2007) standards. The chestnuts were washed three times in tap water and cut in half before boiled in water with 2 g of salt, for 30 minutes. The chestnuts cooled to room temperature (18 ± 2°C) and were placed in coded white Pyrex dishes. Mineral water and toasted were given to the tasters to clean off their palates. A Quantitative Descriptive Analysis (QDA) was performed with descriptors adapted from Warmund (2015) which allowed the development of the sensory profile of each fruit, using a structured 5-point scale (1 - less intense, 5 - more intense; ISO 4121(2003)). The evaluated attributes were: detachability, characteristic odour, initial firmness, dissolubility, sweet taste, acid taste, bitter taste, astringency, chestnut flavour, hazelnut flavour, almond flavour, butter flavour, caramel flavour, yeast flavour, mustard flavour, fruity/floral flavour and earthy flavour.

Statistical analysis The StatView 4.0 software was used for statistical analysis of chestnut production, calibre, density and chemical composition and comparisons between treatments were made with Fisher's test, with a significance level of 5%. The results are presented as mean values ± standard error (SE). The analysis of the chestnut's sensory profile was performed using a spider graph and the results were submitted to the analysis of variance (ANOVA, one factor) and the Duncan's test was applied at 5% significance.

The chestnut's sensory attributes from the different treatments were also submitted to a Principal Components Analysis based in a covariance matrix (Cov-PCA) performed by the Statistica 2010 software (Statsoft Inc., 2012). Also a Principal Components Analysis based in a correlation matrix (Corr-PCA) was performed to correlate the chestnut sensory attributes and the chemical composition in 2016. The Corr-PCA was also used to correlate the chestnut's chemical composition by treatment, in both years.

Results

Edaphoclimatic conditions During the months of the vegetative cycle (May-October), 2016 was warmer and drier than 2015. The GDD was 2.348 °D and 2.504 °D and the total precipitation was 355 mm and 213 mm in 2015 and 2016, respectively (Fig. M-2). In 2016, June, September and October were drier (9, 22 and 62 mm, respectively) than the same months of 2015 (58, 76 and 166 mm, respectively). 2016 was also hotter in September and October (20 °C and 15 °C, respectively) comparatively to 2015 (17 °C and 13 °C, respectively). The studied years had lower precipitation in July (-90%) and August (-47%) when compared to the mean values of the decades 1980-2010 (15 and 17 mm in July and August, respectively). The spring of 2016 was more humid than 2015 or than the mean values of the decades 1980-2010, but the end of the summer was much drier in 2016 than the referred dates. Concerning the mean monthly air temperature, 2015 had a hot spring and, in both studied years, the T_{med} on July and August was higher comparing with 1980-2010. The T_{med} on July and August of 2016 was also higher than the mean of the decades 1980-2010.

In which concerns the soil, it was classified as hapli-dystric cambisol (FAO, 2014) derived from schist. In the experimental area the soils are moderately evolved (cambisols), with an average thickness of 100 cm, with the C horizon showing many coarse gravel and cobbles due to the deep ripping. Soils present a medium texture class (loam).

As expected, the soil moisture was higher during the summer period (July, August and September) in the irrigated trees and, in spite of similar amounts of water furnished in both systems, the SI modality had generally lower soil water content than the TI, explained by the largest wetted area and consequently less infiltration through the soil's depth. So, the mean soil water content on the 10-40 cm deep was 12.9% and 11.8% (NI), 17.1% and 16.4% (TI) and 15.8% and 12.9% (SI) for 2015 and 2016, respectively. During the fruit maturation (October) the mean soil water content was 22.9% and 15.1% (SI), 23.8% and 17.8% (TI) and 24.3% and 13.8% (NI) for 2015 and 2016, respectively.

Soil and leaves mineral analysis Between 0 cm and 29 cm soil's deep, the soil had 2.9% of organic matter, 32.9 mg kg^{-1} of extractable P_2O_5 and 124.0 mg kg^{-1} of extractable K_2O and pH (in H_2O) of 4.9; the degree of base saturation (DBS) was 63.2% and the effective cation exchange capacity (ECEC) was 4 cmol$_c$ kg^{-1}.

In this study, the leaves' minerals varied similarly for all treatments across the cycle (Tab. M-2) and the analysis of variance shows an important effect of the date in the N (55%) and Ca (66%) content. The N slightly declined along the cycle (from 22.5 to 20 g kg^{-1}) contrarily to P (from 2.1 to 3.7 g kg^{-1}) and Ca (from 4.8 to 10.1 g kg^{-1}). By its turn, the K slightly increased until September (from 11.6 to 14.1 g kg^{-1}) from when it dropped (8.9 g kg^{-1}). The leaves' content on Cu, Fe and Mn increased along the time (7.7 to 14.7 mg kg^{-1}, 19 to 57 mg kg^{-1} and 543 to 758 mg kg^{-1} for Cu, Fe and Mn, respectively) contrarily to the B that varied from 30 mg kg^{-1} in July to 26 mg kg^{-1} in October. However, some differences were found in the mineral leave's content between treatments: in general non-irrigated trees had lower N (-10%), P (-7%) and Ca (-12%) content than the mean of the irrigated treatments (21.4 g kg^{-1}, 2.7 g kg^{-1} and 10.4 g kg^{-1} for N, P and Ca, respectively) which reflect lower root's absorption mostly because of the reduced soil moisture. Exception was for Ca in July and for P in October. This may indicate that in July the soil moisture was not yet a constraint for Ca absorption and the higher P leave's content in October reflects less translocation of this mineral to the fruit which may did not occurred in the irrigated trees. The TI modality had higher content on K in the end of the summer (12 g kg^{-1}) which reflects the higher soil moisture and thus more K available comparing with SI treatment (7 g kg^{-1}). The date*treatment interaction mostly affected the variation of Mg (40%) and Mn (31%).

Chestnut's production, calibre and density The irrigated treatments had a higher chestnut production in both years being for 2015 and 2016, respectively: 0.98 and 0.75 kg m^{-2} in NI, 1.11 and 0.92 kg m^{-2} in TI and 1.15 and 1.01 kg m^{-2} in SI modality.

According the data on Tab. M-3, the fruit size was affected by irrigation since the bigger fruits were found on the irrigated treatments (78 fruits kg^{-1}) compared with NI (107 fruits kg^{-1}) on the both years, with significance in 2016 (123 fruits kg^{-1} in NI, 89 fruits kg^{-1} in TI and 78 fruits kg^{-1} in SI). The fruit size decreased from 2015 to 2016 in all treatments (63 fruits kg^{-1} and 97 fruits kg^{-1} for 2015 and 2016, respectively) and irrigation did not avoid by itself the decreased of fruit's size from 2015 to 2016 in spite of the less variation in TI and SI modality than in NI. The year was the responsible of 27.5% of variation on the calibre and only 10% is explained by the interaction year*treatment. In what concerns chestnut density no differences were found between treatments in both years and the mean was 1.2 g mL^{-1}.

Chestnut's chemical composition The chestnut's chemical composition is shown on Tab. M-4. The values of DM increased from 2015 to 2016 (45.9 and 49.4 g $100g^{-1}$ FW, respectively) but no significant differences were found between treatments in any of the years under study, nor in the average of the two years, which is positive since irrigation did not increased chestnut's moisture in a way that could affect it market value. Similarly to the DM, also the contents of ashes, starch, crude fat and crude protein, were not affected by irrigation in the average of the two years and the exception was for the soluble sugars (SS). In fact, although without significant difference in 2016, the SS were statistically higher in 2015 for NI (8.4 g $100g^{-1}$ DM) than SI (7.3 g $100g^{-1}$ DM) or TI (5.9 g $100g^{-1}$ DM). In 2016 the SS were lower (6.8 g $100g^{-1}$ DM) than in 2015 (7.2 g $100g^{-1}$ DM) but without significance among treatments.

Some statistical differences in CP, OM, ashes and starch were observed among treatments in 2015 but not in 2016. The CP increased from 2015 (4.5 g $100g^{-1}$ DM) to 2016 (5.9 g $100g^{-1}$ DM) in all treatments. In 2015, the CP ranged from 4.2 g $100g^{-1}$ DM in SI treatment to 4.80 g $100g^{-1}$ DM in NI treatment. In 2016, the SI presented the highest CP value, 6.2 g $100g^{-1}$ DM. The ashes content slightly decreased from 2015 (2.5 g $100g^{-1}$ DM) to 2016 (2.3 g $100g^{-1}$ DM) and it was significantly higher in 2015 for NI (2.6 g $100g^{-1}$ DM) being the values of TI and SI modalities of 2.5 g $100g^{-1}$ DM and 2.4 g $100g^{-1}$ DM, respectively. In 2015, the starch content was significantly lower in NI (56.9 g $100g^{-1}$ DM) than TI (58.7 g $100g^{-1}$ DM). Concerning CF, it decreased from 2015 to 2016, especially for TI (2.3 to 1.9 g $100g^{-1}$ DM) but no significant differences were found and the average of two years was 1.8 g $100g^{-1}$ DM for NI and SI and 2.1 g $100g^{-1}$ DM for TI.

When the Corr-PCA was performed to understand the correlation of the treatments, according to the chemical composition and production (Fig. M-3), the graphic clearly separates the non-irrigated treatment in the lower axis mainly due to the soluble sugars' influence. The treatments of 2015 are all at the right of the axis mainly due to the starch content and nut weight. The year 2016 is on the left side of the axis and what contribute more for this separation is the chestnut's calibre and crude protein.

Chestnut's sensory profile The sensory profile of each chestnut sample is shown graphically in Fig. M-4 for each treatment, where the mean of the values assigned by the tasters to each attribute is marked on the corresponding axis. The characteristic odour, initial firmness and bitter taste were felt more intensely in SI chestnuts. The sweet taste was felt more intensely in NI whilst in TI the chestnuts were felt as having less initial firmness but higher dissolubility and same sweetness as SI. However, the results of the analysis of variance and the Duncan test revealed no significant differences for all of these attributes between the samples analysed.

The Fig. M-5 shows the PCA resulting for the chestnut's sensory attributes projected onto the first two PCs as well as the treatments. The PC1 explained 79.44% of the total variance and the characteristic odour and initial firmness are the values with largest contribution in PC1. The attributes that best correlated with PC2 (that accounted for 20.56% of total variation) were the sweet taste. The NI dropped on the sweetness group. The sweetness is given by the soluble sugars which had in fact higher levels in NI chestnuts (Tab. M-4). Although not statically differences were found, the tasters were able to felt the difference between samples which is an outstanding result.

Correlation between chemical and sensory data All the sensory attributes and chestnut chemical composition of 2016 were analysed using a correlation analysis (Corr-PCA, Fig. M-6) resulting that the different treatments were disposed in different quadrants of the graphic. The PC1 explained 55.62% of the total variance, while the PC2 explained 44.38%. Both, PC1 and PC2, explained 99.98% of the total variance.

The initial firmness, detachability, starch and chestnut flavour had similar contribution in PC1 where the TI modality is located, in the right side of the PC1 axis, while the SI and NI chestnut samples are in the left side.

The production, calibre, sweet taste and soluble sugars are the values with largest contribution in PC2 being the irrigated treatments putted on the upper side of the axis and the NI under it.

Discussion

The hotter and drier conditions in 2016 from June to October led to more water being furnished through irrigation, once the Ψw_{md} frequently reached values lower than -1.2 MPa. Actually, the influence of air temperature on the water potential of the chestnut tree is reported in other studies (Gomes-Laranjo *et al*. 2006, Gomes-Laranjo *et al*. 2008, Mota *et al*., 2014). Nevertheless, the more water furnished in 2016 was not perceptible in the readings of the soil water content and, in fact, the soil moisture was lower in 2015 probably indicating higher levels of soil evaporation. This fact, plus the highest temperatures, may have contributed to the lowers values of the Ψw_{md} in 2016. According to MacCutchan and Shackel (1992) in non-limiting soil moisture the Ψw_{md} is highly correlated with the air vapour deficit pressure but in this study this correlation was not accessed. So, it remains the uncertainty if the watering was actually enough to keep the water potential in the desired values or, eventually, it is admissible that this reference value of Ψ_{md} = -1.2 MPa might be lower for irrigation scheduling on the adult trees during the hot summer. Deeper studies on soil-plant-climatic relationships are needed to better manage irrigation on the chestnut tree.

The spring of 2016 was more humid comparing with the spring of 2015 but, at the end of the summer, it was much drier. This fact, parallel with the high GDD, may have contributed for the decrease of the production from 2015 to 2016, aspect that highlights the importance of the rainfall in the end of the summer when the chestnut is developing and maturation occurs (Pinto *et al.* 2007, INRB 2008). Thus in the absence of rain in the end of the summer the irrigation positively contributes for chestnut calibre and production. The importance of available water one month prior the harvest is also referred by other authors (Breisch 1995, Pimentel-Pereira *et al.* 2007) and, considering the climatic conditions of last years and the predicted long dry summers (Miranda *et al.,* 2002), the irrigation on chestnut trees has a huge potential.

According to INIAP (2006) the soil of the experimental site is classified has having a good organic matter level, high level of extractable K_2O but low level of extractable P_2O_5 and it is acid. This soil can be considered a typical one where the chestnut groves grow in the northeast of Portugal (Portela *et al.* 2007, Arrobas *et al.* 2018) and, according to Dengiz *et al.* (2011), its features (deep, moderate fertile and acid soil) including the low P level, meet the optimal conditions for *Castanea sativa*. Interestingly, our results corroborate those described by Arrobas *et al.* (2018) since the leaves did not revealed lower content in P, although trees were growing in soils classified with low levels of P. The plant nutrient uptake is the result of the absorption, translocation, and incorporation into the plant's organs and its efficiency can be correlated with the dry matter production (Dengiz *et al.*, 2011). It is expected that soil's moisture influences the absorption of nutrients and consequently affects the plant's nutrition and fruit quality. Indeed, the understanding of the mineral's leaves variation along the cycle is important to understand the nutrients' mobility within the plant organs and to adjust nutritional programmes. In what concerns the nutrient's variation in the leaves along the cycle, the N, P and Ca are in accordance with Raimundo (2003) who registered, from July to November, a decreased in N (from 20 to 10 mg kg^{-1}) and an increased in P and Ca (2.1 to 3.1 mg kg^{-1} and 4.6 to 10.4 mg kg^{-1}, respectively. The drop of K in the leaves in October reflects the translocation of K to the fruit since it requires great amounts of K during maturation. Actually the chestnut has higher content of K comparing with the other minerals as reported by several studies (Raimundo 2003, Pereira-Lorenzo *et al.* 2006, Díaz-Gomez *et al.* 2006, Ferreira-Cardoso 2007, De Vasconcelos *et al.* 2010, Dinis 2011). In October, the decrease of K in the leaves was more evident in NI followed by the SI modality reflecting the dry soil conditions with more difficulty in K absorption. The K root's absorption difficulty, during this stage due to dry soil is also suggested by Arrobas *et al*. (2018). Nevertheless, the TI treatment (with higher soil moisture) also reduced the K leaves content. So, fertilization with potassium during fruit maturation looks important since the apparently high level of K in the soil is not enough to accomplish the chestnut requirements. The leaves' content on Fe and Mn increased along the months which reflect the natural solubility of these minerals in the acid soil (Dengiz *et al.* 2011). According to Portela *et al.* (2011) the minimal critical value of B concentration in chestnut's leaves is 20 mg kg^{-1} and values above it (until 100 mg kg^{-1}) are preferable to promote good pollination. In the present study, the B leaves' content was lower but above 25 mg kg^{-1} during flowering in all treatments. Curiously, B content consistently decreased along the cycle in NI but in the irrigated treatments the B increased in the beginning of September, reflecting it root's absorption and a key moment for B fertilization. In TI, the B dropped to values similar to NI in October which may reflects B mobilization to other organs, probably to the roots where it can be storage for the next cycle. Considering Portela *et al.* (2007) the mean reference of chestnut leaves' mineral content in Trás-os-Montes region are 24 g kg^{-1} (N), 2.3 g kg^{-1} (P), 13.5 g kg^{-1} (K), 9.4 g kg^{-1} (Ca), 3.6 g kg^{-1} (Mg) and 1.9 g kg^{-1} (S). Concerning the micronutrients the same author reports mean values of 174 mg kg^{-1}, 1.195 mg kg^{-1}, 38.5 mg kg^{-1}, 29 mg kg^{-1} and 82 mg kg^{-1} for Fe, Mn, Zn, Cu and B, respectively. No visible symptoms of magnesium deficiency were observed and the ratio K/Mg (mean 6.1) and N/Mg (mean 11) were within the reference values given by Portela *et al.* (2003) who suggests that K/Mg > 10 and N/Mg > 24 represent situations of Mg deficiency. So, in the end, all plants of this experiment were in minimal good nutrition's conditions suggesting that the NI trees used nutrients from deeper soil layers and that irrigation positively affected nutrients uptake from the top soil layers where actually are more nutrients comparing with the deeper layers. However, it must be kept in mind the effect of irrigation on the soil's nutrients distribution. According to Komosa *et al.* (1990 a,b) the nutrient distribution in the soil is affected by irrigation and by ammonium-nitrate fertigation in such a way that, for one hand, the nutrients are available to the plant due to fertigation but, for another hand, the nutrients are susceptible to vertical leaching and horizontal translocation originating a decreased in phosphorus, potassium and magnesium in the wetted area and their accumulation in border zones around the wetted area. Further studies on the chestnut's fertility are needed to encourage good nutritional programmes, especially through fertigation, because it better accompanies the nutrients dynamic.

In what concerns fruit size, the irrigation positively influences the size of the nuts. This is in accordance with Martins *et al.* (2011) which also found bigger chestnuts in irrigated treatments. According to the same author, calibres between 60 to 90 fruits kg^{-1} can be more expensive, about twenty cents of euro, than calibres above 90 fruits kg^{-1}. The chestnut's calibre is influenced by edapho-climatic conditions (Ferreira-Cardoso 2007, Martins *et al.* 2010), and in our study the temperature seemed crucial on the final fruit's size. Actually, according to Dinis *et al.* (2011), in a study about the morphological and chemical diversity of chestnut trees under different GDD, the best calibre (40-60 fruits kg^{-1}) were reached when the GDD (May - October) ranged between 2,000 to 2,200 °D. Outside this range, Dinis *et al.* (2011) observed a decay until 50% on the fruit size. In our study the decay on the fruit size, when GDD (May-October) varied from 2,348 to 2,504 °D, was 90% for NI, as opposed to significantly lower declines in irrigated trees, which was 45% and 24% for TI and SI, respectively. It can be said that in warmer years irrigation contributes for less variation in fruit size, and thus greater production regularity.

The chestnut's dry matter results are in accordance with those obtained by Ferreira-Cardoso (2007) for 'Judia' cultivar in Bragança (45 g $100g^{-1}$ FW) and by Dinis *et al.* (2011) in 2007 (47.3 g $100g^{-1}$ FW), although our values were lower than the ones found by the same author in 2006 (64.2 g $100g^{-1}$ FW). However, De La Montaña *et al.* (2004) obtained slightly higher results in Italian varieties (moisture content ranged between 48.4 and 59.4 g $100g^{-1}$ FW) as well as Poljak *et al.* (2016) in traditional Croatian chestnut variety (56.7 g $100g^{-1}$ FW). According to Breisch (1993) moisture content higher than 60 g $100g^{-1}$ FW can promote fungus development during the chestnut's conservation. Thus, the percentages of dry matter found in this study (< 50 g $100g^{-1}$ FW in all treatments) were within the recommended value which highlights a conscientious water management, since the irrigated chestnuts had adequate water contents for stability.

Concerning the crude protein, it increased from 2015 to 2016 in all treatments, contrary to the findings of Dinis *et al.* (2011) that found higher crude protein content in the lowest temperature sum. Instead, in our study it was in 2016 (2,504°D) that we observed the highest CP. Our results also did not corroborate with the inverse relationship found between dry matter and crude protein by Ferreira-Cardoso and De Vasconcelos (2009). In 2015, the crude protein content (between 4.2 to 4.8 g 100g^{-1} DM) present similar values to those found by Dinis *et al.* (2011) for the same variety in rainfed conditions in the same region.

Ashes are the set of minerals and are dependent of the climate and also of the soil fertility. However, irrigation did not clearly affect their content as expected and, on the contrary, the NI condition had higher ashes content in 2015 than the treatments TI and SI, being the values in accordance with the literature data. Indeed, the average ashes content in other cultivars of the sweet chestnut ranged from 1.02 to 3.22 g 100g^{-1} DM (De La Montaña *et al.* 2004, Pereira-Lorenzo *et al.* 2006, Ferreira-Cardoso 2007, Borges *et al.* 2008, Barreira *et al.* 2009, Sacchetti *et al.* 2009). It was also verified the inverse correlation between ashes and DM contents.

The crude fat slightly decreased from 2015 to 2016 especially for TI and this is contrarily to the expected, since Dinis *et al.* (2011) observed that at lower temperature sum the crude fat content is reduced. Corroborating with Ferreira-Cardoso (2007) the crude fat content seems independent of the crude protein content. It is well known that the lipid content of chestnut is low (Beaubatie 1979, Ferreira-Cardoso 2007) comparing with the dry fruits. In general, the crude fat values were lower than those found by Dinis *et al.* (2011) for 'Judia' cultivar in Bragança region (mean of 3 g 100g^{-1} DM) and are within the values for different varieties referred by other authors, which ranged from 1.2 to 2.4 g 100g^{-1} DM (Borges *et al.* 2008, Choupina and Silva 1992, Oliveira and Maia 1987, Rotundo *et al.* 1988, Üstün *et al.* 1999). Still, the possible differences found in literature for the chestnut's crude fat may be explained by the conditions (solvent used and environmental temperature) during the crude fat extraction (Ferreira-Cardoso 2007). In the end, although no significant differences were found, the TI had higher content of crude fat, which is positive, since most of the lipids present in the crude fat are triglycerides, an important source of energy (Ferreira-Cardoso 2007).

Inversely to the crude protein, the starch content decreased from the coldest to the hottest year, similarly to the findings of Dinis *et al.* (2011). This is also in accordance with Ferreira-Cardoso (2007), which found an inverse relationship between starch and crude protein. In 2015, the starch content was significantly lower in NI than TI which reveals that trees were in more comfortable conditions in the irrigated treatment. Dinis *et al.* (2011) also found lower starch content in stressed conditions mainly related with the higher temperature sum. The decreasing was also observed on the soluble sugars (7.1 to 6.7 g $100g^{-1}$ DM in 2015 and 2016, respectively) which was expected since the soluble sugars come from starch hydrolysis (Pereira-Lorenzo *et al.* 2006). However, the higher content of soluble sugars in 2016 for NI rather than in TI or SI may reflect the harder conditions that trees were submitted. Again, the effect of irrigation was more evident in 2015 than 2016 which lead us to deduce that water constraint is effectively limitative on the chestnut's quality and size within a range of adequate temperatures or temperature sum. This fact assumes importance if we consider the predicted increasing on temperatures due to climatic changes (Miranda *et al*., 2002).

The overall results of the Principal Components Analysis revealed closer proximity of the chestnuts from SI and NI treatment due to the soluble sugars, detachability and the sensory attribute "initial firmness" but, although the sweetness is given by the soluble sugars (Ferreira-Cardoso 2007), the tasters felt it more in the NI chestnuts which is an outstanding result since the market value is given by the sweetness of the chestnut besides the fruit size (Dinis *et al.* 2011, Ferreira-Cardoso 2007, Martins *et al.* 2011). Moreover, in an earlier study (Künsch *et al.*, 2001), sensory criteria used for selecting suitable *C. sativa* cultivars for roasting included size, detachability, aroma, sweetness and texture attributes, as these chestnut sensory characteristics are well appreciate by consumers. On the other hand, the calibre and chestnut's production approximate the two irrigated treatments of each other and this is also positive since the big fruit size is very valuable in the market and the high production brings more revenue to the producers.

Conclusions

In a year that the summer has been excessively prolonged with excessive temperatures and without rainfall, this study points out important results for the chestnut crop. So, this study aimed to understand the effect of irrigation, through different irrigation systems, on the chestnut's quality, size, chemical composition and tastiness as well as plant's nutritional status. Overall results suggest that the soil moisture increases mineral absorption and minerals leaves' content, especially in the end of summer. It was observed that climatic conditions of the year, especially the temperature sum, affected more the fruit's features than the treatments. However, the positive effect of irrigation on the chestnut size was clear and also the chemical analysis allowed us to state that irrigation did not negatively affect the chemical composition of the chestnut. In the end, irrigation increases the commercial value of the chestnut because increase its size keeping their nutritional value and sensory characteristics. Regardless of the non-existence of significant differences between irrigated treatments, the overall results of fruit calibre, firmness and tastiness, namely sweetness, of the chestnuts obtained from the sprinkler system, suggest that this type of irrigation suits perfectly to achieve high chestnut yields and quality.

Acknowledgments

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Tables and Figures

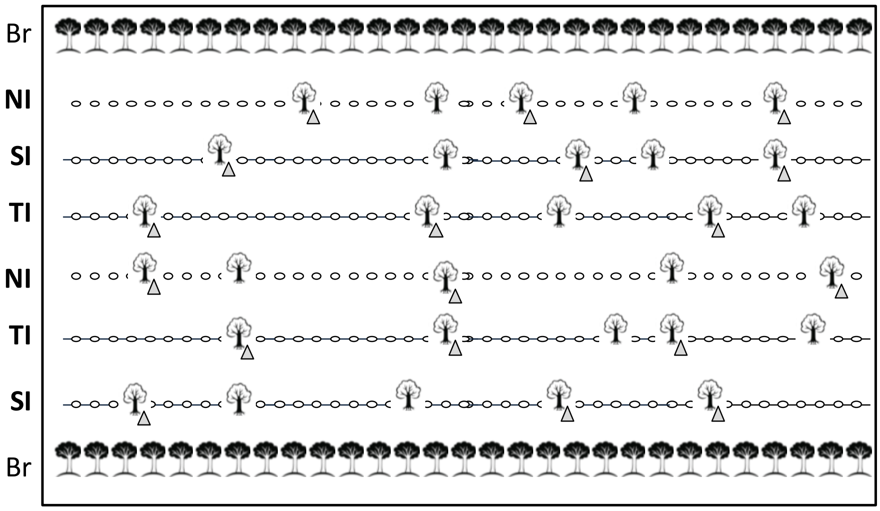

Fig. M-1- Experimental plot in 2015 and 2016 with micro-sprinkler system (SI), drip system (TI), non-irrigated trees (NI) and border trees (Br). The triangles (Δ) represent the location of the access tubes of Diviner 2000. Sample trees are represented by trees ( ).

Tab. M-1- Irrigation period, number of irrigation events and total water volume applied in to the drip system (TI) and micro-sprinkler system (SI) in 2015 and 2016.

Year	Treatment	Irrigation Period	Nº of irrigation events	Total Water Volume $m^3\ ha^{-1}$
2015	TI	Jul 23rd - Sep 11th	9	461
	SI	Jul 26th - Sep 11th	9	479
2016	TI	Jul 20th - Sep 30rd	19	871
	SI	Jul 20th - Sep 30rd	19	979

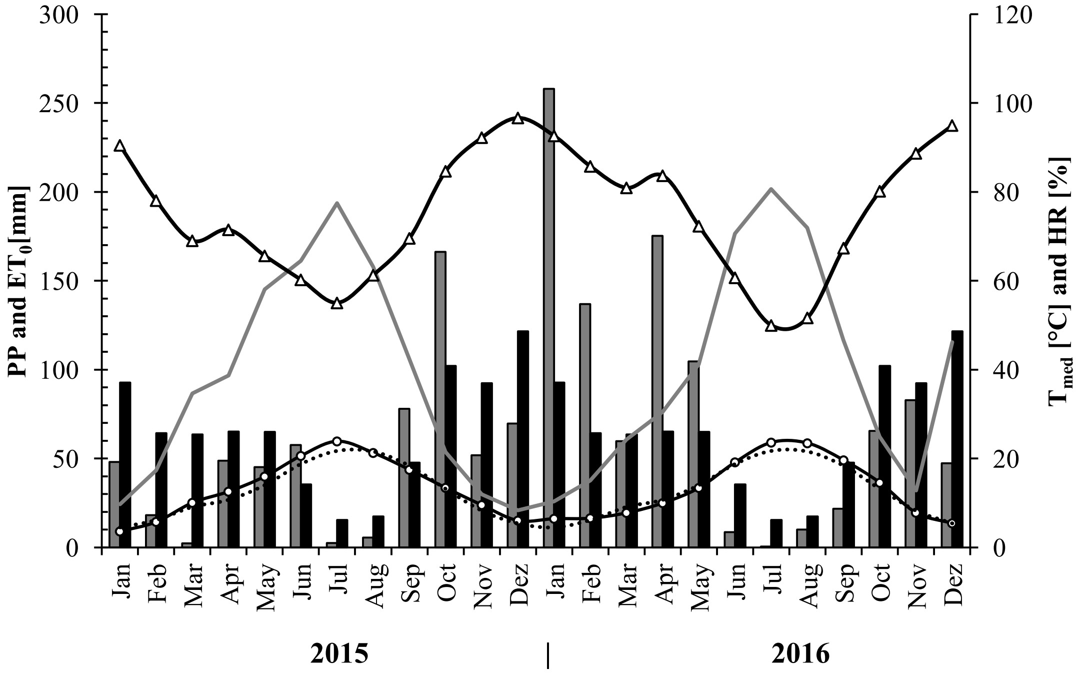

Fig. M-2 - Monthly total precipitation (PP, mm) for 2015 and 2016 (grey columns) and on the average of the decades 1980-2010 (black columns); Evapotranspiration (ET_0, mm, grey line), mean monthly air's temperature (T_{med}, °C) during 2015 and 2016 (○) and on the decades 1980-2010 (dashed line) in Bragança region, air relative humidity (HR, in %, Δ) . Retrieved from IPMA 2015, 2016, 2018.

Tab. M-2 -Chestnut leaves' mineral content for macronutrients and micronutrients for non-irrigated (NI), drip irrigated (TI) and micro-sprinkler irrigated (SI) trees, in different dates along the vegetative cycle.

Date	Treatment	Macronutrients (g kg^{-1})						Micronutrients (mg kg^{-1})				
		N	P	K	Ca	Mg	S	B	Fe	Zn	Mn	Cu
07/07/16	NI	21.7	1.9	11.5	6.0	2.1	0.5	32.0	11.0	21.0	562.0	7.0
	TI	22.3	2.3	11.3	4.4	2.0	0.7	27.0	4.00	21.0	524.0	7.0
	SI	23.5	2.2	12.1	4.1	1.0	0.7	31.0	2.0	22.0	544.0	9.0
03/08/16	NI	18.7	1.9	12.8	6.3	2.2	0.8	30.0	8.0	14.0	691.0	6.0
	TI	20.9	1.9	11.9	4.4	2.0	0.5	27.0	3.0	23.0	603.0	8.0
	SI	20.2	2.0	12.6	9.6	2.6	0.6	26.0	9.0	24.0	673.0	6.0
05/09/16	NI	19.3	2.0	13.9	7.2	2.3	0.4	29.0	5.00	24.0	686.0	16.0
	TI	21.4	2.7	15.8	8.9	2.5	0.7	39.0	6.00	33.0	687.0	9.00
	SI	20.6	3.0	12.5	8.9	2.4	0.5	41.0	10.0	25.0	613.0	12.0
03/10/16	NI	18.4	4.1	7.80	9.40	1.7	1.0	25.0	76.0	20.0	933.0	14.0
	TI	21.2	3.6	12.0	11.0	2.3	0.8	24.0	71.0	27.0	749.0	15.0
	SI	20.4	3.5	7.00	9.8	1.3	1.2	30.0	65.0	25.0	592.0	15.0
Average	NI	19.5	2.5	11.5	7.2	2.1	0.7	29.0	25.0	19.8	718.0	10.8
	TI	21.5	2.6	12.8	7.2	2.2	0.7	29.3	21.0	26.0	640.8	9.80
	SI	21.2	2.7	11.1	8.1	1.8	0.8	32.0	21.5	24.0	605.5	10.5
Variation	NI	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	TI	109.9	106.1	110.9	99.30	106.0	100.0	100.9	84.00	131.6	89.20	90.70
	SI	108.5	108.1	96.10	112.1	88.00	111.1	110.3	86.00	121.5	84.30	97.70
Analysis of Variance (%)												
Date		55	24	-28	66	16	35	-42	84	29	28	87
Treatment		2	8	-36	-5	20	-39	-38	-16	-18	15	-9
Date*treatment		5	17	-72	-11	40	-78	-75	-31	-37	31	-18
Residual		38	51	236	51	24	181	255	63	127	26	40
Total		100	100	100	100	100	100	100	100	100	100	100

Tab. M-3 - Calibre (fruits per kilogram, mean ± SE) and density (g mL^{-1}) for non-irrigated (NI), drip irrigated (TI) and sprinkler-irrigated (SI) systems, in 2015 (n=185) and 2016 (n=211). Values with different letters are significantly different, within the year, according to Fisher test ($p<0.05$).

Treatment	Calibre (fruits kg^{-1})			Density (g mL^{-1})		
	2015	2016	Average	2015	2016	Average
NI	64.5 ± 4.2	122.7 ± 8.54 a	107.1 ± 7.51 a	1.13 ± 0.02	1.26 ± 0.01	1.23 ± 0.01
TI	61.4 ± 2.1	88.9 ± 5.14 b	82.1 ± 4.32 b	1.17 ± 0.03	1.21 ± 0.03	1.20 ± 0.03
SI	62.7 ± 3.8	77.7 ± 8.54 b	74.2 ± 2.67 b	1.14 ± 0.02	1.24 ± 0.02	1.22 ± 0.02
Analysis of Variance (%)						
Year		27.45			-48.78	
Treatment		4.87			-74.18	
Year*treat.		9.75			-148.37	
Residual		57.92			371.34	
Total		100.00			100.00	

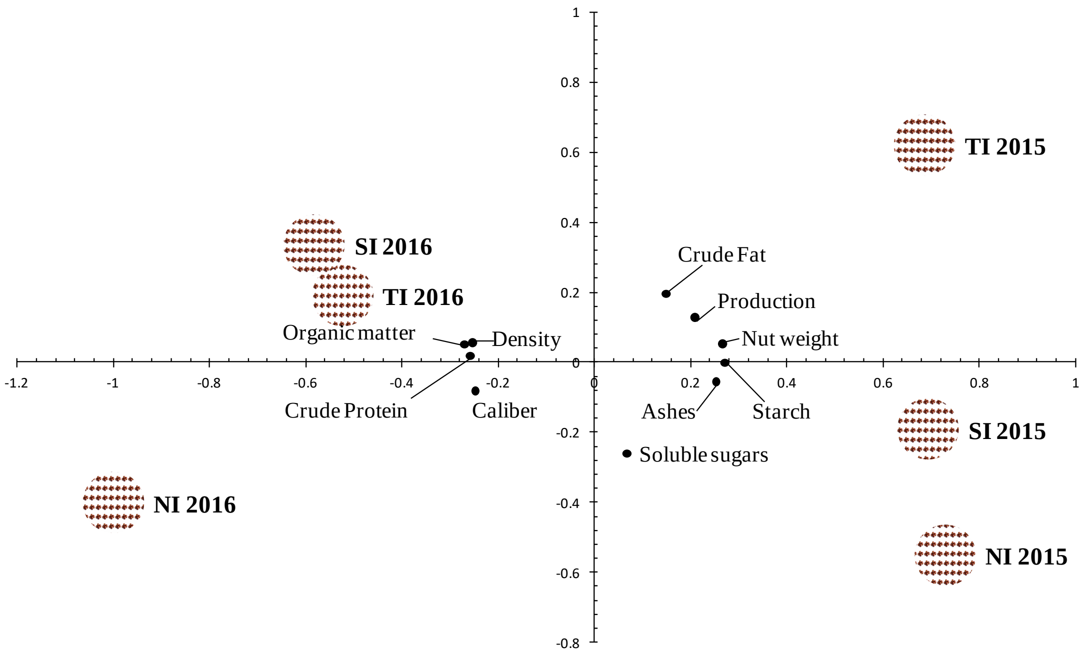

Fig. M-3- Principal Components Analysis based on correlation (Corr-PCA) projection of the chestnut chemical composition and production in 2015 and 2016. NI - non-irrigated, TI - drip irrigated and SI - micro-sprinkler irrigated.

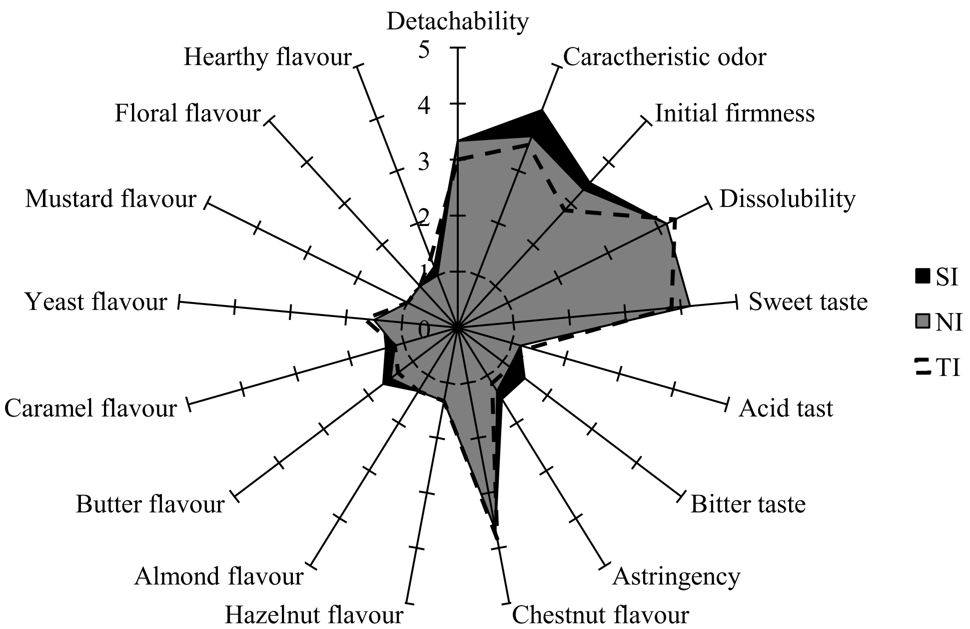

Fig. M-4 - Sensory profile of the cooked chestnuts from non-irrigated (NI), drip irrigated (TI) and micro-sprinkler irrigated (SI) treatment in 2016. The structured scale defines 1 point as less intense and 5 points as more intense.

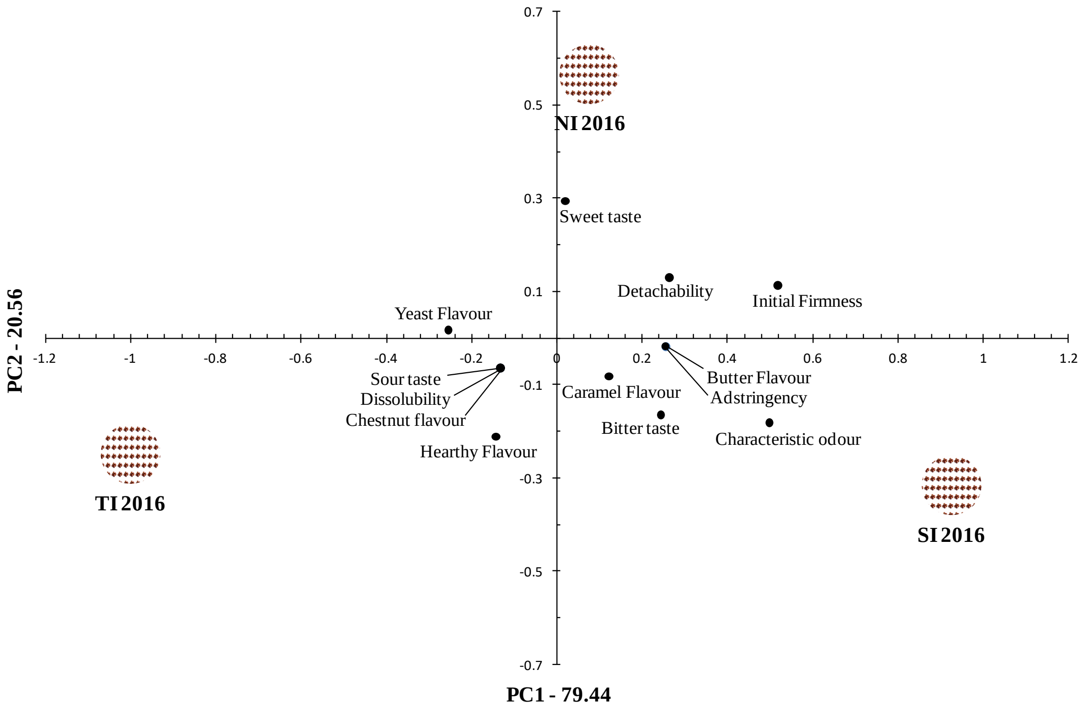

Fig. M-5 - Principal Components Analysis based on covariance (Cov-PCA) projection of the sensorial attributes evaluated in the cooked chestnuts. NI - non-irrigated, TI - drip irrigated and SI - micro-sprinkler irrigated.

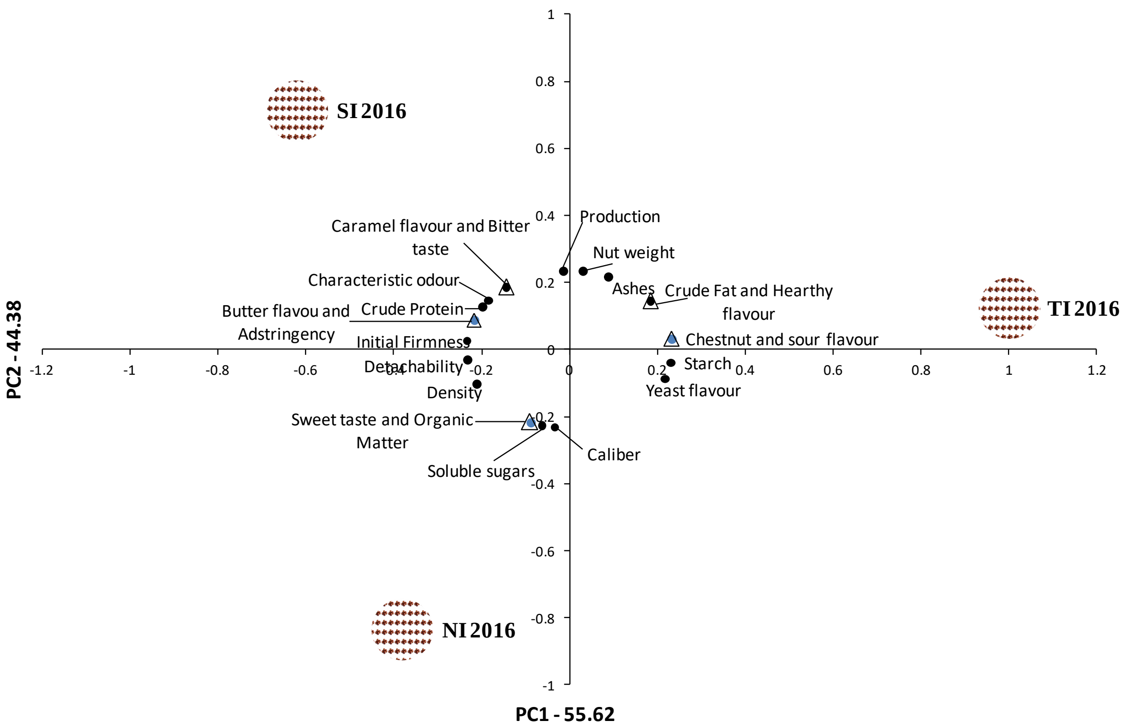

Fig. M-6 - Principal Components Analysis based on correlation (Corr-PCA) of chemical and sensory data obtained in the 2016 harvest. NI 2016 - non-irrigated, TI 2016 - drip irrigated and SI 2016 - micro-sprinkler irrigated.

Tab. M-4 - Dry matter (DM), organic matter (OM), ashes, soluble sugars (SS), starch, crude fat (CF) and crude protein (CP) in the chestnuts from non-irrigated (NI), drip irrigated (TI) and sprinkler-irrigated (SI) systems, in 2015 (n=108) and 2016 (n=115), average of two years, and respective standard error (± SE). Values with different letters are significantly different among treatments according to Fisher test (p<0.05).

Treatments.	DM ($g\ 100g^{-1}$ FW)	OM ($g\ 100g^{-1}$ DM)	Ashes ($g\ 100g^{-1}$ DM))	SS ($g\ 100g^{-1}$ DM))	Starch ($g\ 100g^{-1}$ DM)	CF ($g\ 100g^{-1}$ DM)	CP ($g\ 100g^{-1}$ DM)
				2015			
NI	45.3 ± 0.39 a	97.4 ± 0.03 b	2.58 ± 0.03 a	8.38 ± 0.47 a	56.9 ± 0.63 b	1.87 ± 0.29 a	4.80 ± 0.15 a
TI	46.4 ± 0.26 a	97.5 ± 0.02 a	2.46 ± 0.02 b	5.93 ± 0.39 b	58.7 ± 0.53 a	2.25 ± 0.09 a	4.50 ± 0.13 ab
SI	45.8 ± 0.11 a	97.6 ± 0.04 a	2.40 ± 0.04 b	7.30 ± 0.05 ab	57.8 ± 0.59 ab	1.84 ± 0.08 a	4.20 ± 0.12 b
				2016			
NI	49.8 ± 0.10 a	97.8 ± 0.06 a	2.23 ± 0.06 a	7.17 ± 0.13 a	48.3 ± 0.36 a	1.75 ± 0.03 a	5.90 ± 0.17 a
TI	48.4 ± 1.00 a	97.7 ± 0.01 a	2.27 ± 0.01 a	6.59 ± 0.25 a	48.5 ± 0.63 a	1.89 ± 0.11 a	5.70 ± 0.17 a
SI	50.1 ± 1.80 a	97.7 ± 0.03 a	2.27 ± 0.03 a	6.50 ± 0.50 a	48.1 ± 0.67 a	1.82 ± 0.15 a	6.20 ± 0.16 a
				Average			
NI	47.6 ± 0.40 a	97.6 ± 0.07 a	2.40 ± 0.07 a	7.78 ± 0.31 a	52.6 ± 1.19 a	1.81 ± 0.17 a	5.35 ± 0.23 A
TI	47.4 ± 0.18 a	97.6 ± 0.03 a	2.36 ± 0.03 a	6.26 ± 0.30 b	53.6 ± 1.39 a	2.07 ± 0.09 a	5.10 ± 0.26 A
SI	48.0 ± 0.15 a	97.7 ± 0.03 a	2.33 ± 0.03 a	6.90 ± 0.36 ab	53.0 ± 1.24 a	1.83 ± 0.07 a	5.20 ± 0.40 A
				Analysis of variance (%)			
Year	80.83	69.01	69.01	-11.76	98.15	5.61	82.31
Treatment	5.85	7.48	7.48	-25.20	-0.07	-12.18	4.45
Year*Treat	11.70	14.97	14.97	-50.40	-0.15	-24.36	8.90
Residual	1.63	8.54	8.54	187.37	2.08	130.94	4.35
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

VI. SOIL AND PLANT WATER RELATIONSHIP AND THE WATER MANAGEMENT

N. Monitorizar para regar: o caso do castanheiro (*Castanea sativa*)

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Resumo

O castanheiro é uma cultura que beneficia com a rega devendo esta ser gerida de forma sustentável, do ponto de vista da racionalização do uso de recursos naturais (água) e da rentabilidade económica da exploração agrícola (custos energéticos, mão-de-obra e produtividade do souto). Dentro do âmbito dum estudo que possui como objetivos principais apurar o efeito da rega no castanheiro, otimização de um sistema de rega assim como a sua gestão, o presente artigo tem como enfoque avaliar a relação entre os parâmetros planta, solo e clima por forma a permitir a gestão da rega no castanheiro mais ajustada ao produtor. Em 2015, num souto adulto da variedade 'Judia' localizado em Bragança, compararam-se árvores regadas e árvores não regadas. Monitorizou-se o potencial hídrico de ramo, a humidade do solo e parâmetros meteorológicos. Ao longo do ciclo vegetativo o potencial de ramo desceu de -0.6 MPa para -1.6 MPa, mas foi mantido perto -1.2 MPa nas árvores regadas. Nestas últimas, a humidade do solo aos 30 cm variou entre 15 e 22%, já nas árvores não regadas esteve abaixo de 13%. O potencial de ramo está bem correlacionado com a humidade do solo, mas é flutuável com as condições ambientais. A produção foi 20% maior nas árvores regadas relativamente às não regadas, mesmo com uma gestão de rega que se considera deficitária. O produtor beneficia do uso de equipamentos de monitorização ambiental e de humidade do solo que tenham registo contínuo automático e não destrutivo.

Palavras-chave: Castanheiro, gestão da rega, humidade do solo, monitorização, potencial hídrico.

Abstract

It is assumed that chestnut tree benefits from irrigation but it should be managed conscientiously. This article aims to evaluate the relationship between different soil-plant-atmosphere intervenient to guideline de chestnut producer to the best commitment for water management in the chestnut. In 2015, in a chestnut orchard of 'Judia' variety located in Bragança, it was compared watered and no watered trees. It was measured stem water potential, soil moisture and meteorological parameters. Throughout the growing season the stem water potential dropped from -0.6 MPa to -1.6 MPa, but in watered trees it was kept near -1.2 MPa. Soil moisture at 30 cm in watered trees varied between 15 and 22% and it was below 13% in non watered trees. The stem water potential is well correlated with soil moisture, but it is floatable with environmental conditions. The yield was 20% higher in watered trees even with deficit irrigation. The producer benefits from the use of equipment that allows automatic and continuous records without destructive methods.

Keywords: Chestnuts, water management, stem water potential, soil moisture and monitoring.

Introdução

Nas últimas décadas, assistiu-se à evolução de várias culturas perenes de sequeiro extensivo, refira-se como exemplo a cultura da oliveira, da amendoeira ou da nogueira, para um sistema de cultivo mais intensivo que vai de encontro às preocupações atuais relacionadas com a rentabilidade, valorização da qualidade do produto, alterações climáticas e sustentabilidade económica e ambiental. Estes mesmos desafios colocam-se igualmente no setor da "castanhicultura" português pelo que é de se esperar que este seja imbuído de maior modernidade e tecnologia.

A maior região produtora de castanha portuguesa, Trás-os-Montes, é regularmente afetada por períodos de seca estivais que podem pôr em causa a produtividade dos soutos, nomeadamente nos soutos jovens e se instalados em solos pouco profundos, compactos e pedregosos (Martins *et al.*, 2010). Sendo a água uma das maiores, senão a maior, condicionante na produtividade das culturas, a introdução da rega no castanheiro é uma realidade próxima. A gestão conscienciosa da água permite um acréscimo da rentabilidade e da regularização da produção da castanha (Breisch, 1995) preservando simultaneamente o uso sustentável deste recurso que é natural, mas escasso.

A gestão da rega tem como base responder a três principais questões: como, quando e quanto regar. A primeira prende-se com o tipo de sistema de rega a adotar que varia consoante os recursos hídricos, edáficos, topográficos, económicos e humanos (Pereira, 2007). Apesar de estarem a decorrer ensaios sobre diferentes sistemas de rega no castanheiro, este tema não será alvo de análise neste artigo.

Quando e quanto regar são a base para as programações das rotinas de rega numa exploração agrícola e implicam a recolha e análise de dados de todos os intervenientes do sistema contínuo solo-planta-clima. O produtor deve saber quando deve iniciar uma rega e quanto tempo deve regar, isto é, qual quantidade de água a aportar nessa rega (Lopez, 2005).

Existem vários instrumentos para monitorização dos intervenientes solo-planta-clima. Contudo, irão ser referidos os que estão mais acessíveis no mercado nacional, sem esquecer as características que os tornam mais interessantes sob o ponto de vista de utilização pelo produtor, como sejam o valor do investimento, a facilidade de instalação e a simplicidade na obtenção de dados. Assim, ao nível do clima, interessa conhecer as condições meteorológicas (p.e., temperatura, precipitação e humidade relativa) recentes e atuais através de uma estação meteorológica local ou próxima. Devem ainda ser consideradas as previsões meteorológicas para os próximos dias (dados que podem ser obtidos junto do Instituto Português do Mar e Atmosfera - IPMA) para que a rega possa ser racionalizada de acordo com as previsões de precipitação ou não. A tomada de decisão de regar ou não, assume particular importância em determinados estados fenológicos das árvores. No caso do castanheiro, é importante que este esteja em conforto hídrico desde a floração até à colheita (Breisch, 1995), sendo os períodos da floração, divisão celular do fruto e seu engrossamento os mais sensíveis (Breisch, 1995). O período de ocorrência dos diferentes estados fenológicos depende maioritariamente da variedade de castanheiro, da localização do souto e das condições climáticas decorrentes do ano. A variedade 'Judia', na Terra Fria de Trás-os-Montes, tipicamente tem a floração a meados de junho, o engrossamento da castanha ocorre de meados de julho até meados de outubro, quando começa a maturação da castanha, estando esta pronta para apanha a partir da terceira semana de outubro (Pinto *et al.*, 2007).

A nível da planta, é usual o recurso a câmaras de pressão para medição do potencial hídrico foliar. Este equipamento permite avaliar o potencial hídrico foliar de base (Ψ_{base}), o potencial hídrico foliar do meio-dia (Ψ_{folha}) e o potencial hídrico de ramo (Ψ_{ramo}). A quantificação do potencial hídrico, embora seja uma medição direta sobre o estado hídrico da água, é um método destrutivo que requer tempo de leitura, deslocação e registo manual. O Ψ_{ramo} tem sido indicado como o mais sensível e razoável na deteção do estado hídrico de culturas perenes (Shackel *et al.*, 1997) como a amendoeira, a nogueira, a ameixeira e a oliveira (McCutchan and Shackel 1992, Gómez-del-Campo 2013, Lampinen and Shackel 2015). Ao contrário doΨ_{base}, as leituras não são feitas antes do amanhecer e, comparativamente com o potencial hídrico do meio-dia, o Ψ_{ramo} tem um intervalo de tempo de leitura mais alargado (Gómez-del-Campo 2013, Fulton *et al.* 2014). No caso do castanheiro, oΨ_{base} e oΨ_{folha} são os mais estudados (Gomes-Laranjo *et al.*, 2008). Considera-se que o castanheiro tem um nível hídrico adequado quando Ψ_{base} se encontra dentro do intervalo -0.4 a -0.6 MPa (Martins *et al.*, 2010) e que a taxa fotossintética é máxima quando Ψ_{folha} está perto de -1 MPa (Gomes-Laranjo *et al.* 2008, Martins *et al.* 2010). Não existe conhecimento acerca dos valores ótimos de Ψ_{ramo} no castanheiro bem regado. No presente estudo consideraram-se, como valores de referência, valores de Ψ_{ramo} doutras fruteiras estudadas (McCutchan and Shackel 1992, Lampinen and Shackel 2015) e de dados retirados em 2013/14 no mesmo ensaio do presente estudo. Durante 2014, nas mesmas árvores mas sem aplicação dos tratamentos, os potenciais hídricos foram monitorizados ao longo do ano (Tab. N-1). Assim, definiu-se iniciar a rega quando Ψ_{ramo} fosse igual ou inferior a -1.2 MPa, não sendo definitivo que este valor seja o indicativo de castanheiros em condições de rega plena sem qualquer constrição hídrica.

A nível do solo, existem análises específicas que permitem conhecer alguma das suas características como sendo a textura, a profundidade, a capacidade de campo e o ponto de emurchecimento, importantes para interpretação dos resultados obtidos a partir de equipamentos colocados no solo. Refira-se, como exemplo, a humidade do solo que pode ser aferida pela tensão da água no solo através de tensiómetros ou sensores da Watermark, ou baseada na constante dielétrica do solo através de sondas TDR (*time domain reflectometry*) ou ainda através de sondas capacitivas (Hubel Verde, 2015). A automatização e o registo contínuo de valores são possíveis com alguns destes equipamentos, facilitando o acesso aos dados por parte do utilizador. O maior constrangimento no uso dos sensores de solo, nomeadamente em árvores adultas, está relacionado com o enorme e irregular volume de solo ocupado pelas raízes (Martins *et al.* 2010; Silva 2010) o que condiciona a total cobertura do solo (seja horizontalmente seja verticalmente) pois isso acarretaria um custo elevadíssimo ao produtor. Desta forma, deve-se assumir um compromisso de monitorizar diferentes profundidades do solo, no mínimo até aos 80 cm, e optar por se colocarem sensores em zonas representativas e distintas no souto. Quando regadas, as árvores absorvem a água maioritariamente pelas raízes superficiais (Garnier *et al.*, 1986) sendo que humedecendo o solo até aos 40 cm já é observado um efeito positivo da rega no castanheiro (Mota *et al.*, 2014).

O presente estudo debruça-se sobre a temática da gestão da rega no castanheiro, mais precisamente em determinar quais os parâmetros que devem ser monitorizados, tendo em conta a experiência existente doutras culturas e o escasso conhecimento sobre rega no castanheiro. Constitui objetivo deste trabalho de investigação avaliar a relação entre os parâmetros de solo-planta-clima e aferir sobre a utilidade dos equipamentos de monitorização para gestão da rega no castanheiro.

Material e métodos

Local O ensaio foi instalado em Santa Comba de Rossas, Bragança, num souto adulto de sequeiro, variedade Judia com cerca de 22 anos, com compassos de 10 metros na entrelinha e 5 metros na linha. O sob coberto é mantido em pastoreio com pastagem semeada. O solo tem uma textura média, de pH (H_2O) de 5 e com 1,5% de matéria orgânica.

Tratamentos Fizeram-se dois tratamentos: árvores regadas (RR), tendo-se estudado 19 árvores (n =19), e árvores não regadas (NR), tendo-se selecionado 11 árvores (n=11). Em RR, a rega iniciava-se quando o Ψ_{ramo} médio das árvores fosse igual ou inferior a -1,2 MPa. Foi definido o término de cada rega quando a média do conteúdo de água no solo (θ) aos 30 cm fosse cerca de 22% (cm^3 H_2O 100 cm^{-3}solo).

Para o cálculo deste valor considerou-se que o ponto crítico de humidade para o castanheiro é 50% da água utilizável, a capacidade de campo do solo é 32,8% e o ponto de emurchecimento 11,9% (vide abaixo *Medições no solo*). Definiu-se, assim, a água facilmente utilizável entre 22% e 32,8% de humidade.

Medições na planta. As árvores foram selecionadas, tendo em conta a máxima similaridade entre elas, e foram monitorizadas a cada 7-10 dias, de 5 de junho a 2 de outubro de 2015. O potencial hídrico de ramo (Ψ_{ramo}) foi medido com recurso a uma câmara de pressão (Modelo "pump-up", PMS Instrument® Corvallis, Oregon, USA) de acordo com a metodologia recomendada pelo fabricante e adaptado de Fulton *et al.* (2014). As medições ocorreram entre as 12 h e as 14 h, numa folha de um ramo frutífero, localizada o mais perto possível do ramo principal, do lado sombreado. A folha foi coberta com papel de alumínio e um saco de plástico no mínimo uma hora antes das medições. O potencial hídrico foliar (Ψ_{folha}) e de base (Ψ_{pd}) foram pontualmente medidos.

*Medições no solo***.** O conteúdo de água no solo foi avaliado a cada 7-10 dias, com uma sonda capacitiva (Diviner 2000, Sentek Technologies), desde 9 de julho a 2 de outubro. Em cada um dos tratamentos foram instalados seis tubos de acesso, um por árvore, a cerca de um metro do tronco. A sonda regista os valores a cada 10 cm de profundidade até aos 80 cm. Para efeitos de definição do término de rega foi tido como referência os dados obtidos pelo método da placa de pressão (Silva *et al.*, 1975) realizado no ano de 2007, no mesmo solo (Afonso Martins, comunicação pessoal, 3 de outubro 2014). Segundo este método, a média do conteúdo de água no solo nos 30 cm a pF 4.2 (ponto emurchecimento) foi de 11,3% e a pF.2 (capacidade de campo) foi de 30%. Em 2015, no sentido de comparar os dados laboratoriais com dados retirados no terreno, determinou-se a capacidade de campo no local, realizando-se uma medição da humidade do solo, com a sonda capacitiva, 24 horas após um longo período de chuvas outonais. Nessas condições, o conteúdo de água à capacidade de campo aos 30 cm foi de 32,8%. O teor mínimo de água no solo foi observado nos meses mais secos nas árvores não regadas e foi constante ao longo desse período. Esse valor mínimo de humidade aos 30 cm foi de 11,9%, e foi considerado o teor de água presente no solo quando a castanheiro já não consegue extrair mais água, e que se aproxima do coeficiente de emurchecimento verificado laboratorialmente. Em cada tratamento, foram instalados três sensores de humidade do solo da Watermark (Irrometer) a 30, 60 e 80 cm de profundidade e um sensor de temperatura do solo. Os valores destes sensores eram registados em intervalos horários num monitor e transmitida via GPRS (serviço geral de pacotes por rádio) para um servidor, de forma a haver um acompanhamento constante da evolução do teor de humidade do solo ao longo do perfil.

*Medições meteorológicas***.** Em 2014 foi instalada, no souto, uma estação meteorológica modelo 2900 ET (Spectrum Technologies), que registou valores horários da temperatura do ar, temperatura no ponto de orvalho, humidade relativa, precipitação, direção e velocidade do vento. A estação 2900 ET também calcula os valores de evapotranspiração de referência (ET_0) de acordo com a equação de Penman-Monteith. Além disso, possui capacidade de proceder ao cálculo da evapotranspiração cultural (Et_c), se definido o coeficiente cultural (valor não conhecido no castanheiro). Foi determinado o défice de pressão de vapor (DPV) existente às 13 horas para encontrar a correlação com o $\Psi_{ramo.}$ O défice de pressão de vapor (DPV), sendo a diferença entre a pressão de vapor atual ($e°_a$) e a pressão de vapor quando o ar está saturado ($e°_s$), é um indicador da capacidade evaporativa do ar (Allen *et al.*, 1998). A $e°_a$ foi calculada com base na temperatura do ponto de orvalho ($T_{orvalho}$) segundo a equação (Allen *et al.*,1998):

$$e°a \ = 0{,}6108 \, exp[(17{,}27 \, Torvalho)/(Torvalho + \ 237{,}3)]$$

A $e°_s$ foi calculada com base na temperatura do ar às 13h (T_{ar}) segundo a equação (Allen *et al.*, 1998):

$$e°s \ = 0{,}6108 \, exp[\ (17{,}27 \, Tar)/(Tar + \ 237{,}3)]$$

Foi também calculado o somatório de graus dias (ºD). O seu cálculo é feito segundo a equação:

$$\sum \ 〚(Tm - T0) \times N〛$$

em que *Tm* é a temperatura média mensal (°C), T_0 a temperatura de base que se considera 6°C no castanheiro (Gomes-Laranjo *et al.*, 2008) e *N* o número de dias do mês.

Produção de Castanha. Nas árvores de estudo foi delimitada com recurso a uma fita métrica, uma área de colheita, por baixo da copa da árvore. As castanhas foram apanhadas em três datas distintas de colheita e pesadas à saída do campo. Foram recolhidos três ouriços por árvore em estudo, para determinar o número de castanhas chochas e boas. As castanhas boas foram posteriormente usadas para determinar a densidade. Após a pesagem das castanhas (com casca), a densidade foi calculada dividindo o peso fresco da castanha (g) pela diferença obtida no volume de água (mL) após imersão das castanhas em água. Para a determinação da matéria seca, utilizaram-se castanhas sem casca (n=36, em NR e n=72 em RR), tendo sido pesadas em fresco e após a permanência de uma semana na estufa a 60°C.

Resultados e discussão

Os meses de julho e agosto foram os meses mais secos e quentes (Fig. N-1) registando uma temperatura média mensal mais alta (22°C e 19°C, respetivamente) havendo dias em que a temperatura máxima superou os 35°C. As primeiras chuvas após o período seco ocorreram a 15 e 16 de setembro totalizando os 94 mm do mês, sendo que em outubro a precipitação ocorreu mais distribuída pelo mês, totalizando nesse mês 195 mm. O somatório de graus-dia até final de outubro foi de 2308°C. Este valor está dentro do expectável para a maturação da castanha (2100 a 2500°C após floração) (Gomes-Laranjo *et al.*, 2007) e está dentro do intervalo de valores médios encontrados por Dinis (2011) na região de Trás-os-Montes no ano de 2006 (2551°C), 2007 (2155°C) e 2008 (1958°C).

No início da campanha, o Ψ_{ramo} foi de -0.6 MPa e o valor mínimo encontrado foi de -1,6MPa em NR a 21 de agosto (Fig. N-2). Em média, o Ψ_{ramo} foi de -1,1 MPa e -1,2MPa em RR e NR, respetivamente.

No período que decorreu entre os meses de junho (floração) e nas duas primeiras semanas do julho (fruto vingado), o Ψ_{ramo} dos dois blocos oscilou entre -0.6 e -1.1MPa (Fig. N-2). Neste período não foi feita qualquer rega, pelo que todas as árvores se encontravam nas mesmas condições nesta importante fase fenológica. Os resultados do Ψ_{ramo} e do conteúdo de água avaliado no solo (18,3%, 21,1% e 22,4%, aos 30, 60 e 80 cm, respetivamente) sugerem que o período de floração, polinização e vingamento do fruto tenha decorrido naturalmente sem limitação hídrica. A estação 2900 ET registou uma precipitação acumulada de 823,2 mm entre outubro 2014 e junho 2015. A recarga hídrica no solo resultante desta precipitação terá sido suficiente para, nas condições particulares de junho de 2015, a floração ter decorrido sem problemas de disponibilidade de água no solo.

A partir de 15 de julho, fase do início do vingamento das castanhas, o Ψ_{ramo} encontrava-se abaixo do limiar de -1,2 MPa, valor definido para iniciar a rega, e o conteúdo de água no solo baixou para 12,5% (Fig. N-3). Tipicamente, o Ψ_{ramo} foi sempre menos negativo (algumas vezes não significativamente) em RR entre 25 julho (data da primeira rega) e 11 setembro. A partir da primeira rega (25 julho) até 13 de setembro, enquanto no bloco NR o solo apresentou níveis de água de 12 a 13 %, no bloco regado o nível de hidratação atingiu um máximo de 23% a 5 de agosto. É evidente que a decisão de rega está dependente da definição do grau de hidratação do solo que se pretende. Depois da chuva de setembro, o nível de humidade do solo nos dois blocos assim como o Ψ_{ramo}, ficaram iguais conforme o demonstram os registos obtidos a 23 setembro (Fig. N-2, Fig. N-3).

Os dados do Ψ_{ramo} e o conteúdo da água no solo (Fig. N-4,A) são relacionáveis, apresentando um coeficiente de regressão elevado aos 60 cm (r^2 = 0,76) e menor aos 30 cm (r^2 = 0,51). Correlação idêntica é referida na literatura para a oliveira (r^2 = 0,68) (Gómez-del-Campo, 2013), para a nogueira (r^2 = 0,61) (Fulton *et al.*, 2002) e para a videira (r^2 = 0,63) (Williams and Araújo, 2002) em estudos sobre rega deficitária. Comportamento idêntico ocorre com o Ψ_{ramo} e a tensão da água no solo (r^2 = 0,60) aos 30 e 60 cm (Fig. N-4,B). A correlação entre planta e solo tem que ter em conta que o Ψ_{ramo} integra, além das condições de solo, condições climáticas e condições particulares da cultura instalada (Gómez-del-Campo, 2013). Por outro lado, a valorização desta correlação está também dependente do facto de os sensores estarem limitados no espaço pelo que, tratando-se de nomeadamente de árvores adultas, não se consegue monitorizar todo o volume de solo ocupado pelas raízes nem apreender completamente a redistribuição hidráulica da água que ocorre no sistema radicular e que influencia o estado hídrico da árvore.

Os dados sugerem que existe influência da rega no Ψ_{ramo}, mas a sua variação é influenciada por outros fatores, designadamente pelo deficit de pressão de vapor (Fig. N-2) muito embora a correlação encontrada neste estudo, nas árvores regadas, tenha sido muito baixa (r^2 = 0,29) (Fig. N-5) comparativamente com estudos de outros investigadores (McCutchan and Shackel 1992, Lampinen and Shackel, 2015) que encontraram uma elevada correlação (r^2 > 0,8) entre DPV e o Ψ_{ramo} em fruteiras regadas sem limitações de hídricas do solo. Esta relação permitiu aos autores definir, para determinado DPV e em solos sem limitações hídricas, um valor de referência para $\Psi_{ramo.}$ A partir daí, os produtores gerem a rega consoante as condições atmosféricas e o Ψ_{ramo} pretendido, que numa estratégia de rega deficitária pode não ser próximo do valor limite definido (Shackel *et al.*, 1997).

Os sensores da Watermark possibilitam o registo contínuo dos dados e o seu acesso pode ser feito pela internet ou através dum serviço de mensagens diretamente para o telemóvel do produtor (Hubel Verde, 2015). Assim sendo, o produtor pode acompanhar a evolução da humidade do solo em tempo real e construir um histórico de dados ao longo dos anos, reduzindo os custos com deslocações ao souto especificamente para a tarefa de recolher dados do solo. Por estas razões correlacionou-se a tensão de água no solo (sensores da Watermark) com o conteúdo de água no solo (sonda Diviner 2000), por forma a encontrar valores de referência para futura gestão da rega com base nestes sensores (Fig. N-6). Os dois equipamentos apresentam-se bem correlacionados (r^2 = 0,9) o que traduz, não só, a correta instalação dos sensores da Watermark mas também a possibilidade de serem utilizados para gestão da rega. Assumindo o pressuposto para este trabalho em que foi estabelecido o limiar de Ψ_{ramo} = -1,2 MPa para regar, e que a este valor, corresponde a um conteúdo de água de 15% é agora plausível que nos sensores da Watermark os valores se situem entre 90-120 cbar durante o ciclo vegetativo no período de verão (Fig. N-4,B).

Um foco de interesse indubitável é perceber se a rega influenciou a produção de castanha Assim, verificou-se que as árvores regadas produziram 21% mais que as árvores não regadas, com produções médias por árvore de 52,9 kg, contra a 43,7 kg por árvore em NR (Tab. N-2). Também em RR foi registada uma maior percentagem de castanhas boas (71%) e com maior calibre (62 castanhas kg^{-1}). Estes resultados sugerem que as sucessivas regas (totalizando 47 mm de água aportada) feitas durante as semanas correspondentes ao vingamento e engrossamento do fruto, foram importantes para causar estas diferenças.

Tendo em conta o valor médio diário da ET_0 nos meses de julho e agosto (4,8 mm) o aporte de água via rega ao longo do ciclo foi muito pequeno (47 mm). De acordo com Ferrini and Nicense (2000) um castanheiro europeu adulto necessita de uma precipitação média de 33 mm durante os meses estivais, abaixo da qual a produção pode ser fortemente reduzida. Tendo em conta as pequenas diferenças encontradas entre tratamentos, nomeadamente no aumento da produção, apreendeu-se que foi realizada uma rega mínima que não dando lugar a desperdício de recursos, conseguiu efeitos na produtividade.

Conclusão

As condições edafoclimáticas são importantíssimas no comportamento hídrico do castanheiro e devem ser constantemente acompanhadas. Nas condições presentes, a um potencial hídrico do ramo da ordem dos -1,2 MPa, correspondem a humidade do solo entre 90 e 120 cbar, medidos pelos sensores da Watermark, sendo que estes dois parâmetros estão bem correlacionados. A gestão da rega baseada nestes sensores que permitem o registo em contínuo e a comunicabilidade dos registos mostra-se uma opção interessante para o produtor, pela criação de um histórico de base de dados sem requerer deslocação ao local e também porque não é um método destrutivo. Nestas condições, ficou também demonstrada a importância da rega como fator promotor da produção, dado que esta foi maior 21% nas árvores regadas em relação às não regadas.

Futuramente, é imperativo continuar a desenvolver investigação direcionada para as necessidades de rega no castanheiro, de forma a encontrar o coeficiente cultural que permita determinar os valores de potencial de ramo de referência e, simultaneamente, proceder a estudos de viabilidade económica determinando o ponto de equilíbrio entre investimento e benefícios na produção.

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Tabelas e Figuras

Tab. N-1 - Potencial hídrico foliar de base (Ψ_{base}), potencial hídrico foliar ao meio-dia (Ψ_{folha}), potencial hídrico de ramo (Ψ_{ramo}) em MPa, referentes ao ano de 2014.

Data	n	Ψ_{base} (Mpa)	n	Ψ_{folha} (Mpa)	n	Ψ_{ramo} (Mpa)
09-07-2014	30	-0,38 ± 0,02	30	-1,08 ± 0,03	30	-0,65 ± 0,05
24-07-2014	30	-0,27 ± 0,01		nd ± nd		nd ± Nd
05-09-2014	30	-0,56 ± 0,02	28	-1,88 ± 0,03	27	-1,40 ± 0,05
26-09-2014	30	-0,34 ± 0,02	30	-1,27 ± 0,03		nd ± Nd
Média ± erro padrão		**-0,39 ± 0,02**		**-1,41 ± 0,03**		**-1,02 ± 0,05**

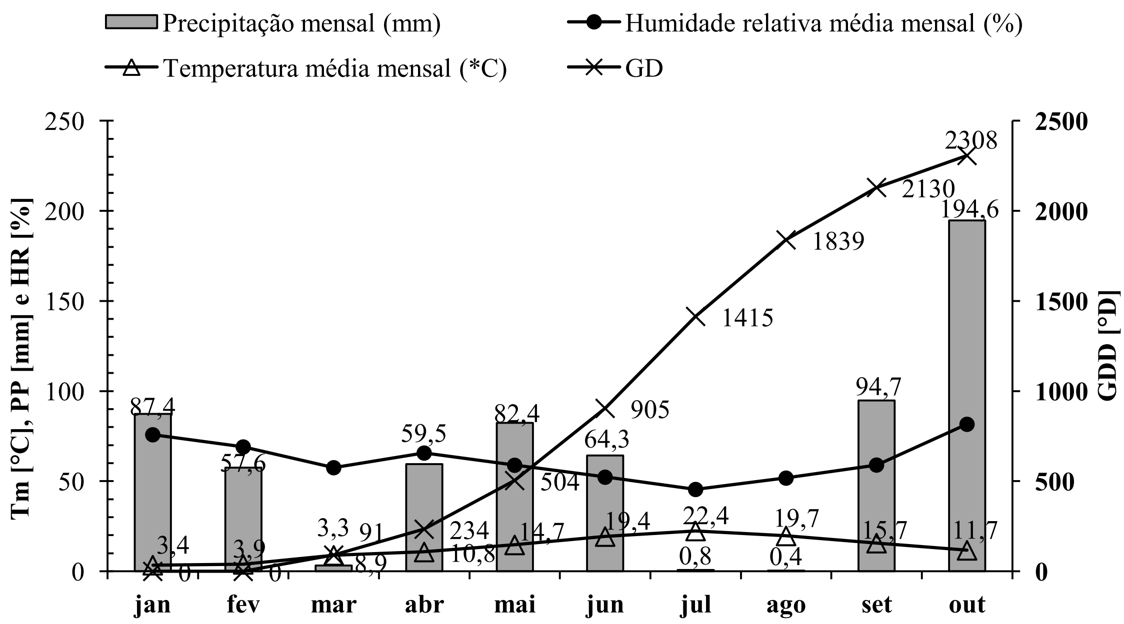


Fig. N-1 - Valores de temperatura média mensal (T_m, °C), humidade relativa do ar média mensal (HR, %), precipitação total mensal (PP, mm) e somatório graus dias (GDD, °C) de janeiro 2015 a outubro 2015, registados pela estação meteorológica ET 2900.

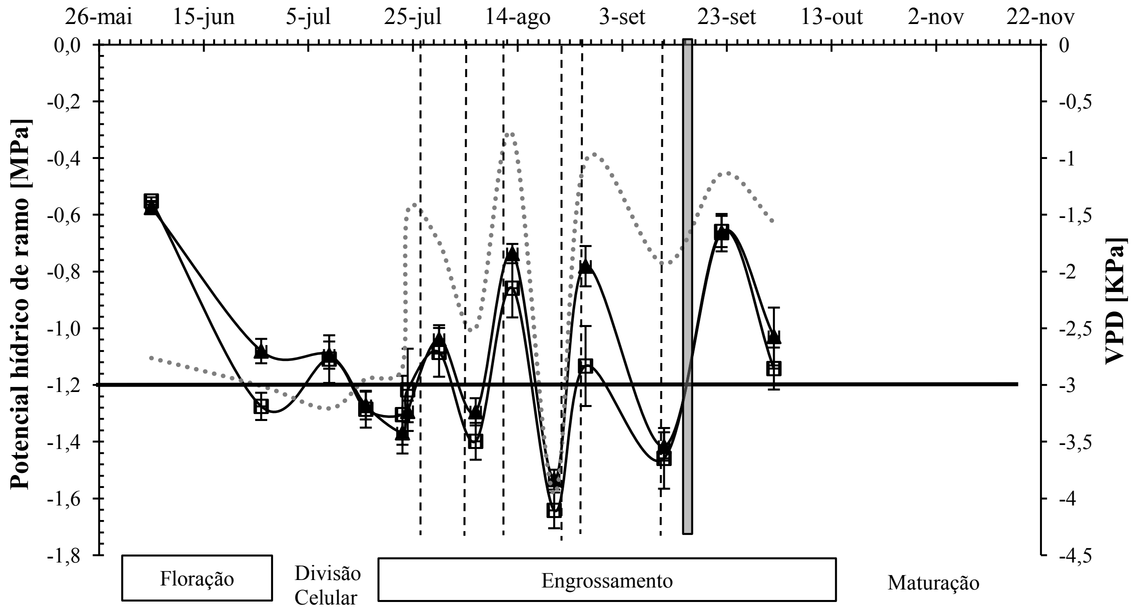


Fig. N-2 - Evolução do potencial hídrico de ramo (MPa) e do Deficit Pressão Vapor (VPD) (KPa, linha cinzenta) ao longo do estudo para tratamento não regado (NR, □) e regado (RR, ▲) em 2015. Barras verticais representam desvio do erro padrão. Linha horizontal indica o valor do potencial hídrico de ramo abaixo do qual se iniciava rega (-1,2MPa). Linhas verticais a tracejado indicam as datas de rega (26 de julho, 5 de agosto, 12 de agosto, 22 de agosto, 26 de agosto e 11 de setembro). A barra vertical cinzenta, entre os dias 15 e 16 de setembro, assinalam dias de chuva, com precipitação total de 94 mm.

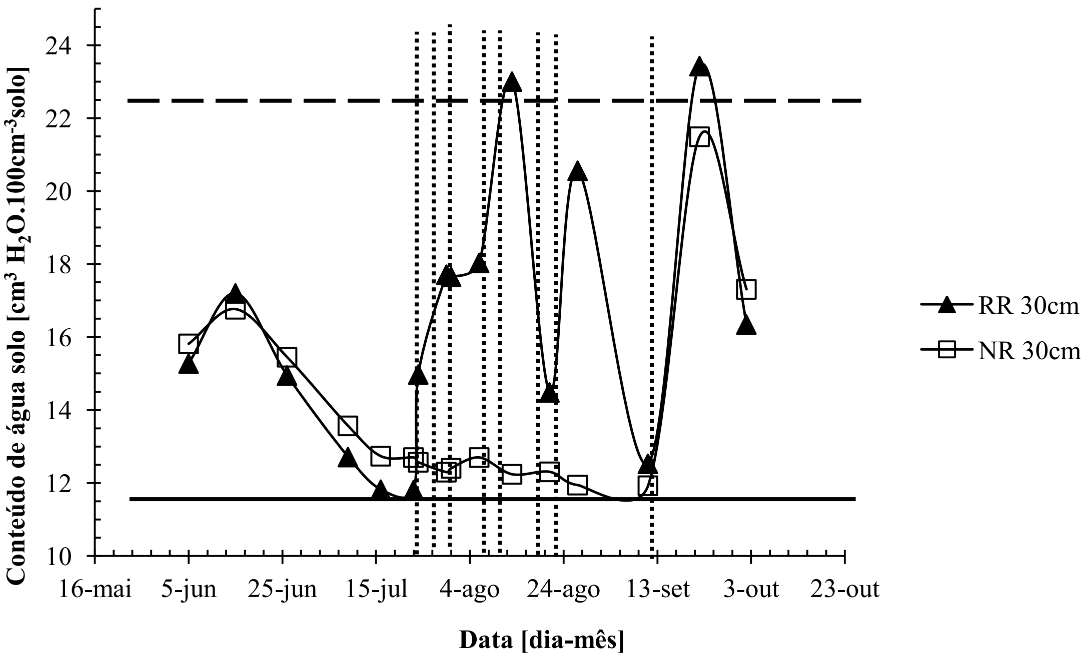
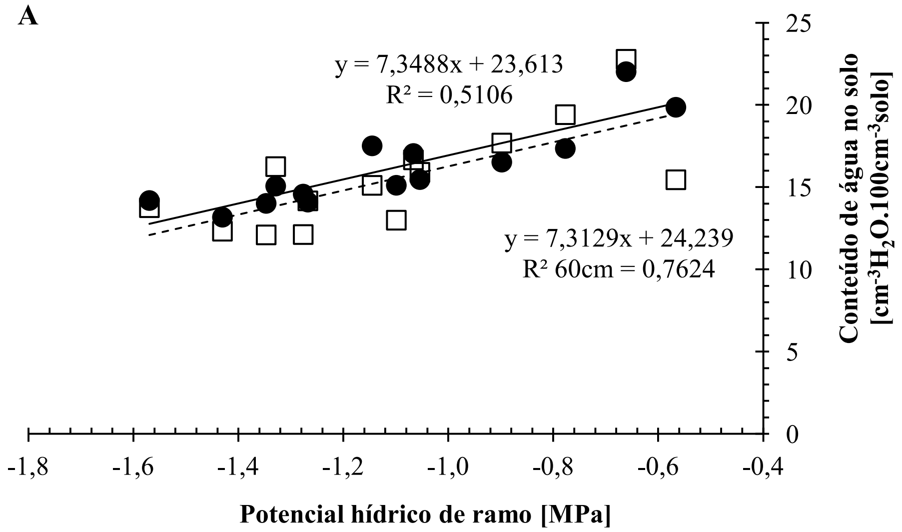


Fig. N-3 - Evolução do conteúdo de água no solo (cm^3H_2O.100cm^{-3} solo) aos 30cm, para tratamento regado, (RR, ▲) e não regado (NR, □) em 2015. A linha vertical tracejada indica as datas de rega. A linha horizontal contínua indica o teor de água de solo no ponto de emurchecimento (11,9%). A linha horizontal tracejada indica o teor de água médio entre a capacidade de campo (32,2%) e o ponto de emurchecimento.



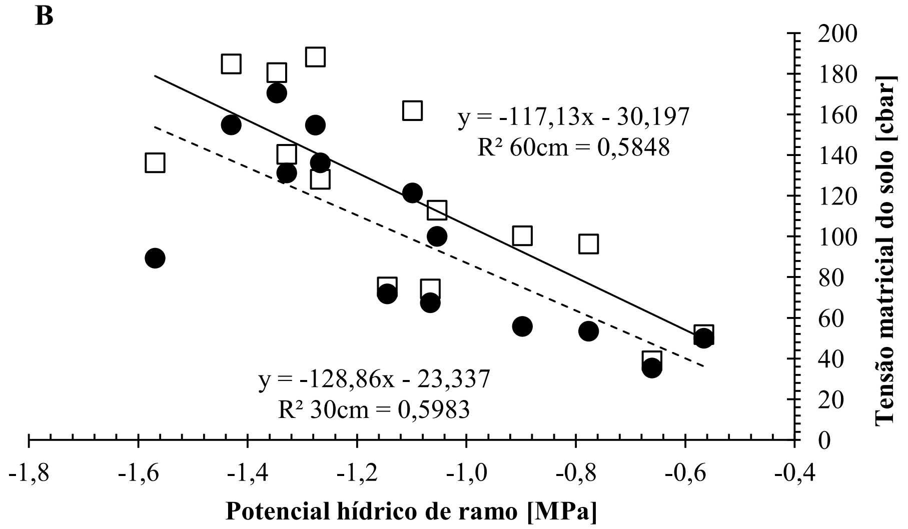


Fig. N-4 -Correlação entre potencial hídrico de ramo (MPa) e conteúdo de água no solo (cm^{-3} H_2O 100 cm^{-3} solo, gráfico A) e potencial hídrico de ramo (MPa) e tensão matricial do solo (cbar, gráfico B) para os 30cm de profundidade (□) e 60 cm (●) em 2015. Linha contínua corresponde à linha de tendência aos 30cm e a linha a tracejado corresponde à linha de tendência aos 60cm.

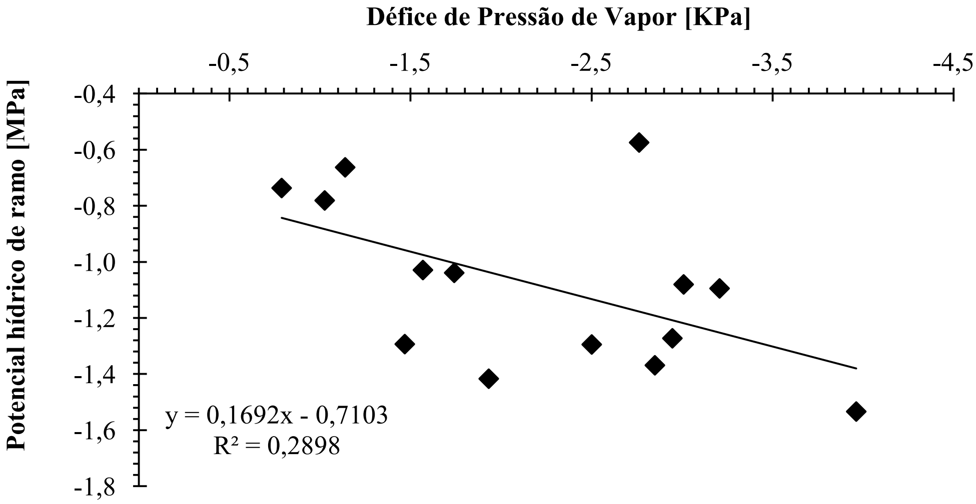


Fig. N-5 - Correlação entre potencial de ramo (MPa) das árvores regadas e Défice de Pressão de Vapor (KPa) calculado às 13 horas em 2015.

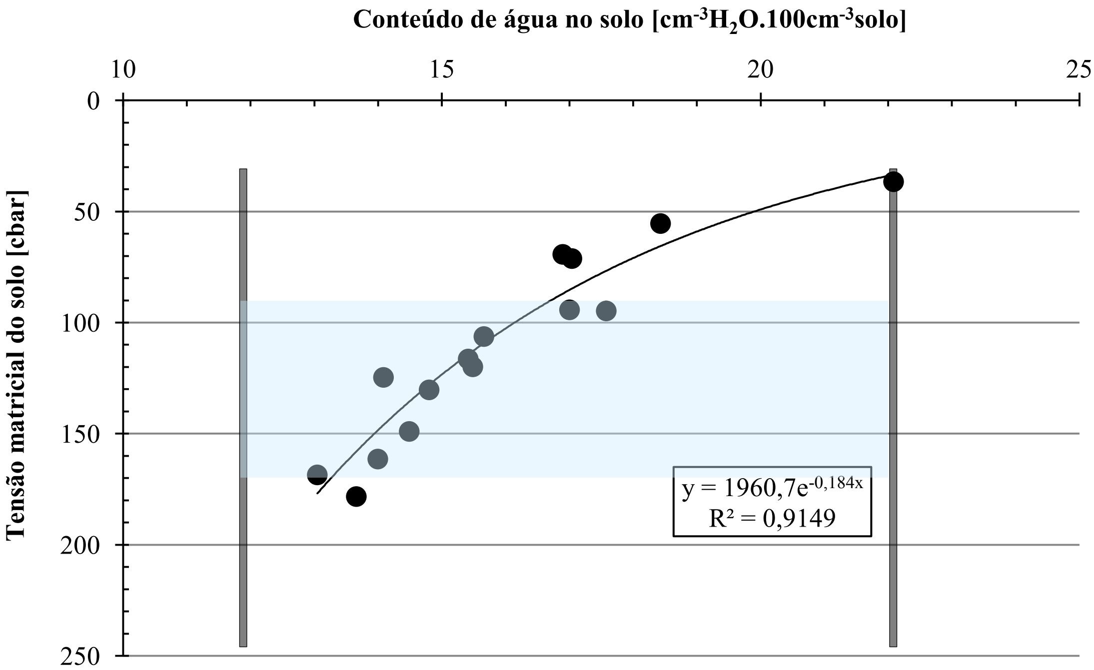


Fig. N-6 - Correlação entre conteúdo de água no solo ($cm^3H_2O.100cm^{-3}$solo), medido com o Diviner 2000/Sentek Technologies, e a tensão matricial do solo (cbar), medido com a Watermark/Irrometer, a todas as profundidades. As barras verticais cinzentas indicam o conteúdo de água no solo no ponto de emurchecimento (12%) e o conteúdo de água no solo a partir do qual a água se encontra facilmente disponível para a planta (22%). O sombreado indica o intervalo de valores que os sensores da Watermark devem apresentar para que a água seja facilmente absorvida.

Tab. N-2 - Produção de castanha por árvore (kg), percentagem de castanhas boas ou chochas por ouriço (%), calibre (fruto kg^{-1}), densidade (mg mL^{-1}) e matéria seca da castanha (%), em 2015, e respetivos desvio padrão (sd) e erro padrão (se). Nível de significância 5%, teste de Fisher.

Tratamento	Produção por árvore			Castanhas boas			Castanhas chochas			Calibre			Densidade castanhas			Matéria Seca		
	kg	sd	se	%	sd	se	%	sd	se	(fruto kg^{-1})	sd	se	(mg mL^{-1})	sd	se	%	sd	se
RR	46.4	19.0	3.87	69.2	25.0	2.94	30.8	25.0	2.94	69.6	23.7	4.84	1.15	0.07	0.02	46.1	0.50	0.20
NR	41.9	19.2	5.53	63.5	32.5	5.42	36.3	32.5	5.42	65.1	13.5	3.90	1.12	0.06	0.01	45.3	0.76	0.44
TOTAL	44.2	19.1	4.70	66.3	28.7	4.18	33.6	28.7	4.18	67.3	18.6	4.37	1.14	0.06	0.02	45.7	0.63	0.32

O. Relating plant and soil water's content to encourage smart irrigation on chestnut trees

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203 (2018) 30-36

Resumo

Os castanheiros deparam-se com constrangimentos devido à escassez de água no solo durante o verão, uma vez que ocorre baixa precipitação durante este período do ano. O presente estudo tem como objetivo definir uma metodologia para melhorar de maneira inteligente a utilização da água de rega no castanheiro. Com base nos parâmetros de fotossíntese, é feita uma transposição para o teor de água no solo e para o potencial matricial do solo, por forma a permitir uma otimização da programação de rega em castanheiros. O ensaio foi instalado num solo argiloso no nordeste de Portugal entre 2013 e 2016 com sistema de micro aspersão e irrigação por gotejamento. O potencial hídrico de ramo, a taxa fotossintética, o teor de água no solo e o potencial mátrico do solo foram monitorizados durante o ciclo vegetativo (junho a outubro). O potencial hídrico de ramo foi dependente da temperatura do ar e da humidade do solo. A maior taxa fotossintética (9 a 11 μmol CO_2 m^{-2} s^{-1}) foi obtida quando o potencial hídrico de ramo variou entre -1,2 a -0,5 MPa e a regressão entre este parâmetro e o teor de água no solo foi de r^2 = 0,38. Segundo esta relação, é admissível accionar a rega sempre que a sonda registre valores na ordem dos 16% sendo que a rega deverá manter a umidade do solo próxima a 23%. A regressão entre o conteúdo de água no solo e o potencial mátrico foi de r^2 = 0,43 podendo a programação de rega ser desencadeada sempre que sensor 'Watermark' a 30-60cm de profundidade estiver acima de -100 cbar. Desta forma, garante-se bom estado hídrico da planta, embora esta também dependa da temperatura do ar.

Palavras-chave: *Castanea sativa* M., gestão hídrica, humidade do solo, fisiologia.

Abstract

Chestnut orchards are facing new limitations due to scarce of soil water during summer times, mainly attributed to the low precipitation amount typically occurred on such period. The present study aims to define a methodology to improve in a smart way the utilization of water on chestnut irrigation. Based on leaf gas exchanges parameters, there is done a transposition for the soil water content and matric potential, to allow an optimization of the irrigation scheduling in chestnut trees. Trial was installed in a loamy soil at the northeast of Portugal between 2013 and 2016 with micro-sprinkler and drip irrigation system. Stem water potential, photosynthetic rate, soil water content and soil water potential were monitored during the vegetative cycle (June to October). The stem water potential was dependent on air's temperature and soil moisture. The higher photosynthetic rate (9 to 11 μmol CO_2 m^{-2} s^{-1}) was reached when midday stem water potential ranged between -1.2 to -0.5 MPa and the regression between stem water potential and soil water content on the top 10-40 cm of soil was of r^2 = 0.38. According to these, it was admissible to trigger irrigation when the probe registers 16% and watering must keep soil's moisture near 23%. The regression between stem and soil water potential was of r^2 = 0.43 and irrigation scheduling may be triggered when 'Watermark' sensor at 30-60cm soil depth is above -100 cbar to promote good tree water status although this last is air temperature dependent.

Keywords: *Castanea sativa* M., water management, soil moisture, physiology.

Introduction

Portugal had 35.595 ha of chestnut trees with a total production of 27.628 t in 2015 (INE, 2015). The chestnut tree is mainly found in rainfed conditions but the irrigated area is growing: from the new 835 ha planted within 2007-2013 about 23% are in irrigation conditions (PRODER, 2014). Irrigation increases chestnut productivity and fruit size (Breisch, 1995) but so far only Martins *et al.* (2010, 2011) studied the effect of irrigation in chestnut trees under different soil's management and soil-plant relationship was approached. Additionally, only a field study made in France and developed by Jayne (2005) can be consulted, although it did not approach the soil-plant relationship. The soil-water-plant relationship is deeply dependent on plant's physiology and morphology as well as on soil's features (Clothier and Green 1994, Meinzer *et al.* 2004). It is difficult to establish a clear and straight relationship between soil and plant water status since climatic conditions also intervenes (Kenneth *et al.* 1997, Naor 2006, Sanjit *et al.* 2012) but preferably all the factors must be consider for a correct water management. In the absence of models that integrate all the factors, in practice, irrigation can be programmed based in one factor alone or in two. The midday stem water potential (Ψw_{md}) has been indicated as the most sensitive and reasonable in the detection of water status of perennial crops such as the prune tree (McCutchan and Shackel 1992, Shackel *et al.* 2000,2000a, Lampinen *et al* 2004), pecan tree (Sanjit *et al.*, 2012) and walnut tree (Fulton *et al.*, 2002). Similar conclusions were found in vineyards (Williams and Araújo 2002, Williams *et al.* 2012), olive trees (Gómez-del-Campo, 2013) or peach trees (Mirás-Avaloz *et al.,* 2016). However, Ψw_{md} is relatively new in terms of on-farm adoption and has the disadvantage of not being an automatic method leading that fruit growers are more accustomed to guide their irrigation decisions by adopting a water budget method using climate based estimates of crop evapotranspiration or methods of soil moisture monitoring (Girona *et al.* 2002). The understanding of a correlation between Ψw_{md} and soil water content overcomes this disadvantage because soil moisture can be monitored by probes in an automatic and continuous way (Munoz- Carpena, 2015). Additionally, the Ψw_{md} indicates when irrigation should start, but it does not indicate how long the irrigation should last; something that can be overcome by placing soil water sensors to record when the effective root depth is wet (Gómez-del-Campo, 2013). In which concern the soil moisture-based optimized irrigation it consists of keeping the soil within a target moisture range by replenishing the plant water uptake with irrigation. This practice reduces the potential for soil water excess and leaching of agrochemicals present in the soil, however it requires selection of a suitable method for soil moisture estimation (Munoz-Carpena, 2015).The soil moisture can be approached by indirect methods such as volumetric or by tensiometric methods and the decision for one or another depends on the cost, accuracy, response time, installation, management and durability (Munoz-Carpena, 2015). The first method measures the amount of water in the soil either by weight or volume, and the second measures the potential energy status of a small parcel of water in the soil. We define smart irrigation as the one that is based on controllers that reduce outdoor water use by monitoring and using information about site conditions (soil and climatic features). Ideally this controller should also access plant's physiological parameters to better meet the plant water needs but so far technology is not there yet. However, and in a tentative to get close to this smart irrigation in a crop that usually is rainfed, this study aims to define reference soil water values, both by using volumetric or tensiometric methods, departing from plants' water status and photosynthetic productivity, for proper irrigation on chestnut trees.

Material and methods

Several steps were followed to achieve the purpose of the study. First the photosynthetic rate was used to infer which plant's water potential reflects the most adequate water status. Later a regression between Ψw_{md} and soil water content / soil water potential was established to define the soil values from where it can be decide the irrigation. The data used in this regression was gathered during three years (2013, 2015 and 2016) from watered and non watered trees located in two different experimental plot described forwards. More details can be consulted in Mota *et al.* (2014) and Mota *et al.* (2018).

Orchard characterization The experiment was conducted during 2013, 2014, 2015 and 2016 in the northeast of Portugal, 862 m altitude, on a commercial orchard planted in 1993, with compass 5 by 10 m. The rootstocks were seedlings from *Castanea sativa* M. grafted with 'Judia' and 'Longal' variety. The soil is kept with seeded pasture since plantation. The soils are cambisols, with 100 cm of thickness and C horizon shows many coarse gravel and cobbles. Soils are loam and, on the toppest 10 to 60 cm, the organic matter is about 3 % and has 26 and 115 mg kg^{-1} of extractable P_2O_5 and K_2O (Egnér-Rihem method) respectively, and pH (H_2O) of 4.7. The moisture contents at field capacity (FC) and wilting point (WP) were determined with a pressure plate apparatus at 10 KPa (pF value 2) and 1500 kPa (pF value 4.2), respectively (Tab. 0-1). In this method, undisturbed soil sample is placed on a porous ceramic plate in a chamber and saturated with water. A pressure of 10 or 1500 kPa is applied until equilibrium in water content between the plate and the soil sample is reached at which time soil water content is determined (Klute, 1986).

Experimental plots In the following plots, border trees were kept around the study area and between each tree sample. In 2013/14, a micro sprinkler irrigation system was installed in twenty four trees and irrigation started at August 28th in 2013 when stem water potential measured at 09:00 h GMT fell below -0.6 MPa (full irrigated treatment, FI) or -0.8 MPa (deficit irrigated treatment, DI). In each irrigation event, the water furnished was about 30 mm. As far as our knowledge, there are no studies about the stem water potential of the chestnut trees so the definition of this threshold took into consideration Martins *et al.* (2010) and Brown *et al.* (2014) that refer an hydric comfort level when the predawn water potential is within -0.4 and -0.6 MPa, and thus we admitted a slight decreased of these values at 9AM. Twelve non irrigated trees (NI) were kept for control. Five sample trees per treatment were selected (Fig. 0-1, left). Each sprinkler had a debit of 40 L h^{-1}, placed 1.5 m away from the trunk, and wetting an area of 13 m^2. The mean total amount of water (W) furnished during the vegetative cycle in 2013 was of 1040 m^3 ha^{-1} (1490 m^3 ha^{-1} and 590 m^3 ha^{-1} for FI and DI, respectively). 2014 was a very humid year and no irrigation was done since the tree water potential did not always reach the values to initiate the irrigation and, when it did, irrigation was not initiated since the weather forecast indicated rain for the following days, as it happened. In 2015/16 two types of irrigation systems were installed under the purpose of other study which aimed an economical comparison (Mota *et al.*, 2018), each one in forty trees, as follow: TI – drip irrigation – two pipes per tree row, emitters spaced 1 m with debit of 3.6 L h^{-1}; SI – sprinkler irrigation – one suspended pipe with emitters every 5 meters with debit of 50 L h^{-1}. Forty non irrigated trees (NI) were kept for control. Ten sample trees per treatment were selected (Fig. 0-1, right). In 2015 the mean W was 470 m^3 ha^{-1} (461 and 479 m^3 ha^{-1} for TI and SI, respectively) and in 2016, the W = 925 m^3 ha^{-1} (871 and 979 m^3 ha^{-1} for TI and SI, respectively). In both years, the first irrigation started on the third week of July and it was triggered every time $\Psi w_{md} < -1.2$ MPa and the mean water amount given in each irrigation event was about 5 mm. The decision to change the tree water potential threshold for -1.2 MPa was based on the preliminary data of 2013 which indicated that the highest photosynthetic rate was achieved when the midday stem water potential (Ψw_{md}) was around -1 MPa. Plus we decided to define a value below it in a tentative to create a deficit irrigation condition that for one hand saves water and for another hand did not prejudice to much the photosynthetic rate.

Tree water status Plant water potential was assessed by measuring midday stem water potential (Ψw_{md}) with a Scholander-type pressure chamber (model "pump-up", PMS Instrument® Corvallis, Oregon, USA) between 12:00 h and 13:30 h GMT. In 2013, measurements were registered weekly from August to September in ten irrigated trees on two leaves per tree (n = 20) and in five non-irrigated trees on two leaves per tree (n=10). In 2015/16, measurements were registered weekly from June to September in twenty irrigated trees on one leaf per tree (n = 20) and in ten non-irrigated trees on one leaf per tree (n=10). Sample leaves were from the fruiting branches on the outer north side of the canopy, located as close as possible to the main branch. Leaves were covered with aluminium foil and put into a plastic bag for at least one hour before excision as recommended by Fulton *et al.* (2014). The readings did not differ more than one hour between trees.

Gas exchange Net photosynthesis at midday (A_{md}), was determined between 12:00 to 13:00 h GMT with an Infrared Gas Analyser (mod. LC*pro*+, Analytical Development Co®, Hoddesdon, UK). In 2013, were sampled three leaves per tree in ten irrigated trees (n = 30) and in five non-irrigated trees (n = 15), weekly from August to September. In 2015/16, there were sampled two leaves per tree in twenty irrigated trees (n = 40) and in ten non-irrigated trees (n=20) once in July and once in August. *Soil water content.* Soil water content (θ) was estimated with a capacitance probe (Diviner 2000, SENTEK Technologies). In 2013, six access tubes were installed near the irrigated trees and three access tubes near the non-irrigated trees, one single tube per tree. In 2015/16 twelve access tubes were installed near the irrigated trees and six access tubes were installed near non-irrigated trees, one single tube per tree. The access tubes were located 1.5 m from the chestnut tree's trunk, below the canopy. Readings were registered weekly about 48h after irrigation from 10 cm up to 80 cm in depth. The soil water content is expressed in cm^3 H_2O $100cm^{-3}$soil (or simply in %).

Soil water potential. In 2015/16, soil water matric potential ($\Psi w_{m\ soil}$) was estimated using three loggers (Monitor 900M, Irrometer) installed each one near one tree from each treatment of NI, TI and SI. Each logger had connected one soil temperature sensor at 15 cm depth and three 'Watermark' sensors each at 30, 60 and 80 soil depth. The monitor recorded the values every hour and sent them through a modem for a website where values could be consulted continuously.

Meteorological data. Monthly precipitation (PP), mean air temperature (T_{med}), mean air relative humidity (HR) and evapotranspiration of reference (ET_0) were obtained from the monthly agro-meteorological bulletin provided in the website of the Portuguese Institute of Sea and Atmosphere. Daily maximum air temperature (T_{max}) was registered by a meteorological station (model ET 2900, Spectrum Technologies) located in the trial.

Statistical Analysis. A model of polynomial regression was used with the Statview 4.0 (Abacus Concept) to evaluate the relationship between the stem water potential and the photosynthetic rate; the stem water potential and the mean soil water content at 10-40 cm and 50-80 cm soil depth; and the stem water potential and the mean soil water matric potential on the 30 and 60 cm soil depth. Comparisons within treatments were made with Fisher test ($p < 0.05$).

Results and Discussion

The study covered four years with similar features to what climatic conditions are concerned (Fig. 0-2), exception to 2014 which had a very wet summer (total PP = 37.5 mm in July and August) comparing with 2013, 2015 and 2016 (9.6, 7.9 and 10.6 mm, respectively). Moreover the T_{med} during the summer (July, August and September) of 2014 was lower (19°C) and the HR was higher (63%) than the other years and thus the stem water potential rarely reached the threshold for watering and, when it did reach, the irrigation was not initiated due to climatic forecast of rain on the following days. So, no irrigation was done in 2014 and the data was not included. The total annual precipitation in 2013, 2014, 2015 and 2016 was of 823, 747, 593 and 971 mm, respectively and are near the ones mentioned by Breisch (1995) for good growth of *C. sativa* (800-900 mm year^{-1}), but the water deficit was very low from March to September, especially in July and August. This fact reflects the importance of the soil for storing water during the winter to further ahead meet the water requirements of the tree during the vegetative period. Actually it is well known the behaviour of the higher plants to absorb water from deeper layers and distribute it all over the plant to overcome the water constraints during the summer (Garnier *et al.* 1986, David *et al.* 2013, Nadezhdina *et al.* 2008, Martins *et al.* 2010). Still, irrigation helped the plants to overcome the water constraints during the summer as it can be seen by the higher stem water potential in the irrigated trees comparing with the none irrigated trees along the months (Fig. 0-3). During the irrigated period (July, August and September) the mean Ψw_{md} was -1.13 ± 0.07 MPa and -1.32 ± 0.12 MPa for irrigated and non irrigated treatment, respectively. For the same period, the mean soil water content (θ_{avg}) on the top 10 - 40 cm was 14.7 % and on the soil layers at 50-80 cm depth it was 16.3 % and both were within the readily available water on this soil (which is the fraction of total available water that a crop can extract from the root zone without suffering water stress, being the total available water calculated as the difference between FC and WP for a certain root depth (Oliveira, 2003). On the other hand, in none irrigated trees the θ_{avg} on the top 10 - 40 cm was 12.0 % and in the soil layers between 50 - 80 cm depth the θ_{avg} was 14.4 %, both values very close or even below to the wilting point for these soil layers determined in the laboratory (Tab. 0-1). Therefore, it is admissible that irrigated plants were in minimal soil water comfort due to the irrigation events. The high values of net photosynthesis found in our study strengthen this affirmation. However, it is noteworthy that air's temperature also plays an important role in the stem water potential, especially evident in August and September. For instance, comparing 2013 with 2016 in the irrigated treatments (Fig. 0-3, up), the θ_{avg} at 10-40 cm soil depth was lower in the first year and the θ_{avg} at 50-80 cm was similar between the years. However, the Ψw_{md} was clearly lower in 2016 where T_{max} was 34°C and 31°C (August and September, respectively) while in 2013 where T_{max} was 29°C and 26 °C showed higher Ψw_{md}. Same findings are reported in Mota *et al.* (2017) for chestnut trees that refers some influence of the vapor deficit pressure on the stem water potential. In other fruit trees, like in prune tree, a strong relationship between vapor deficit pressure and stem water potential is reported by McCutchan and Shackel (1992).

According to Gomes-Laranjo *et al.* (2007) the optimal growth temperature for the European chestnut tree is 24°C when the maximal photosynthetic rate ($A_{|100|}$) is achieved, which for the Portuguese varieties the mean value is about 10 µmol CO_2 m^{-2} s^{-1}. From our results, the A_{md} tendentiously decreases with the Ψw_{md} according to the regression found ($y = -3.9708x^2 - 5.922x + 8.3508$, $r^2 = 0.35$) being the $A_{|100|}$ (11 µmol CO_2 m^{-2} s^{-1}) reached when Ψw_{md} ranged between -0.5 to -0.8 MPa (Fig. 0-4). Admitting breaks of 10% in the maximal photosynthetic rate ($A_{|90|}$) the Ψw_{md} would be around -1.2 MPa. This is coherent with Gomes-Laranjo *et al.* (2007, 2008) which found that the $A_{|90|}$ is reached when leaf water potential is of -1.6 MPa which somehow equates a stem water potential close to -1.2 MPa. The leaf water potential is lower than the stem water potential because it is measured on a transpiring leaf and a strong correlation between the stem and leaf water potential was found by other authors in vineyards and pecan trees (Williams and Araújo 2002, Sanjit *et al.* 2012). According to Lampinen *et al.* (2015) by keeping the Ψw_{md} about 0.1 to 0.2 MPa below the fully watered baseline (which is -1MPa for almonds and prunes) it can be assured that trees do not get into deficit conditions and that there is no over-irrigation. Therefore, for the chestnut tree it is admissible to infer that Ψw_{md} = -1.2 MPa is a balanced value to get a good photosynthetic productivity and assures a comfortable water status at midday. Still, more studies are needed to support this affirmation especially because it can differ depending on the soil type and it hydraulic conductivity and texture, plant age, chestnut variety and phenological stage. For instance, some studies in olive trees (Moriana *et al.* 2012) or in vineyards (Girona *et al.* 2006) indicate the possibility to change the stem or leaf water potential thresholds for irrigation along the vegetative cycle.

However, and for the purpose of the present study, a relation between Ψw_{md} and θ_{avg} on the 10 – 40 cm and on the 50-80 cm soil depth was plotted to further define which soil water content mostly guarantees the Ψw_{md} close to -1.2 MPa. The correlation found in this study was higher between Ψw_{md} and θ_{avg} at 10-40 cm (r^2 = 0.38) than with θ_{avg} at 50-80 cm (r^2 = 0.31) (Fig. 0-5). These values are close, although lower, to some values found in the literature. Gómez-del-Campo (2013) found a logarithmic function between relative extractable water and Ψw_{md} with r^2 = 0.77 for an olive orchard. By its turn, Williams and Araújo (2002) found a linear regression between θ and Ψw_{md} with a correlation of r^2 = 0.63 in vineyards. Also, Sanjit *et al.* (2012) in pecan trees found a linear regression between θ_{avg} and Ψw_{md} with r^2 = 0.73 and r^2 = 0.80 in sandy and clay soils, respectively. In high trees a straight relationship between soil water content and water potential is not easy to obtain due to the great and irregular root volume and the difficulty to cover it with soil sensors (Gómez-del-Campo, 2013) besides the influence of external factors such as the climatic conditions. This is especially true in adult trees that were in rainfed conditions during almost twenty years as the ones in our study, which may explained the lower correlation between stem water potential and soil water content, and most probably deeper roots than the 80 cm also influence the whole tree water status but sensors at that soil depth are not practical to install. Still, from our results, we may now to infer that the irrigation scheduling based on soil capacitance probes in loam soils, as the one in the experiment, can take as reference the moisture on the top soil layers and it should be such that irrigation starts when θ_{avg} (10-40 cm) is close to 16% and must be kept near 23%, to guarantee good levels of water potential and photosynthesis in the chestnut trees.

If the producer chooses to irrigate based on $\Psi w_{m\ soil}$ it is essential to know the soil type because, depending on it and its water's retention capacity, for the same $\Psi w_{m\ soil}$ the soil water content differs and it is important to know the soil curves (Brady 1990, Oliveira 2003, Munoz-Carpena 2015). In our study, a polynomial regression (Ψw_{md} = 1E-05$(\Psi w_{m\ soil})^2$ - 0.006 ($\Psi w_{m\ soil}$) - 0.753) was found between the Ψw_{md} of irrigated trees and $\Psi w_{m\ soil}$ on the average 30cm to 60 cm soil depth with a correlation of r^2 = 0.43 (Fig. 0-6). Therefore, we consider that the best commitment for irrigation schedule in loam soils, as the one in the experiment with adult trees, is to keep values near -100 cbar on the firsts 30-60 cm of soil depth to assure an adequate Ψw_{md}, depending on air's temperature. These values are coherent with soil curves for different soil types (Lopes *et al.*, 2003) but is important to retain that the 'Watermark' sensors measures the degree of water retention in the soil (Lopes *et al.,* 2003) and its interpretation must be well understood by the irrigation manager. Additionally, in very clay soils and in crops tolerant to dry, these sensors may not be the ideal ones since they are limited to reading up to 250 cbar. Additionally, the general stabilization of the Ψw_{md} even with the lowest values of Ψw_m soil could indicate that deeper roots than the ones analyzed contributed for the stabilizing of the Ψw_{md}. Surprisingly, the correlation found between the 'Watermark' sensor at 80cm and the Ψw_{md} was very weak (data not shown) as well as it was lower between Ψw_{md} and θ_{avg} at 50-80 cm soil depth (Fig. 0-5). For one hand it can be admissible that roots deeper than the 80 cm layer may have influenced the stabilization of the tree water potential since trees have twenty years and surely a very deep volume. For another hand, this behaviour on the stabilization of the Ψw_{md} can also reflect an anisohydric response of the chestnut tree when facing soil drying and subsequent water stress. Plants that display anisohydric characteristics do maintain control over leaf water potential, but at a diminished rate when compared to isohydric plants that are constantly regulating their leaf water potential due to hydraulic and chemical signals (Limpus, 2009). As soil water potential declines so too will the leaf water potential until it reaches threshold at which point stomata will begin to regulate water loss (Jones, 2007). However, it is not easy to categorize a plant as completely isohydric or anisohydric since the same species can actually integrate both responses as referred by Moriana *et al.* (2012) for olive trees.

Further work is needed to give more robustness to the physiological and soil values found in this study, especially in different soil types and water regimes. Nevertheless, the findings of our work are valuable to encourage the smart irrigation on the chestnut tree which has currently facing a more intensive vision on its cropping.

Conclusion

The adult chestnut tree benefits with irrigation since the stem water potential at midday are higher comparing with the non irrigated trees as well as the photosynthetic rate. The irrigation can be programmed based on different soil moisture sensors as soon as the irrigation manager is aware of their limitations especially to what concern to the non-straight relationship between soil water status and plant water status. The procedure to obtain the soil water values of reference starting from their relationship with plant parameters such as photosynthetic rate or plant water potential, is not simple to achieved due to the intervention of other factors, such as the climatic features, deep soil roots and internal physiological regulation that are not easy to approach and that surely play an important role in the plants behaviour. Deeper studies that consider all the biotic and abiotic factors that interfere in the chestnut tree should be developed to be the basis of a proper smart irrigation.

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Tables and Figures

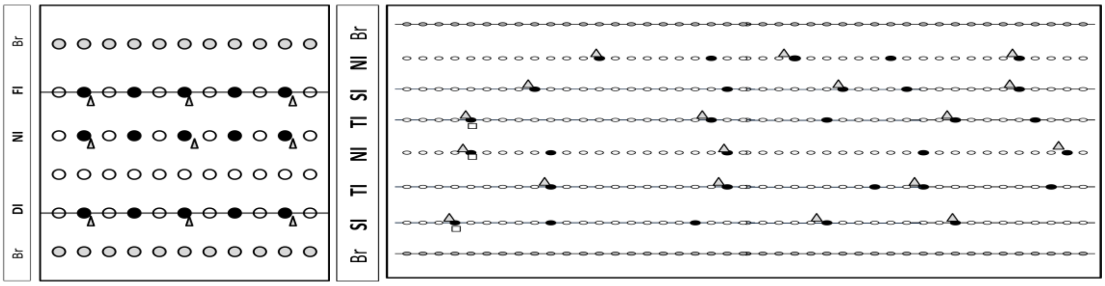


Fig. 0-1 - Experimental plots: left - in 2013/14 with micro-sprinkler system (FI and DI), non irrigated trees (NI) and border trees (Br); right: in 2015/16 with micro-sprinkler system (SI), drip system (TI), non irrigated trees (NI) and border trees (Br). The triangles (Δ) represent the location of the access tubes of Diviner 2000, the squares (□) represents the location of the logger onto where three 'Watermark' sensors were connected. Sample trees are represented in full circles (●).

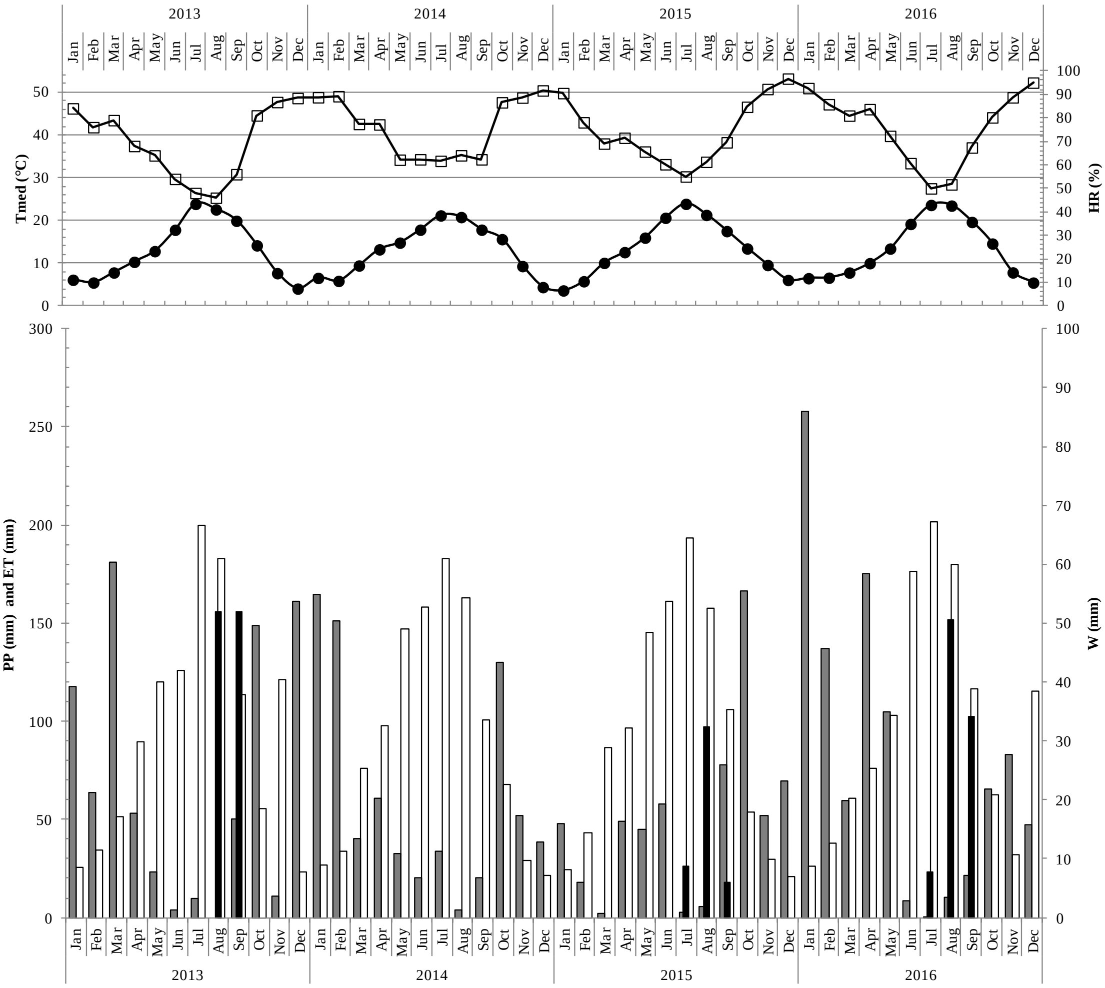


Fig. 0-2 - Monthly total precipitation (PP, grey column, mm), total monthly evapotranpiration of reference (ET_0, white columns, mm), average of the water applied in the two irrigated treatments in 2013 (FI - full irrigated and DI - deficit irrigated) and in 2015/2016 (SI - micro-sprinkler irrigation and TI - drip irrigation) (W, black columns, mm), monthly mean air temperature (T_{med}, full circles, °C) and monthly mean air relative humidity (HR, open squares, %), during the year 2013, 2014, 2015 and 2016. Source: IPMA, 2013, 2014, 2015, 2016.

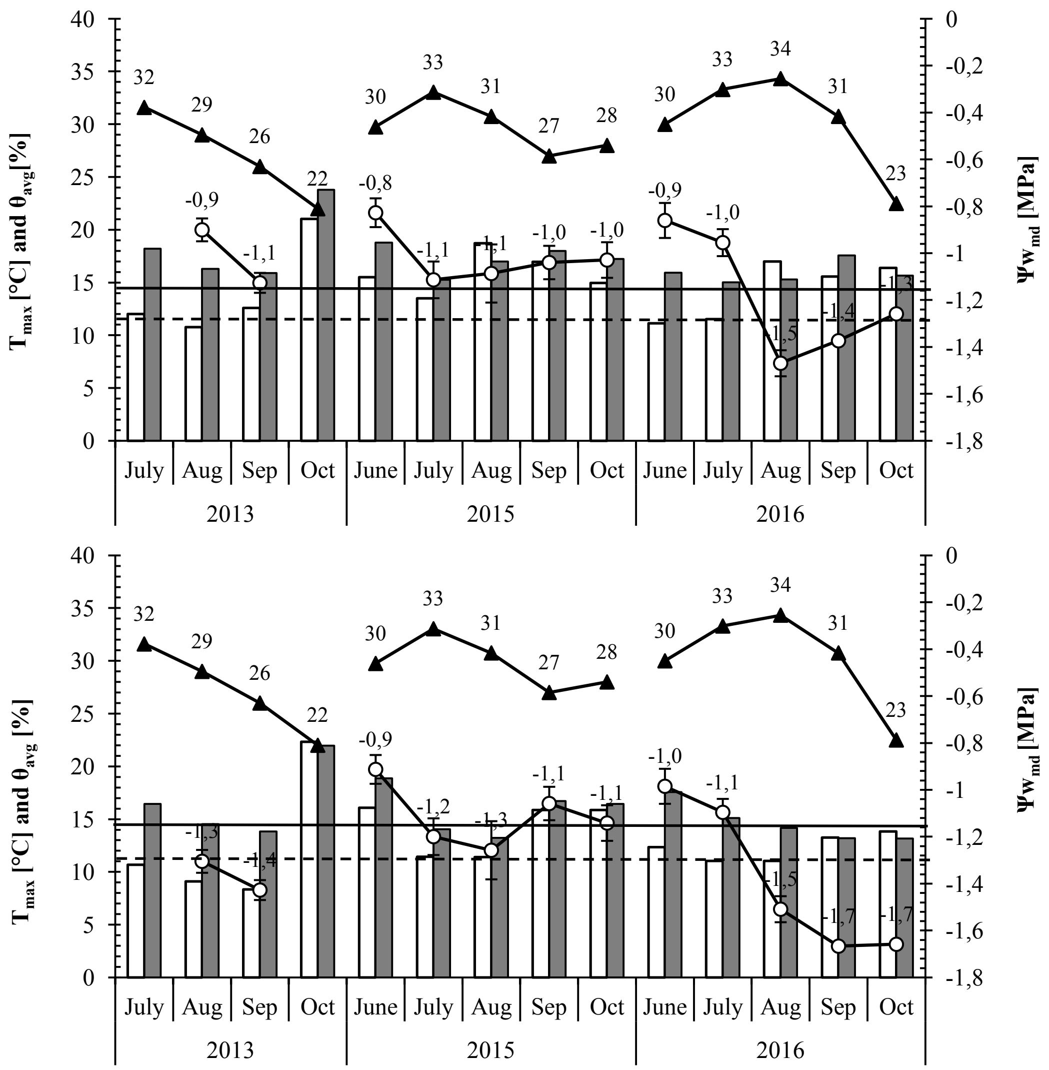


Fig. 0-3 - Season pattern for irrigated treatment (up figure) and non-irrigated treatment (low figure) of the monthly mean midday stem water potential (Ψw_{md}, ○, MPa); mean of the daily maximum temperature occurred in the measuring days (T_{max}, ▲, ºC), monthly mean soil water content (Θ_{avg}, %) on the 10 to 40 cm depth (white columns) and on the 50-80 cm depth (grey columns). Dashed line represents the soil water content at the wilting point at 10 cm and at 80 cm determined in laboratory by the method of the pressure plate. Bars are standard error for Fisher test ($p<0.05$).

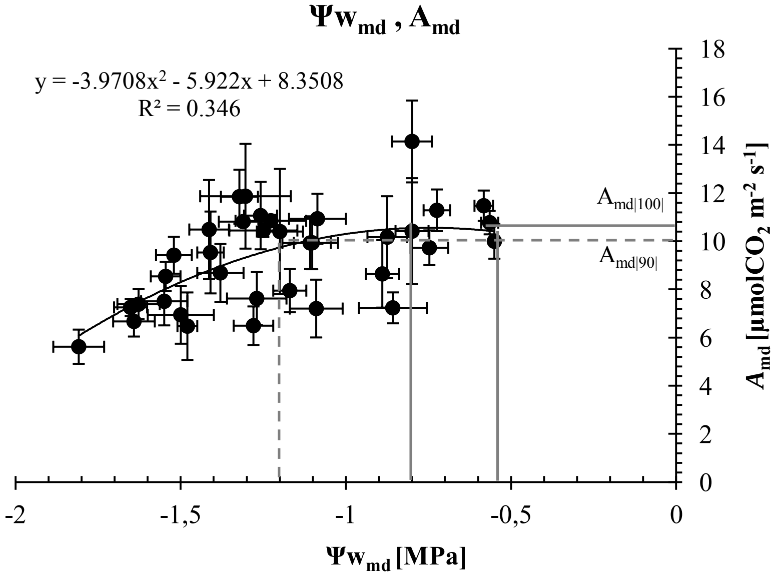


Fig. 0-4 - Photosynthetic rate (A_{md}, $\mu molCO_2\ m^{-2}\ s^{-1}$) and midday stem water potential (Ψw_{md}, MPa) regression for all irrigated and non irrigated trees. $A_{|100|}$ is the maximal photosynthetic rate found with the regression and $A_{|90|}$ is the admissible decay from the maximal photosynthetic rate (-10%). Vertical bars are the standard error for A_{md} and horizontal bars are the standard error for the Ψw_{md}.

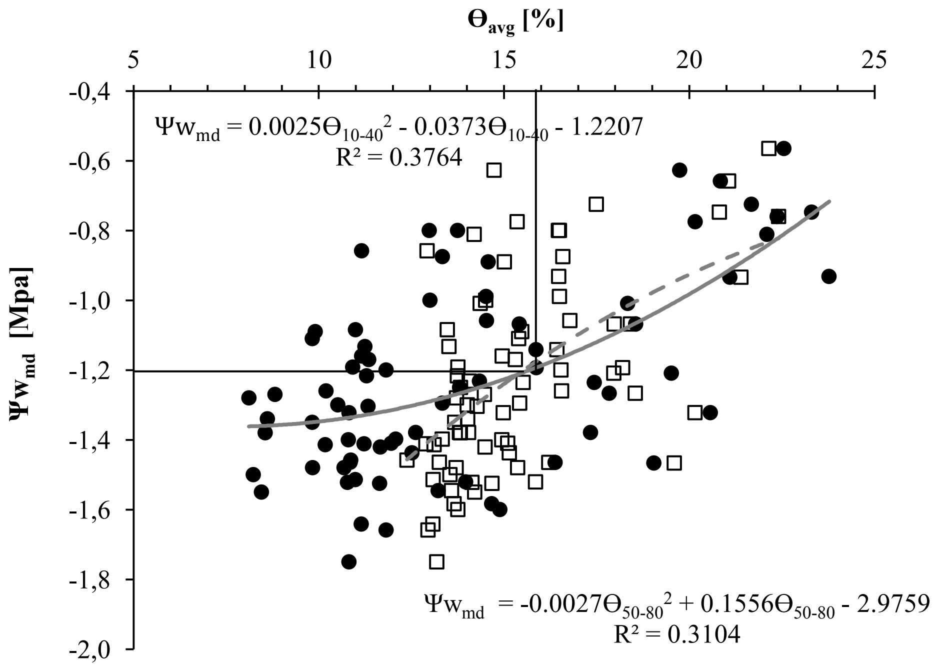


Fig. 0-5 - Regression between midday stem water potential (Ψw_{md}, MPa) for all irrigated and non irrigated trees and the mean soil water content (Θ_{avg}, %) of the toppest 10 - 40 cm (full circles) and of the 50-80 cm soil depth (open circles). Regression curve for the top layers (Θ_{10-40}) are in full and for deep layers (Θ_{50-80}) are in dashed.

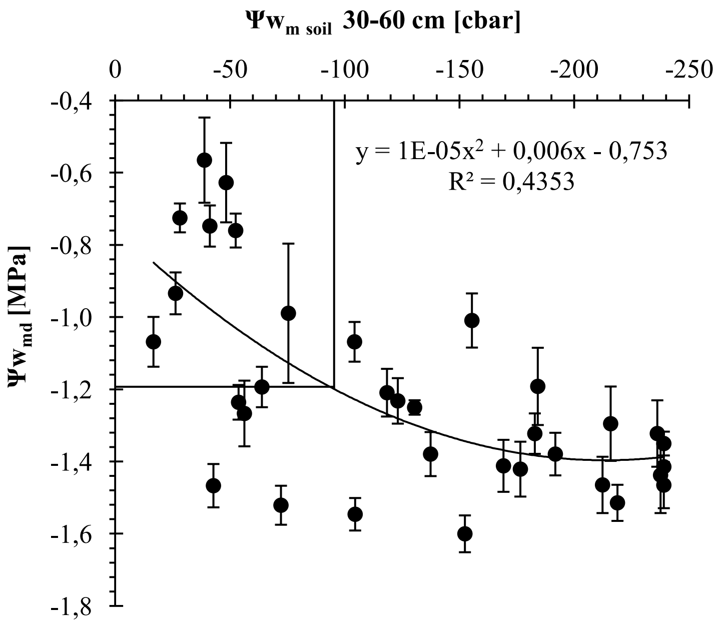
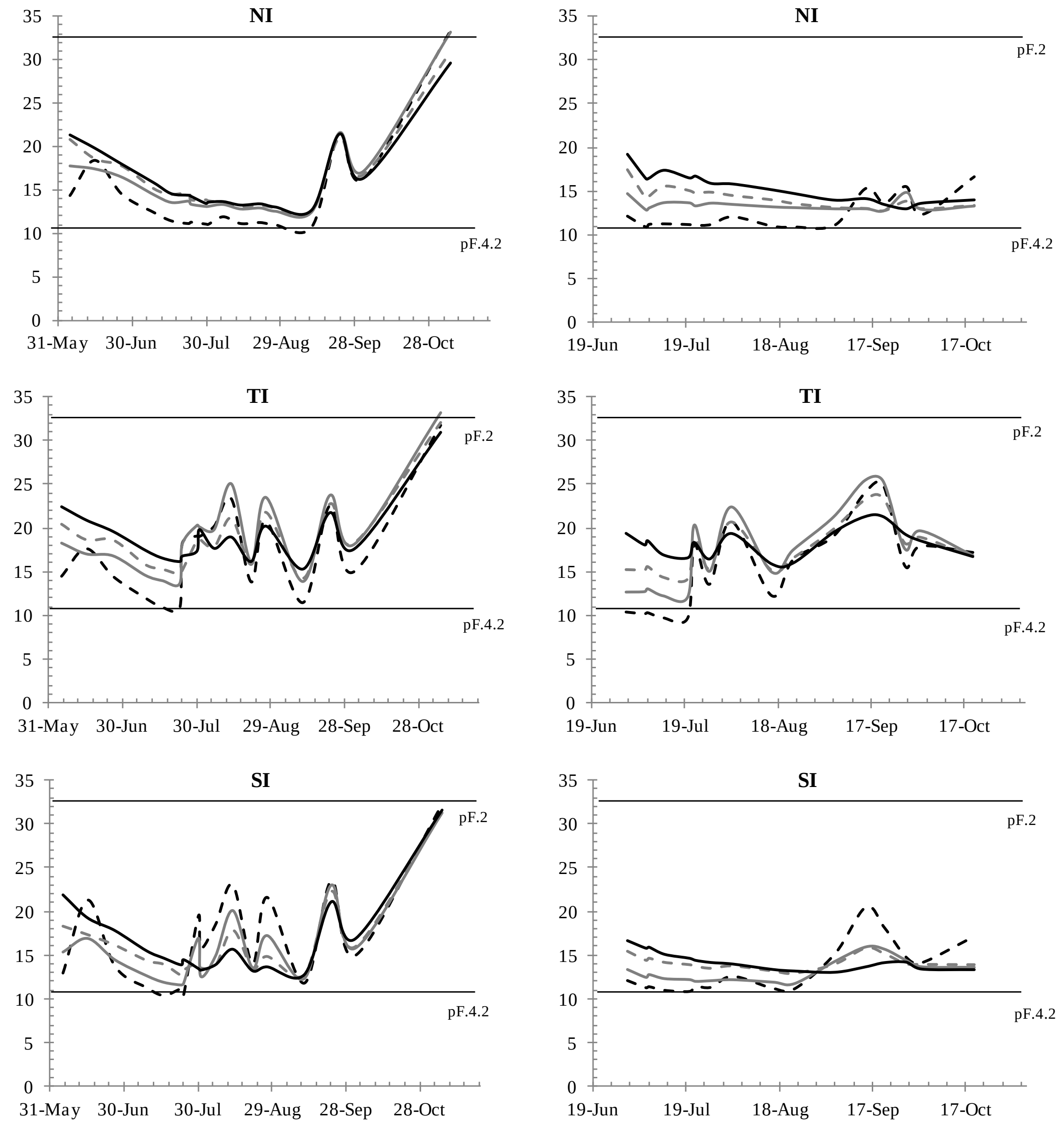


Fig. 0-6 - Midday stem water potential (Ψw_{md}, MPa) of watered trees and soil water matric potential average of 30 and 60 cm ($\Psi w_{m\ soil}$, cbar) relationship. Vertical bars represent the standard error for Ψw_{md}.

Tab. 0-1 - Bulk density and volumetric water content at field capacity (FC) measured with a pF value of 2.0 (10 KPa) and permanent wilting point (WP) measured with a pF value of 4.2 (1500 KPa) on different soil depths from an adult chestnut orchard in the northeast of Portugal, obtained in laboratory by the method of the pressure plate.

Soil depth	Bulk density	Soil water content (%) at different pF's			
(cm)	(g cm^{-3})	2	2.5	3	4.2
10	1.47	29.85	25.51	21.27	11.43
30	1.45	33.42	28.78	23.15	14.63
60	1.49	35.20	32.15	26.19	17.22
80	1.49	30,81	27.01	22.40	14.90



Supplementary Fig. 0-1 - Variation of the soil water content (%) at 20 cm (dash black line), 40 cm (full grey line), 60 cm (dashed grey line) and 80 cm (full black line) soil's depth for non irrigated (NI), drip irrigated (TI) and micro-sprinkler irrigated (SI) treatments in 2015 (left) and 2016 (right). Horizontal black lines represents the water content on the 25-30 cm soil depth on the field capacity (pF.2) and on the wilting point (pF.4.2) measured in the laboratory by the pressure plate method.

VII. ECONOMICAL ANALISYS OF THE CHESTNUT ORCHARD WHEN IRRIGATED VS. NON-IRRIGATED

P. Study on yield values of two irrigation systems in adult chestnut trees and comparison with non-irrigated chestnut orchard

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Resumo

Para avaliar qual dos dois sistemas de rega se revela mais eficiente em castanheiro, foram estudados três tratamentos: sistema de gota-a-gota - TI; sistema de micro-aspersão - SI; sistema não irrigado - NI. O estudo abrange dois anos no nordeste de Portugal. A rega foi ativada sempre que o potencial hídrico de ramo era inferior a -1,2 MPa. O estudo considera os custos com equipamentos, água e mão-de-obra e os proveitos da venda das castanhas. O ano 2016 foi mais quente tendo sido fornecida mais água (93 mm) do que em 2015 (47 mm). Foi fornecida um pouco mais em SI (73 mm) do que em TI (67 mm). A produção foi 27% superior nas árvores regadas (48 kg árv.$^{-1}$) do que em NI (38 kg árv.$^{-1}$) e em relação à área da copa (kg m^{-2}), TI produziu 18% mais do que o controlo NI, assim como o SI produziu mais 29%. Os custos anuais foram maiores em SI (4654 € ha^{-1}) e TI (4549 € ha^{-1}) do que em NI (1530 € ha^{-1}), tendo a maior receita compensado o investimento (22126 € ha^{-1} TI, 21984 € ha^{-1} SI e 16174 € ha^{-1} NI). Os lucros das árvores regadas pode ser 22% ou 37% maior do que as não irrigadas, para 1 ha ou 5 ha, respetivamente.

Palavras-chave: *Castanea sativa* Mill., gestão da água, potencial de ramo, produção, balanço económico

Abstract

Different types of irrigation systems can be used in chestnut orchards. To understand which one grants higher yield values treatments were applied in adult trees: drip system - TI; micro-sprinkler system - SI; non-irrigated system - NI. The study covers two years in the northeast of Portugal. Irrigation was triggered every time stem water potential was lower than -1.2 MPa. The study considers costs with the equipment, water and labour, and the income from the chestnuts' sale. Due to the hotter conditions of 2016 more water was supplied (93 mm) than in 2015 (47 mm). Little more water was furnished in SI (73 mm) than in TI (67 mm). Production was 27% higher in irrigated (48 kg tree^{-1}) than in NI trees (38 kg tree^{-1}) and in relation to the canopy's area (kg m^{-2}) the TI produced 18% and SI 29% more than NI. Annual costs were higher with irrigation (4654, 4549 and 1530 € ha^{-1} for SI, TI and NI, respectively) but the higher income (22126, 21984 and 16174 € ha^{-1} for TI, SI and NI respectively) makes up for the investment. The profits from irrigated trees can be 22% or 37% higher than in non irrigated ones, for 1 ha or 5 ha, respectively.

Keywords: *Castanea sativa* Mill., water management, water potential, production, economic.

Introduction

Over the past decades global chestnut production has slowly integrated new techniques of agricultural production transitioning from a forestry crop to a fruit crop. This is especially true in China, the world's largest chestnut producer (1.650.000 t, FAO 2012), in some orchards in France (Vernol, 2013) and Chile (Valderrama, 2016). However, this is not as common as it seems in Portugal, the third largest European chestnut producer with 27.337 t in 35.436 hectares (INE, 2015). Nevertheless, Portuguese producers have been implementing some new techniques on chestnut orchards such as ink disease resistant rootstocks, hybrid varieties, irrigation, adequate fertilizations and high tree densities (Gomes-Laranjo *et al.*, 2016). How to water a chestnut orchard is a common discussion topic within the Portuguese chestnut sector that aims to define which type of irrigation system is better suited for the chestnut tree. According to Pereira and Trout. (1999) there are three main categories of irrigation systems: 1) surface/gravity irrigation systems - those that depend on gravity to spread the water across the surface of the land; 2) sprinkler systems - water is pressurized with a pump, distributed to areas of the fields through pipes or hoses, and sprayed across the soil surface with rotating nozzles or sprayers; and 3) micro irrigation/drip or trickle systems - these systems use regularly spaced emitters on or in the tubing to drip or spray water onto or into the soil. As far as we know there was only one trial conducted by Jayne (2005) that compares different types of irrigation system in a chestnut orchard being those the drip, sprinkler and micro sprinkler systems. However, the choice of the type of irrigation system is not merely dependent on a singular crop but it must consider several factors such as water availability and its purity, soil permeability and its water storage capacity, topography, value of production, labour costs, energy costs, capital and technology requirement (Pereira, 2004). According to INE (2015) in Portugal only 447 ha are actually irrigated and on the newest 835 ha planted within the year 2007-2013, 23% are irrigated (PRODER, 2014). In France it is frequent to irrigate chestnut orchards below 50 years of age (Vernol, 2013) and in Chile, the irrigation became common in the new chestnut plantations (Valderrama, 2016). The irrigation systems found in the different orchards of these countries vary from the drip system (with one or two pipes per tree row) to the micro-sprinkler system (with the pipe suspended above the tree trunk and the emitters inverted). Both these trickle irrigation systems operate at low pressure therefore they require less energy for water pumpage resulting in fewer costs when compared to other high pressure irrigation systems (Talens 2009, MSU 2017). According to some authors (Pereira 2004 and MSU 2017) the drip system has the advantage that can be used in conditions unsuitable for other irrigation methods on steep and undulating slopes, in very sandy soils and in fields with widely varying soils. Because drip irrigation makes it possible to place water precisely where it is needed and to apply it with a high degree of uniformity it lessens both surface runoff excess water running off the lower end of the field and deep percolation water flowing down through the soil past the root zone where cannot be used by the crop. These features make drip irrigation potentially much more efficient than other irrigation methods which can translate to significant water savings. But drip irrigation can only achieve this level of high efficiency if the system is carefully designed and managed so as to prevent such problems as emitter clogging and differences in emitter flow rates stemming from pressure variations in the irrigation system or from differences in emitters and flow passages originating in the manufacturing process (Talens 2009, MSU 2017). The micro-sprinkler system suspended meets two of the chestnut growers' expectations: the weeds are better controlled with proper equipment rather than using herbicides and the largest wet area increases the probability to enhance mushroom production which represents a supplementary income to the producer (Marques 2007, Martins *et al.* 2011).

The main intention of this work is to evaluate the costs and benefits of two different irrigation systems installed on an adult chestnut orchard and in the end to assess their usefulness to chestnut production based on a study of profitability. This study relies on data obtained from experimental research of two years about water management in an orchard of adult chestnuts trees that can be consulted for more details in Mota *et al.* (2017).

Material and Methodology

Site description The trial was conducted during 2015 and 2016, in Sortes, a small town belonging to the Bragança Council, located in the northeast of Portugal (41°39'28.16"N; 6°50'37.09"W) at 862 m above sea level. It was done in a commercial chestnut orchard planted in 1993. The total study area has 1.5 ha and has border trees around it and within sample trees. The rootstocks are seedlings from *Castanea sativa* Mill. and they are grafted at 2 m height with 'Judia' variety scions. Trees are spaced 5 meters by 10 meters, with a plant density of 200 plants per hectare. Since the first years of plantation the soil is kept with seeded legumes (annual reseeding and perennial) and grass-plot (annual and perennial) that are cut for straw-bale in June. The soil, at 30 cm deep, has a medium texture, pH of 5.5, 3.1% of organic matter, low values of phosphorous (39 mg P_2O_5 kg^{-1}) and a medium level of potassium (101 mg K_2O kg^{-1}) measured by Égner-Riehm method (Egnér *et al.*, 1960).

Treatments Two types of irrigation systems were used on the chestnut orchard: a drip system (TI) (Fig. P-0-1, left) and a micro sprinkler system (SI) (Fig. P-0-1, right) and a control treatment with no irrigation besides precipitation (NI). The irrigation was triggered when the midday stem water potential (Ψw_{md}) was bellow -1.2 MPa. The irrigation system features are shown in Tab. P 0-1. Each one of these treatments corresponds to 0.5 ha (about 100 trees).

Both irrigation systems shared the main intake structure which includes a submersible water pump and a compression system equipped with a threaded wedge valve, a disc filter (John Deere Water 7000), a water counter (Arad Multijet) and a 500-litre hydro pneumatic flask and accessories. The main intake structure also includes an irrigation controller (Progrés Agronic 2500) and the fertigation system. The fertigation system is composed by two 500-litre deposits for fertilizer and one injection pump (Doseuro A175N-47-19, 226 L h^{-1} 8 kg). Water comes from borehole. This water bore was made 30 years ago and its cost is not considered on this study.

Data collection <u>Plant, soil and climatic data:</u> For the purpose of water management, from June to October of 2015 and 2016, the Ψw_{md} was monitored every 7-10 days in ten trees per treatment (n = 30). Ψw_{md} was measured using a pressure chamber (Model "pump-up" PMS Instrument® Corvallis, Oregon, USA) according to the methodology recommended by the manufacturer and adapted by Fulton *et al.* (2014). One leaf per tree was covered by an aluminium foil and plastic bag for at least 40 minutes before excision. The Ψw_{md} readings were made between 12:00 h and 13:30 h. The soil water content (θ) was monitored every 7-10 days with a capacitive probe (Diviner 2000, Sentek Technologies) from July to October. Access tubes were installed about one meter from the tree's trunk, one tube per tree, in six trees per treatment (n = 18). The probe registers the soil water values every 10 cm until 80 cm depth. To give an overview of the climatic conditions of 2015 and 2016, general meteorological data was gathered from the agro-meteorological bulletins given by the Portuguese Institute of the Sea and Atmosphere (IPMA 2015, 2016) which uses data from a meteorological station located 20 km away from the study site. Growing degree-days (GDD, ºD) was calculated according to Cesaraccio *et al.* (2001):

$$\Sigma\text{Temperature (ºD)} = (T_{med} - T_0) * n$$

where "T_{med}" is the average temperature of each month, "T_0" the base temperature, which was considered 6 ºC for chestnuts (Gomes-Laranjo *et al.*, 2008) and "n" the total days of each month.

Chestnut production and price Chestnut's orchard yield. An area of harvest beneath the canopy of each tree (n=30) was delimited using stripe tape (Fig. P 0-2). The nuts that dropped within the delimited area were caught and weighted on the field with a manual scale. Chestnut production per tree is given in kilograms of fresh weight (FW). The chestnut orchard yield is given in t FW hectare^{-1}. The production per meters squared of the tree's canopy (kg FW m^{-2}) was also calculated. Chestnuts' calibre. Thirty urchins were collected from each treatment in 2015 and 2016. The healthy chestnuts (n = 185 in 2015; n = 211 in 2016) were used to determine the calibre (fruits per kilogram). The chestnuts were weighted (fresh weight) in a digital scale. Chestnuts' market price. The average value of the chestnut market price was consulted in the website of the governmental database - System of Agricultural Market Information (GPP-SIMA, 2017). In Portugal, the chestnut is marketed in bags of 50 kg. The price is dependent on the calibre and on the period of harvesting; being higher in the early and late seasons. The harvest of 'Judia' in the Trás-os-Montes region occurs during the mid-season.

Economic, natural and labour resources Economic resources. The economic resource refers to the investment made in the acquisition and installation of the irrigation system as well as the equipment for monitoring trees (pressure chamber) and soil (capacitance probe). It also includes the maintenance and the electric costs for the pump of the irrigation system. The maintenance cost equates to 3% of the total investment. Water resources. The water resource refers to the water volume (W, in m^3) used during the year for irrigation and its cost. The average water cost was calculated taking as reference the price of 0.06 € m^{-3}, given after an informal survey on different entities' data. Labour resources. The labour resource considers the time spent on monitoring the soil and tree parameters needed for irrigation decision as well as the time spent on chestnut harvesting. This last parameter depends on chestnut production, variety and weather conditions. According to the chestnut orchards owners' registries, in general, a person can harvest about 25 kg h^{-1} (200 kg day^{-1}) originating harvest's cost of 0.20 € kg^{-1}. Two minutes per tree are needed to monitor its Ψw_{md} is about two minutes, including covering the leaf with aluminium foil and plastic bag but excluding the forty minutes needed before the readings. Ten trees were monitored per treatment, at least once a week, costing 1.7 € per week per treatment. The other types of labour such as pruning, fertilization, hay cut or phytosanitary interventions were not accounted for.

Study on yield values The data gathered from chestnut production and from the economic, water and labour resources found in the experimental trial was used to evaluate the yield values achieved on the chestnut orchard. The data is extrapolated for one and for five hectares in orchards with similar conditions to the studied one such as plant's density and chestnut's production per tree. The main intake structure, pressure chamber and capacitance probe are investments considered separately for each irrigation system type.

Statistical analysis Results of soil water content, Ψw_{md}, tree production and chestnut calibre were analysed using the StatView 4.0 (Abacus Concept) software and comparisons were made with Fisher test ($p < 0.05$).

Results

Plant and climatic data and irrigation events The average values of monthly maximal (T_{max}) and minimal (T_{min}) air temperature, and monthly relative air humidity (HR) as well as the monthly cumulative precipitation (PP) along the months of 2015 and 2016 are shown in Fig. P 0-3. The rainy period typically goes from September to May. In 2016 the period between June and October was drier (total PP of 211 mm) when compared to 2015 (total PP of 310 mm) and it had higher T_{max} in August, September and October (32°C, 28 °C and 21°C respectively). The total degree-day from May to October was of 2,348 °C in 2015 and 2,504 °C in 2016.

The monthly mean of Ψw_{md} (± se) in 2015 was of -1.08 ± 0.06 MPa for TI and FI and -1.15 ± 0.09 MPa for NI. The monthly mean Ψw_{md} in 2016 was of -1.14 ± 0.09 MPa (TI), -1.15 ± 0.06 MPa (SI) and -1.34 ± 0.08 MPa (NI) (Fig. P 0-4). Concerning the annual mean soil water content for the 10-40 cm depth it was higher in 2015 (14% in NI; 17% in TI; 15% in SI) than in 2016 (12% in NI; 16% in TI; 13% in SI).

In 2016, because of the drier and hotter conditions, the Ψw_{md} was generally lower than in 2015 which led to different irrigation events and total water volume allocated in each year (Tab. P 0-2). For both years, the irrigation period started in the third week of July (end of flowering) but it finished later in 2016 (in the end of September). The water supplied in 2015 was 53% and 49% lower than in 2016 for TI and SI, respectively.

Chestnut production and market price In 2015 the harvest occurred from October 22th until November 11th while in 2016 it started one week later (October 28th until November 25th). The chestnut production per tree was about 27%, 16% and 33% higher in 2015 than in 2016 for TI, SI and NI respectively (Tab. P 0-3). The chestnut orchard yield on TI was 9.7 t FW ha^{-1}, 9.6 t FW ha^{-1} in SI and 7.7 t FW ha^{-1} in NI. The production per canopy's area reduced from 2015 to 2016 about 21%, 10% and 31% for TI, SI and NI respectively. In both years, the NI trees had the lowest chestnut production (0.87 kg m^{-2}) while TI and SI had 1.0 and 1.1 kg m^{-2}, respectively, which represents 18% and 29% more production than NI. In spite of the variation in nut production within treatments there was not a statistical difference.

The calibre (fruits per kilogram) was higher in 2016 compared to 2015 for all treatments which mean that fruits were smaller in this year (Tab. P 0-4). In both years, the calibre was always higher in NI (93 fruits kg^{-1}) than in TI (75 fruits kg^{-1}) or SI (70 fruits kg^{-1}). Statistical analysis revealed no difference on the calibre in 2015 but irrigated trees had significantly bigger fruits in 2016 than non irrigated ones.

Market prices of 50 kg bags of the ‘Judia’ variety sold during the harvest period of both years are given in Tab. P 0-5 The chestnut harvest occurred during the mid-season of Trás-os-Montes region then the called ‘frequent price’ is the one considered for ‘Judia’. The frequent price slightly increased in 2016 (2.2 € Kg^{-1}) compared with 2015 (2.0 € Kg^{-1}).

Economic, natural and labour resources Tab. P 0-6 shows the economic resources used in the trial of 2015 and 2016, in 0.5 ha. The costs of the investment in irrigation systems in 2015 includes the material and installation of the main intake structure (5,429.92 €), the fertigation equipment (1,813.72 €) and the distribution system for TI (2,282.90 €) and SI (2,659.47 €). The main intake structure and fertigation system were, in practice, common costs for both TI and SI systems but they are considered separately. The SI is slightly more expensive not only due to the materials but because installing the emitters on the pipe and extending the pipe over the trees requires more time and labour. In 2016, the economic resources were the annual maintenance costs which are considered to be 3% of the investment. Regarding water resources, more water was used in 2016 than in 2015 for both treatments and costs varied from 14 € to 29 € in half a hectare. The cost to harvesting in these two years was 967 €, 959 € and 765 € per 0.5 ha for TI, SI and NI respectively.

Study on yield potential From the data gathered over these two years is now possible to show the yield potential of the investment on irrigation system in 1 ha of an adult and healthy chestnut orchard with 200 trees of the ‘Judia’ variety (Tab. P 0-6). The total investment in the drip system is of 16,521 € ha^{-1} and 17,274 € Kg^{-1} for the micro-sprinkler system, including pumping system, water hole, compression system, fertigation system, irrigation controller, distribution system and monitoring equipment. The amortization of these investments is calculated over eight years and the annual maintenance cost is considered to be 3% of it (Tab. P 0-7). The total annual volume of water furnished varies depending on the year’s weather conditions (defined as hotter or mild year when GDD > 2400°D or below GDD < 2400°D, respectively) and stem water potential. So, considering 2015 and 2016, it can range from 460 – 870 m^3 ha^{-1} in TI and from 480 to 979 m^3 ha^{-1} in SI system with annual costs varying from 28 to 52 € ha^{-1} and 29 to 59 € ha^{-1} for TI and SI, respectively. The chestnut production can range from 6.6 to 8.7 t FW ha^{-1} in NI, 8.5 to 10.8 t FW ha^{-1} in TI and 8.9 to 10.3 t FW ha^{-1} in SI. According to Martins *et al.* (2011) calibres above 90 could depreciate 0.20 € per kilogram within the same period of harvest. For 2015, all calibres of the different treatments were below 90 (Tab. P 0-4) so the market price considered was 2.2 € Kg^{-1}. However, in 2016, the market price for NI was of 2.0 € Kg^{-1} while for TI and SI it was 2.4 € Kg^{-1}. In general, the profits generated due to the benefits of the irrigation system can increase up to 42% in the hotter years, in comparison to non-irrigated systems during the amortization period and certainly they increase after it.

Tab. P 0-8 shows the cost of the investment in detail for each irrigation system on five hectares. The investment on irrigation can be up to 23,756 € in 5 ha (SI) and 19,990 € in 5 ha for TI.

The investment is naturally higher than for one hectare but some components have similar costs such as the fertigation system, water hole and the irrigation controller. As a consequence the profits will be up to 59% higher than in NI, in the hotter years (Tab. P 0-9).

Discussion

Water management based on the Ψw_{md} of the chestnut tree is very dynamic because it implies frequent readings of the tree water status which by its turn reveals a particular answer to the specific weather and soil conditions (Shackel *et al.*, 2011) resulting in irrigation events that are not fixed. In this case, irrigation events occurred every time the Ψw_{md} was lower than -1.2 MPa. According to Mota *et al.* (2014) in a previous study on the same orchard, the Ψw_{md} at -1.2 MPa reflects a good photosynthetic rate and good soil moisture. Under the hotter temperatures and long dry period in 2016 chestnut trees revealed a great need of water and more irrigation events were programmed. Independently of the irrigation system, the Ψw_{md} was identical between irrigated trees and the same number of irrigation events occurred although the SI had more water furnished. Based on this fact alone, the drip system looks like a better option because with less water than the micro sprinkler system, the production was identical. Still, the mean annual water used in this study (666 m^3 ha^{-1} in drip and 729 m^3 ha^{-1} in micro-sprinkler) was much lower than the water used in a study carried out by Jayne (2005). In Jayne (2005) the micro sprinkler system on the full (100% ET_0) and deficit (50% ET_0) modality used 2,570 and 2,020 m^3 ha^{-1}, respectively, while the drip system used 940 and 1,420 m^3 ha^{-1} on the deficit and full modality, respectively. Naturally these differences are related with the irrigation strategy followed by the author together with the different ages and density of trees, tree variety, regional climatic conditions and soil type. For instance, in Martins *et al.* (2011) the irrigation schedule followed from 2006 to 2008 was based on the predawn leaf water potential and irrigation was triggered when it was lower than -0.6 MPa. As a result, the water volume was lower (mean of 767 m^3 ha^{-1}) than those used in Jayne (2005) and it was within the values found in our study. Therefore, the irrigation strategy based on Ψw_{md} rather than in ET_0 suggests a better use and savings of water. Actually, Lampinen *et al.* (2001) and Shackel *et al.* (2000) also refer water savings in prune trees when irrigation scheduling is based on Ψw_{md}. The use of Ψw_{md} for irrigation scheduling has the inconvenient of the time required for bagged leaves to reach equilibrium with the stem as well as the interval of readings (1300 to 1500HR) which restricts the hectares that can be monitored by one person with a pressure chamber (Fulton *et al.*, 2001). However, the same author found out that in prune, almond and walnut trees the shaded leaves in the interior of the canopy rapidly align with stem water potential (minimum of 10 minutes) once transpiration is stopped with a reflective impermeable bag. Thus, it is relevant to test the same procedure on chestnut trees to save time and reduce costs with the monitoring.

According to INE (2016) the total national chestnut production decreased from 2015 to 2016 and fruit size was smaller. The chestnut production decreasing was noticeable in this study in all treatments but irrigated trees had less variation than the control, and the micro-sprinkler trees revealed more stability from 2015 to 2016. The high temperatures in 2016 may explain the decrease of the production. For instance, in July (T_{max} = 32°C) when flowering occurred, there were several days with temperatures above 30°C which may have constrained pollination and the photosynthesis rate which is maximal when temperatures are between 24 to 27 °C (Gomes-Laranjo *et al.,* 2008). It remains unknown if there was a possible effect of the micro-sprinkler on the decreasing of the air temperature below the tree canopy that may have helped the chestnut production. The productivity calculated in our study was in terms of fresh weight and above 7 t FW ha^{-1}. The average dry matter (DM) of the Portuguese varieties is of around 45 to 50% (Portela *et al.* 2007, Ferreira-Cardoso 2007). Therefore, the yield found in our study is higher to the ones reported by Martins *et al.* (2010, 2011) which referred, for 40 years-old 'Longal' variety with 70 trees ha^{-1}, chestnut production between 19 to 27 kg of DM per tree, resulting in yields of 2 to 3 t FW ha^{-1}. This yield and ours are clearly far away from the national yield reported by INE (2015) which is around 0.8 t ha^{-1}. However it must be keep in mind that the statistics for national chestnut productivity includes non productive chestnut tree area (new plantations or very old trees), areas with high tree's mortality without replacement, areas with high incidence of diseases (ink and cancer) which lowers production (Marcelino *et al.*, 2000) and areas where bad soil preparation or maintenance constraints chestnut trees' production (Raimundo, 2003). On the other hand, national statistics exclude the chestnuts that are traded in the parallel market which is underestimated as well as the ones for auto consume by the producers (Gomes-Laranjo *et al.*, 2016). For these reasons, we consider that the yield found in this study is close to the realistic situation of the Portuguese 'Judia' variety production in healthy and adult chestnut orchards although the trees' density is uncommonly high. Dinis *et al.* (2011) found different calibres in 'Judia' variety depending on the temperature sum and bigger fruits (46 to 66 chestnuts kg^{-1}) were found when degree-days (from May to October) ranged from 2000 to 2200 °D. In our study, with higher degree days (> 2400 °D) , chestnuts were bigger in irrigated treatments (73 chestnuts kg^{-1}) and the calibres were within the values found by Pimentel-Pereira *et al.* (2007) for 'Judia' variety (71 to 79 chestnuts kg^{-1}). In the portuguese market, which is mainly for fresh consumption, the differences in price due to the calibre are not very clear but the industrial market privileges big chestnuts with calibres between 50 to 90 chestnuts kg^{-1} (Breisch 1993, Ferreira-Cardoso 2007). The calibre is influenced by edapho-climatic conditions (Ferreira-Cardoso 2007, Dinis *et al.* 2011) and the watering, whatever the irrigation system, helps to achieve bigger chestnuts as shown in Martins *et al.* (2011) and in our results. Curiously, Jayne (2005) found bigger chestnuts in the non irrigated trees and in trees irrigated with the drip system at 50%ET_0. This may be explained by the reduced number of fruits per tree which allow them to increase their size due to more assimilation but this was not verified in our study.

Finally, the most important is to evaluate either if the investment on the irrigation system is profitable or not on an adult orchard already in production. In summary, irrigated trees produce 27% more chestnuts than none irrigated trees increasing the annual income from 16,174 € ha^{-1} to 22,055 € ha^{-1}. This additional income pays the costs with amortization, water, maintenance and labour and still generates a profit of more than 17,000 € ha^{-1} which easily increases after the amortization period. Non-irrigated trees are also a viable solution but with lower profits (14,644 € ha^{-1}). In

Martins *et al.* (2011) a brief income estimate is presented for irrigated and non-irrigated chestnut trees both with seeded pastures which are more like to our irrigated treatments and NI modality, respectively. According to the author, the chestnut production generates 2,775 € ha^{-1} and 4,198 € ha^{-1} (70 trees ha^{-1}), for none irrigated and irrigated trees respectively. These outputs can even increase up to 3,851 to 5,835 € ha^{-1} if the forage and commercial mushrooms are marketed (Martins *et al.,* 2011). In our study there was not taken in consideration the expected increase of production due to fertigation or tree's maturity which will naturally increase the income in all treatments, as well as there was not considered the forage and mushrooms production. Still, the income estimated by our study is higher than in Martins *et al.* (2011) either due to tree's density or due to the higher market price in 2015 and 2016. The price considered by Martins *et al.* (2011) was of 1 to 1.2 € kg^{-1} and becomes clear the high valorisation that the chestnuts' have had over the last decade.

The gain obtained with irrigation in one hectare can easily be higher if the irrigation system is expanded to more area because the investment in the main intake structure is virtually the same for one or more hectares due to common equipments. This was clear when comparing the profits from one with five irrigated hectares. The profits can increase 22% up to 37% more in one and in five hectares, respectively, when comparing to the non-irrigation system. There is an evident economy of scale when more hectares are irrigated because costs per unit go down (Duffy, 2009; Rasmussen, 2013). The drip system appears to be a better option because, for similar income, it uses less water which is important when the water is scarce. However, specific crop practices can constrain the decisions of which irrigation system is preferable. For instance, the drip system with pipes resting on the soil constraints the use of a brush cutter to control weeds or can be dragged by cattle feet. The weed controls on drip systems could be overcome by the use of herbicides but these are harmful for the soil biotic life and prejudicial to the chestnut production as previous studies have shown (Raimundo, 2003). In alternative, the suspended irrigation system overcomes these constraints. Also, the size of the wetted area can be a key point if mushroom production is to be considered. The mushrooms appear naturally in chestnut orchards (Marques, 2007) and their production and diversity is enhanced by irrigation (Martins *et al.*, 2011). In drip systems the wetted area is smaller than with the sprinkler system (Pereira, 2004) and this last one may be interesting if the intention is to irrigate chestnuts trees and at same time to improve mushrooms production. However, micro-sprinkler system can easily wet the chestnut trunk which is not desirable if there is a presence of *Cyphonectria parasitica* since it developed well in humid conditions (Magalhães *et al.*, 2016). Future studies about mushroom production and its additional income for chestnut orchards under two different irrigation systems should be conducted. Also, studies about irrigation on young trees should be conducted aiming the reduction of plant mortality on the first few years as well as to anticipate the beginning of nut production. Additionally, the subsurface irrigated system can be an interesting option for new plantations because of water savings (Payero *et al.*, 2005) and the restrictions on the crop practices would be overcome. However, it must be highlighted, that whatever the irrigation system, its performance is dependent of the project design, proper installation and maintenance, and proper water management (Pereira 2004, Payero *et al.*, 2005).

Conclusion

Bellow the current market prices, the investment on irrigation in adult chestnut trees is safe in rainfed adult and healthy chestnut orchards with similar features as the ones studied. However, more than the costs with the investment, the mushroom's production and crop practices may be decisive in the moment of choose the type of irrigation, as soon as there is water availability guaranteed.

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Tables and Figures

Fig. P-0-1- Photos of the irrigated systems plots. A- Drip system, two pipes per row of chestnut trees. B- micro-sprinkler system with suspended pipe and inverted emitters.

Fig. P 0-2 - Delimited area of harvesting below the trees canopy by a red stripe tape for determination of chestnut production per tree.

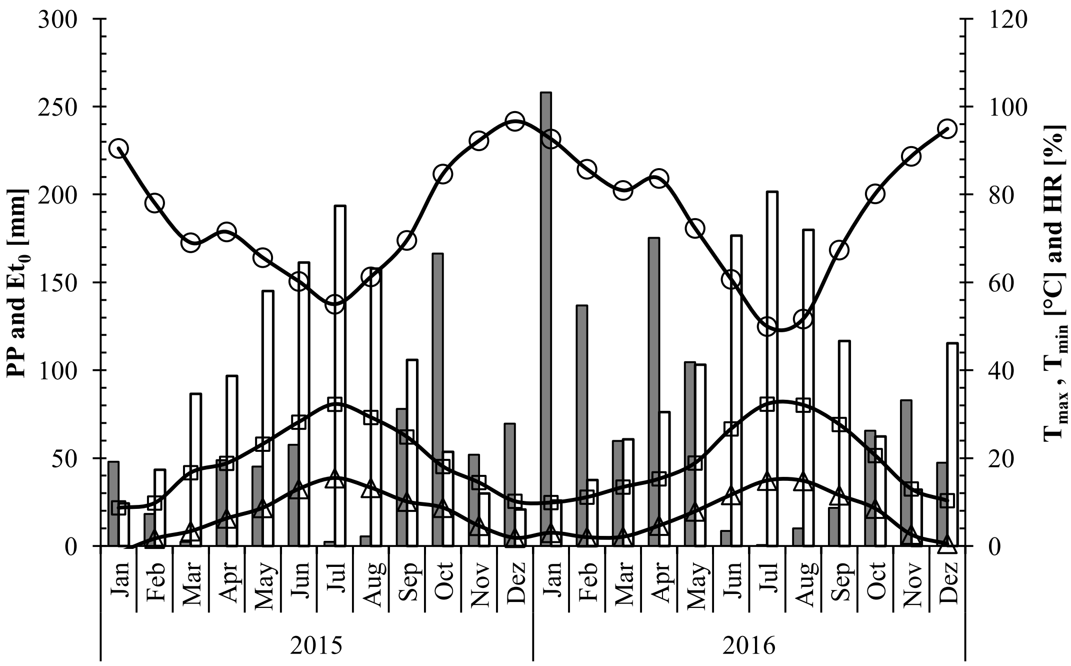

Fig. P 0-3 - Mean monthly maximal (□, T_{max}) and minimal (Δ, T_{min}) temperature (°C), mean monthly relative air humidity (HR, ○, %), total monthly precipitation (PP, grey bars, mm) and total evapotranspiration of reference (ET_0, white bars, mm) for 2015 and 2016 (source: IPMA 2015, 2016).

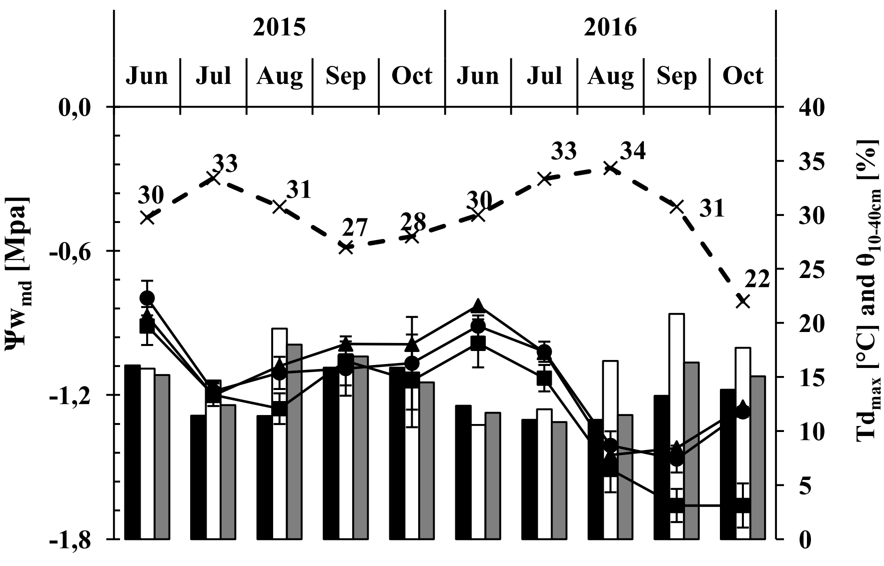

Fig. P 0-4 -Monthly mean of midday stem water potential (Ψw_{md}, MPa) for non-irrigated (NI, ■), drip irrigated (TI, ●) and micro-sprinkler irrigated (SI, ▲) treatment with vertical bars as standard error (se). Monthly mean soil water content on the average 10 to 40 cm soil depth ($\theta_{10-40cm}$, %) for NI (black bars), TI (white bars) and SI (grey bars). Monthly mean maximum air temperature on the measurement days (Td_{max}, °C) is represented by dashed line.

Tab. P 0-1 - Irrigation system features and hydraulic data for drip and micro sprinkler systems given by the irrigation system provider (Magos Irrigation System).

Irrigation System Features		
	Micro Sprinkler system	**Drip system**
Planting area	0.5 ha	0.5 ha
Plant spacing	10 m x 5 m	10 m x 5 m
Irrigation emitters	JDW Rondo	JDW Hydro PC
Emitters spacing	10 m x 5 m	10 m x 1 m
Emitters debit	51 L h^{-1}	3,6 L h^{-1}
No. of emitters by tree	1	5
No. of lines by tree row	1	2
Hydraulic data		
Daily water needs for planting area	8 m^3 day^{-1}	8 m^3 day^{-1}
Irrigation rate	1,02 mm h^{-1}	0,72 mm h^{-1}
Flow rate by sector	6 m^3 h^{-1}	4 m^3 h^{-1}
Flow rate by hectare	11 m^3 h^{-1}	8 m^3 h^{-1}

Tab. P 0-2 - Irrigation period, number of irrigation events and total water volume supplied to drip system (TI) and micro sprinkler system (SI) in 2015 and 2016.

Year	Treatment	Irrigation Period	Nº of irrigation events	Total Water Volume (mm)
2015	TI	Jul 23rd - Sep 11th	9	46.1
	SI	Jul 26th - Sep 11th	9	47.9
2016	TI	Jul 20th - Sep 30rd	19	87.1
	SI	Jul 20th - Sep 30rd	19	97.9

Tab. P 0-3 - Mean chestnut production per tree (kg of fresh weight.tree^{-1}) and per square meter of canopy area (kg of fresh weight.m^{-2}) with respective standard error (± se) for drip (TI), micro sprinkler (SI) and non-irrigated (NI) treatments in 2015 and 2016. Comparisons were made within treatments. The values with the same letter per column are not significantly different, according to the Fisher test, 5%.

Treat.	Chestnut production					
	(kg tree^{-1} ± se)			(kg m^{-2} ± se)		
	2015	2016	Average	2015	2016	Average
NI	43.7 ± 5.7a	32.8 ± 7.9a	38.3 ± 4.7a	0.98 ± 0.2a	0.75 ± 0.1a	0.87 ± 0.2a
TI	54.1 ± 3.0a	42.6 ± 8.5a	48.4 ± 4.0a	1.11 ± 0.1a	0.92 ± 0.2a	1.02 ± 0.1a
SI	51.6 ± 6.8a	44.3 ± 10.3a	47.9 ± 6.2a	1.15 ± 0.1a	1.05 ± 0.3a	1.10 ± 0.1a
	%			%		
NI	100	100	100	100	100	100
TI	124	130	127	113	123	118
SI	118	135	127	117	140	129

Tab. P 0-4 - Chestnut calibre (number of fruits per kilogram of fresh weight) with respective standard error (± se) for drip (TI), micro sprinkler (SI) and non irrigated (NI) treatment in 2015 and 2016. Comparisons were done within treatments on the same year. The values with the same letter, per column, are not significantly different according to the Fisher test, 5%.

Treatment	Calibre		
	(Fruits per kilogram ± se)		Fruits kg^{-1}
	2015	2016	Average
NI	64.5 ± 4.23a	122.71 ± 8.54a	93.61
TI	61.4 ± 2.12a	88.99 ± 5.14b	75.20
SI	62.7 ± 3.75a	77.71 ± 8.54b	70.21
	%		%
NI	100%	100%	100%
TI	95%	73%	83%
SI	97%	63%	80%

Tab. P 0-5 - Chestnut market price to the producers in 2015 and 2016. Minimum price (Min), maximum price (Max) and the most frequent price (Frequent). Source: GPP-SIMA, 2017.

	2015			2016			Average		
Price (€)	Min	Max	Frequent	Min	Max	Frequent	Min	Max	Frequent
	1.6	2.4	2.0	1.6	2.7	2.2	1.6	2.6	2.1

Tab. P 0-6 Units and costs of the economic, water and labour resources in each 0.5 ha of drip system (TI), sprinkler system (SI) and non irrigated system (NI) in 2015 and 2016, in an adult chestnut's orchard with 200 trees per hectare.

Treatment/description		2015			2016		
		Total units		Total costs	Total units		Total costs
Economic resources							
TI	|Irrigation system |	1	un	9,526.5 €	1	un	285.8 €
SI		1	un	9,903.1 €	1	un	297.1 €
NI		0	un	- €	0	un	- €
TI	|Monitoring Equipment |	1	un	2,000.0 €	1	un	60.0 €
SI		1	un	2,000.0 €	1	un	60.0 €
DI		0	un	-	0	un	
Water resources							
TI	|Water consumption|	230.4	m^3	13.8 €	435.6	m^3	26.1 €
SI		239.7	m^3	14.4 €	489.6	m^3	29.4 €
NI		0	m^3	- €	0	m^3	- €
Labour resources							
TI	|Monitoring|	6	weeks	10.2 €	9	weeks	15.3 €
SI		6	weeks	10.2 €	9	weeks	15.3 €
NI		0	weeks	- €	0	weeks	- €
TI	|Harvesting|	5.41	t	1,082.0 €	4.26	t	852.0 €
SI		5.16	t	1,032.0 €	4.43	t	886.0 €
NI		4.37	t	874.0 €	3.28	t	656.0 €

Tab. P 0-7 Annual costs during the amortization period (€ ha^{-1}), annual income (€ ha^{-1}) and profits (€ ha^{-1}) generated in one hectare of an adult chestnut orchard with tree density of 200 plants per hectare with drip system (TI), micro-sprinkler system (SI) and in non irrigated system (NI), considering a hotter (hot- growing degree days > 2400°D) and less hotter (mild - growing degree-days < 2400°D) year.

System	Annual costs (€ ha^{-1})									Yield (€ ha^{-1})								
	Amortization	Maintenance	Water resources			Labour resources			Annual income			Profits			Profits (%)		
			hot		mild	hot		mild	hot		mild	hot		mild	hot		mild
NI	0	0	0	to	0	1,312	to	1,748	13,120	to	19,228	11,808	to	17,480	100	to	100
TI	2,065	496	28	to	52	1,704	to	2,164	20,448	to	23,804	16,156	to	19,027	137	to	109
SI	2,159	518	29	to	59	1,772	to	2,064	21,264	to	22,704	16,786	to	17,904	142	to	102

Tab. P 0-8 - Investment costs (in euros, €) of different components of drip (TI) and micro-sprinkler (SI) irrigation systems on five hectares, including the equipment for monitoring leaf water potential and soil water content.

System	Water hole and pump (13 m^3 h^{-1})	Compression system	Valves collector	Fertigation system	Controller	Main pipes	Secondary pipes and emitters	Equipment monitoring	Total investment
TI	7,200	3,522	466	1,632	1,028	1,169	2,973	2,000	19,990
SI	7,200	3,522	466	1,632	1,028	1,169	6,739	2,000	23,756

Tab. P 0-9 - Annual costs during the amortization period and income for five hectares of a chestnut orchard more than 20 years old and with a tree density of 200 plants per hectare with drip system (TI) and micro-sprinkler system (SI) and in non irrigated system (NI), considering a hotter (hot- growing degree days > 2400°D) and less hotter (mild - growing degree-days < 2400°D) year.

System	Annual costs (€ 5ha^{-1})									Yield (€ 5ha^{-1})								
	Amortization	Maintenance	Water resources			Labour resources			Annual income			Profits			Profits (%)		
			hot		mild	Hot		mild	hot		mild	hot		mild	hot		Mild
NI	0	0	0	to	0	6,560	to	8,740	65,600	to	96,140	59,040	to	87,400	100	to	100
TI	2,499	600	138	to	261	8,520	to	10,820	102,240	To	119,020	90,483	to	104,840	153	to	120
SI	2,969	713	144	to	294	8,860	to	10,320	106,320	To	113,520	93,634	to	99,224	159	to	114

VIII. CONCLUSION

Q. General Discussion

The main objective of this work - to evaluate the contribution of irrigation on the increasing productivity and stabilization of the annual production through a water management based on soil and plant water relations - was being achieved along this work. Firstly, it became clear that irrigation indeed increased the chestnut productivity by increasing the chestnut production without negative effects on nut's chemical and sensorial quality; this is important insofar as it avoided an accentuated decrease on the chestnut production in the hottest and driest year. Secondly, the water management based on the plant water potential revealed to be a good tool for irrigation programmes that, complementary with the use of soil's moisture automatic devices, create good conditions for a conscious water management.

This study used two of the most important Portuguese varieties, 'Longal' and 'Judia', which are largely cropped in the Bragança Region. The former, an ancient variety mostly found in old orchards in the Portuguese chestnut's region, reveals more edapho-climatic plasticity (Pimentel-Pereira *et al.,* 2007). By its turn, due to the better nut calibre of 'Judia', the new plantations mostly use this last. Moreover, 'Judia' is known to have better performances in wetter and colder conditions than 'Longal' reflecting its origin from the Padrela Mountains, Valpaços Council (Rosas *et al*., 1998). Throughout the work, in both varieties, the irrigation showed benefits on the chestnut tree by generating higher plant water potentials (Fig. K-2, Fig. L-2, Fig. N-2), higher photosynthetic and transpiration rates (Tab. J-1, Fig. K-4, Fig. K-5, Fig. L-4), higher chestnut production (Tab. J-2, Tab. K-1, Tab. P 0-3) and higher nut size (Tab. P 0-4). Other photosynthetic traits, such as the leaf relative water content (Fig. K-3), the leaf pigments (Supplementary Fig. K-4) and the chlorophyll's fluorescence (Tab. L-1, Fig. L-3, Supplementary Fig. K-3), showed little difference between treatments and were without practical commercial utility as water management's tools. The exception goes to the chlorophyll fluorescence method because it is easier to use and automatic, albeit being currently unaffordable to the producers. In our study, the $PI_{ABS,}$ which gives the overall photosynthetic performance, was sensitive to the plant water status as supported by other authors (Genty *et al*. 1987, Christen *et al.* 2007 and Zivcak *et al.* 2008). Deeper studies of the chlorophyll fluorescence on the chestnut tree must be developed in order to guideline the use of this methodology for water management purpose.

In 2013, in spite of the production per tree been higher in the irrigated modalities, the biggest sizes were noticed in the non irrigated trees. This result suggests the importance of rainfall in the late September together with less chestnuts' load per tree. The 2013's results not only revealed the importance of watering the top soil to allow higher midday stem water potential (Fig. J-1, Fig. J-2) but also the importance of the deeper roots on the re-establishment of the plant water during the night. The importance of the water availability to enhance the chestnut's developing in the late summer was very perceptible in 2016 when no rain occurred in September and the chestnut's growth was faster and the final size bigger on the irrigated trees (Fig. L-5). The importance of watering in the final stage of the nut growing is also mentioned by Breisch (1995), Bounous (2014) and Gomes-Laranjo *et al* (2007, 2008).

This study was made in adult trees, with good and well developed roots, that have grown in their entire life in rainfed conditions in a deep loamy soil that has a good total available soil water (Tab. H-4, Tab. H-2). Nevertheless, in the end, the trees still benefitted with the irrigation. Therefore, our results suggest that the beneficial effect of the irrigation would be even more effective if introduced in shallowly soils or soils without proper preparation during plantation. In this case, the roots cannot expand properly a fact that often occurs in the chestnut's stands in Trás-os-Montes region (Portela *et al.*, 2007, Borges *et al*, 2016). However, Martins *et al.* (2010) suggested a negligible effect of the irrigation on the soil and tree water potential in 40-year-old trees, cultivar Longal, growing in similar climatic and soil conditions as the ones in our study. The same authors considered that, in spite of the higher nut production in their irrigated and seeded pasture modality when compared with the non-tillage with herbaceous vegetation cover modality; the irrigation was ineffective thereupon suggesting other strategies of irrigation application in order to enhance its efficiency. Martins *et al.* (2010) studied a modality of sprinkler irrigation and the amount of water used was 217 mm, 78 mm, 220 mm and 70 mm in 2003, 2004, 2005 and 2006, respectively. In our study, the irrigation was the drip and the micro-sprinkler systems which, together with a conscious water management based on the tree water potential, brought higher chestnut production with less water (mean of 104 mm, 47 mm and 93 mm in 2013, 2015 and 2016, respectively) than that used in Martins *et al*. (2010). In summary, we consider that younger trees than those studied by Martins *et al* (2010) together with a different irrigation system and strategy make positive difference in the chestnut's production that could arise up to 20% more when compared without irrigation.

In our study, the effect of the air temperature was reflected in the production decrease from 2015 to 2016 but the irrigation added commercial value to the chestnuts because it increased thei size without prejudice of the chemical composition as well as at the sensorial attributes level (Chapter 0-M). The chestnut's biochemical analysis (Tab. M-4) revealed no significant differences in most of the parameters analysed in 2016 (dry matter, organic matter, ashes, soluble sugars, crude fat and crude protein) but differences were noticed in 2015 in all of them with exception to the crude fat. So, this suggests that in the hard years, as was the case of 2016, the irrigation does not interfere in the chestnut quality but valorises it due to the higher size. In the end, overall results suggested that chestnuts from non irrigated trees were sweeter than the irrigated ones but the difference was not so high as to affect consumers' decision to eat it or not. Therefore, further chestnut sensorial proofs must be done, not only by a professional panel but also with the final consumers, to better understand their preferences and to define limits of perceptible sweetness that make a difference at buying decision level.

The plant nutrition is strongly important to the success of the chestnut production. Apparently, all trees of the trial were in good nutritional conditions considering the leaf mineral analysis (Tab. M-2) and the reference values given by Portela *et al.* (2007). The leaf mineral analyses suggest better assimilation of the nutrients in the irrigated trees despite no significant differences had been perceptible on the chestnut's sensorial analysis. Because none mineral analysis was made it is hard to conclude about the influence of irrigation on the minerals absorption and translocation to the chestnut or to storage organs. The evolution of the total chlorophyll on the leaf along the vegetative cycle together with the leaf mineral analysis (Supplementary Fig. K-4, Tab. M-2) suggest the importance of the nitrogen until the end of August and, from then on, the potassium seems to be the most important nutrient to furnish in quantity. Some studies focussing on chestnut nutrition highlight the importance of nitrogen, potassium, magnesium and boron in production success (Portela *et al.* 2003, Portela *et al.* 2014, Arrobas *et al.* 2018). Other studies (Zhang *et al.* 2013, Monteiro *et al.* 2017) highlight the importance of the silicon nutrition in the chestnut trees to enhance it resilience to the water deficit and ink disease. The holistic chestnut's nutritional information given in this work together with the studies mentioned above open the way to further studies focussing on the development of proper fertigation programmes for the chestnut tree.

The analysis of the soil-plant water relationship in 2013 given in (Chapter I-K) suggests the possibility of using the midday stem water potential rather than the predawn or dawn water potential to scheduling the irrigation. Other studies corroborate the sensitivity of the midday stem water potential for irrigation scheduling and even expose some fragilities of the predawn water potential (Ameglio *et al.* 1997, Donovan *et al.* 2001, William and Araújo 2002, Girona *et al.* 2006, Choné *et al.* 2011). Following the results of 2013 together with the data gathered for 2015 and 2016, the referenced values of the midday stem water that best translated good photosynthetic productivity were between -0.8 to -1.2 MPa (Fig. K-7, Fig. 0-4). Shackel *et al.* (1997) also suggests that at -1.2 MPa the stem water potential of almond and prune trees are in non-limited water conditions for a given air vapour pressure deficit. In the future, more studies should be conducted in order to analyse what the response of the chestnut tree is, in terms of the stem water potential, under non-limited soil's water conditions and specific air vapour deficit pressure and air's temperature to define exactly in under which values of the stem water potential the chestnut tree has better performances.

So, in what concerns the climatic conditions, two of the years were clearly different in the opposite way: 2014 and 2016 (Fig. G-1).The first had a very untypical humid summer and the last year had a very dry one. The influence of the climatic conditions on the physiological response of the chestnut tree was visible: in 2014 the irrigation was not triggered because the water potential was high during the vegetative cycle (Tab. N-1) and in 2016 the irrigation was triggered more times because the stem water potential was stubbornly lower than -1.2 MPa. This suggests that even with more water furnished, when the air's temperature is very high, the stem water potential remains very low or at least, it remains lower than our predefined objectives that were considered optimal to the chestnut tree (bellow -1.2 MPa). The same happened to Moriana *et al.* (2012) where the irrigation was triggered every time the stem water potential was below -1.2 MPa through the whole season. However, the authors' decided to change the irrigation scheduling depending on the phenological stage: before the beginning of the massive pit hardening the stem water potential threshold value was −1.2 MPa and after the beginning of this period it was −1.4 MPa because, in 2005, in spite of the great amount of water it was impossible to decrease the stem water potential below -1.4 MPa. By the end of their work, the new threshold stem water potential values according to the phenological stage were considered reliable for scheduling the irrigation under non water-stress conditions. In the chestnut tree it may be acceptable to expect stem water potentials above -1.2 MPa until the end of flowering (middle July), depending on air's temperature and also depending on the winter's rainfall together with the soil's water storage capacity. From August on, within logic of a deficit irrigation strategy, the water furnish must be such that the stem water potential can decreased down to -1.4 MPa. Further studies are needed to readjust the chestnut stem water potential thresholds depending on the phenological stages that better translate the non water-stress conditions. In the future, also the irrigation scheduling based on the soil water balance should be integrated for comparison and validation of the stem water potential based-method, as made by Moriana *et al.* (2012).

However, and in spite of the utility of the stem water potential as a sensitive parameter for irrigation scheduling, this is a destructive, non-continuous and not automatic procedure. Therefore, in this study, an attempt was made to establish a relationship between the stem water potential and the soil water content/soil matric water potential that helped to define soil thresholds values that can be used for water management and, in addition, that are able to be continuously registered by proper devices (Chapter I-N, A). In the end, for the soil of the study area, the results suggested that irrigation should begin when the soil water content is at least at 16 $cm^{-3}H_2O.100\ cm^{-3}$soil and the soil matric water potential between -90 to -120 cbar (Fig. N-4, Fig. 0-5, Fig. 0-6). It is important to have a careful reading of these soils' thresholds values, as it is with the definition of the stem water potential thresholds, because these soil's threshold mostly depend on the soil's type and on the soil's water tension curve (Lopes *et al*., 2003) Besides, it must be highlighted that the water-potential/soil moisture are not straight related due to several factors: climatic condition's influence, plant's (an)-isohydric responses, root's volume, soil's devices displacement, etc. Then, in a context of the practical use of irrigation strategies based on soil and plant parameters, it is recommended to evaluate it individually on each chestnut orchard.

In what concerns the two irrigation systems comparison no special difference on the tree water potential or gas exchange measurements was found between the irrigated modalities. In the hottest year, the chestnut production was higher in the hanging micro-sprinkler system modality but none evaluation was made in what could be the contribution of the micro-sprinkler system in decreasing the air's temperature or the increasing of the air humidity below the trees canopy. The economic study (Chapter VII-P) revealed good yields either in not irrigated or in the irrigated adult in healthy chestnut trees which is very positive for the chestnut producers. However, the profits generated were higher on the irrigated orchards especially in the ones with large areas where the profitability of the investment is higher (Tab. P 0-7, Tab. P 0-9). In terms of the investment, this is lower in the dripper system. Since the overall results do not single out any particular irrigation system, it can be said that it mainly depends on the investment cost, on the water availability (the micro-sprinkler consumes slightly more) and on the agricultural practices, especially weed's control, pasturing or mushroom production. Although these parallel economic activities were not taken into account in this study it is known that they add to chestnut orchard profitability and that irrigation enhances forage and mushroom growth (Martins *et al*. 2011, Marques *et al*. 2007). On the same Chapter VII-P it is revealed high revenues from the chestnut production (mean of 18.000 € ha^{-1}, Tab. P 0-7, Tab. P 0-9) but it should be noted that these values are far from the Portuguese chestnuts orchards' reality. The main reason is due to the very high tree's density that was considered (200 trees per hectare) and that do not correspond to the majority of the chestnut's orchards density which typically ranges from 70 to 100 trees per hectare. Besides, most of the Portuguese chestnut orchards are affected by the ink or cancer diseases which naturally affect the chestnut's productivity. Finally, the productivity of the chestnut tree depends on the variety and on the variety adaptation to the edapho-climatic conditions. Deciding or not to invest in irrigation systems for chestnut trees must consider all the possibilities mentioned and it is necessary to develop a detailed crop's account to help the investment decisions.

R. Final considerations

The work reported in this dissertation opens new perspectives on chestnut tree irrigation. Still, further and deeper studies should be carried out, guided by the following suggestions for future work:

- So far, the chestnut tree has been treated commonly as a "multifunction" tree inserted in an agro-forestry system. Comprehensibly, evolution to the orchard system has been slow, gradually accompanying the knowledge acquired and shared by the chestnut community, framed in complex social, demographic and market trends.
- Climatic changes are a reality and the sooner agricultural practices adapt, the earlier the chestnut sector will overcome the obstacles imposed by climate evolution, together with the incidence of plagues and diseases.
- The irrigation is just one of the agricultural practices that a chestnut's grower may embrace to answer the previous considerations.
- Considering that the water resources are scarce a proper and conscious water management is mandatory advising deeper acknowledgement on the soil-plant water relationship.
- The soil-plant water relationship is very complex. To better understand its dynamics, more and more frequent measurements monitoring the soil, plant and climatic parameters are required. Also, a larger number of devices, cover area, number of repetitions and registering of the data are necessary. Despite these considerations are mostly important in a scientific context, the chestnut sector must embrace the benefits of the use of the technology.
- Deeper studies are needed to add robustness to plant water potential thresholds under irrigation during the vegetative cycle. In addition, the soil-plant relationship should be adjusted for each new situation in what concerns the variety and soil type.
- The effect of the irrigation on the chestnuts tree resilience against to the ink disease should be addressed.
- The fertigation must be explored as a new tool to cover the chestnut nutritional requirements.

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