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Évaluation des performances des cultures annuelles en agroforesterie Méditerranéenne sous différents régimes hydriques : Cas des systèmes agroforestiers à base d'oliviers au Maroc

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CHAPTER I. General Introduction

1. General background

1.1 Why do we need other agronomic strategies?

The world's population growth has quadrupled in the last century (Elferink and Schierhorn, 2016). This growth is expected to reach 9.7 billion by 2050 (Mouël et al., 2018). Consequently, food demand is expected to rise between 59% and 98% between 2005 and 2050 (Valin et al., 2014). However, about 821 million people are suffering from hunger in 2017 worldwide, a number that will continue to increase in the coming years. To fulfill population's food demand, food production should double in the coming decades (Waldron et al., 2017). In addition, climate change is associated with higher temperatures (Akompab et al., 2013), more extreme drought (Myers et al., 2017), rainfall variability (Olayide et al., 2016), leading to much more dramatic consequences on crop performance (Fuhrer et al., 2006). The global temperature is expected to increase by 1.5 to 5 degrees by the end of the 21st century, compared to the reference period 1971-2000 (Nadal-Sala et al., 2019). The negative impact of climate change occur at several spatial scales: global, regional, and national (Gosling et al., 2011) and in several sectors, including agriculture (Arnell et al., 2019). The impact of climate change on agriculture differs from one region to another, e.g., agricultural productivity is expected to decrease in Southern Europe but is expected to increase in Northern Europe due to climate change (Iglesias et al., 2012; Olayide et al., 2016).

In the last decades, Mediterranean regions are suffering from significant land ressources degradation including soil loss by erosion (Zdruli, 2014) and a declining availability of water (Gilmont, 2015). Particularly, the pressure on water resources will be more intense with climate change and an increasing dependency on water supply is expected e.g. irrigation use in these regions (Lionello et al., 2014). Mediterranean basin is vulnerable to climate change and is expected to become warmer and drier in the future (Hallett et al., 2018). On average, the temperature is expected to increase by about 3.5°C until the end of this century, the average of annual and regional precipitation reduction is expected to be more than 10% (Calbó, 2010). The spatial variations of climate change are not similar between the Mediterranean regions (Fig.1) (Saadi et al., 2015). The Middle East and North Africa are subject to intense demographic pressure and a growing food import dependency (Wright and Cafiero, 2011). Today, the region has one of the highest cereal dependency rates in the world, which is expected to increase further (Marty et al., 2017). The North African countries, with 51% of cereal dependency, the highest in the Mediterranean region (Marty et al., 2017), make the region more vulnerable to climate change fluctuations. Overall, these climate changes raise major threats for the global food production (Vogel and Meyer, 2018), which will face daunting and complex challenges.

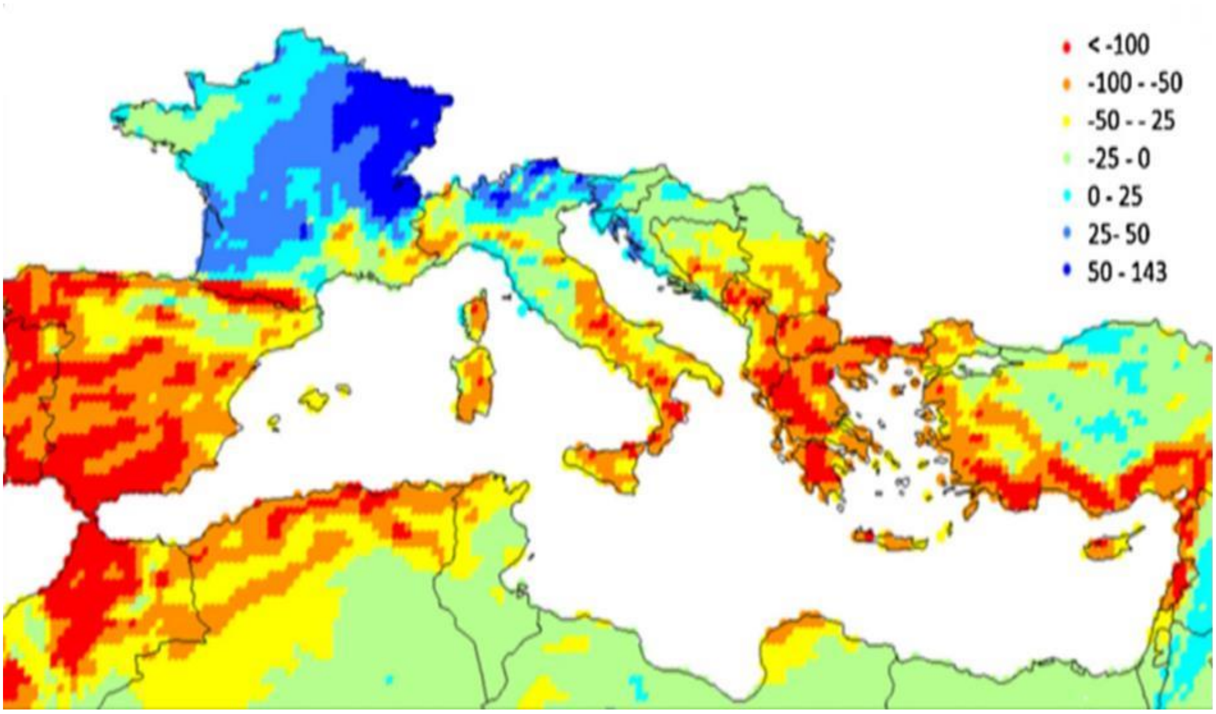

Figure 1: Mean annual precipitation differences (mm) in the Mediterranean regions between 2000 and 2050 (Saadi et al., 2015).

1.2 How can food insufficiency be reduced? What are the possibilities?

Facing these threats, new cropping strategies should be developed to drive production systems towards more sustainable and resilient production situations.The resilience of a cropping system is considred as its ability to return to an equilibrium situation after a temporary perturbation (Holling, 1973). Sustainable intensification was considered essential in reaching the trade-off between fulfilling food demand and conserving natural resources (Cassman, 2017). Sustainable intensification (SI) was invented in the late 1990s (Pretty and Bharucha, 2014). It is defined as a process where yields are significantly improved without too many negative environmental impacts (The Royal Society, 2009). Ecological intensification can provide many ecosystem services, such as reducing chemical inputs for pests and weed control (Pretty and Bharucha, 2015), reducing fertilizers use through integrated legume crops (Sheaffer and Seguin, 2003). Sustainable intensification requires many systemic approaches such us rotation and conservation agriculture (Pretty and Bharucha, 2014), mixed cropping systems (Pretty et al., 2018) . In adition, cropping systems diversification occurs through several forms and at different spactial scales at field and landscape level e.g. agroforestry, hedgerows, corridors .. (Altieri et al., 2015). However, crop yield is still a determining factor for the adoption of sustainable land design and practices. Mixing crops , which consist of growing several crops together in the same field (Malézieux et al., 2009), is recognized as an effective option to achieve sustainable agricultural development goals (Kumar et al., 2019). For example, crop intercropping is defined as growing two or more species simultaneously in the same land area (Ofori and Stern, 1987). Introducing legumes as an intercrop enhance crop production and symbiotic N_2 fixation e.g. in barely-pea (Chapagain and Riseman, 2014) and maize-cowpea intercropping system (Dhonde et al., 2016). Other mixed systems e.g. tree and crop mixing may maximize the potential benefits of intercropping systems.

1.3 What is agroforestry? What are the agroforestry systems?

Agroforestry, which consists of the combined trees and annual crops on the same area, can be a promising approach of ecological intensification (Jose, 2009). A wide range of agroforestry practices has been documented for many centuries. The classification of agroforestry systems is proposed according to local conditions such as practices and diversity of associated components (Nair, 1985). Four main groups of agroforestry systems can be identified (i) Agrisilviculture system, which consists of crops and trees/shrubs combination, (ii) Silvopastoral system, which associates animals and trees in the same areas, (iii) Agrosilvopastoral system, which in addition to animals and trees contains annual crops,and (iv) Other systems having a multipurpose use such as windbreaks, beekeeping with trees/shrubs (Atangana et al., 2013). In recent decades, traditional agroforestry systems, especially those which introduce crops in orchards, have received growing interests (Santoro et al., 2020). Agroforestry showed a wide range of regional and global adaptation around the world (Beillouin et al., 2019). In Europe, total agroforestry practices, including silvopasture, silvoarable and home-garden practices, cover 19.77 million hectares, of which 1.8% combine arable farming with trees (Mosquera-Losada et al., 2018). In Latin America, agroforestry areas cover up to 357 million hectares (Cerda et al., 2019). In some regions in Asia, the land under agroforestry was around 170 million hectares between 2008/2010 (FAO, 2019). Traditionally, in Africa, annual crops were grown with trees in the same land area (Viswanath et al., 2018). In Sub-Saharan Africa, for example, agroforestry covers 60 million hectares (FAO, 2019).

In Mediterranean regions, agroforestry systems are typical rural landscapes (Dupraz and Liagre, 2008). Several examples of combinations were described in southern Mediterranean Europe such as: associations of olive trees with cereals and forage, e.g., oats, barley, or vetch in south-eastern Sicily (Rühl et al., 2011; Paris et al., 2019), introductions of olive groves and riparian vegetation in cork oak woodlands have also been described in south-western Portugal (Marinelli, 2010). Other types of associations of annual crops such as barley and other forage crops in vineyards, pistachio, and olive groves were reported in turkey (Krishnamurthy et al., 2019). In North Africa as well, the oases systems is a particular forms of agroforestry system containing three floors: date palm floor, tree floor, e.g., pomegranate, fig, vine, almond and olive, and annual crop, e.g., vegetables, cereals, alfalfa (Belarbi A., Boayad A., Diaou M., 2004; Daoui and Fatemi, 2014; Benaoun et al., 2014). Other fruit-based agroforestry systems were practiced in the Mediterranean regions, e.g., walnut, olive, fig, almond trees (ArenasCorraliza et al., 2018; Lauri et al., 2019; Papanastasis et al., 2009; Poussin et al., 2008; Razouk et al., 2016; Camilli et al., 2018).

2. Agroforestry an opportunity for sustainable intensification?

2.1 What are the expected benefits of agroforestry?

Agroforestry systems provide several environmental benefits (Kizos and Plieninger, 2008; Jose, 2009; Flinzberger et al., 2020). Soil conservation is one of the main benefits of tropical humid (Blanco Sepúlveda and Aguilar Carrillo, 2015), sub-tropical (Chirwa, W. and Quinion F., 2012), and arid agroforestry (Paningbatan et al., 1995; Jiang et al., 2017), thanks to the presence of crop roots in the topsoil layers (Béliveau et al., 2017). Indeed, deeper root systems of trees, e.g., walnut in Mediterranean agroforestry (Cardinael et al., 2015a) may permit trees to get resources (water, nutrients) from deeper soil layers, that are not available to crops and limit their loss, e.g., nutrients leaching (Cannell et al., 1996). The introduction of legume crops-trees in humid (Isaac et al., 2014) and temperate (Mthembu et al., 2018) agroforestry enhance symbiotically fix atmospheric nitrogen which may be a sustainable option to reduces fertilizer inputs, while N symbiotic fixation was lower in Mediterranean agroforestry (Mahieu et al., 2016; Sanna et al., 2019). Agroforestry enhance long-term carbon sequestration (e.g., through crop residues incorporation) in semi-arid, sub-humid, humid, and temperate regions (Montagnini and Nair, 2004), tropical (Muchane et al., 2020), and temperate (Albrecht and Kandji, 2003; Oelbermann et al., 2004) which minimize the negative impact on global climate change. Consequently, residues decomposition can improve soil organic matter (Zeng et al., 2010) and may contribute to maintaining soil fertility through the release of nutrients in the soil continuum in tropical (Ong et al., 2007; Tscharntke et al., 2011) and in Mediterranean agroforestry (Le Bissonnais et al., 2017). Several studies showed that agroforestry might be an effective means to reduce weed pressure and harmful insects in temperate agroforestry (Dupraz et al., 2009). Agroforestry is recognized to offer many socioeconomic benefits, for example, through the introduction of cash crops (Reyes et al., 2005). System productivity in agroforestry was improved compared to monospecific crops thanks to the sum of associated crops yields (H., 2015), in semi-arid agroforestry (Bai et al., 2016 ; Zhang et al., 2016; 2018) and Mediterranean agroforestry (Panozzo et al., 2019). Facing to climate change, agroforestry system adoption may be an effective way to stabilize cropping systems performance (Hufnagel et al., 2020), and lead to farmers' incomes improvement, particularly in dry areas (Krishnamurthy et al., 2019).

2.2 What are the challenges of agroforestry today?

Facing climate change, increasing system performance through species diversification is one of the most important and expected beneficial outputs of agroforestry (Montagnini and Metzel, 2017), which presents today the biggest challenge of agroforestry adoption (Patel et al., 2015). According to several studies in temperate, Mediterranean, and semi-arid agroforestry, trees reduces understory crop yields (Puri and Bangarwa, 1992; Lott et al., 2000; Muthuri et al., 2005; Bertomeu, 2012; Bai et al., 2016; Artru et al., 2017; Gao et al., 2013; Wang et al., 2017; Inurreta-Aguirre et al., 2018; Fowe and Carole, 2019; Razouk et al., 2016; Qiao et al., 2020). However, agroforestry enhances the land and resource-use efficiency through a complementary yield resulting from both trees and annual crops (Zhang et al., 2007) using the land equivalent ratio (LER) (Mead and Willey, 1980). Fruit-based agroforestry systems showed high land-use efficiency, e.g., Ginkgo based agroforestry in humid Sub-tropical agroforestry (Cao et al., 2012), walnut-based agroforestry (Duan et al., 2019) under tropical agroforestry, and in semi-arid agroforestry, e.g., apricot-based agroforestry system (Bai et al., 2016), jujube-based agroforestry systems (Zhang et al., 2013), olive-based agroforestry systems (Panozzo et al., 2019), e.g., mango-based agroforestry (Hasan et al., 2020). However, agroforestry performance depends on the trade-offs between negative, neutral or positive interactions between system components (Cerda et al., 2019). Therefore, it is necessary to acquire knowledge on the functioning of Mediterranean agroforestry systems and on the interactions (negative, neutral or positive), that can take place between associated species. Thus, the study of the performance of associated species is essential to assess the major determinants affecting yields in order to predict improvement paths for associated systems.

3. Tree-crop interactions in agroforestry

3.1 What are the possible relationships in the tree-crop combination?

Tree-crop combination induces two types of interactions (Ong and Leakey, 1999): negative interactions or competition and positive interactions or facilitation/complementarity. On one hand, competition (negative interactions) is defined as the sum of effects that the presence or growth of one crop leads to a reduction in the performance of another (Tilman, 1990) and, therefore, negatively affect one or both crops. Within the association, competition can occur for underground resources, e.g., water and nutrients and aerial resources for light from tree leaves (Luedeling et al., 2016). Another aspect of competition can be observed in agroforestry and is not primarily related to the resource such as allelopathy, which inhibits the growth of a crop by emitting chemical compounds into the soil (Nazir et al., 2007). On the other hand, facilitation is defined as an improvement of plant growth due to environment amelioration thanks to another plant (Bronstein, 2009). Finally, complementarity, particularly for resource use, may occur between crops, and it is defined as a different use of resources when species are co-existing (Barry et al., 2019).

3.2 Light sharing: from negative to a positive key role

Competition for light is one of the critical interactions between trees and crops in agroforestry (Ong et al., 2014). Trees presence induce a reduction of light intercepted by understory crops (Dufour et al., 2020). Trees' shade effect increase with the crown tree size (Jackson and Palmer, 1977), trees density (Singh et al., 2007) and row orientation (Huxley et al., 1994). Indeed, the vertical and horizontal arrangements of species determine the distribution of light in the system (Luedeling et al., 2016). Tree shade leads significantly reduces photosynthetic radiation (PAR) (Dufour et al., 2013), net assimilation (NA) (Reynolds et al., 2007), inducing crop growth reduction (Sgarbossa et al., 2020) and, therefore crop yields (W. Zhang et al., 2018; Qiao et al., 2018). In this situation, tree management practices such as tree pruning may be used to enhance light availability for understory crops (Dufour et al., 2020). However, this negative effect on understory crops may be partially compensated by modifying the microclimate of the system in hot and dry climates (Massetti et al., 2019). Under such conditions, trees shade creates a beneficial microclimate through reducing increasing the relative air humidity (Campi et al., 2009), buffering extreme temperatures (Rigal et al., 2020), leading a reduction of evapotranspiration (Coussement et al., 2018) and leaf damages caused by heat and cold waves (Vaast et al., 2016). Another key factor may reduce aboveground negative interactions, which consists of temporal complementarity, which may occur when trees and crops use resources at different times as indicated thanks to tree leaf phenology. Temporal complementarity may occurs with introducing leafless trees during the growing season (Broadhead et al., 2003), e.g., deciduous apricot trees (Forey, 2016). A partial complementarity may occur at the beginning of the crop cycle, with evergreen trees when they have winter dormancy, e.g. Olive trees (López-Bernal et al., 2020).

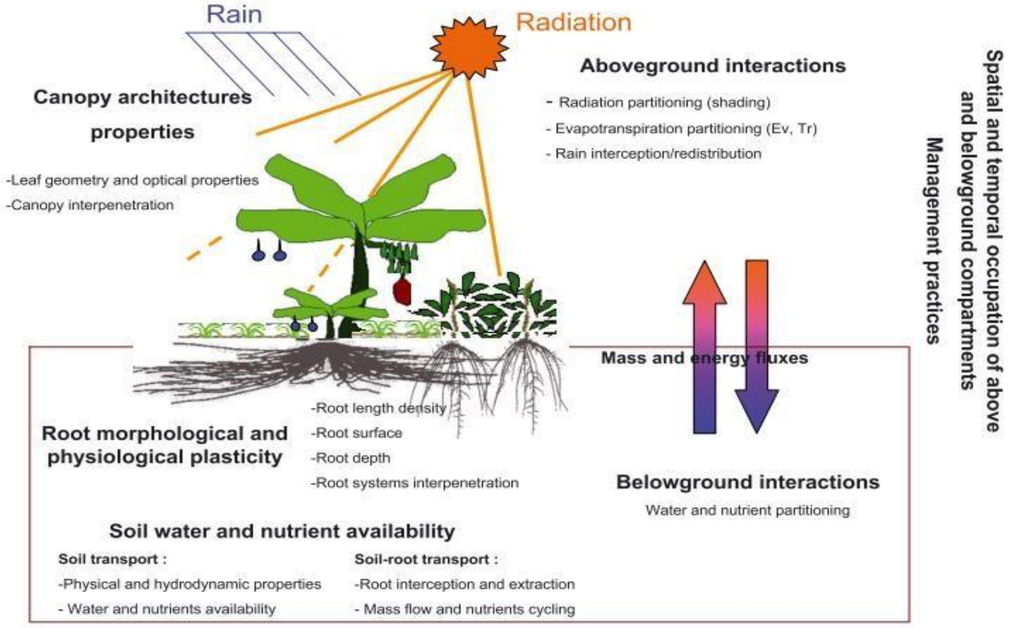

Figure 2: Above and below-ground interactions in an agroforestry system (Gaba et al., 2015).

3.3 Water sharing: competition vs. complementarity

Below-ground competition for water and nutrients occurs when crop roots of system components grow in the same soil layers and use the same resources (Jose et al., 2004). According to Zhang et al., 2018, the below-ground competition was higher in the topsoil layers, mainly when understory and trees developed shallow root systems and may be more severe during the beginning of the growing season (Noordwijk et al., 2015). Gao et al., 2018, reported that competition for water in temperate jujube-based agroforestry occurs under relatively wet conditions in the shallow soil layer. In addition, deep-rooted trees may exploit the deepwater resources in the soil (Liu et al., 2020), which may reduce competition for underground resources. Hydraulic redistribution is a passive process driven by water potential gradients between soil layers depending on the location of dry and soil layers in the soil profile, this process is known as hydraulic lift (Bayala et al., 2008), water can move downwards (reverse hydraulic redistribution) or sideways (Fig. 3) (Prieto et al., 2012). These transport processes appear to be important in Mediterranean-type climates, where rainfall is seasonal (Burgess and Bleby, 2006). In the temperate agroforestry study, trees showed a different rooting pattern leading to a better vertical separation of the two root systems (Bouttier et al., 2014), which may favor better resource use efficiency. In a Mediterranean agroforestry example, the interspersed walnut trees showed root plasticity that allowed the trees to access water tables via roots deeper than the crops (Cardinael et al., 2015). However, legume integration into agroforestry (e.g., acacia, soybean, faba bean…) can enhance nitrogen soil content (Duchene et al., 2017;Isaac and Borden, 2019).

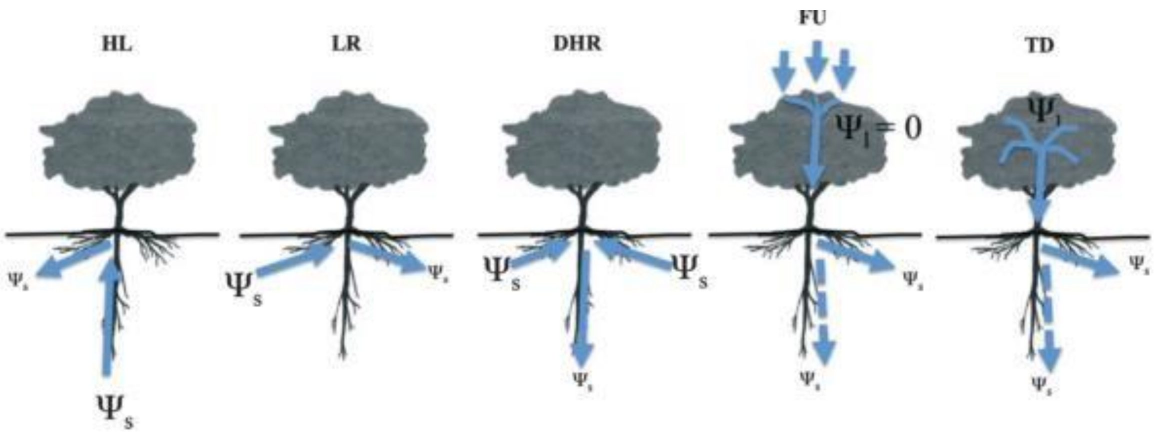

Figure 3: Scheme of different types of hydraulic redistribution: Hydraulic lift (HL) is movement of water from wet deeper soil layers to shallow dry layers (Van Noordwijk and Lusiana, 1998), downward hydraulic distribution (DHR) refers to water movement from wet shallow soil to deeper soil layers (Burgess and Bleby, 2006). Lateral redistribution (LR) is the water movement in the same soil layer with different water potentials. HR of fog water (FU) occurs through the transfer of fog water absorbed by leaves to the roots and then to the soil. Tissue dehydration (TD) occurs at the end of long droughts water moves from above tissues to soil (Prieto et al., 2012).

4. Does the Stress Gradient Hypothesis hold to agroforestry system interactions?

Varying with time and resource availability, interspecific interactions in mixed cropping system affect crop growth and yield production (Tan et al., 2020), depending mainly on natural resources, e.g., rainfall (Latiri et al., 2010; Tafoughalti et al., 2018) and soil fertility (Tsubo and Walker, 2004). Negative (competition) and positive (facilitation) interactions can co-occur when cultures grow at the same time (Mariotti et al., 2009). It is difficult to decompose because of above and below interactions, e.g., light sharing between intercropped species and access to soil resources by each species, which are difficult to measure under field conditions (Malagoli et al., 2020). However, the final result of a plurispecific system that results from the dynamics of interactions (Bedoussac and Justes, 2011) can be a good indicator of the functioning of the association. In reality, the effect of crop association on system performance integrates both positives and negatives relations (Lai et al., 2018).

4.1 How do plant-plant interactions vary according to the stress gradient hypothesis?

The net effect of these interactions, which depend on species characteristics as well as environmental conditions (Fernández et al., 2007) (Dohn et al., 2013) is still in debate (Mazía et al., 2016). In this sense, the Stress Gradient Hypothesis (SGH) suggests that facilitative interactions gain in importance and outweight negatives interactions with increasing environmental stress (Callaway et al., 2002;Holmgren and Scheffer, 2010) (Fig 4.). Stress is defined by environmental conditions that limit the ability of producers to convert energy into biomass (Maestre et al., 2009). The stress gradient hypothesis 'SGH' was originally proposed in ecology (Tirado and Pugnaire, 2005). Positives interactions occur through various mechanisms integrating resource improvement (Callaway, 1995) and the refuge from physical stress (Tirado and Pugnaire, 2005). The 'SGH' was mostly investigated in a wide range of plant communities in natural ecosystems e.g. in salt marsh, alpine and arid ecosystems (Lawrence and Barraclough, 2016), savannah (Moustakas et al., 2013) and including treepasture, shrub-pasture, shrub-tree interactions (Rivest et al., 2011). In most tested situations, the SGH was evaluated neighboring plant-plant interactions on a target species performance or community performances (e.g. grasses, shrubs) (Maestre et al., 2006; LÓpez et al., 2016). Indeed, one of the main examples of positive interactions highlighted in natural ecosystems is the "nurse plant" effect (Callaway and Walker, 1997) in which a plant can improve the growing conditions of the neighboring plant e.g. providing more water through generated (Butterfield et al., 2016), which may enhance seed germination (Ren et al., 2008).

In natural ecosystems, the SGH was assessed under a wide range of semi-arid climate, for example along the aridity gradient of the Western Mediterranean region (Rey et al., 2016), in Spain and South America (Tirado and Pugnaire, 2005), and in north-eastern savannas in South Africa (Moustakas et al., 2013b; O'Brien et al., 2017; Armas et al., 2011). The hypothesis has evolved several types of gradients: biotic (e.g. settlement and growth of other species, predation) and abiotic gradients (e.g. temperature, rainfall, aridity gradient) (Hart and Marshall, 2013). Numerous evaluations of the hypothesis were made along an aridity gradient (Armas et al., 2011; Moustakas et al., 2013; Michalet et al., 2014; Ziffer-Berger et al., 2014; Butterfield et al., 2016; LÓpez et al., 2016). In this context, the meta-analysis results (Dohn et al., 2013) revealed a shift from negative to positive interactions of trees on understory grass production with decreasing rainfall, which shows the validity of the hypothesis. In addition, (Moustakas et al., 2013b) have shown that the presence of trees has a facilitating effect in drier sites (mean annual precipitation ≤ 550 mm). An experimental assessment of the SGH showed that shrub-annual interactions tended to shift from negative to positive towards the driest site, but temporal variation showed more negative shrub effects in drier years (Metz and Tielbörger, 2016).

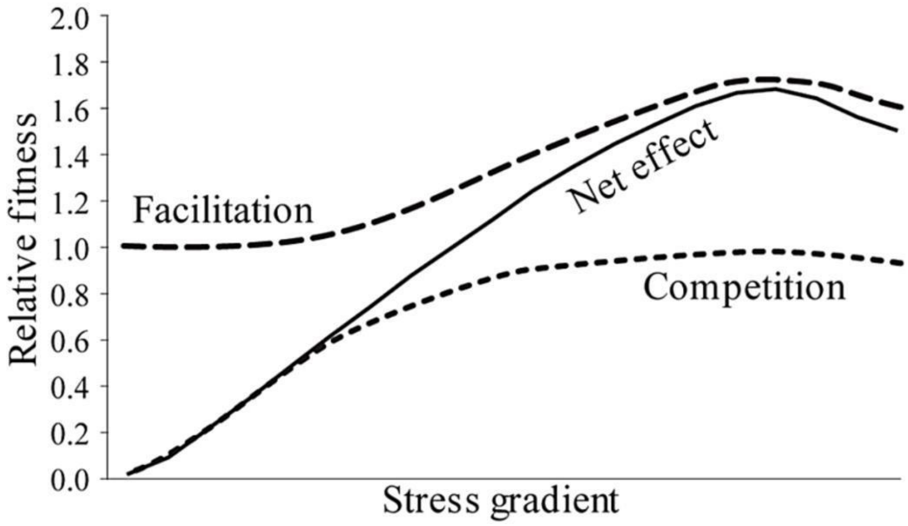

Figure 4: The importance of positive (facilitation) and negative interactions (competition) (Malkinson and Tielbörger, 2010).

4.2 Can the stress gradient hypothesis be considered differently?

The stress gradient hypothesis was studied on tree/shrub-grass which reflects relatively the two component of agroforestry one perennial and one annual herbaceous. Understand the functioning of tree-crop interactions and predicting the outcome of tree-crop interactions on agroforestry systems performance is therefore challenging under climate changes a key question measuring the success of agroforestry systems. Inspired by the 'SGH', a beneficial effect of tree shade 'nurse effect' may occur under dry conditions. Microclimate modification, which consists of more moderate temperature (Peng et al., 2015), higher air humidity (Campi et al., 2009), and reduced evapotranspiration (Coussement et al., 2018), lead to better crop growth (Lott et al., 2009; Moustakas et al., 2013; Mugunga et al., 2017). Agroforestry systems shown potential for optimizing microclimatic conditions for good crop growth under humid subtropical conditions characterized by dry hot summers (Kohli and Saini, 2003) e.g. wheat tillering. In addition, modifiying microclimate conditions for understory crop under dry agroforestry, may be promoting to enhance crop grain filling and quality (Liu et al., 2018). However, trees shade reduces crop growth under favorable conditions (Cubbage et al., 2012) due to lower light interception and photosynthesis rates (Zhang et al., 2018; Rivest et al., 2009). In Mediterranean areas, autumn and winter are usually cold and rainy seasons with low evapotranspiration rates (Milner et al., 2012; Saadi et al., 2015). In more humid climates, the negative effects of trees are likely to be less severe, making it easier to gain an overall advantage. Mediterranean climate is characterized by rainy winters and dry hot summers (Arenas-Corraliza et al., 2018) which may induce water stress during the dry season. Therefore, we expect that tree-crop interactions will be strongly negative during winter/spring when water availability was high leading to a crop growth penalization. However, positive interactions may become more significant during the post-anthesis stage where drought (terminal hot heat, less rainfall …) occurred.

4.3 Can negative interactions be reduced by monitoring cultural practices.?

Crops management optimization in agroforestry is still limited. The selection of appropriate crop species e.g. shade tolerant, cropping technologies (Catacutan and Naz, 2015) as well as the suitable mixture is a real limit of agroforestry systems (Kay et al., 2019). However, agroforestry monitoring is a key element in providing a "win-win" relationship between crop and trees. Farming practices may have a significant effect in improving productivity and reducing negative interactions. For example, the choice of the spatial arrangement of crops (e.g. planting distance (Wang Qi et al., 2017) is also a key success. Competition for resources (light, water and nutrients) is more intense closest to the trees row, leading to a greater loss of yield (Newman et al., 2007;Campi et al., 2009). The appropriate trees density, which depend on tree size and age, may lead to improve the crop performance. According to (Singh et al., 2007), Mature trees with less than 200 trees.ha^{-1} density may improve understory performance. In addition, light interception determine the photosynthetic efficiency (Nadir et al., 2018) received by the understory crop and may reduce crop growth (Dufour et al., 2013). Tree shoot pruning is a potential tool for managing above-ground competition for light leading to enhance light availability to understory crop (Dufour et al., 2020). Other practices were suggested to reduce underground competition, such as tree root pruning in agroforestry, which could limit root development in shallow soil horizons (H. D. Inurreta-Aguirre et al., 2018). In addition, the main advantage of intercropping, including grain legumes, reduces fertilizers inputs (Hauggaard-Nielsen et al., 2008) through the capacity of legumes to fix the atmospheric nitrogen can enhance soil nitrogen available (Dwivedi et al., 2015) for trees, and thus have positive effects on tree production.

5. Objectives and study hypotheses:

The general objective of the thesis is to assess the relevance of agroforestry systems to deal with the current challenges, particularly with increasing aridity, optimizing the productivity of cropping system. Based on a theoretical framework provided by the SGH, which promote more positives interactions within associations with increasing aridity. Our study focus on olive-based agroforestry system evaluation through analyzing tree effects on crop performance, and system productivity comparatively to sole cropping system. The adopted approach included a quantitative assessment of crop performance as the result of the different interactions (positive and negative) according to water availability gradient. Thus, we used the annual crops growth response to interspecific interactions as well as the agronomic performance (yield and yield components) of crops and system. Precisely, this thesis aims to (i) evaluate barley performance in olive-based agroforestry system along aridity gradient; (ii) to evaluate the growth parameters determining of yield variability in an olive-based agroforestry system at field scale; (iii) to identify the best olive tree-crop combination that contributes to the best productivity of the land.

The main hypothesis of this work can be formulated as following:

Inspired by the theoretical framework of the stress gradient hypothesis, crop diversification in agroforestry modulates negative interactions in dry areas, but leads its increase with the increase of water availability.

Sub-hypothesis 1: Crop performance (yield and yield components) depends on the ability of the associated species to establish positives interactions.

Sub-hypothesis 2: The development of negative interactions starts at early growing crop stages (from the beginning of the crop cycle).

Sub-hypothesis 3: Yield components will not be similarly impacted by negatives treecrop interactions.

Sub-hypothesis 4: The validity of the stress gradient hypothesis 'SGH' is partial, where positive relationships occur during warm seasons when olive trees negatively affect crop growth before flowering but improve grain filling after flowering under water-limiting conditions (Fig.5).

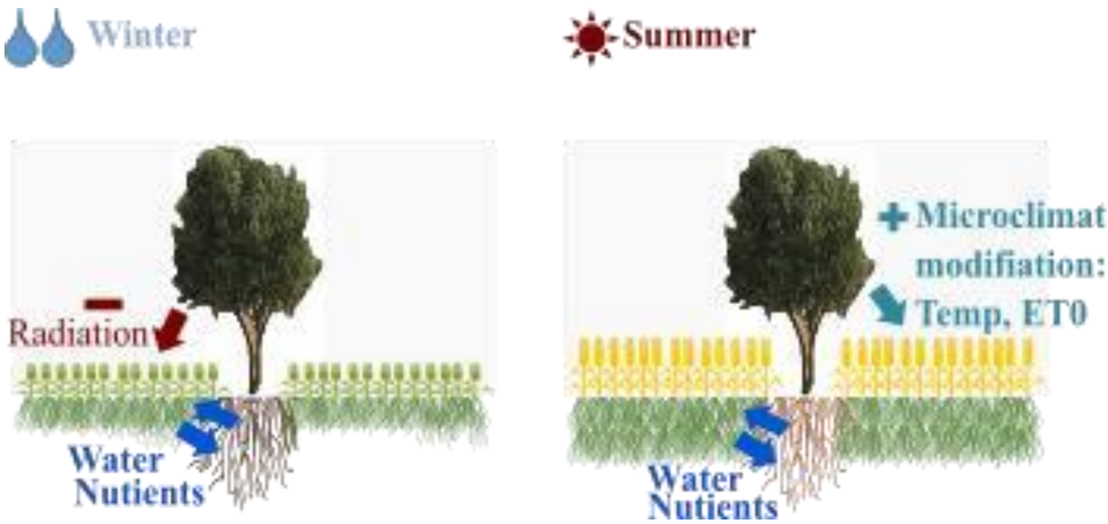

Figure 5: Presentation of the fourth Sub-hypothesis.

6. Organization of the manuscript:

This work is structured according to 6 chapters (Fig.6). The second chapter presents the sites of the surveys and experiments as well as the methods used to address the research problem. The third chapter analyzes agroforestry systems compared to sole crops according to an aridity gradient at three sites in northern Morocco, aiming to evaluate the stress gradient hypothesis and identify pedoclimatic and farming factors affecting crop performance. This chapter is presented in the form of an article submitted for publication to the journal Agriculture, Ecosystems & Environment. The fifth chapter aims to make a conceptual modeling through dynamic assessment of water flows within a pure cropping and agroforestry system. The sixth and last chapter corresponds to a general discussion of the results obtained, clarifying the research biases and the field of the validity of the results, the scientific perspectives.

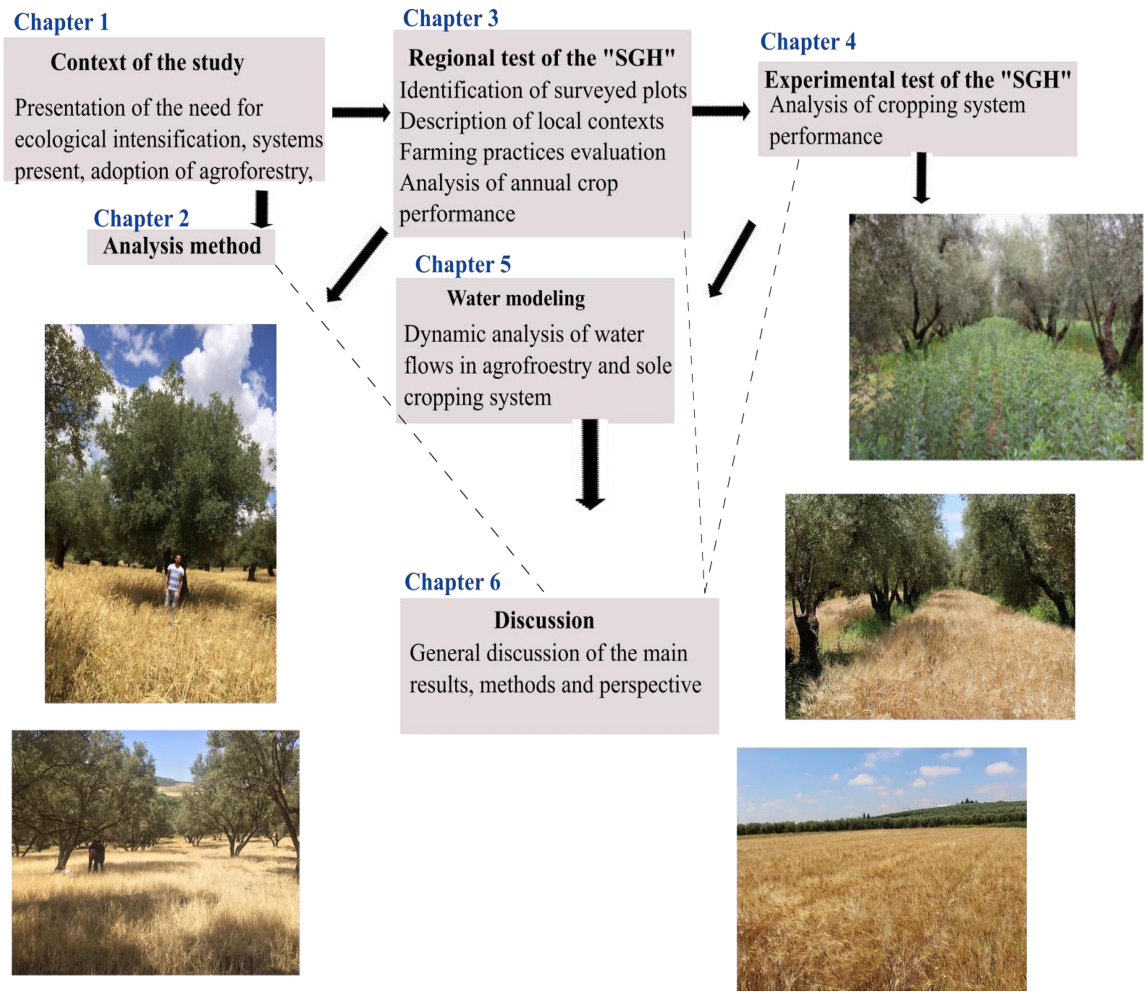

Figure 6: General methodology of the thesis.

CHAPTER II General Methodology

1. General approach

Agroforestry consists of growing two or more crops on the same unit area (Malézieux et al., 2009), allowing to increase and maintain land productivity (Bai et al., 2016) through optimizing the use of environmental resources (Zhang et al., 2007). However, agroforestry success will be driven by resources availability especially water, which is considered to be the most limiting resource (Butterfield et al., 2016) in arid and semi-arid areas. The evaluation of agroforestry systems performances according to a water availability gradient is the object of our study which consists in an innovative approach to analyze the hypothesis of stress gradient (Holmgren & Scheffer, 2010) on cropping systems. Therefore, the approach followed in this thesis work was based on a comparative analysis of sole and olive based agroforestry system. This evaluation is organized around three levels of evaluation whose objective was to bring more information to understand these systems: a general evaluation level “the regional diagnostics”, a most precise level “experimental analysis” which will be finally completed with a mechanistic evaluation of water flows in agroforestry and sole crops by Biswat model.

The used approaches were presented bellow (Fig.7). The first one consists on evaluation of barley performance under trees in agroforestry and in sole cropping system surveyed on a regional scale along an aridity gradient. In this part of our study, we used data from surveys made during 2016/2017growing season in three sites in northern Morocco, which allow us to analyze an existing agroforestry system (olive trees-barley) and sole barley taking into account the agricultural practices. The second approach provide more information to olive-annual interactions based on an experiment which gave more light on the effect of olive trees on two crops among the most associated with the olive tree: a legume and a cereal. Finally, based on hydric data from the experimentation (part 2 of the study) the evaluation of the Biswat model (third approach) was carried out followed by a modeling analysis of the water flows in agroforestry and in cultivation alone.

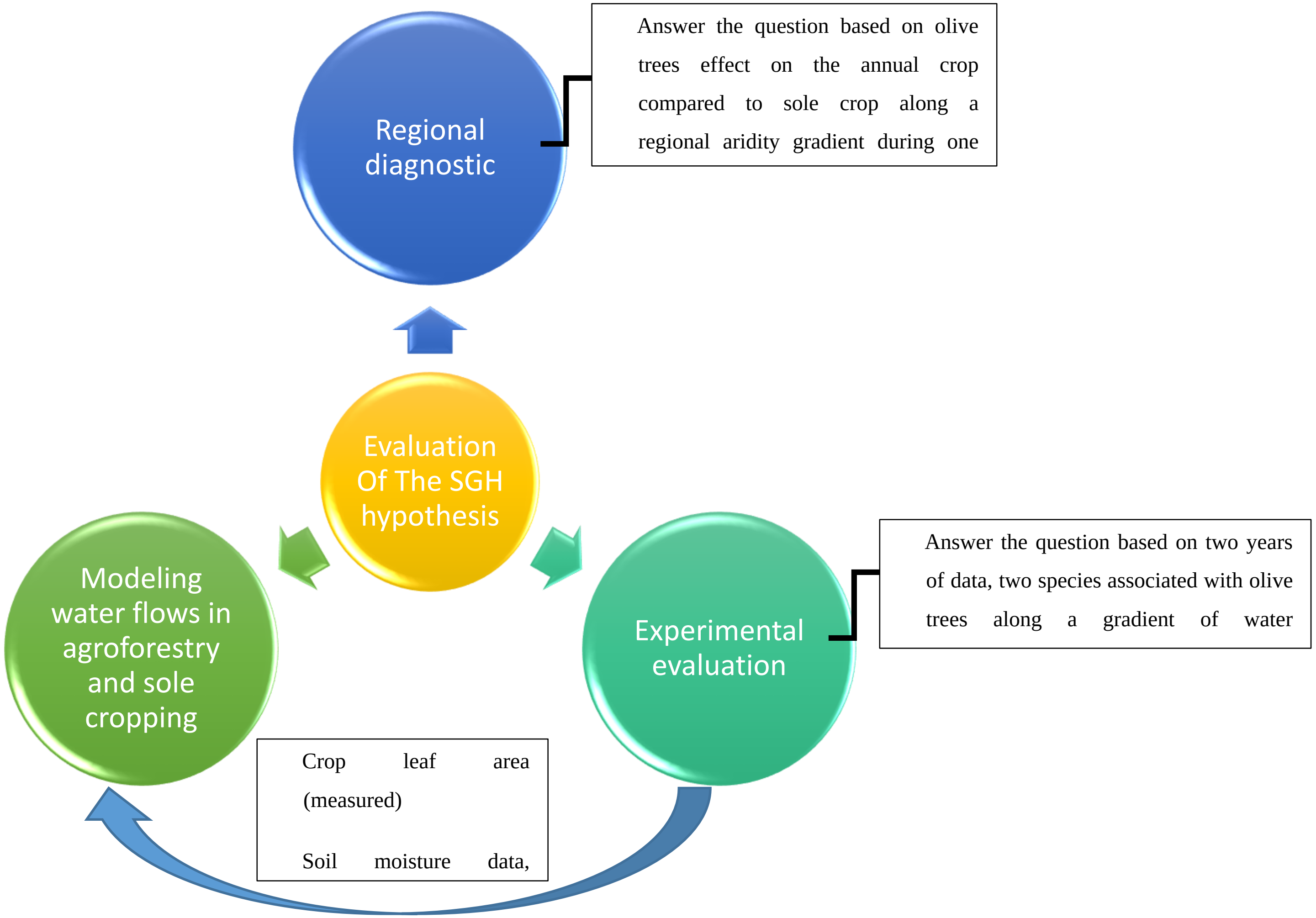

Figure 7: The different approaches followed in the study.

2. Study sites

Among the oldest perennial and evergreen crop in the Mediterranean basin, olive tree presents a typical landscape cultivation which returns to an old time (Loumou & Giourga, 2014). Olive farming is one of the pillars of economic development in these regions (Fraga, 2019), which provide 95% of the world supply of olive oil (Balkan & Meral, 2017). North Africa and particularly Morocco is one of the 7 main producers of olive oil (Balkan and Meral, 2017) and second main producer of olive cans (El Mouhtadi et al., 2014) in the world. Covering 60% of the arboreal Moroccan area, the olive tree is the first fruit tree in the country with a contribution of nearly 5% to the gross domestic product (GDP) (Dugué, 2014). In addition, Morocco developed a new strategy “The Green Morocco Plan” in 2008 aiming to improve agricultural production including the olive sector by 2020 and the introduction of high productivity cereals based on modern (Saidi, 2011) and adapted technologies to climate change (Akesbi, 2012). According to this strategy, Moroccan olive production will be more important due to the extension of olive orchard up to 12 M ha by 2020 (Boulal et al., 2012) as well as the reconversion of cereals to olive groves (Balaghi et al., 2010). However, drought, especially through rainfall reduction (Abdelhedi & Zouari, 2018), led to agricultural production decline. Consequently, olive orchards especially those growing in rainfed field are localized in northern Morocco (49% of total olive growing area, table 1)(International olive council (IOC), 2019), cannot escape the threats of climate change. Other crops from olive based agro-system such as cereals (e.g. barely) and legumes (e.g. lentils, chickpea…) including local varieties can be found (Aumeeruddy-thomas et al., 2016). According to Razouk et al., 2016, the olive groves (about 75%) are generally associated with annual crops (e.g. wheat, faba bean…) especially for food but also for livestock feed (vetch, forage peas…).

Table 1: Area of olive cultivation by region.

Regiones	Rainfed area (ha)	Irrigated area (ha)	Total (ha)
Fez-Meknes	299.911	46.375	346.286
Marrakesh-Safi	47.151	167.950	215.102
Tanger-tétouan-AlHoceima	160.432	2.306	162.737
Oriental	55.598	67.005	122.603
Beni Melal-Khénifra	33.281	46.796	80.077
Rabat-Salé-Kénitra	56.727	9.408	66.135
Souss-Massa	2.506	16.950	19.455
Draa-Tafilalet	1.546	14.262	15.808
Casablanca-Settat	3.506	11.319	14.826
Guelmim-Oued Noun	-	2.157	2.157
Total	660.658	384.528	1.045.186

Thanks to its geography, Morocco climate is characterized by the diversity of its bioclimatic sub-zones such as: per-humid, humid and sub-humid in altitude, semi-arid in the Atlantic plains and the Oriental, arid (Sabir et al., 2020) inducing a variation of average annual rainfall going from 100 mm to 2000 mm. According to (Sabir et al., 2020), a wide range of soil types also were identified in Morocco with more or less complex landform (plains, mountains…).

2.1. Study sites: the survey approach

Our study focused on 3 districts province, which allows us to present a rainfall gradient ranging from 461 mm to 707 mm. Taza (34°13'12.20 "N, 4°01'02.72"O), Meknes (34°03'33.14 "N, 5°31'35.62"O) and Ouezzane (34°47'43.25 "N, 5°34'02.34"O) were located in Northeastern Morocco. Rainfed olive-based agroforestry system was widely practiced in these three regions. Secondly, 7 farms from each cropping system (agroforestry and sole annual crop ‘control’) and region were selected locally on the basis of the following characteristics which were common in all studied fields: (i) rainfed cropping systems (since plantation) (ii) mature olive trees and 'Picholine Marocaine' variety.

Ouezzane study site “Wet site”: is located in the pre-Rif area and characterized by medium altitude mountains (below 350 meters) (Hajjam et al., 2018). The climate is sub-humid Mediterranean with a dry summer season with temperatures and with a cold to mild winter (adpn, 2020). The province is surrounded by mountains of medium altitude with an average annual rainfall of 707 mm (Chafchaouen wheather station). The average of temperature is 19.5°C *(https://fr.tutiempo.net/)*. The climatic water deficit in Ouezzane is (CWD= - 467.32 mm). A wide diversity of cropping systems can be observed in the region including sole crops e.g. cereals, chickpeas, faba beans… (Bouvet and Guillaume, 2014), or mixed cropping systems e.g olive trees, fig.... Rainfed orchards e.g. fig (Salih, 2020) and olive trees was wide spread in Morroco.

Meknes study site “Medium Arid site”: is localized between two mountainous the pre-rif and the western middle Atlas (hcp, 2017). The climate is characterized by a Mediterranean semi-continental climate, with cool and rainy winters and hot and dry summers (hcp, 2017). The mean annual precipitation and temperature are 484 mm and 19 °C respectively *(https://fr.tutiempo.net/)*. The climatic water deficit (CWD = - 695.82 mm). The agricultural area covers 142500 ha of which 53.7 % is reserved for cereal crops, 12.1 % for legumes and 23.8 % for fruit plantations. Known its olive groves, Meknes also called “Meknassa Zaitouna” (Denis et al., 2011) is the capital of the olive tree. Other crops also exist in this region such as market gardening and oilseed crops (hcp, 2017).

Taza study site “Arid site”: is located between the rif and the Atlas. The climate is arid semi-continental. The average rainfall (461 mm) (*https://fr.tutiempo.net/*) occurs between October to May and a hot and dry season (between June and September) (Haji et al., 2012). The average temperature is 21°C. The climatic water deficit is (CWD= - 793.63 mm). Cereals and legumes are the main crops in the region (80.2 %). The dominant fruit tree species are olive and almond, with 64.1 % and 32 % respectively (Abdelmajid et al., 2012).

2.2. Study sites: the experimental approach

The second step of our study consist on an experimental evaluation. The experiment was conducted in an olive orchard in north-eastern Morocco (Sefrou Province), at the 'La Providence Verte' Louata farm (33°53'48.26''N, 4°40'25.63''O) during 2017-2018 and 2018-2019. The region was characterized by a semi-arid climate with a dry and hot summer and a cold wet winter. The average annual temperature and precipitation over 29 years were 19°C and 473 mm, respectively. During the experiment, the total rainfall (from October to July) was 429 mm and 345 mm in 2017-2018 and 2018-2019 respectively. Agroforestry systems and the orchard control were both located in the same olive grove. Sole crops were sown in an adjacent open field plot (100 m apart) with similar soil properties. In the top 0-0.6 m, soil has a sandy clay loamy texture (table 2). Both soils were calcareous with an average pH equal to 9, 1.62 % organic matter and 0.09 % total Nitrogen.

Table 2: Some soils characteristics of the experimental field Louata, Morocco (Source: Labomag).

	Agroforestry plot	**Sole cropping plot**
Soil layer (m)	0-0.60	0-0.60
Granulometry (%)		
Clay	28	28
Silt	21	17
Sand	54	55
Soil fertility		
Organic matter (%)	1.72	1.53
Total N (%)	0.10	0.08
C/N ratio	10.31	10.53
CEC meq/100g	12.27	9.93
pH	8.98	9.02
calcaire total (%)	64.78	72.07

Calcaire active (%)	12.75	13.12
Majors component (mg/Kg)		
CaO	10292.50	10322.17
P-olsen	23.33	50.83
K2O	158.33	177
MgO	1108.67	876
Soil Salinity		
Cl (Extrait1/5, mg/100g)	4.92	2.82
Electrical conductivity (Extrait 1/5, mS/cm à 25°C)	0.18	0.16
NaO2 meq/100g	158.17	91.67

3. Target species

In this work, we study olive based-agroforestry system (Olea europea, subsp. *europaea*, cv. 'Picholine marocaine') comparatively to sole cropping system. Traditionally cultivated, the main variety of olive trees in Morocco is picholine variety (Olea europea, subsp. europaea, cv. 'Picholine marocaine'), which cultivated in 90% of the orchards (El Mouhtadi et al., 2014). Phenological stages of olive trees were described by 8 principal growth stages (Fig.8) (Sanz-Cortés et al., 2002). However, alternate behavior, which consists on the production of a heavy fruit crop in the "On" year followed by an "Off" year in which the tree may produce no or limited fruit yield(Kour et al., 2018). This phenomenon is widespread in olive trees.

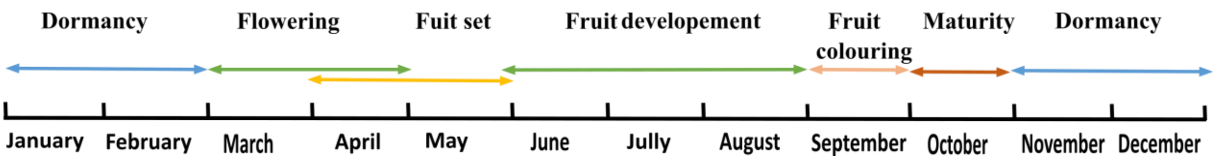

Figure 8: Development of olive trees during the growing season (Walali et al., 2004).

In addition to the production of olive trees, cereals play an important role in the agricultural production in Morocco (Fig.9) (Akka Aït EL Mekki, 2006). Wheat, durum wheat and barley present the most important cereals in Morocco (Balaghi et al., 2013). According to Balaghi et al., 2013, these three cereals have a common sowing period which starts from the end of October until December depending on rainfall. In addition, cereal crops growing cycle includes several growing stages starting with seed germination, emergence, tillering, stem elongation, flowering and grain filling (Alaoui, 2004). In addition, legumes are a very old crop, which were located in regions with favorable rainfall. According to (Harbouze et al., 2019), 48% of the total legumes area were destined to faba bean. Faba bean crop cycle is defined by several key stages such as emergence, leaf stage, flower buds, early flowering, young pods, limit abortion stage, late flowering and Maturity (*https://www.terresinovia.fr/-/les-stades-reperes-de-la-feverole*). These annual crops (e.g. wheat, barley, faba bean…) may be found associated with olive trees (Razouk, Daoui, Kajji, et al., 2016).

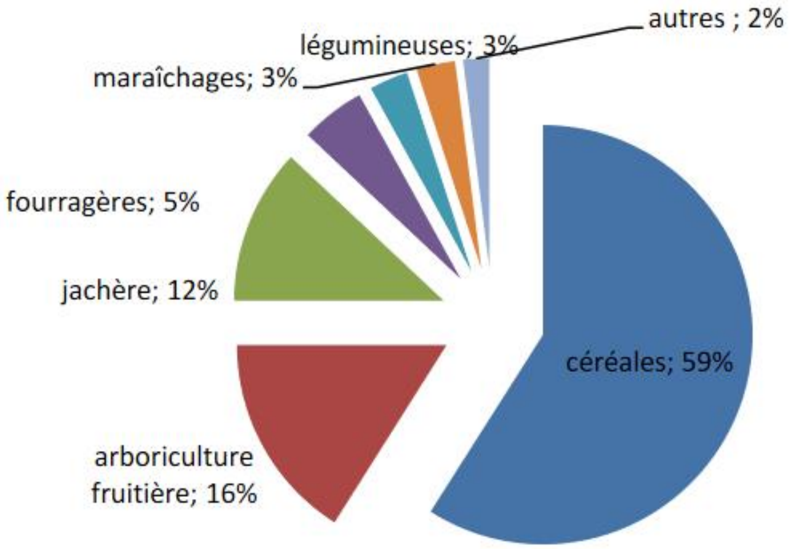

Figure 9: Distribution of the useful agricultural area by crop (Harbouze et al., 2019).

4. Overview of the different data sets

Several types of data were obtained according to the followed approach during this work such us:

Crop management data: Agricultural practices applied to annual crop (Survey approach)

Climate & soil data: Rainfall, temperature, soil texture… (Survey & experimental approach)

Yield data and yield components: Grain and straw yields, Number of ears/Pods… (Survey & experimental approaches)

Yield protein content: Experimental approach

Soil moisture data: Experimental and modeling approaches

Survey approach data: In this section, we studied the performance of an annual crop: barley (Hordeum vulgare L.) in olive based-agroforestry system (Olea europea, subsp. *europaea*, cv. 'Picholine marocaine') and in sole cropping system, considering the effect of resulting variables of agricultural practices and pedo-climatic conditions obtained from surveys along a gradient on the yield and its components. For the data collection in this section, we initially collaborated with several actors: professors from the IAV-Institut (Agronomic and Veterinary Institute, Morocco), DPA (Provincial Directorate of Agriculture) and ONCA (National Office of Agricultural Consulting) that allowed the delimitation of olive based-agroforestry areas. Consequently, three sites of study were selected (presented before). In each studied sites, 14 farms were selected including 7 farms from each cropping systems (olive-barley agroforestry system and sole barley) leading totally to 42 selected farms equitably distributed over the three study sites.

The farms were selected according to the common following criteria: (i) farmer's availability to answer the questions, (ii) non irrigated cropping systems 'Rainfed' and (iii) mature orchard where 'Picholine Marocaine' was the planted olive trees variety. Data were collected during field visits based on direct observation and small discussions with farmers. These discussions were structured around the following themes (see supplementary materials):

- Field localization, area (ha)
- Planting ages (year) and trees density (trees.ha^{-1})
- Specific agricultural practices applied to crops in both cropping systems
- Annual crop 'barley' biomass sampling at harvest on a total of 9 quadrats of 0.25 m^2 (9 quadrats / plot) in agroforestry ,in order to take into account the effect of olive trees in the plot, and 3 quadrats (3 quadrats / plot) in sole barley.
- Soil sampling (granulometric analysis, chemical soil analysis : pH, total C,P_2O_5 K2O, OM and total nitrogen)

Experimental approach data: this section allowed us to evaluate olive trees effect on crop growth and yields along a water availability gradient. For this reason, three different water regimes were simulated using drip irrigation where two thirds of sub-plots of each type of system ('AF', 'OR', 'SC') were equipped with ten ramps equipped with drippers spaced 40 cm apart, and having a flow rate of 2 $l.h^{-1}$. The remaining sub-plots were not irrigated to have rainfed controls. In each water regime, crops and trees received the same amount of water. For technical reasons, three water regimes were not randomly distributed but arranged in adjacent areas. A frequential analysis of rainfall of the past 29 years (Fig.10) was used to determine the amount of water addition needed to simulate typical 'wet' (563 mm), 'normal' (471 mm), and 'dry' (356 mm) years. We defined three levels of water supply: high water supply ('water++'), a medium water supply ('water+'), and no water supply ('Rainfed') to simulate. However, the challenge in such water manipulation was to re-adjust the amount of water addition dynamically with rainfall each month. In 2018, rainfall was already sufficient to consider the year as a 'normal' year (429 mm). We, therefore, added water to simulate a very 'wet' year (+ 159.1 mm) and a moderately wet year (+ 72.7 mm). In 2019, rainfall was more typical of a 'dry' year (345 mm). We took the advantage to simulate a 'moderately dry' year (+ 50 mm), and a 'normal' year (+ 100 mm) with lower water addition than in 2018.

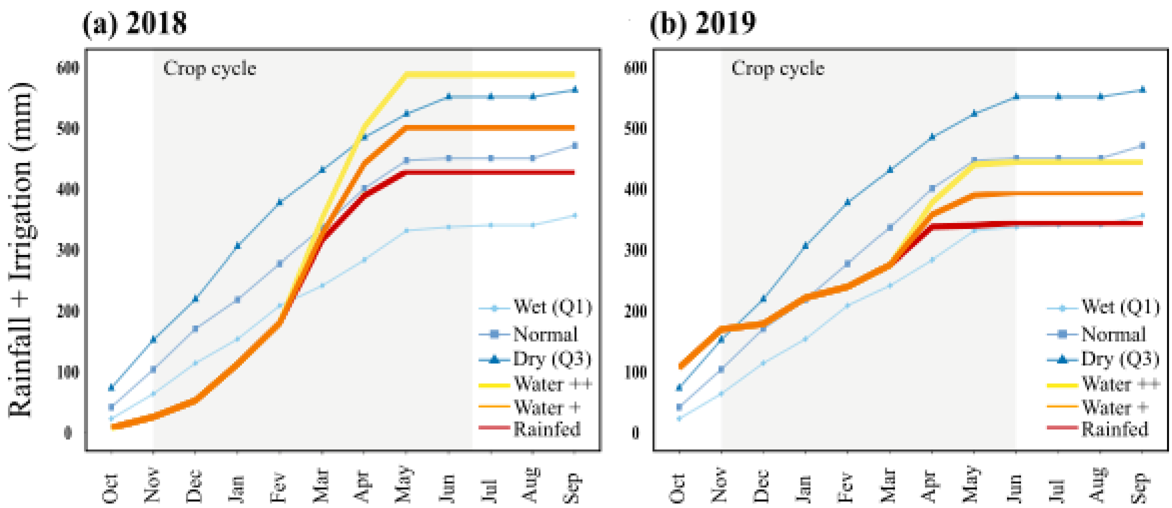

Figure 10: Rainfall frequency analysis over the past 29 years showing the total cumulated water supply (rainfall + irrigation) in 2018 (a), and 2019 (b), in relation to long-term quantiles (Q1: ‘dry’ years; Q2: ‘normal’ years; Q3: ‘wet’ years). The three water regimes are indicated as follows: ‘Water++’ water supply (yellow), ‘Water+’ water supply (orange), and ‘Rainfed’ modality (red). The dark green rectangle represents the crop growth cycle except in 2018 crop harvest in ‘AF’ was later and shown in clear green.

Crop performance evaluation was done based on crop growth assessment using 10 randomly selected plants avoiding border in each sub-plot at the flowering stage in 2018 and

2019. Plant ramification was determined by counting the number of viable tillers for wheat and branches for faba bean. At harvest, crop plants were entirely harvested at ground level using hand-clippers, taking four randomly selected 0.25 m^{-2} quadrats in 2018 or five adjacent 1 m lines in 2019 avoiding borders in each sub-plot. The olive yield per tree was estimated at harvest in each sub-plot on 9 selected trees. Olives were harvested by hand, and all fresh fruits weighed before transportation to the olive oil mill. Land equivalent ratio (LER) for crop grain and olive yields of each agroforestry system was calculated following Mead and Willey (1980), accounting for the reduction of cultivated area under trees (- 43 %) compared to sole crops. Both grain and straw protein content as indicators of crop quality were calculated. Nondestructive near-infrared spectroscopy (NIRS) analyses were performed for each plant sample after fine grinding. We used a scanning spectral range of (400–2.498 nm), which covers the widest wavelength range, as well as the visible spectrum to collect the spectral data of whole grains and straw biomass. Soil water content was measured with a capacitance profile probe (PR2/6, Delta-T Devices, Cambridge, UK) biweekly and weekly in 2018 and 2019 respectively. The PR2/6 probe used in the experiment measures soil moisture at 6 depths down to 100 cm at: 10, 20, 30, 40, 60 and 100 cm. The PR2 probe was combined with an HH2 moisture meter, which displays the profile probe readings through a voltage output converted to the square root of permittivity.

Modeling approach data: The third step of our study consist on a mechanistic evaluation of water flows in olive-wheat agroforestry system, sole olive trees and sole wheat. The model evaluation were made based on measured humidity data from the experiment (second approach of the study) on the studied cropping systems (olive-wheat agroforestry, sole olive trees and sole wheat).

The Bis-Wat model (Bi-specific water model, Bertrand et al., 2018) is a water balance model using a 2 dimensions pattern adapted to multi-species systems composed of two species in a row, which allows to simulate in daily time steps the soil water deficit perceived by f mono or bispecific crops. The main simulated outputs of the water balance were evaporation of water from the soil, transpiration of each species, runoff and drainage. It simulates the scene corresponding to the two-dimensional pattern delimited in width by the distance from the tree to the middle of the inter-row and by soil depth (figure below). Soil is defined by a number of soil layers and vertical columns in order to take into account water add with localized irrigation which were chosen by the user. In addition, the model uses integrative concepts aimed at simplifying the representation of a complex agro-system. Biswat uses the radiation interception efficiency for one or two crops to estimate the ET0. In addition, the model allows to estimate the perception of water stress (FTSW) of each species, even when they share the same soil layers and estimate root growth (in depth and width) based on thermal time (Bertrand et al., 2017).

Input data collection:

Two sources of data (Table 3) were used in order to be able to analyze the water dynamics of our cropping systems. Field measurements and observations were completed by data taken from the literature in order to overcome the difficulty of measuring them on the experiment.

- Climate variables: rain (mm), minimum and maximum temperature were obtained from mini meteorological station of the farm where the experiment was made and ET0 (mm) was estimated using the adjusted Thornthwaite equation (Trajkovic et al., 2019)

$$ET_{0TH,i} = \frac{16Ni}{360} \times \left(\frac{10Ti}{\sum_{i=1}^{12}(0.2\,Ti)^{1.514}}\right) \times 0.016 \times \sum_{i=1}^{12}(0.2Ti)^{1.514} + (0.5)$$

With: Ni: The maximum possible duration of sunshine (h day^{-1}); Ti: mean air temperature in the i^{-th} month (°C).

- Tree/ crop shoot architecture was described by using radiation interception efficiency (RIE) which was determined using (Eq.1) including the leaf area index which was measured for wheat at flowering using the leaf portable area meter (LICOR LI-3000C, Lincoln, Nebraska). However leaf area index of olive tree was determined from literature (de Saint Roman, 2019).

Eq 1: $\boldsymbol{RIE} = \mathbf{1} - \boldsymbol{e}{-}\boldsymbol{K}\times\boldsymbol{LAI}$, with: k: the extinction coefficient ranging from 0 to 1; LAI: leaf area index at flowering for wheat.

- Because of the laborious work to describe trees and crop root architecture, such as the length and depth of roots, which has been obtained from the literature (Table 3).

- Soil water parameters (e.g. field capacity and wilting point) were measured using soil samples collected from the experimental field.

- θminus is the critical humidity for each soil layer for a plant (m3.m-3) due to the complexity of its measurement in the field, this parameter was considered to be equal to the permanent wilting point for both species.

Table 3: Biswat input parameters.

Parameter	Source
ErdMax_B_mm & ErwMax_B_mm: Maximum Effective Rooting Depth and Width respectively of the annual crop	(Farahani and Bruggeman, 2008); (Farahani and Bruggeman, 2008)
ErdMax_A_mm & ErwMax_A_mm: Maximum Effective Rooting Depth an Width respectively of olive tree	(Abid Karray et al., 2008); (Fernández et al., 1992)
θ_{FC} : Soil water content at field capacity for each soil layer ($m^3.m^{-3}$)	Measured
θ_{WP}: Soil water content at wilting point for each soil layer ($m^3.m^{-3}$)	Measured
θ_{minus}: Critical humidity for each soil layer for a plant ($m^3.m^{-3}$)	Equal to θWP

5. Statistical analysis

Surveys approach: The analysis of the data from the surveys was initiated by a Multiple Factor Analysis (MFA), where data was structured into groups in order to summarize those that best describe our plots (individuals). The variables are organized in groups as follows: the first group (a categorical variable specifying the nature of crop precedent), the second group presents cropping practices, the third group presents the soil variables, and the fourth group presents the climatic variables. Then, a mixed linear model was used to estimate the cropping system effects, agro-climatic indicator (quantitative data is the first axis of MFA results), soil indicator (qualitative data is the second axis of MFA) and their interactions on grain and straw yield. The linear mixed was used to test the effect of cropping system, soil, and agroclimatic variables on intercrop yield at the quadrat level. *More details were provided in chapter 3*

Experimental approach: We tested the differences in crop growth, yield components, final grain yield, and grain protein content using ANOVAs with three factors: (1) type of system ('AF', 'OR', 'SC'), (2) water addition ('High' water supply, 'Medium' water supply, 'Rainfed') and (3) year (2018, 2019). Each crop species (durum wheat and faba bean) was tested separately. After significant ANOVA ($p < 0.05$), the means were compared with Tukey multiple comparison test. The relationships between final grain yields, total aboveground biomass at the flowering stage, and yield components were tested with linear regressions.

CHAPTER III. How does the intercropped barley performance vary along an aridity gradient? Assessment of olive-barley interactions in response to pedoclimatic factors and smallholder practices in northern Morocco

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Abstract:

Agroforestry systems can be an effective means of maintaining or even enhancing crop yields under climate change in the drylands. In agroforestry, trees compete with crops for soil resources, but they can also improve the growing conditions of understory crops under drought by providing shade. Inspired from ecological theory, the stress gradient hypothesis (SGH) suggests that positive interactions become more important than negative interactions between trees and crops with increasing environmental stress (e.g. aridity). To test the predictions of the SGH in agroforestry, we assessed and compared the variations of barley biomass and grain yield at harvest in olive agroforestry (AF) and sole crops (SC) along a regional aridity gradient in northern Morocco. We surveyed 42 plots (21 in agroforestry, 21 in sole crops), described the farming practices with the farmers, and sampled soil and plants in 9 and 3 quadrats respectively in "AF" and "SC" in each selected plots. The climatic water deficit varied from – 467.32 mm to – 793.63 mm between the wettest (Ouezzane) and the driest (Taza) sites. We found that the most intensive farming practices at the driest sites and the least intensive at the wettest sites, both in AF and SC. Overall, barley yields in AF were reduced by 55% compared to SC. Grain yield differences along the aridity gradient were 0.474 $g.m^{-2}$ but grain yield differences between AF an SC was the lowest at the driest site. The number of grains per unit area was the most impacted yield component. In contrast, intensification did not improve yields. Our results suggest that positive interactions between olive trees and crops can gain in importance under increasing drought, making the impact of competition less significant. They reveal the relevance of the SGH in guiding novel agroforestry systems based on fruit e.g. olive trees in a drier future.

1. Introduction

Drylands agriculture is facing several threats, most significantly, climate change (SeifEnnasr et al., 2016), which led to less availability of natural resources (e.g., rainfall reduction…) (Tramblay et al., 2012) and consequently reduced crop productivity for a continuously growing population (Kmoch et al., 2018). Agroforestry, which combines annual crops and trees in the same unit area (Malézieux et al., 2009), was considered as an effective means to mitigate the imbalance between the rapidly growing population and the limited arable land resources (Gao et al., 2013). Agroforestry promotes many benefits through e.g., enhancing soil fertility (Zhang et al., 2018), and especially the maintenance or even the improvement of food production under climate change (Lin, 2007). For these reasons, farmers have traditionally used several fruit trees (e.g., fig, carob, and quince) as a base for agroforestry system to enhance their income and feed livestock. In southern Mediterranean regions such as Morocco, agroforestry is frequent and represents a traditional practice including a diversity of agroforestry systems such as silvopastoral systems (Laouina, 2010), oasis systems (Daoui and Fatemi, 2014), almond and olive tree-based intercropping systems (Daoui and Fatemi, 2014; Kmoch et al., 2018). Several surveys conducted with Moroccan smallholder farmers have shown that about 75% of olive orchards are associated with several species of cereals such as barley (Razouk et al., 2016), which shows a wide range of adaptation to climatic conditions as well as to low input cropping systems (Amri et al., 2005).

Further to the potential positive advantages of agroforestry systems, many interactions can occur between trees and crops (Pinto et al., 2005) that may be neutral, beneficial or potentially harmful (Reynolds et al., 2007). The balance between belowground and aboveground interactions determines resource use and trees impacts on crop yields. The reduced performance of crops in complex systems is generally attributed to negative interactions (Callaway et al., 2002). Trees reduce crop productivity through reducing light availability to understory crops (Yang et al., 2016). Intense competitions for water and nutrients may also occur between tree and crop rooting systems (Singh et al., 2012). However, microclimate modification due to tree shading can have a major beneficial impact on crop performance (Li et al., 2010) by buffering hot air temperatures during the final stages of development mainly in water development stages water-limited areas (Lott et al., 2009). In addition, the net balance of tree-crop interactions within agroforestry system depends on several factors such as climatic conditions (O'Brien et al., 2017) such water availability.

Moreover, negative interactions for water is the main determinant of crop productivity in semi-arid agroforestry (Livesley et al., 2004). According to the 'Stress-GradientHypothesis' (SGH), negative interactions (competition) between species shift to positive interactions (facilitation) with increasing abiotic stress (He et al., 2013). In sub-humid areas, receiving more than 800 mm year^{-1}, acacia has a negative impact on cereal yield, suggesting that yield improvement was shown with lower rainfall (Bayala et al., 2012). The effects of trees also provide a facilitative effect in drier sites (MAP < 550 mm), allowing an improvement in understory crop biomass through the tree 'nurse' effect (Moustakas et al., 2013). In addition, the net balance of tree crop interactions depends on tree density (Singh et al., 2007) and other agronomic practices (e.g., seed rate, fertilization, weed management…) applied to the intercrop (Kaur et al., 2014). The SGH hypothesis has been initially tested in different habitats (e.g. plant communities, savannah and park) and climates (Armas et al., 2011), but its validity has not been tested in agroforestry systems. Recent examples in semiarid conditions are promising (Gao et al., 2018) where a deeper use of water resources by jujube in agroforestry was observed in dry conditions leading to a complementary use of water.

In this study, we investigated how environmental and management factors can modify tree-crop interactions and influence the intercrop yield across a rainfall gradient. The assessment was done on barley intercropped in olive groves under contrasting water situations in Northern Morocco. Our hypotheses derived from the 'SGH', which were: (i) olive trees enhance crop yields under the driest situation where crop intensification is expected to be lower; (ii) olive trees may reduce yield variability and improve understory crop yield stability under stressful environmental conditions; and (iii) Cropping system intensification through fertilizers application and weeding should improve understory crop yields and minimize the yield gap in the wettest conditions.

2. Materials and methods

2.1 Study site

Our study covered a wide range of olive-based agroforestry systems in the Pre-Rif mountains and the Sais plain in northern Morocco (Fig. 11). We studied three representative locations known for their rich diversity of agroforestry systems and farming practices: Ouezzane (34°47'43.25 "N, 5°34'02.34"O, 614 m), Meknes (34°03'33.14 "N, 5°31'35.62"O, 504 m) and Taza (34°13'12.20 "N, 4°01'02.72"O, 513 m). The climate is semi-arid with a strong Mediterranean influence, alternating hot and dry summers with cold and wet winters. The rainy periods occur between October and April. The average annual temperature and precipitation vary from West to East and ranged from 17.8. °C and 707 mm (Ouezzane), 18,4

°C and 484 mm (Meknes) to 20 °C and 461 mm (Taza) (data from the Chefchaouen weather station),. In order to characterize the climate of the studied sites, the Normalized Precipitation Index (SPI, Pathak and Dodamani (2019)) was calculated using the SPI (Rstudio), package. This index indicates meteorological drought and defines the number of standard deviations in precipitation that the cumulative precipitation observed on a given time scale would deviate from the long-term average. Another drought index was calculated to evaluate the water climatic deficit in the three regions.

2.2 Aridity gradient

The changes in climatic conditions from West (Ouezzane) to East (Taza) resulted in an aridity gradient. Site aridity was assessed based on the climate water deficit index (CWD), calculated as the difference between the annual precipitation (P) and the cumulated evaporative demand (ET_0). We used the Thornthwaite equation to estimate ET_0 and represent seasonal and temporal moisture availability (Dilts et al., 2015). For each site, ET_0 was calculated at monthly intervals for the studied year and for the last 7 years using the data available at https://fr.tutiempo.net/climat, Aridity ranged from -467.3 mm at the wettest end of the gradient (Ouezzane) to – 695.8 mm (Meknes) and – 793.6 mm (Taza) at the driest end of the gradient.

Eq1: $\mathrm{ETP(mm)} = \boldsymbol{F}(\Lambda) \times \mathbf{16} \times \left(\mathbf{10} \times \frac{T_m}{I}\right)^{a}$

Where: Tm: is the average of monthly air temperature in °C a: is a defined

coefficient as : $a = 6.75\times10^{-7}\times I^3 - 7.71\times10^{-5}\times I3 + 1.75\times10^{-2}\times I + 0.49239$ I: annual

thermal index: I=Σ im

im: is a monthly thermal index defined as: $\mathrm{im} = \left(\frac{Tm}{5}\right)^{\mathbf{1.514}}$

F(ʎ) : is a correction factor taking into account the latitude and the number of daylight hours

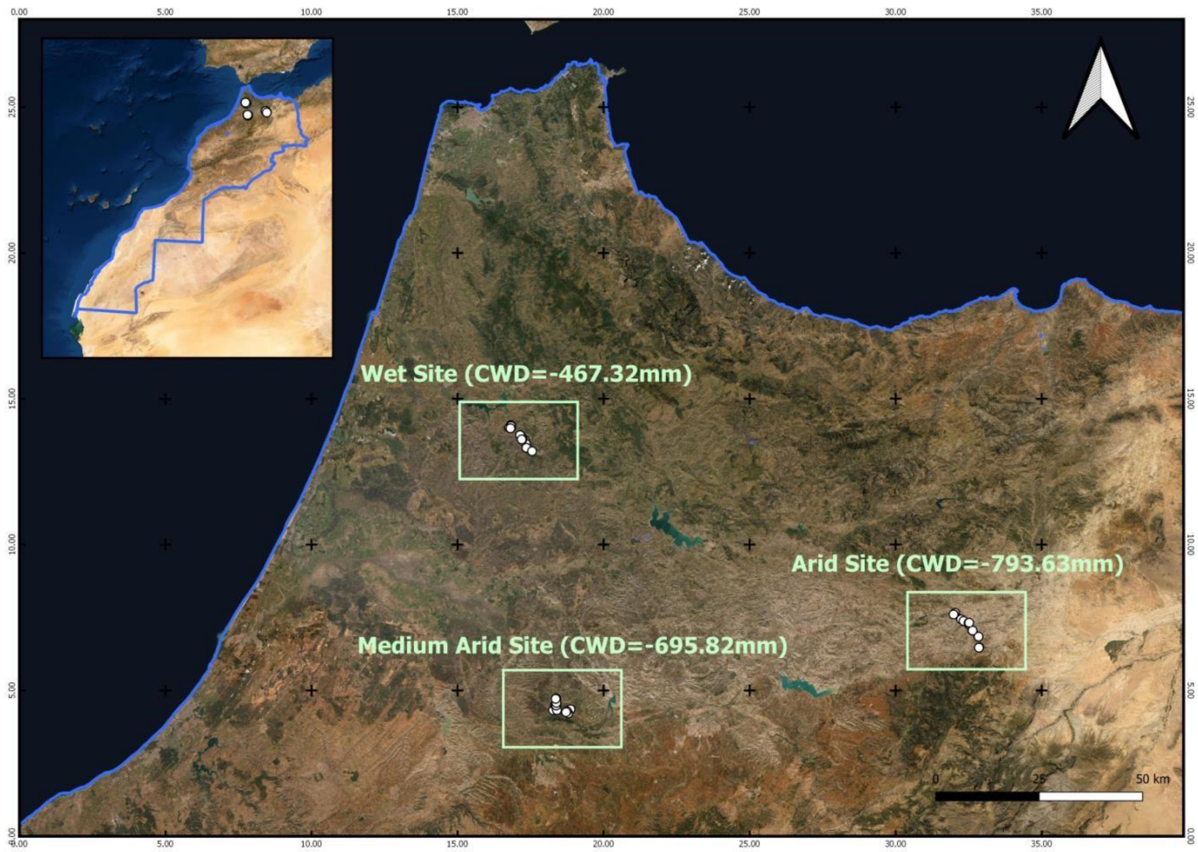

Figure 11: The study area is located in Northern Morocco

2.3 Field data collection

Study area:

Creation of plot network

A total of 42 plots (21 in agroforestry, AF; 21 in sole crops, SC) were identified along the aridity gradient, with an equal distribution between the three main locations (Ouezzane, Meknes, Taza). Criteria to select AF plots were (i) the variety of olive trees (*Olea europea*, subsp. *europaea*, cv. 'Picholine marocaine' representative of most olive groves and agroforestry systems); (ii) the age of olive groves (trees age > 25 years old to have a mature agrosystem); and (iii) the species of intercrops (barley was the most during study year in 2016/2017). As far as possible, SC plots (barley) were selected in the same farm or close to the AF plots in order to have reliable controls and comparison. We held 42 interviews with farmers, which covered 14 fields in each type of cropping system (AF vs. SC).

Farmers survey

Farming practices were described with farmers in 2017 and the most relevant drivers of barley yield were identified for both types of agrosystems (AF and SC). We held 42 interviews with farmers, which covered 14 fields in each type of cropping system (AF vs. SC). The survey included descriptive variables like field size, crop management, including information on seeds variety, sowing dates and farm management (management of crop residues, weeding and fertilization). For AF plots, additional information was collected like planting density and age of trees. Finally, nine variables were used to describe annual crop management plans of barley, namely the sowing date, the sowing rate, the sowing method (manually or mechanically), the crop variety, the amount of nitrogen (N) and phosphorus (P) fertilization, and the amount of herbicide used.

2.4 Soil sampling

For each plot, multiple 42 soil samples were randomly taken at a depth of 0 to 30 cm, using a 5 cm-auger. Samples were aggregated at the plot level to conduct the chemical analyses. The soils were then air-dried and analyzed in the laboratory for granulometric analysis, pH, total C, K2O, OM and total nitrogen. The useful water reserve (UR) of plots was determined from laboratory moisture measurements of the field capacity and at the permanent wilting point, while bulk density was extracted from soil maps (FAO, 2007).

2.5 Crop sampling

Barley samples were taken in 2017 at harvest, in order to estimate grain yield and yield components in both cropping systems. Barley total biomass (straw and grain) and grain yield was estimated through plant sampling on a total of 9 quadrats of 0.25 m^2 (9 quadrats / plot) in agroforestry and 3 quadrats in sole barley. A higher number of quadrats was needed in AF plot to consider the spatial heterogeneity created by trees (e.g., shade). Plants samples were oven-dried to a constant weight at 70°C during 48 h. Yield components were also assessed (e.g., number of spikes per unit area, number of grains per unit area and thousand-grain weight).

2.6 Statistical analysis:

The analysis of the data from the surveys was initiated by a Multiple Factor Analysis (MFA), in which the variables were structured into four distinct groups: (i) the nature of preceeding crop (e.g., legume or cereal) ,(ii) farming practices (e.g., amount of nitrogen, phosphate and amount of herbicide), (iii) soil variables (e.g., clay content, sand content, total nitrogen, organic matter, soil water holding capacity and K2O content), (iv) the climatic variables (e.g., the minimum and maximum temperature of the study year, and of the last 7 year in average, the CWD index of the year of study and of the last 7 year in average). The two first axes of the MFA were used to summarize the aridity gradient and the management gradient between plots. The coordinates of each plots gave their position along both gradients and then were used as explanatory variables in the next steps.

A linear mixed modelling approach was used to estimate the effects of cropping system (AF vs. SC), local aridity (first axis of MFA), soil fertility management (second axis of MFA) and their interactions on barley grain and straw yield. We compared the ‘full’ model to a series of ‘reduced’ models with less variables and finally to a ‘null’ model (Table 4). The model selection was carried out using Akaike Information Criteria corrected for small sample size (AICc): The lowest the AICc, better the fit to the data. Models with ΔAICc between 2 and 5 were considered equivalent to each other. In addition, we calculated the marginal R^2 (R2m) and conditional R^2 (R2c) to evaluate the explanatory power of random and fixed factors, respectively.

The relationships between final grain yields and yield components were tested with simple linear regressions. The data were analyzed using R software (R Development Core Team 2009-2018, version 3.6.0) and the "FactoMineR" and "Factoextra" package for MFA analysis, “lme4” package for mixed models and AICcmodavg package for marginal and conditional R^2 and MuMIn package for AICc. Finally, the yield gap was calculated as the average of the differences between the barley yield in sole cropping ‘SC’ and in agroforestry ‘AF’ divided by barley yield in ‘SC’ considered as reference.

Table 4. Model selection for the relationship between barley grain yield, as explained by cropping system, ('agroclimatic'), and soil management variables ('pedological'). The selection was based on AICc values. The best model the lowest AICc is shown in bold. Models with ΔAIC<5 were considered as equivalent to each other. The marginal and conditional R2 (R^2m and R^2c, respectively) are given for each model.

	AICc	**ΔAICc**	**R^2 m**	**R^2 c**
(intercept)	2945	106.4	0	0
~ system	2858	19.14	0.30	0.30
~ agroclimatic	2946	107.3	0	0
~ system × agroclimatic	2840	1.41	0.36	0.36
~system × pedological	2858	19.01	0.31	0.32
~ system × agroclimatic + system × pedological	2842	3.76	0.36	0.37
~ system × agroclimatic × pedological	**2839**	**0.00**	**0.38**	**0.39**

3. Results

3.1 Description of agrosystems and farming practices

The majority of plots in the three study areas varied from 0.1 ha to 2.5 ha. AF and SC plots size had an average size of 1.24 ha and 0.57 ha in Ouezzane (‘wet site’), 1.34 ha and 0.82 ha in Meknes (‘medium site’), and 1.11 ha and 0.68 ha in Taza (‘dry site’). Tree density were 74 trees.ha^{-1} in Ouezzane, 89 trees.ha^{-1} in Meknes and 76 trees.ha^{-1} in Taza Most orchards in Ouezzane (85 %) and Meknes (70 %), olive trees showed a traditional plantation design (not rows of trees), while 100 % of orchards were planting in rows. Olive plantations age ranged from 35 to 150 years, the oldest olive plantation was found in Meknes (95 years), while the mean tree age was 55 years old in both Ouezzane and Taza. Olive trees were regularly pruned in 100 % of orchards in Meknes, less frequent in 57 % in Taza and 14 % of cases in Ouezzane. In most cases (95.3 %), farmers used traditional varieties of barley in AF and SC plots. Only a very small proportion used commercial varieties in Taza. In both types of cropping system, the majority of farmers (64,3 %) sowed barley early (October-November), while less than 33.3 % sowed later in early December and only 2.4 % in early January. Three types of succession were identified: cereals (e.g., wheat), legumes (e.g., faba bean…) and fallow land. However, the majority of farmers cultivated legumes before barley (55 %), particularly in Meknes (72 %) and Taza (57 %). 19% of cropping systems was unfertilized and mainly in agroforestry.

Agro-pedoclimatic factors variation along the aridity gradient: MFA was carried out for all soils, climates and agronomic practices applied to barley. The first two main components of the MFA (MFA1 and MFA2) together explained 42.6 % of the environmental and management variability between the plots (Fig. 12). The two main components give an overview of the covariation between the variables that contribute most to the heterogeneity of the individual fields. The MFA1 (22.70 %) captured the variations in local aridity and revealed that the water climatic deficit were positively correlated with the farming practices (N fertilizer rate, P fertilizer rate). The MFA2 (19.90 %) captured the variations in soil texture and fertility (K_2O, MO and Total Nitrogen). Soil fertility covaried positively with the percentage of silt and clay, and negatively with the percentage of sand. Fertilization appeared to be correlated with a high water deficit while fertility attributes appear to be influenced by soil texture. Overall, MFA1 could be interpreted as an agro-climatic gradient indicating the levels of aridity and the level of agricultural intensification. Similarly, MFA2 could be interpreted as a pedological gradient.

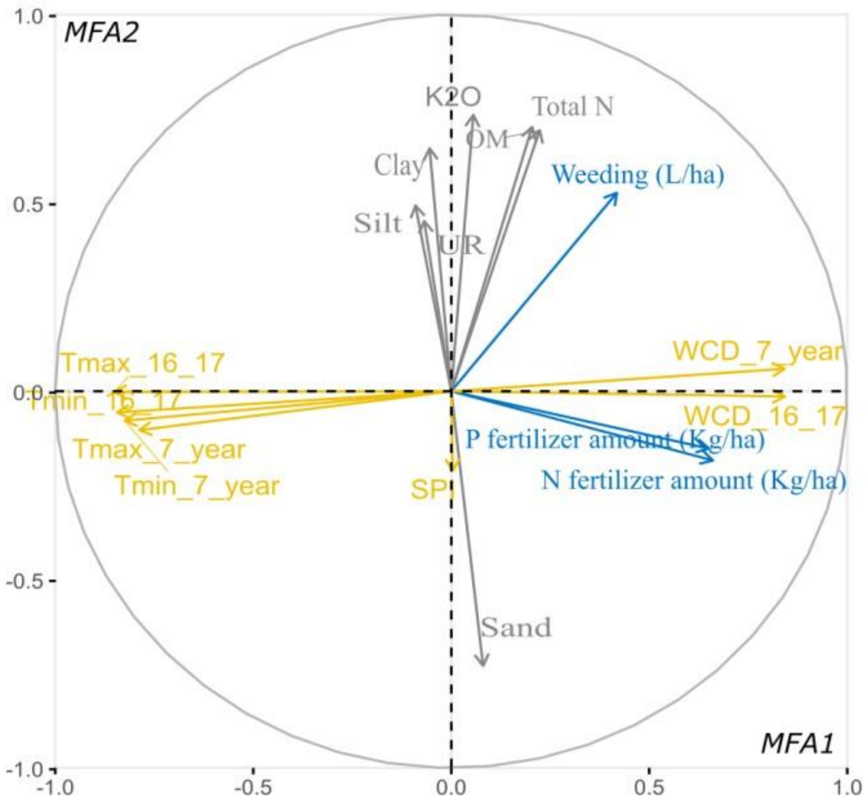

Figure 12: MFA loading plot of farming practices (blue) and climate (yellow), and soil attributes (grey). MFA1 (agro-climtic gradient) and MFA2 (pedologic gradient) explained 22.7 % and 19.9 % of the total variability, respectively.

3.2 The response of barley production to aridity and farming practices

The highest barley grain yield at harvest were found in Meknes (129.6 $g.m^{-2}$) and Taza (113.1 $g.m^{-2}$) comparatively to Ouezzane 'wet site' (76.6 $g.m^{-2}$). The average grain yield gap between SC and AF ranged from 0.37 to 0.66 ($g.m^{-2}$). In addition, the average straw yield gap ranged from 0.47 to 0.65 ($g.m^{-2}$). Grain yield gaps between SC and AF differed significantly between sites ($p = 0.019$, Fig. 13A; However, there was no significant differences in straw yield gaps ($p=0.139$, Fig. 13B).

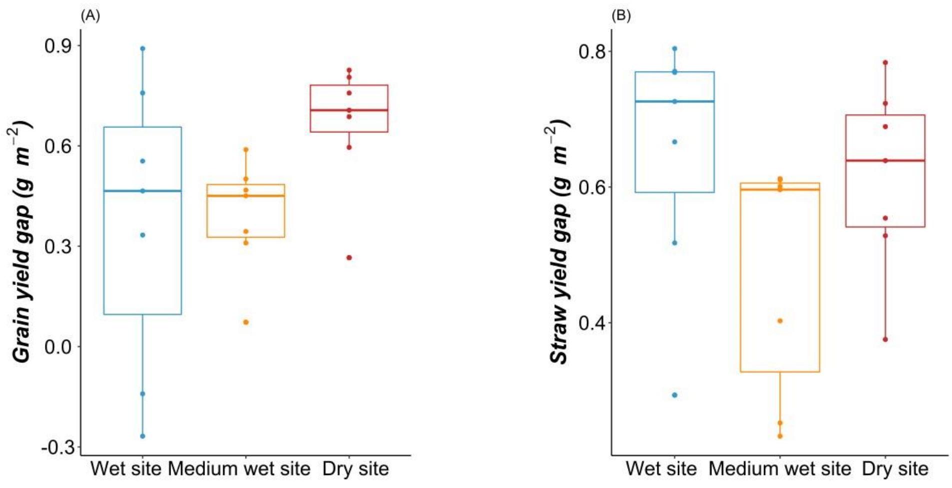

Figure 13: Grain (A) and straw (B) yield gaps between SC and AF (g.m^{-2}) at harvest for barley. Boxplot color indicates the aridity gradient: (blue: Ouezzane, 'wet' site; orange: Meknes, 'Medium wet' site; red: Taza, 'Dry' site.

Grain yield variations were best explained by the model that combines cropping system, agroclimatic (coordinates of plots on MFA1) and pedological (coordinates of plots on MFA2) conditions as fixed effect (R2 m = 0.38, R2 c = 0.39, Fig 14, Table 4).

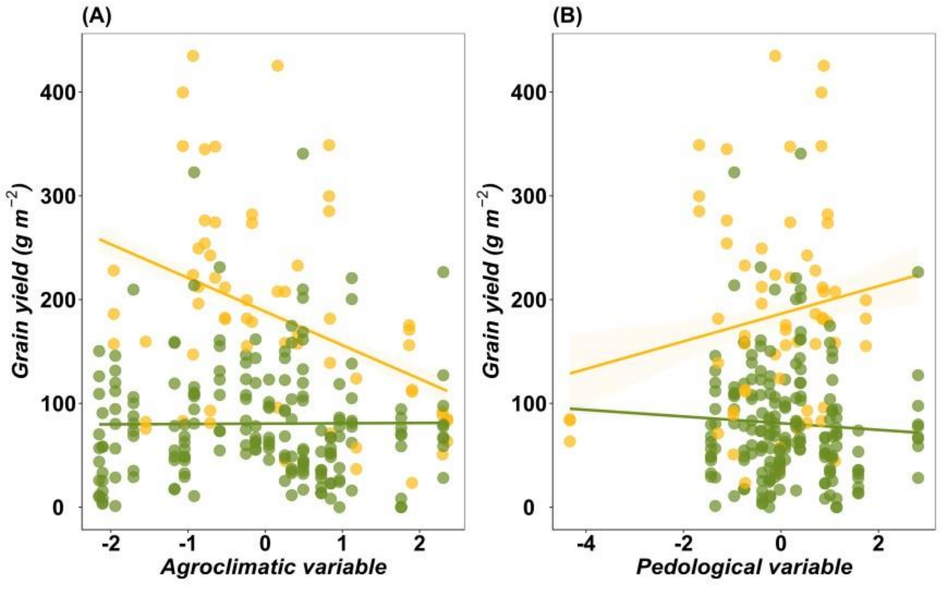

Figure 14: Grain yield variations along (A) the agroclimatic and (B) the pedologic gradient. Colors indicate the type of cropping systems: 'AF' (green) and 'SC' (yellow). Colored lines present the predicted effect of the agroclimatic and pedological variables according to the best mixed model.

The cropping system had a significant effect on both grain ($p<0.001$) and straw ($p<0.001$) yields. Overall, grain and straw yields were 56 % and 59 % lower in AF than in SC.

The agro-climatic and pedological gradients both also had a significant impact but only on grain yield (p= 0.005, p= 0.008, respectively, Table 3). Grain yield decreased with increasing aridity. The two-way interaction between cropping system and the agro-climatic gradient was significant only for grain yield (p<0.001). Grain yield decreased more in SC plots than in AF plots when increasing aridity (Fig.14). The three-way interaction between cropping system, and the agro-climatic and pedological gradients was significant both for both grain (p = 0.017, Table5) and straw yields (p<0.001, Table 5).

The number of grains per unit area was a significant determinant of barley grain yield in AF (r^2 = 0.90, p< 0.001, Fig. 15A) and SC (r^2 = 0.94, p< 0.001, Fig. 15A) plots. Significant variations in the number of spikes partially explained the variations in the number of grains of barley in SC (r^2= 0.21, p = 0.038, Fig. 15A) but not in AF (r^2= 0.07, p= 0.227, Fig. 15B) plots. Cropping system had a significant effect on thousand-grain weight (p<0.001). Thousand-grain weight was 19 % and 18 % higher in SC than in AF under medium (Meknes) and dry (Taza) sites. The two-way interaction between cropping system and the agro-climatic gradient was significant for thousand-grain weight (p<0.001). The three-way interaction between cropping system, and the agro-climatic and pedological gradients was significant for thousand-grain weight (p = 0.003).

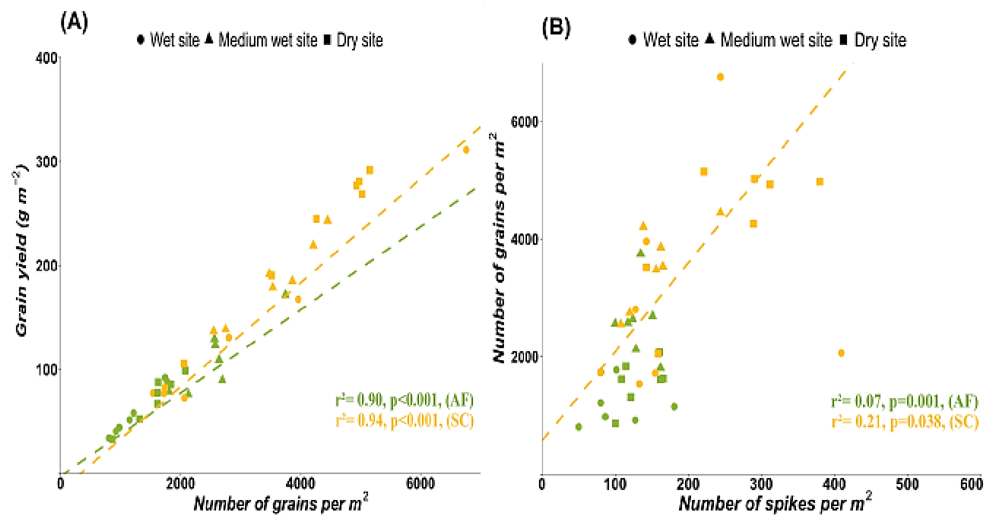

Figure 15: Relationships between (A) barley grain yield (g.m^{-2}) and the number of grains (m^2) (A); and (B) between the number of grains (m^{-2}) and the number of spikes (m^{-2}). Linear regressions were performed separately for agroforestry (light green lines) and sole crops (yellow lines). The circles correspond to Ouezzane (wet site), the triangles to Meknes (medium site), and the rectangles to Taza (dry site).

Table 5. Test of fixed factor of the best linear mixed-model for grain and straw yields.

Fixed factors	χ^2		**df**		**p-value**	
	Grain yield	Straw yield	Grain yield	Straw yield	Grain yield	Straw yield
system	120.7	149.0	249	249	p<0.001	p<0.001
agroclimatic variable	3.58	0.279	249	249	p= 0.005	p= 0.596
pedological variable	1.92	0.883	249	249	p= 0.008	p= 0.347
system × agroclimatic	17.16	0.347	249	249	p<0.001	p= 0.555
system × pedological	<0.001	1.16	249	249	0.178	p= 0.280
system × agroclimatic × pedological	5.72	13.66	249	249	0.017	p<0.001

4. Discussion

4.1 Olive trees reduce barley productivity, but promote more stable yields along the aridity gradient.

In dry semi-arid areas, introducing trees can improve crop productivity and buffering heat stress (Krishnamurthy et al., 2019). Overall, crop yields are the result of environmental factors (e.g. topography), soil fertility, and climatic conditions (e.g., rainfall, temperature…) (Glover et al., 2013). However, the appropriate agronomic practices according to local pedoclimatic conditions are still far from optimal in agroforestry. Our study showed a significant reduction in barley yields in agroforestry. The magnitude of yield reduction was around 55 % on average, more than other examples from temperate and Mediterranean areas. Comparable yield reductions have been recorded for wheat under a dense shade, e.g., under paulownia trees (Li et al., 2008) or artificial shelters (Artru et al., 2017), suggesting that the shade provided by mature olive trees was significant for crop yields. However, the density of olive trees in the studied fields was on average 80 trees per hectare not higher than recommended trees density in agroforestry, which is usually below 200 trees.ha-1 (Singh et al., 2007) suggesting that tree shade was not the major limiting factor. To reduce shade effect, pruning was used to restore light availability to understory crops (Dufour et al., 2020) and reduce tree water requirements (Jackson et al., 2000). On farm level, olive tree pruning was not maintained as a regular management practice, leading to tree crown development and more intense shade. Laborers unavailability and high cost of pruning were the main causes that did not encouraged farmers to adopt pruning permanently.

In a Mediterranean climate, we expected that tree shade would have strong negative effects under the wettest conditions, where light, more than water, may limit crop yield, leading to significant differences between agroforestry and sole crops (Temani et al. *in press*). In contrast, we expected that tree shade would improve crop growth and yield under waterlimiting conditions by buffering heat (Peng et al., 2015) and water stresses (Campi et al., 2009). However, the reduction of barley grain yield was on average, 70 % in the driest conditions compared to 55 % in the wettest conditions. The thousand-grain weight was also lower in agroforestry compared to sole cropping. Contrary to what Mugunga et al. (2017) suggested, these results suggest that the expected positive effects of olive trees did not improve grain filling through beneficial microclimate modifications (e.g. solar radiation reduction, cooler temperature…). The reduction of final crop grain yields in agroforestry rather was a direct consequence of the reduced grain number per unit area (Xie et al., 2016; Kimura et al., 2018; Zhang et al., 2019) and grain weight. The reduction of the number of grains in agroforestry may be explained by an intense competition during tillering reducing the number of spikes (Sharif et al., 2010). We showed that grain yield differences between AF and SC plots are highest in the wettest site, suggesting that agroforestry may promote more stable crop yield (Nasielski et al., 2015). The ability of agroforestry to buffer large yield differences along the gradient of aridity can be considered as a partial validity of the SGH predicting a positive outcome of positive tree-crop interactions with increasing environmental stress.

Intensified smallholder practices did not impact barley performance

Farming practices in agroforestry play a key crucial role in improving system productivity at small farms (Mbow et al., 2014). Moreover, farming practices variability (e.g., weeding, fertilizer rates…) was probably another leading cause of yield variability. Barley yields were reduced in agroforestry all along the aridity gradient level suggesting that other limiting factors such as fertilizers, impacted yields. The low rate of fertilization implemented in Ouezzane, where water availability was probably less limiting than in the other sites, may have created a situation where nutrients became the limiting factor. Simultaneously, the synchronization between the timing of fertilizer application and heavy rain intensifies nutrients leaching (Kaur et al., 2017), particularly of nitrate, which in turn reduced the total amount of nitrogen available in the soil. Surprisingly, farmers applied high rated of fertilizers in Taza where water was strongly limiting. As expected, fertilization did not increase grain yield under these dry conditions revealing the non-efficient use of nutrients compared than those who apply less in wet conditions. These results may be explained by a water deficit in the dry site due to lower rainfall coupled with high temperatures, which lead to barley yield reduction (Tanaka and Nakano, 2019). In addition, the late crop sowing reduces developmental periods and consequently, final yield (Öztürk et al., 2008). Herbicides application did not result in yield increase, which may be due to inappropriate timing of weed control, inefficient use of herbicides or to low levels of weed invasion (Swanton et al., 2008). Our study reveals the predominance of the local crop varieties, farmers generally preferred local barley varieties for self-consumption and livestock feed because of the higher cost of improved varieties. The decline of barley performance in the agroforestry system under wet site suggests that fertilizer alone may not meet farmers yield expectations and might be due to farmers using lower than recommended fertilizer rates, while intensified agricultural practices especially in the dry site where water is limited may lead to ineffective fertilizers application. Our study emphasizes the necessity to use agricultural techniques that are more adapted to the climatic context and cropping system by using early information on rainfall to help farmers decide to appropriate crop management. Other practices may be developed to enhance complementarity between species in agroforestry, such as root pruning using shallow tillage to limit underground competition for water.

Conclusion

We showed that olive trees caused a significant reduction in final grain yield regardless of the local environmental conditions through the reduced number of grains per unit area. Barley performance reduction along the aridity gradient suggest that water is not the only yield-limiting factor. Indeed, the reduction in barley performance may be due to other limiting factors such as shade, nutrients. Crop management may also affect the understory performance e.g. tree pruning and crop management. On the other hand, we found that barley grain yields differences was lower in dry conditions, this finding may be promoting of sustainable tree-crop interactions. However, it would be interesting to evaluate olive trees yields to verify olive-barley system performance in order to assess if this kind of agroforestry, which is well spread in our context of study, will be advantageous even in an arid climate.

CHAPTER IV. Olive agroforestry can improve land productivity even under low water availability in the South Mediterranean

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Abstract

Agroforestry systems can be an effective means of stabilizing or even enhancing crop yields under climate change. In agroforestry, trees compete with crops for soil resources, but they can also improve the growing conditions of crops under drought by providing shade. They can promote higher crop yields and higher harvest quality. However, the beneficial effect of tree shade may depend on the seasonal pattern of rainfall, which determines the compensation between yield components. In this study, we evaluated the production of two annual crops (durum wheat and faba bean) in olive agroforestry in northern Morocco. We manipulated water supply in a field experiment to span the high inter-annual rainfall variability at the site and tested whether olive trees reduce or improve crop yields. We assessed the effect of water addition on crop growth, yield components, and final yields and estimated the land equivalent ratio of olive agroforestry. Agroforestry limited crop growth and yield whatever the water regime. The magnitude of grain yield reduction was around 50 % on average for both crops in 2018. The number of grains per unit area was the most impacted yield component in both 2018 and 2019. Water addition had limited effects on faba bean yield, but medium supply enhances wheat grain yield by 11%, and the number of spikes per unit area by 13 %. Agroforestry improved individual grain weight by 39 % for wheat and 17% for faba bean, and enhances the protein content of wheat grains and straw by 4 % and 9 %, respectively. However, improvements in protein content and individual grain weight were not sufficient to compensate for yield loss. Overall, we show that agroforestry systems are generally more land productive than sole crops and trees even under arid conditions. We show how changing water supply may impact the performance of olive agroforestry in a drier future.

Keywords

faba bean, Morocco, stress-gradient hypothesis, tree-crop interactions, wheat, yield components

1. Introduction

In the Mediterranean, the rapid population growth increases food demand (Bodirsky et al., 2015), making global food security a major concern (Smith et Glauber, 2019). Despite the increasing use of irrigation, fertilizers, and pesticides (Iglesias et al., 2018), overall food production is insufficient and causes severe environmental degradation. Climate change is likely to induce more frequent extreme drought in the future (Ahmed et al., 2013), adding uncertainty to the already food insecure situation (Sieber et al., 2015). In the South Mediterranean, increasing aridity and drought threaten food production (Iglesias et al., 2011). The yield of rainfed crops entirely depends on rainfall, which is already highly variable from year to year (Latiri et al., 2010; Tafoughalti et al., 2018). Water scarcity also affects the quality of crop production, which dampens the economic and nutritive values of harvests. Today, farmers from these regions need to adopt new sustainable cropping strategies to reconcile crop productivity with conserving water resources.

Inspired by agroecological principles, fruit-tree-based agroforestry systems (FT-AFS) can stabilize or enhance food production under climate change in dry areas (Lin, 2007, Krishnamurthy et al., 2019). The most recognized advantage of agroforestry is the increase in the land- and resource-use efficiency, which results from complementary yield sources and positive interactions between trees and crops (Zhang et al., 2007). Specifically, FT-AFS are high-value tree agroforestry systems (den Herder et al., 2017), which deserve greater attention considering their contribution to food production (Wolz et al., 2018; Lauri et al., 2019). A wide range of FT-AFS exists in semi-arid regions with different tree species, e.g., apple-, apricot- and jujube agroforestry in China (Qiao et al., 2019), almond agroforestry in Iran (Surki et al., 2020), etc. In most cases, FT-AFS have advantageous land equivalent ratios compared to sole crops and trees (Bai et al., 2016 ; Zhang et al., 2016; 2018; Panozzo et al., 2019). In Morocco, olive- (*Olea europaea* L.) agroforestry is widespread (Sofo et al., 2007) and belongs to traditional forms of agriculture and proved its resilience through millennia.

Several species of trees (e.g., fig, carob, quince), cereals (e.g., wheat, barley), grain legumes (e.g., faba bean, chickpea) grow with/under olive trees (Daoui and Fatemi, 2014; Razouk et al., 2016; Lauri et al., 2019). The 'Plan Maroc Vert' aims the rapid extension of olive groves throughout arable lands (El Mouhtadi et al., 2014), opening novel opportunities for extending olive agroforestry beyond traditional forms. However, FT-AFS are absent from most agricultural policies, and they are disappearing (Nahayo et al., 2017; Ickowitz et al., 2019). Instead, sole cropping systems develop, pushed by input-based intensification and mechanization.

In FT-AFS, trees compete with crops for soil resources, but they can also improve the growing conditions of crops under drought, mainly by providing shade. They can promote higher crop yields (Artru et al., 2017; Smethurst et al., 2017) and higher harvest quality (Arenas-Corraliza et al., 2018; Qiao et al., 2019). In natural ecosystems, the 'Stress-GradientHypothesis' (SGH) predicts that negative interactions (competition) between species shift towards positive interactions (facilitation) with increasing abiotic stress (He et al., 2013). The rationale is that tall species like trees can beneficially modify the local environment and play the role of 'nurse' for smaller species like herbaceous crops. Under high-stress conditions, the amelioration of environmental conditions outweighs the direct effects of competition for resources. Although the relevance of the SGH remains unclear in the drylands (Maestre et al., 2005, 2009), meta-analyses suggest that trees have positive effects on biomass productivity when aridity exceeds semi-arid conditions (Moustakas et al., 2013; Dohn et al., 2013). For example, acacia trees have negative impacts on crop yields under humid and sub-humid conditions (rainfall > 800 mm year^{-1}), but improve the yields under semi-arid conditions (Bayala et al., 2012). Indeed, the shade of trees penalizes crop growth under favorable conditions (Cubbage et al., 2012) due to lower light interception and photosynthesis rates (Zhang et al., 2018; Rivest et al., 2009). However, shade creates a beneficial microclimate for crops (Lott et al., 2009; Mugunga et al., 2017) with buffered temperature (Peng et al., 2015), higher air humidity (Campi et al., 2009), and reduced evapotranspiration (Coussement et al., 2018) under more arid conditions. The validity of the SGH needs to be tested in FT-AFS, but recent examples in semiarid conditions are promising (Gao et al., 2018). The SGH formalizes the way trees can mitigate climate change in Mediterranean FT-AFS, and more generally, in the drylands (Luedeling et al., 2016).

The shift from negative to positive effects of trees predicted by the SGH may, however, strongly depend on the seasonal pattern of rainfall. In Mediterranean areas, autumn and winter are usually cold and rainy seasons with low evapotranspiration rates (Milner et al., 2012). In contrast, spring and summer are hot and very dry seasons with high evapotranspiration rates (Cramer and Hoffman, 2015). Water availability is usually high enough to sustain crop growth for most winter crops during their vegetative stage (Arenas-Corraliza et al., 2018). However, water deficit affects crops during their reproductive stage. Consequently, we expect that tree shade would negatively affect crop growth before flowering, especially in the case of evergreen species such as olive trees, which provide a permanent shade. By reducing crop growth, tree shade may also reduce the number of tillers (Inurreta-Aguirre et al., 2018) and spikes for cereals (Sharif et al., 2010), and the number of ramifications and pods for legumes (Lake et al., 2019), and finally, may reduce the number of grains per unit area which is a major yield component for crops (Xie et al., 2016; Zhang et al., 2019). In contrast, we can expect that tree shade would buffer drought stress during grain filling after flowering and improve grain sizes and quality (Campanha et al., 2004; Arenas-Corraliza et al., 2018; Qiao et al. 2019). The microclimate under trees helps to preserve soil water availability, extends the grain filling period (Wang et al., 2015) and improves the biomass remobilization towards grains (Li et al., 2010).

By buffering terminal drought, the loss of yield caused by reduced growth can be compensated by larger grain size and quality. Depending on the seasonal balance between negative and positive effects of tree shade, the compensation between yield components can lead to lower or higher crop yield in agroforestry than in sole crops. In the Mediterranean, summer drought will extend and intensify under climate change. Therefore, the positive effects of tree shade during filling will gain in significance in the future, leading potentially to higher yields in agroforestry. Yield compensation processes might be even more significant in crops with indeterminate growth, such as faba bean, due to their ability to pursue growth after flowering under favorable conditions. Kato et al. (2019) showed that indeterminate soybean varieties have a higher number of pods, grains, and yields than determinate varieties because of prolonged growth. Therefore, as long as trees maintain a microclimate favorable to growth in FT-AFS, the introduction of indeterminate growth crops such as faba bean should promote an increase in yield and system productivity.

Despite their relevance in a drier future, research on FT-AFS in the South Mediterranean has been very minimal. In this study, we provide a quantitative evaluation of cereal (e.g., wheat) and legume (e.g., faba bean) crop productivity in olive agroforestry under contrasting water regimes in Northern Morocco. We manipulated water supply during two successive years to span the entire interannual rainfall variability at the site, and tested the following hypotheses derived from the SGH: (i) olive trees reduce crop yields under the wettest water regimes but improve yields under the driest water regimes; (ii) olive trees negatively affect crop growth before flowering but improve grain filling after flowering; and (iii) overall, olive agroforestry systems are more land-productive than soles crops and trees, especially under the driest water regimes. We assessed the effect of water addition on crop growth, yield components, and final yields of both crops (durum wheat and faba bean) and compared the land equivalent ratios of olive agroforestry systems under the different water regimes.

2. Material and methods

2.1 Experimental site

We conducted a two-year field experiment (2017-2019) in an olive grove in northeastern Morocco (Sefrou Province), at the 'La Providence Verte' Louata farm (33°53'48.26''N, 4°40'25.63''O, 615 m). The climate is semi-arid with hot and dry summers and cold and wet winters. The average annual temperature and rainfall are 19 °C and 473 mm, respectively (1988-2017). Drought generally occurs between May and October. During the crop cycle (October to July), rainfall was 429 mm in 2017/2018 and 345 mm in 2018/2019, which correspond to 'normal' and 'dry' years, respectively . The soil has a sandy clay loamy texture (28% clay and 54% sand) in the top 0-0.6 m layer. Total N content in this soil layer was 0.09%, Olsen-P 37 mg kg^{-1}, and K_2O 167 mg kg^{-1} (Table A.1, Supplementary Material).

The olive grove (*Olea europea,* subsp. *europaea,* cv. 'Picholine marocaine') produces olive oil since its plantation in 1954 (65-years old trees in 2019). The density of olive trees was 200 trees.ha^{-1} with a regular 7×7 m plantation design. Olive trees were all of the similar size (5 m height) and were managed in the same way since the plantation as an irrigated grove. Before the experiment, inter-rows were left uncultivated and regularly weeded mainly with herbicides.

2.2 Experimental layout

We evaluated two different olive agroforestry systems ('AF'), one with intercropped durum wheat (*Triticum durum,* cv. 'Karim') and the other with intercropped faba bean (*Vicia faba,* cv. 'Alfia 17'). We compared agroforestry systems to corresponding sole crops ('SC') and pure olive orchard ('OR') used as controls. Agroforestry systems and the orchard control were both located in the same olive grove (Fig. 16). Sole crops were sown in an adjacent open field plot (100 m apart) with similar soil properties (Table A.1, Supplementary Material). In the olive grove, 27 sub-plots of 490 m² (35 m × 14 m) were assigned to either agroforestry systems (18 plots) or pure olive orchards (9 plots). Similarly, 18 sub-plots of 245 m² (35 m × 7 m) were assigned to sole crops in the open field. The experiment covered an area of 1.47 ha in the olive grove and 0.88 ha for sole crops. The spatial distribution of sub-plots was designed to apply three water regimes in adjacent areas, separated by an empty (uncultivated and non-irrigated) inter-row (see below), with three replicates of each type of system (Fig. 16).

The annual crops were sown in 4 m-wide strips using a mechanical seeder on November 29th in 2017 and December 22th in 2018. A rotation between wheat and faba bean was applied between the two years. The sowing rates were 150 kg.ha^{-1} (0.15 m between lines) for durum wheat and 120 kg.ha^{-1} (0.50 m between lines) for faba bean (Fig. 15). In agroforestry systems, crop strips started 1.5 m far from olive tree rows. The fertilizer application rate was different for wheat (63 kg ha^{-1} N, 34 kg ha^{-1} P in 2018; 30 kg ha^{-1} N, 34 kg ha^{-1} P in 2019) and faba bean (9 kg ha^{-1} N, 23 kg ha⁻1 P in both 2018 and 2019). In 2018, crops were harvested at different dates for sole crops (June 13th) and agroforestry (July 17th) due to significant maturity delay, but not in 2019 (June 11th). Olive trees were harvested in December (December 11th in 2018 and December 13th in 2019).

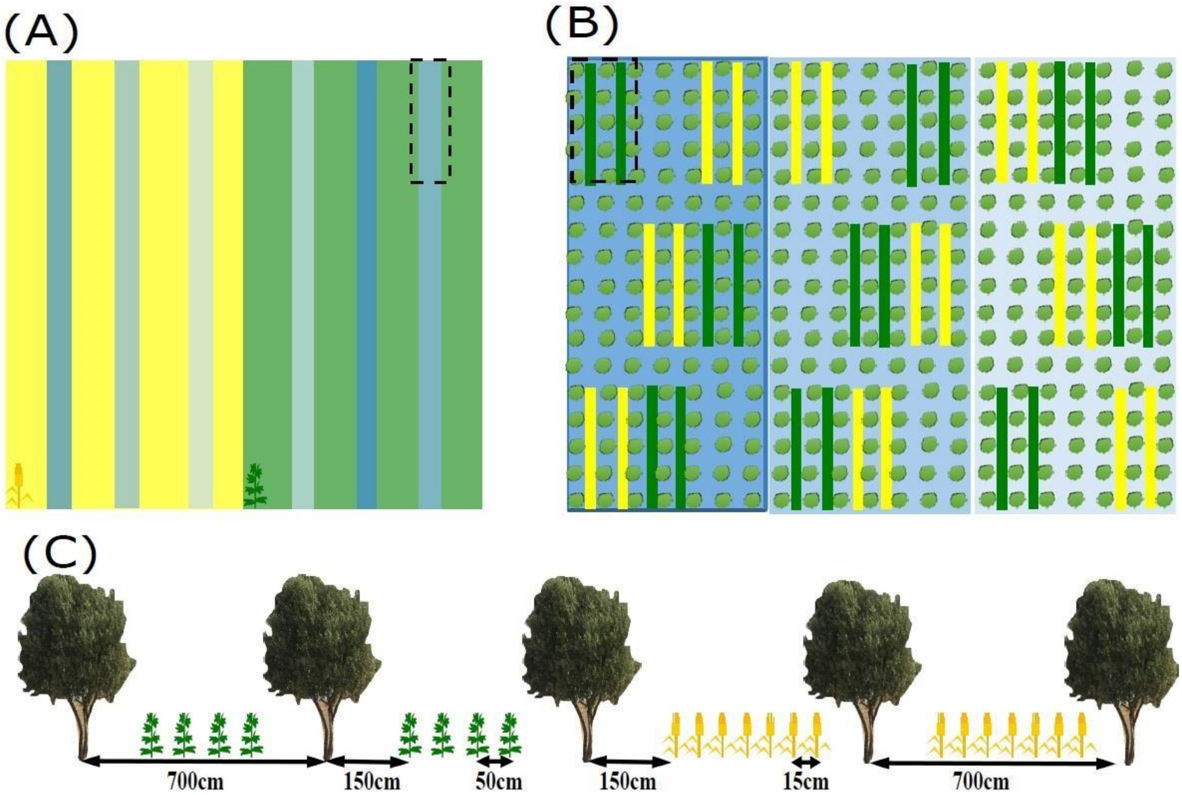

Figure 16 :Experimental layout showing (A) the plot of sole crops (‘SC’), (B) the plot of agroforestry (‘AF’) and pure olive orchard (‘OR’), and (C) a representation of planting design of wheat, faba bean and olive trees. The three water regimes were applied in applied in adjacent areas equipped with drip irrigation and are indicated as follows: ‘High’ water supply (dark blue), ‘Medium’ water supply (mid-dark blue) and ‘Rainfed’ (clear blue). Yellow stripes correspond to sub-plots with durum wheat, and green stripes to sub-plots with faba bean. Black dotted rectangles correspond to sub-plot in agroforestry and in sole crops.

2.3 Water regimes

We simulated three different water regimes using drip irrigation. We equipped twothirds of sub-plots of each type of system ('AF', 'OR', 'SC') with ten laterals emerging from the submain line that carries water coming out from a pump equipped with a sand filter, a water meter and a pressure regulator. Laterals were spaced by 60 cm in ‘AF’ and 70 cm in ‘SC’, equipped with emitters spaced by 40 cm, and had a flow rate of 2 $l.h^{-1}$. Additionally, there was a 7 m empty gap between water regimes in ‘SC’ which was equivalent to the empty inter-row in ‘AF’ to eliminate any possible horizontal water transfer. The remaining sub-plots were not irrigated to have rainfed controls. In each water regime, crops and trees received the same amount of water. For technical reasons, the three water regimes were not randomly distributed but arranged in adjacent areas (Fig. 16).

To represent the entire interannual rainfall variability, we did a frequential analysis of rainfall of the past 29 years (Fig. 17). On this basis, we aimed to determine the amount of water addition needed for a typical 'wet' (563 mm), 'normal' (471 mm), and 'dry' (356 mm) years. We defined three levels of water supply: high water supply ('High'), a medium water supply ('Medium'), and no water supply ('Rainfed') to simulate. However, the challenge in such water manipulation was to re-adjust the amount of water addition dynamically with rainfall each month. In 2018, rainfall was already sufficient to consider the year as a 'normal' year (429 mm). Therefore, we added water to simulate a very 'wet' year (+ 159.3 mm) and a moderately wet year (+ 72.7 mm). In 2019, rainfall was more typical of a 'dry' year (345 mm). We took the advantage to simulate a 'moderately dry' year (+ 50 mm), and a 'normal' year (+ 100 mm) with lower water addition than in 2018. In doing so, our experience spanned a large water gradient.

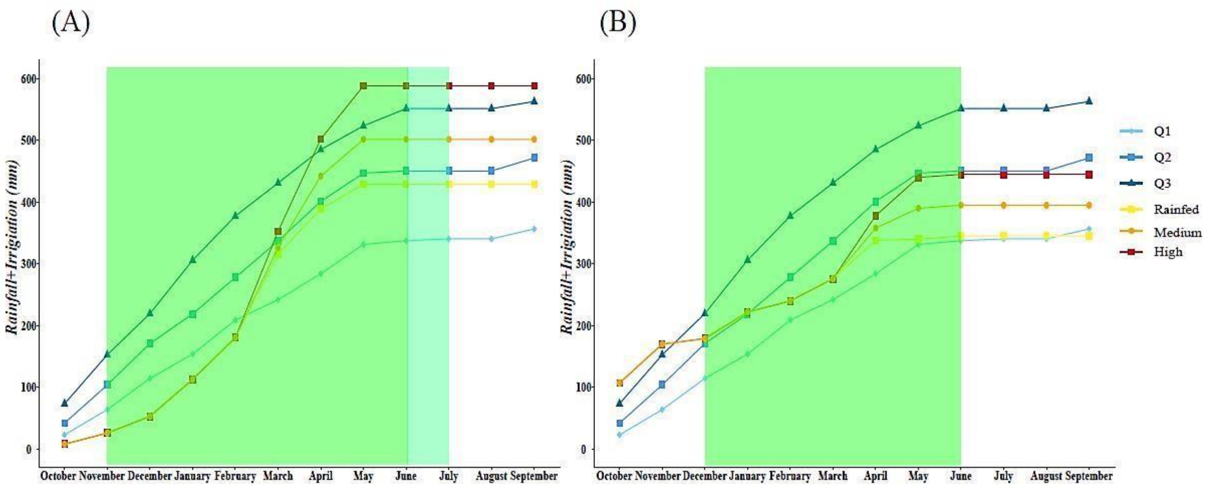

Figure 17: Rainfall frequency analysis over the past 29 years showing the total cumulated water supply (rainfall + irrigation) in 2018 (A), and 2019 (B), in relation to long-term quantiles (Q1: ‘dry’ years; Q2: ‘normal’ years; Q3: ‘wet’ years). The three water regimes are indicated as follows: ‘High’ water supply (red), ‘Medium’ water supply (orange), and ‘Rainfed’ modality (yellow). The dark green rectangle represents the crop growth cycle except in 2018 crop harvest in ‘AF’ was later and shown in clear green.

We distributed irrigation water on a month-basis to fit with natural rainfall distribution. For instance, we did not add water during dry months (e.g., June, July) because no rainfall occurs during these months, even in 'wet' years. However, we added water in spring (e.g., March, April) because differences in spring explained most interannual rainfall variability. Irrigation events were initiated on March to May in 2018. Irrigation periods were applied during 24, 51 and 31 hours for the high water supply and during 6, 28 and 13 hours for the medium water supply during the first, second or third irrigation. In 2019, irrigation began on April to May during 27 and

40 hours for the high water supply and over 13 and 20 hours for the medium water supply at each of the two irrigations. In both years, irrigation duration was eight hours daily.

2.4 Field measurements and sampling

Crop growth was assessed for 10 randomly selected plants avoiding border in each subplot at the flowering stage in 2018 and 2019. Plant ramification was determined by counting the number of viable, non-senescent tillers (for wheat) or branches (for faba bean). Plant biomass was estimated destructively by sampling the entire plants. Plant samples were then oven-dried to a constant weight at 70°C (during 48h) and weighed.

Once they reached maturity, crop plants were entirely harvested at ground level using hand-clippers, taking four randomly selected 0.25 m^2-quadrats in 2018 or five adjacent 1 mlines in 2019 avoiding borders in each sub-plot. Plants were sorted by organs, oven-dried (70°C, 48h), and weighed to determine the total aboveground biomass and the total grain biomass. Yield components were also assessed (e.g., number of spikes/pods per unit area, number of grains per unit area, and thousand-grain weight). The harvest index was calculated as the ratio between grain biomass and total aboveground biomass.

The olive yield per tree was estimated at harvest in each sub-plot on 9 selected trees. Olives were harvested by hand, and all fresh fruits weighed before transportation to the olive oil mill. Due to olive alternate behavior, statistical evaluation of the LERs between years was not possible since yields of the second year (2019) were too low or even null, which does not allow us to test statistical differences. To address this issue, we estimated olive yields over the two years of experiment (see below).

A preliminary assessment of radiation spatial distribution was carried out to estimate shade created by olive trees using a 14 × 14 m grid with a mesh size of 1 × 1 m. The mesearments at each mesh, were made using a LightScount silicon pyranometer (LightScount, Spectrum Technologies, Inc. USA). The photosynthetically active radiation (PAR) spatial distribution was measured at 10 am, 12 pm and 14 pm on a sunny day, which was repeated once during the two years of experiment. Due to the limited number of replications of these measurements, the results were included in the appendix (Fig. A.1, Supplementary Material).

2.5 Crop quality

We determined both grain and straw protein content as indicators of crop quality. Nondestructive near-infrared spectroscopy (NIRS) analyses were performed for each plant sample after fine grinding. We used a scanning spectral range of (400–2.498 nm), which covers the widest wavelength range, as well as the visible spectrum to collect the spectral data of whole grains and straw biomass. The protein level was assessed using an in-house calibration system (PLS Model) developed at the ICARDA quality laboratory (Rabat, Morocco) for both grain and straw. To validate the results obtained by the NIRS method, a subsample of wheat and faba bean was analyzed after harvest using the standard destructive Kjeldahl digestion method for protein content determination. For technical reasons, the analysis was only carried out in 2018.

2.6 Data analysis

We calculated the land equivalent ratio (LER), defined as the relative land area required for sole crops to achieve the same yield than intercropping (Mead and Willey, 1980), using crop grain yield and the average of olive yields over two years for each agroforestry system. The partial land equivalent (pLER) ratio for olive was calculated by averaging olive yields over the two years of experiment (2018 and 2019) to account for the effect of alternate behavior. In addition, the pLER of annual crops were calculated accounting for an area reduction of - 43%, which resulted from the uncultivated strips left on both sides below trees (= 3 m width) in the inter-row (= 7 m width).

Eqn. 1: $$\boldsymbol{LER}_{\mathbf{AF}} = \boldsymbol{LER}_{\mathbf{AF-Olive}} + \boldsymbol{LER}_{\mathbf{AF-Crop}}$$

Eqn. 2: $$\boldsymbol{LER}_{\boldsymbol{AF-Olive}} = \left(\frac{\boldsymbol{Average\ of olive\ yields}_{\boldsymbol{AF}}}{\boldsymbol{Average\ of\ olive\ yields}_{\boldsymbol{OR}}}\right)$$

Eqn. 3: $$\boldsymbol{LER}_{\boldsymbol{AF-Crop}} = \left(\frac{\boldsymbol{Crop\ yield}_{\ \boldsymbol{AF}}}{\boldsymbol{Crop\ yield}_{\boldsymbol{SC}}}\right)$$

The LER indicates a higher (or lower) productivity of agroforestry ('AF') than the corresponding orchard ('OR') and sole crops ('SC') when the value is above (or below) 1. The value is equal to 1 when agroforestry does not impact land productivity. Thus, if olive yields do not differ significantly between cropping systems (‘OR’ and ‘AF’), then, the olive PLER is equal to 1.

We tested the differences in crop growth, yield components, final grain yield, and grain protein content using ANOVAs with three factors: (1) type of system ('AF', 'OR', 'SC'), (2) water addition ('High' water supply, 'Medium' water supply, 'Rainfed') and (3) year (2018, 2019). Each crop species (durum wheat and faba bean) was tested separately. After significant ANOVA ($p < 0.05$), the means were compared with Tukey multiple comparison test. The relationships between final grain yields, total aboveground biomass at the flowering stage, and yield components were tested with linear regressions. All statistical analyses were performed using R (R Development Core Team 2009-2018, version 3.6.0).

3. Results

3.1 Dry matter production at flowering

Dry matter production was higher in 2018 than in 2019 for both wheat ($p< 0.001$) and faba bean ($p< 0.001$) and was significantly lower in agroforestry than in sole crops for both wheat ($p< 0.001$, Fig. 18) and faba bean ($p< 0.001$, Fig. 18). The number of tillers or branches per unit area was also significantly lower in agroforestry for both crops ($p<0.001$, Table 6). Water addition had a significant effect on dry matter production for faba bean ($p= 0.002$) but not for wheat ($p= 0.805$). In 2018, the dry matter production of faba bean was the highest under the wettest water regime (+ 26 % compared to the other regimes). However, water addition did not impact the number of tillers ($p= 0.993$) nor the number of branches ($p= 0.283$).

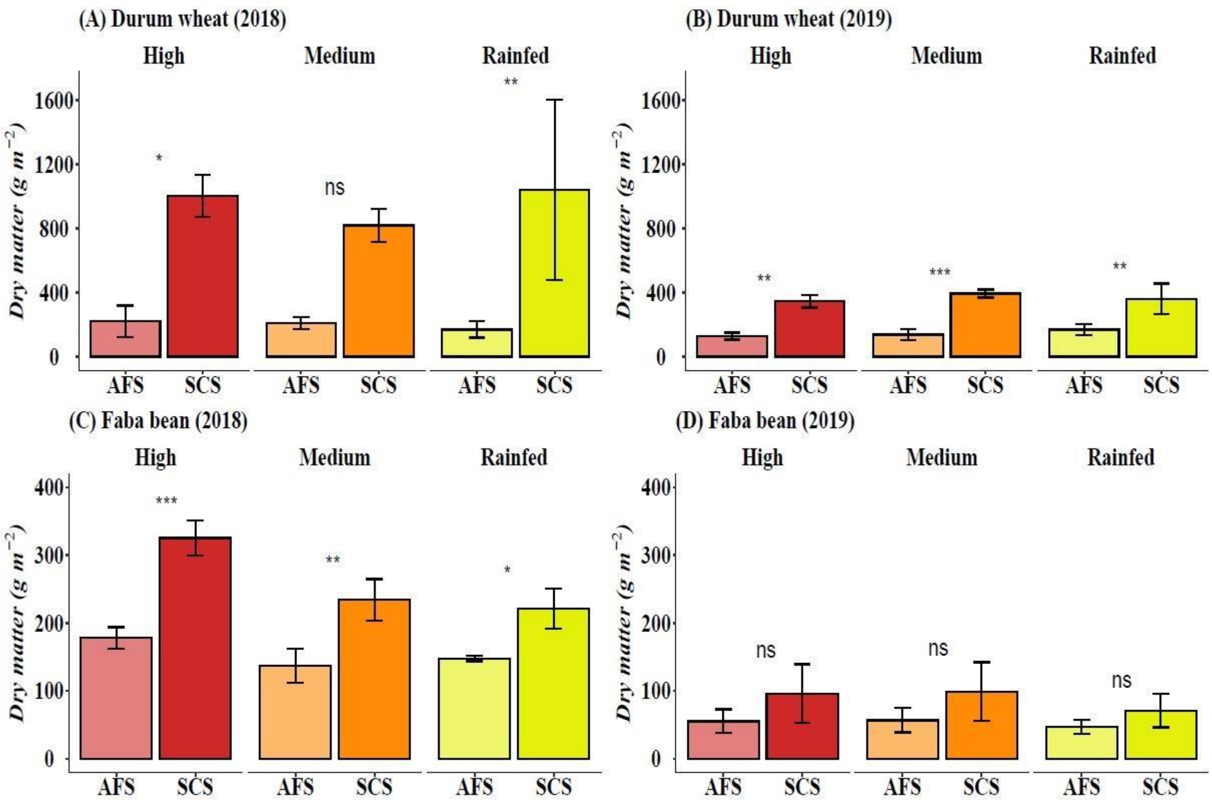

Figure 18: Dry matter (g.m-2 ± sd) at flowering in agroforestry (AF) and sole crops (SC) for durum wheat (A: 2018; B: 2019) and faba bean (C: 2018; D: 2019). Bar color indicates the water regime: (red: ‘High’ water supply; orange: ‘Medium’ water supply; yellow: ‘Rainfed’). Significance level (differences between AF and SC): * *p< 0.05;* ** *p< 0.01;* *** *p< 0.001*.

3.2 Crop yields and yield components

Similarly to dry matter production, grain yield was higher in 2018 than in 2019 for both wheat (277 $g.m^{-2}$ *vs.* 111.2 $g.m^{-2}$, p< 0.001) and faba bean (321 $g.m^{-2}$ *vs.* 35.28 $g.m^{-2}$, p< 0.001). In contrast, straw yields were lower in 2018 than in 2019 for both wheat (755 $g.m^{-2}$ *vs.* 370 $g.m^{-2}$, p< 0.001) and faba bean (263 $g.m^{-2}$ *vs.* 179 $g.m^{-2}$, p= 0.007). Consequently, the harvest index was significantly higher in 2018 than in 2019 for both wheat (p< 0.001, Table 6) and faba bean (p< 0.001, Table 6). In 2018, the grain yield was significantly lower in agroforestry than in sole crops (p< 0.001, Fig. 19) for both wheat (- 50 %) and faba bean (- 48 %). The straw yield was also lower in agroforestry than in sole crops (p< 0.001, Fig. 20), although wheat (- 71 %) was more impacted than faba bean (- 51 %). In 2019, only the grain and straw yields of wheat were affected (p< 0.001). Water addition improved grain yield only of wheat (p= 0.004) but not of faba bean (p= 0.641). It did not impact straw yields (wheat: p= 0.250; faba bean: p= 0.954) nor the harvest index (wheat: p= 0.089; faba bean: p= 0.215).

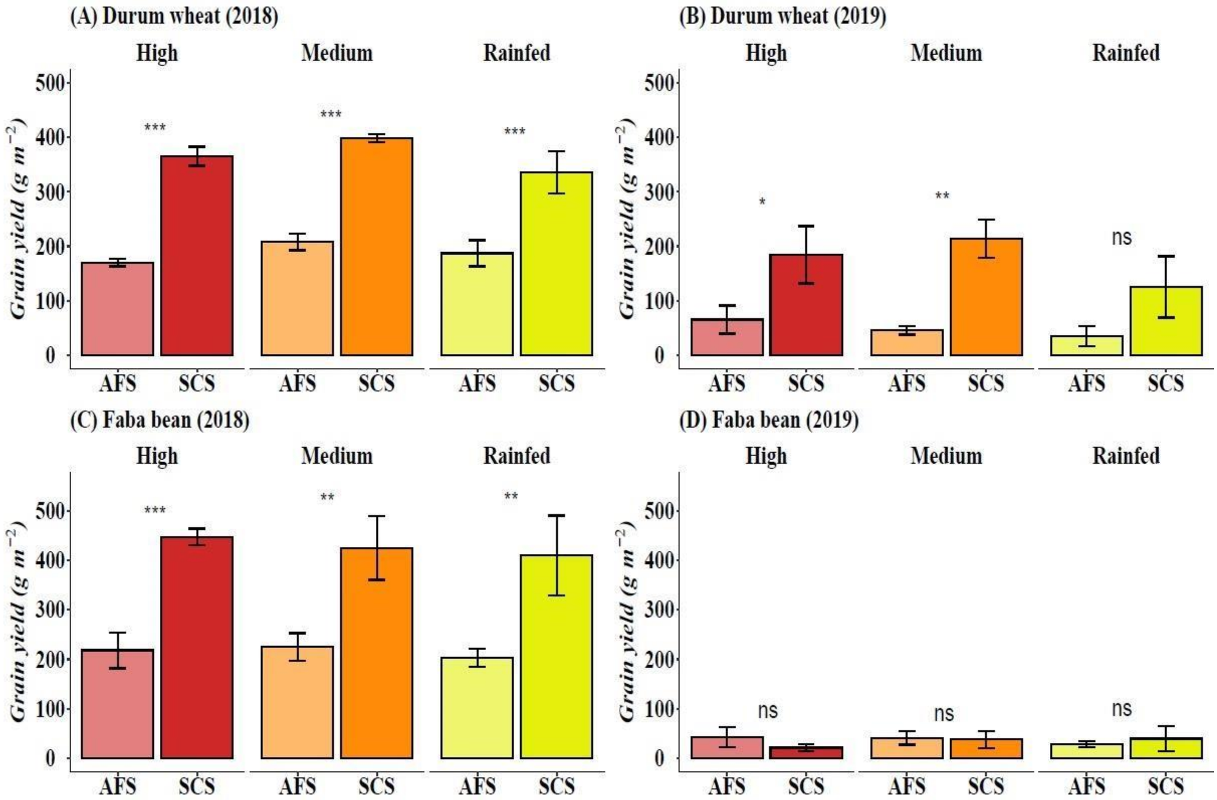

Figure 19: Grain yield (g.m-2 ± sd) at harvest in agroforestry (AF) and sole crops (SC) for durum wheat (A: 2018; B: 2019) and faba bean (C: 2018. D: 2019). Bar color indicates the water regime (red: 'High' water supply; orange: 'Medium' water supply; yellow: 'Rai fed'). Significance level (differences between AF and SC): * p< 0.05; ** p< 0.01; *** p< 0.001.

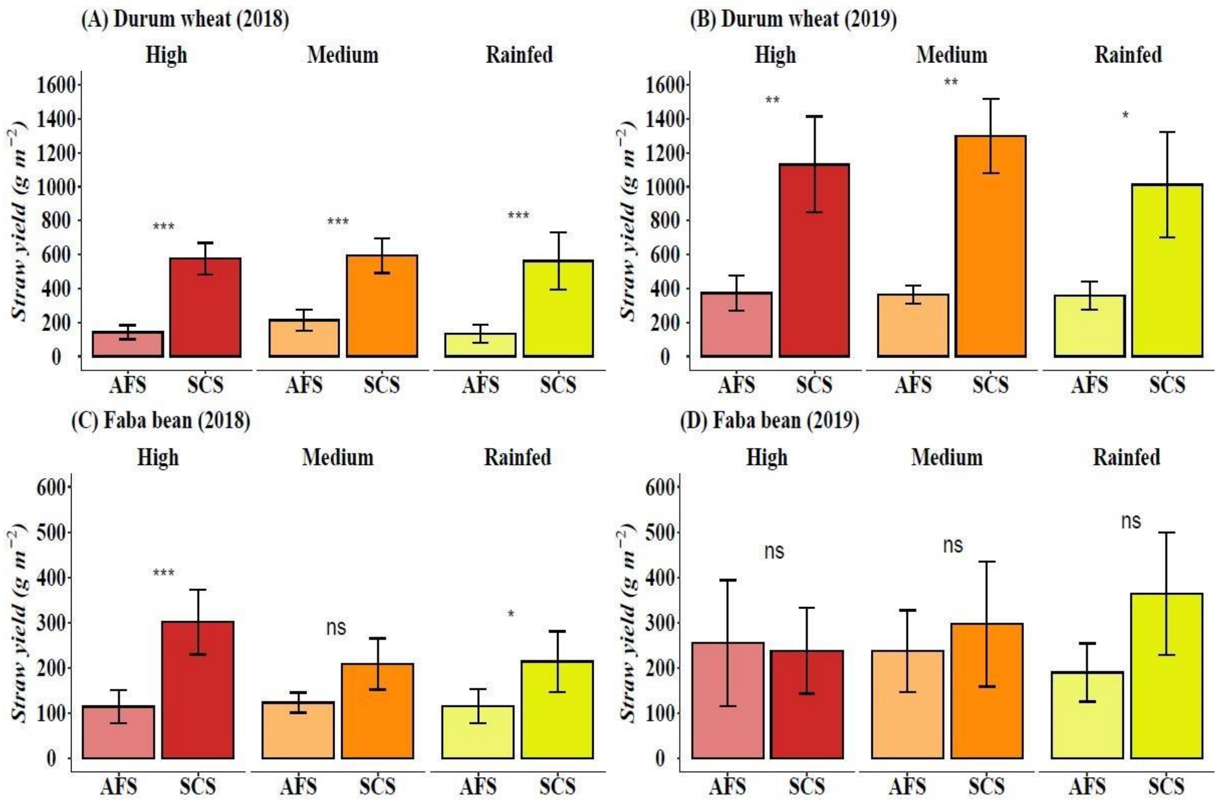

Figure 20: Straw yield (g.m-2 ± sd) at harvest in agroforestry (AF) and sole crops (SC) for durum wheat (A: 2018; B: 2019) and faba bean (C: 2018. D: 2019). Bar color indicates the water regime (red: 'High' water supply; orange: 'Medium' water supply; yellow: 'Rainfed'). Significance level (differences between AF and SC): * p< 0.05; ** p< 0.01; *** p< 0.001.

The number of wheat spikes ($p < 0.001$), faba bean pods ($p < 0.001$) and the number of grains per unit area of wheat ($p < 0.001$) and faba bean ($p < 0.001$) were all significantly lower in agroforestry than in sole crops, especially in 2018 (Table 6). The thousand-grain weight (TGW) was always higher in agroforestry for faba bean (+ 17 %, $p<0.001$) but only in 2018 for wheat (Table 6). Water addition positively impacted the number of spikes ($p= 0.002$; Table 6), the grain number ($p< 0.001$) and the thousand-grain weight of wheat ($p= 0.006$) but did not impact the number of pods ($p= 0.847$; Table 6), the grain number ($p= 0.488$) nor thousand-grain weight of faba bean ($p= 0.286$). For wheat, the highest number of spikes and grains per unit area was observed for the medium water supply in 2018, which corresponds to intermediately wet years , while the highest thousand-grain weight was observed under the highest water supply in 2018 (Table 6). Additionally, the interaction between water addition and cropping system was significant for the number of spikes ($p= 0.018$; Table 6) and the thousand-grain weight of wheat ($p= 0.017$; Table 6).

Table 6: Number of tillers/ branches (m-2 ± s.d), number of spikes/pods and grains (m-2 ± s.d), weight of 1000 grains TGW (g ± s.d) and the harvest index (HI) of durum wheat and faba bean in 2018 and 2019 in agroforestry (AF) and sole crops (SC), according to the three water regimes (High water supply (High), Medium water supply (Medium), and Rainfed). Lowercase letters indicate significant differences between cropping system among water regimes (HSD Tukey test, P≤0.05).

Species	**Year**	**Water supply**	**Number of tillers/ branches per m^2**		**Number of spikes/pods per m^2**		**Number of grains per m^2**		**TGW(g)**		**HI**	
			SC	AF	SC	AF	SC	AF	SC	AF	SC	AF
Durum wheat	2018	High	587.6±31.3	312.4±16.2	429.6±5.03	240.1±21.4	10434±485	3417±331	35.14±0.60	52.12±3.20	0.38±0.02	0.54±0.03
		Medium	656.0±35.5	354.8±104	401.3±19.5	373.1±53.1	11453±545	4889±388	35.09±1.44	43.46±0.25	0.40±0.00	0.49±0.02
		Control	744.8±47.3	280.4±60.5	393.6±38.4	244.1±40.5	9350±109	3858±800	36.42±0.87	53.04±8.44	0.37±0.00	0.58±0.02
	2019	High	395.3±27.0	241.4±21.23	206.0±31.5	211.5±42.2	3904±954	1485±535	46.99±3.03	43.41±2.32	0.14±0.02	0.14±0.02
		Medium	300.9±30.6	231.2±15.5	215.0±33.7	220.2±20.3	4654±555	1391±162	45.83±2.02	32.99±1.89	0.14±0.02	0.11±0.01
		Control	295.0±54.0	224.4±20.4	166.2±33.0	203.0 ±12.0	2796±1003	1111±384	44.00±4.27	30.51±5.09	0.10±0.01	0.08±0.02
Faba bean	2018	High	39.66±0.98	28.33±0.72	378.3±42.1	174.3±32.5	867.6±87.0	386.8±87.0	520.2±34.0	583.3±39.5	0.59±0.04	0.65±0.01
		Medium	38.21±5.13	31.25±3.75	347.0±53.5	186.6±18.5	845.3±90.7	387.5±60.0	505.9±24.7	589.4±24.2	0.67±0.01	0.64±0.01
		Control	36.83±1.96	31.25±2.50	343.6±63.9	165.0 ±25.7	789.3±201	322.8±58.05	534.9±69.1	657.2±83.6	0.65±0.02	0.63±0.03
	2019	High	36.50±7.54	20.11±2.73	25.91±4.04	42.04±15.38	50.66±14.0	76.66±36.2	429.9±103	551.0±31.4	0.08±0.01	0.14±0.01
		Medium	42.50±16.5	17.28±0.49	33.83±11.8	37.79±8.51	74.66±34.5	73.00±12.9	515.7±22.5	548.9±86.8	0.11±0.00	0.15±0.02
		Control	28.00±7.69	17.28±0.49	54.41±16.8	28.25±0.76	80.33±48.6	51.66±7.11	498.2±32.0	546.5±55.7	0.10±0.07	0.13±0.01

The number of grains per unit area was a significant determinant of grain yield for wheat in agroforestry (r^2 = 0.96, $p < 0.001$, Fig. 21A) and in sole crops (r^2 = 0.97, $p < 0.001$), and for faba bean in agroforestry (r^2 = 0.98, $p < 0.001$, Fig. 21B) and in sole crops (r^2 = 0.98, $p < 0.001$). The number of grains varied positively with the number of spikes per unit area in both agroforestry (r^2 = 0.57 $p < 0.001$, Fig. 21C) and sole crops (r^2 = 0.95, $p < 0.001$, Fig. 21C) for wheat, and with the number of pods per unit area in both agroforestry (r^2 = 0.98, $p < 0.001$, Fig. 21D) and sole crops (r^2 = 0.98, $p < 0.001$, Fig. 21D) for faba bean. Despite significant variations in the number of tillers, dry matter production of wheat only partially explained the variations in the number of spikes of wheat either in agroforestry (r^2= 0.22, p= 0.046, Fig. 21E) or in sole crops (r^2= 0.52, $p < 0.001$, Fig. 21E). In contrast, dry matter production strongly determined the number of pods per unit area of faba bean in agroforestry (r^2= 0.83, $p < 0.001$, Fig. 21F) and in sole crops (r^2= 0.74, $p<0.001$, Fig. 21F).

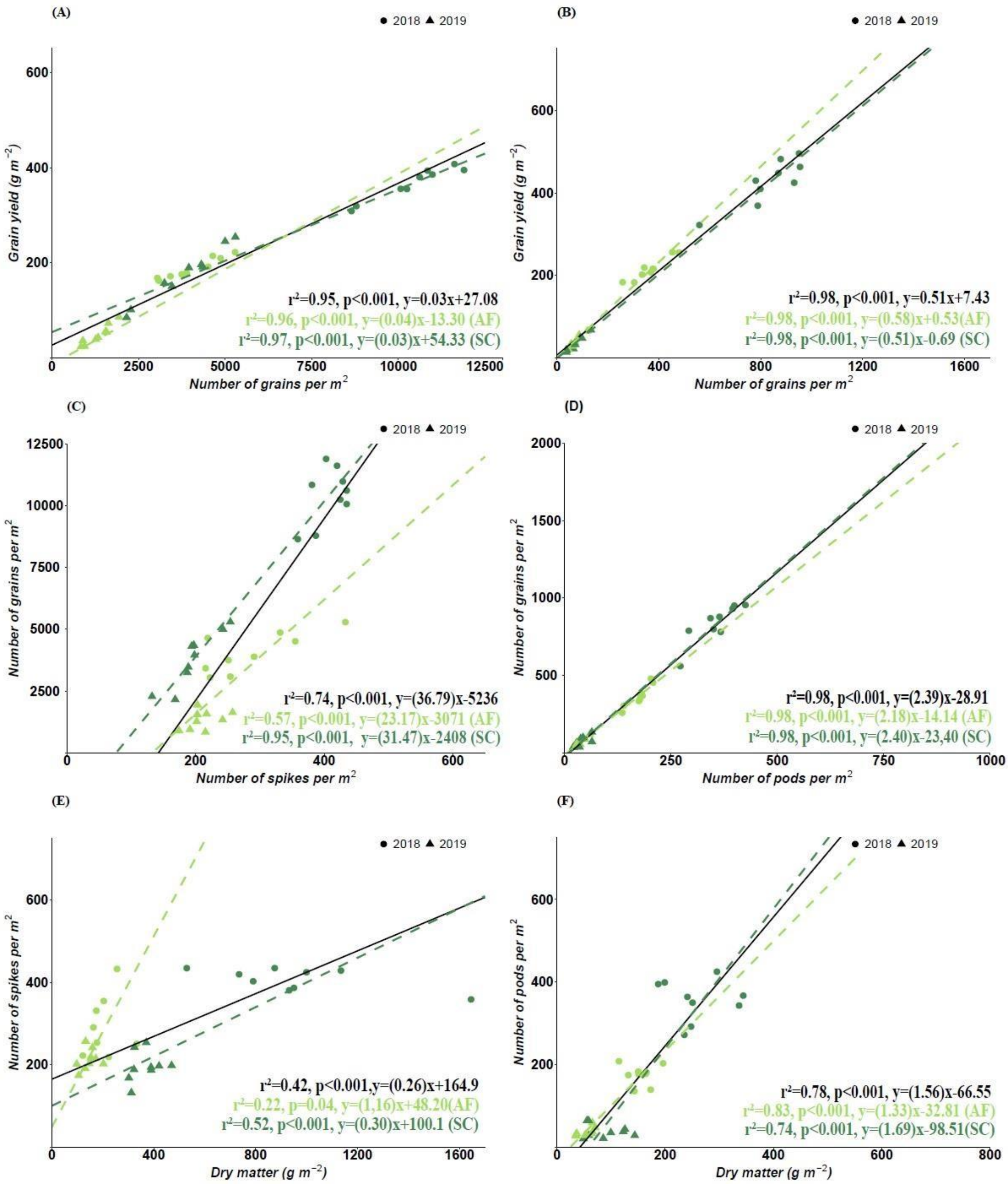

Figure 21: Cascading relationships between grain yield (g.m-2) and the number of grains (m2) for either wheat (A) and faba bean (B); between the number of grains (m-2) and the number of spikes (m-2) for wheat (C) or the number of pods (m-2) for faba bean (D); between the number of spikes (m-2) for wheat (E), or pods (m-2) for faba bean (F) and dry matter (g.m-2) at flowering. Linear regressions were performed for the entire data set (full black lines), or separately for agroforestry (light green lines) and sole crops (dark green lines), in both 2018 (circle shape) and 2019 (triangle shape).

3.3 Crop quality and protein yield

The protein content was higher in agroforestry for both wheat grains (+ 4 %, p= 0.003) and straw (+ 9 %, p= 0.001) compared to sole crops (Table 7). However, the protein content of faba bean did not vary significantly for grains (p= 0.990) and was even lower in agroforestry for straw (- 5 %, p= 0.017). Although the protein content of wheat grains (p= 0.555, Table 7) did not vary between water regimes, the addition of water reduced the protein content of grains of faba bean by 3 % between rainfed and high water supply (p= 0.017). In contrast, water addition positively impacted both the straw protein content of wheat (p< 0.001) and faba bean (p= 0.027). For instance, water addition enhanced the protein content of wheat straw by 8 % between medium water supply and rainfed regime (p= 0.014) while the straw protein content of faba bean increased by 7 % between high water supply and medium water regime (p= 0.026). Despite the positive impacts on protein content, the protein yield was lower in agroforestry for both wheat (p< 0.001) and faba bean (p< 0.001). Water addition improved the protein straw yield of both wheat (p= 0.011) and faba bean (p= 0.026), but the grain protein yield only of wheat with medium water supply (p= 0.032).

Table 7: Grain and straw protein content (% of dry matter basis ± S.E.), grain and straw protein yield (g.m-2 ± s.d) at harvest in agroforestry (AF) and sole crops (SC) of durum wheat and faba bean in 2018, according to three water regimes (High water supply (Hi Grain and straw protein content (% of dry matter basis ± S.E.), grain and straw protein yield (g.m-2 ± s.d) at harvest in agroforestry (AF) and sole crops (SC) of durum wheat and faba bean in 2018, according to three water regimes (High water supply (High), Medium water supply (Medium), and Rainfed). Lowercase letters indicate significant differences between cropping system per water regimes (HSD Tukey test, P≤0.05).

Species	**Year**	**Water supply**	**Grain protein yield (g/m^2)**		**Straw protein yield (g/m^2)**		**Grain protein content per plant (%)**		**Straw protein content per plant (%)**	
			SC	AF	SC	AF	SC	AF	SC	AF
Durum wheat	2018	High	41.76±2.12	20.01±0.89	31.66±4.15	8.26±1.06	11.43±0.35	11.77±0.15	5.49±0.29	5.82±0.27
		Medium	44.37±1.15	24.50±2.47	32.94±2.46	13.17±2.88	11.13±0.09	11.77±0.47	5.54±0.28	6.12±0.24
		Control	37.60±5.13	21.86±2.74	27.90±2.03	7.64±1.13	11.18±0.32	11.68±0.15	4.98±0.22	5.67±0.25
Faba bean	2018	High	86.19±5.05	42.37±6.71	16.71±2.57	6.13±1.26	19.27±0.45	19.42±0.18	5.55±0.15	5.35±0.08
		Medium	83.58±12.9	43.99±5.23	10.93±1.11	6.02±0.54	19.66±0.10	19.57±0.12	5.25±0.24	4.87±0.24
		Control	81.60±14.5	40.52±3.65	11.68±2.75	6.01±1.12	19.97±0.49	19.90±0.19	5.49±0.35	5.21±0.10

3.4 Olive yield

The olive yield was by far higher in 2018 (7.41 ± 1.19 tons.ha^{-1}) than in 2019 (0.16 ± 0.43 tons.ha^{-1}). The strong inter-annual variation (- 97 %) probably reflected the alternate behavior of olive trees. The average of olive yields did not vary between agroforestry and pure orchard (p= 0.110, Fig. 22). Water addition did not impact olive yield (p= 0.131).

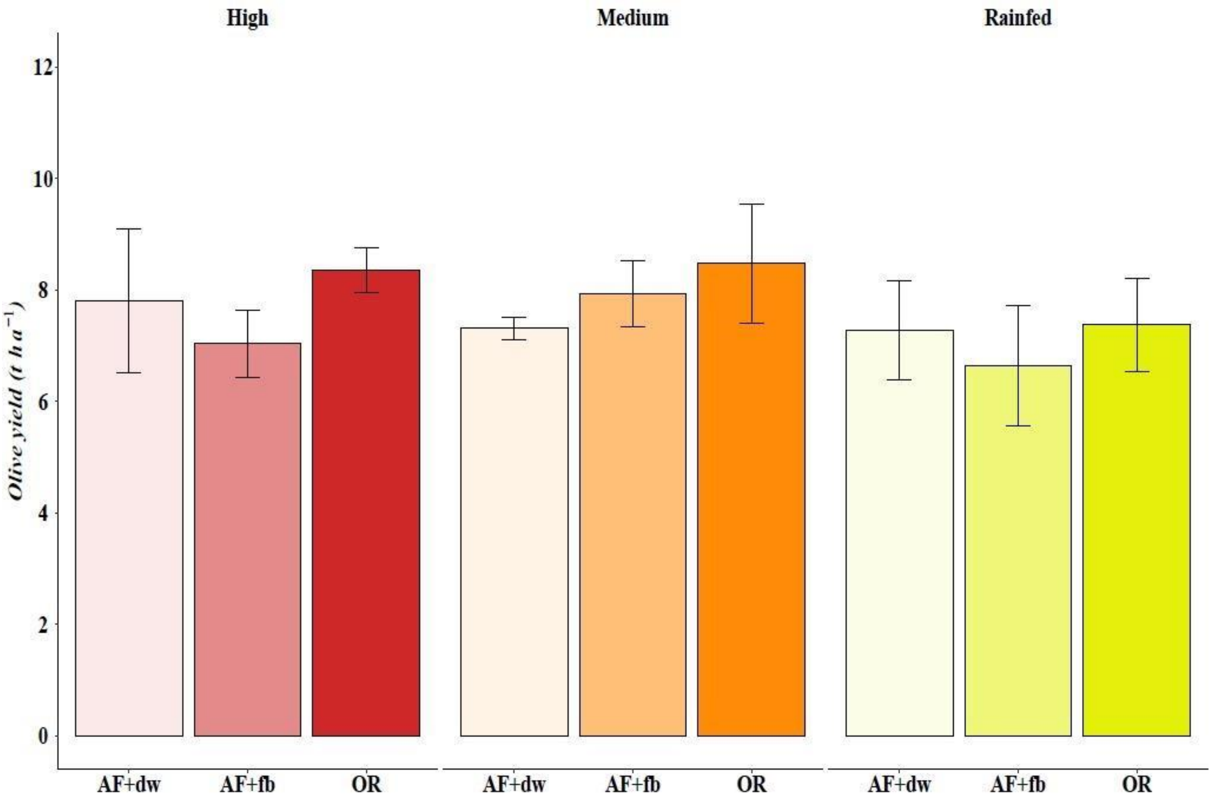

Figure 22: Olive yield (tons.ha-1) in agroforestry with durum wheat (AF+dw), and faba bean (AF+fb), and pure olive orchard (OR). Bar color indicates the water regime (red: 'High' water supply; orange: 'Medium' water supply; yellow: 'Rainfed'). Significance level (differences between AF and SC): * p< 0.05; ** p< 0.01; *** p< 0.001.

3.5 Land equivalent ratio (LER)

In 2018, the land equivalent ratio (LER) was always > 1 and ranged from 1.12 to 1.32 without a clear distinction between wheat and faba bean (Table 8). In 2019, the magnitude of variation was higher, and the LER ranged from 1.12 to 2.35 with a significant difference between wheat and faba bean (p= 0.011). In 2018, the partial land equivalent ratio (pLER) of wheat was higher (p= 0.004, Table 8), while it was higher in 2019 for faba bean (p= 0.031, Table 8). Water addition did not impact LER (p= 0.117) in 2018, nor pLER either for wheat (p= 0.550) or faba bean (p= 0.353) in both 2018 and 2019.

Table 8 : Land equivalent ratios of olive-durum wheat and olive-faba bean agroforestry systems in 2018 and 2019, according to three water regimes (High water supply (High), Medium water supply (Medium), and Rainfed). Partial LERs (pLERs) are indicated in bracket for crops and olive, respectively.

Year	**Water supply**	**LER**	
		Durum wheat + Olive	Faba bean + Olive
2018	High	1.26 (0.26 + 1.00)	1.27(0.27 + 1.00)
	Medium	1.29 (0.29 + 1.00)	1.30 (0.30 + 1.00)
	Rainfed	1.32 (0.32 + 1.00)	1.28 (0.28 + 1.00)
2019	High	1.20 (0.20 + 1.00)	2.35 (1.35 + 1.00)
	Medium	1.12 (0.12 + 1.00)	1.66 (0.66 + 1.00)
	Rainfed	1.19 (0.19 + 1.00)	1.54 (0.54 + 1.00)

4. Discussion

4.1 The shade of olive trees reduces crop yields whatever the water regime

Agroforestry reduced yields and the biomass production of both wheat and faba bean. Although wheat was slightly more affected than faba bean, the magnitude of yield reduction was around 50 % on average for both crops, more than other examples from temperate and Mediterranean areas. The usual magnitude of reduction ranges from -10 to -30 % (*e.g.,* -20 % for wheat under walnut trees in Southern France (Dufour et al., 2013). However, comparable yield reductions have been recorded for wheat under a dense shade, e.g., under paulownia trees (Li et al., 2008) or artificial shelters (Artru et al., 2017), suggesting that the shade provided by mature unpruned olive trees was significant for crops. Contrary to deciduous tree species (e.g., walnut), olive trees provide a permanent shade that impacts the entire crop cycle. Furthermore, the density of olive trees in our experiment was higher than recommended in agroforestry, which is usually below 200 trees.ha-1 (Singh et al., 2007).

Contrary to our first hypothesis, the shade of olive trees affected crops always negatively, even under low water availability. In addition, a little variation of shade is expected during the experiment, mainly due to shoot growth inhibition in the high-yield year (Melgar et al., 2008). Differences in biomass production and yield between agroforestry and sole crops were similar for all water regimes during the two years of experiment. In a Mediterranean climate, we expected that tree shade would have strong negative effects under the wettest conditions, where light, more than water, limited crop growth, leading to significant differences between agroforestry and sole crops. In contrast, we expected that the shade would improve crop growth and yield under water-limiting conditions by buffering heat (Peng et al., 2015) and water stresses. Assuming that trees use water from deeper soil layers than crops, the reduced evapotranspiration under tree shade (Coussement et al., 2018) could increase water availability for crops and result in higher water-efficiency. These expectations are supported by the 'Stress-Gradient Hypothesis' (SGH), which was repeatedly tested under dry-to-sub-humid conditions in several savanna-like ecosystems, including agroforestry systems (Dohn et al., 2013). Positive interactions between trees and grasses were attributed to the water economy under dry conditions.

However, water was probably not the limiting factor of crop growth and yield in our experiment, explaining why differences between water regimes were not significant. Despite low annual precipitations, Mediterranean climates usually have rainy winters with relatively low evapotranspiration rates (Arenas-Corraliza et al., 2018), allowing to fulfill crop demands at the beginning of the growing cycle. Water availability was possibly high enough to support crop growth even under our driest (rainfed) water regime, explaining why adding or saving extra water did not benefit to crops at early stages. Instead, wheat production peaked with medium water additions, suggesting that adding too much water probably caused hypoxia in the rooting zone (Malik et al., 2001), especially in the most clayey soil horizons. In addition, the timing of water supply is of prime importance when considering the impact of water supply. The precipitation events were well-synchronized with the critical crop phases in the first year, making consequences of low water availability probably less significant and explaining the good dry matter production recorded at flowering. In contrast, the lower dry matter production in 2019 might be explained by a delayed sowing and an earlier water stress due to lower precipitations (- 30 % as compared to 2018) coupled with later irrigation. However, the high straw biomass recorded at harvest in 2019 suggests a compensatory vegetative crop growth after re-irrigation (Han et al., 2015), although it didn’t compensate for grain production. In addition, the lower grain yields might be resulted from an early water stress in 2019 during tillering reducing the floral meristem differentiation (Ji et al., 2010), and consequently spikes number. Therefore, a seasonal reformulation of the SGH should therefore refine the predictions of how trees impact underlying crops under Mediterranean climates.

Moreover, low nitrogen input (N) and water availability are both the main limitations to crop productivity, especially of cereals, in semi-arid Mediterranean environments (Cossani et al., 2010). Theoretically, the maximum crop growth is reached when all resources are equally limiting (Sadras, 2004). In addition, adding water at the appropriate timing increased the growth potential of crops, leading to an increase in their nutrient requirements (e.g., nitrogen). Increasing water availability with irrigation without changing the amount of nutrients accordingly may have created a situation where nutrients became the limiting factor. Our results suggest that the global effect of trees in 'water-limited' agroforestry depends primarily on seasonal precipitation and water demand patterns and on a possible shift in limiting factor between water and nutrient such as nitrogen. We argue that the SGH should carefully account for these interactions between co-limiting factors to provide more relevant predictions in 'water-limited' agroforestry.

4.2 Olive trees limit crop growth and reduce the number of grains per unit area

In agroforestry, olive trees negatively affected crop growth during the pre-flowering phase, resulting in a lower biomass production compared to sole crops. They also negatively affected crop tillering/ramification, reducing the total number spikes (wheat) and pods (faba bean) per unit area (Rivest et al., 2009 ; Liu et al., 2015). Reduced crop growth and tillering is quite common in agroforestry (Gill et al., 2009; Kaur et al., 2010; Inurreta-Aguirre et al., 2018) mainly because of the shade provided by evergreen trees such as olive tree at early crop stages during winter. In legumes, nitrogen fixation is related to the provision of photosynthetic assimilates and dry matter production (e.g., soybean, Trang et Giddens, 1980; Mahieu et al., 2016). In turn, reduced growth meant lower canopy expansion, light capture capacity, and lower photosynthetic rates (King et al., 2014), especially during critical stages, which limited grain yield potential (Fan et al., 2018).

The reduction of final crop grain yields in agroforestry was a direct consequence of reduced grain number per unit area. In cereals, the variations in grain number per unit area determine the final yield more than other yield components (Xie et al., 2016; Kimura et al., 2018; Zhang et al., 2019). The number of grains is also a major yield component for legumes (Lake et al., 2019). Since the number of grains per unit area is closely related to the number of spikes/pods, the way trees affected crops at the tillering/ ramification stage (Sharif et al., 2010), mainly through the shade, was critical for crop yield in agroforestry. The reduced number of tillers (wheat) and branches (faba bean) explained more than 50 % of grain yield reduction under olive trees. However, while the number of tillers directly determined the number of wheat spikes, the number of pods of faba bean was also related to plant growth during pod emergence, which is the most critical stage for faba bean grain yield (Lake et al., 2019). Contrary to cereals, indeterminate legumes can increase the number of pods and thereby yield potential by extending the period between flowering and pod set. However, the shade under olive trees limited this phase compared to sole crops, probably because shade did not represent an advantage regarding the water economy.

The lower biomass of spikes and pods was possibly another critical determinant of the lower grain number per unit area under olive trees. Indeed, smaller spikes/pods contain fewer grains (Zhang et al., 2019). The reduction of global crop biomass production led to a lower amount of biomass available to allocate to spikes/pods (Schittenhelm et al., 2004), resulting in smaller spikes/pods with lower grain number potential. Shade may also affect the fertility of spikes in cereals (Sharif et al., 2010; Qiao et al., 2019), generally associated with spike biomass in cereals (Zhang et al. 2019), and reduce the floral initiation and retention in legumes (Rivest et al., 2009; Patrick et Stoddard, 2010). With lower fertility, the fruiting efficiency, *i.e.*, the number of grain per unit of spike/pod biomass, was certainly lower in agroforestry, which added another possible negative effect of olive trees on the grain number per unit area.

In some cases, crops can efficiently acclimate to shade thanks to trait plasticity (Arenas-Corraliza et al., 2018) and maintain light capture and biomass productivity to similar levels than in sole crops, especially during the critical phases. However, even if we noticed significant morphological changes on crops (e.g., stem elongation, increase in leaf area), they were not sufficient to fully compensate for the reduction of light under olive trees. Indeed, it is highly probable that the commercial varieties we used for wheat and faba bean in the experiment were selected to tolerate the high irradiation in sole cropping systems rather than the shade in agroforestry. Looking for crop varieties with adequate physiological and morphological responses to shade will be promising to buffer the effects of trees on crop growth in Mediterranean agroforestry (Arenas-Corraliza et al., 2018). Besides organ plasticity, we suggest that the indeterminate growth habit of legumes is an essential trait for a more significant adaptation to shade, explaining why olive trees impacted less faba bean crops during the second year.

4.3 Olive trees improve grain filling and grain quality

In agroforestry, olive trees improved grain filling and led to higher grain weight and quality at harvest than in sole crops. The thousand-grain weight and the grain protein content were higher for both wheat and faba bean. However, the total gain was insufficient to compensate for yield reductions due to the strongly reduced number of grains per unit area. The apparent positive effects of olive trees resulted from the combination of two different effects. The first was a reduced 'dilution' effect (Artru et al., 2017), crops concentrated more nitrogen into fewer grains (Li et al., 2010) which increased the protein content of the grains (Arenas-Corraliza et al. 2018; Qiao et al. 2019). However, it is rare that resource concentration in a smaller number of grains permits full compensation and reaching yield determined by higher, even less qualitative, numbers of grains.

A real facilitative effect of olive trees also occurred through beneficial modifications of the microclimate by reducing solar radiation and creating a more moderate temperature regime (Peng et al., 2015). Cooler temperatures under trees also delayed the physiological maturity by one month (in 2018) and, therefore, extended the duration of grain filling (Inurreta-Aguirre et al., 2018) allowing a better remobilization of more dry matter in fewer grains. For crops with indeterminate growth, like faba bean, the positive effects might be even higher due to a more extended grain filling period (Wang et al., 2015) related to a higher number of reproductive nodes (Kato et al., 2019). Combined with the lower numbers of grains, the better remobilization of nitrogen of crops towards grains can explain why protein content was higher under trees (Artru et al., 2017; Dufour et al., 2013). However, despite heavier grains, with higher protein content, the reduction in the number of grains per unit area had a more significant impact on grain yield and protein yield in agroforestry.

4.4 Overall, olive agroforestry is more productive than sole crops and trees

Despite lower crop yields, agroforestry systems generally had higher land productivity than sole crops and trees (LER > 1) during the two years of the experiment. Based on this first empirical evaluation in the South Mediterranean, we confirm that olive agroforestry systems can have high LERs and produce high-quality grains, even under more arid conditions than previous evaluation in Europe (Panozzo et al., 2019). However, a better improvement of land productivity might be achieved through a better vertical root complementarity which was probably limited due to the previous orchard management as an irrigated orchard leading to a high root density in the top soil layers down to a 0.6 m depth (Fernández et al., 1991). Contrary to the traditional olive groves, most modern olive orchards with high density (Connor et al., 2014) have uncultivated inter-rows, representing a loss of arable land in a context where food security is a rapidly growing issue. Besides mechanization issues, farmers are concerned about preserving enough resources, mostly water, to support olive production. However, our results reveal that crops did not impact olive yields that much, although the alternate behavior led to a high variability of olive yields. Additionally, the different water regimes did not impact olive yields in the experiment, confirming that olive trees have, in general, high tolerance to water availability fluctuations and water scarcity (Moriana et al., 2003), and also probably to competition for water with intercrops. A step further will be to test different management strategies, especially tree pruning, and adapt the tree density to improve the functioning of the olive agroforestry as a whole. Combinations with faba bean showed higher land productivity during the second year of the experiment, suggesting that legumes might be good crop candidates for Mediterranean agroforestry. Compared to cereals, legumes are less competitive for soil resources (at least for nitrogen) and reach maturity earlier, leaving more resources available to olive trees, especially at the beginning of summer, when trees start to grow actively, and water availability sinks. Moreover, the indeterminate growth habit of legumes may improve the performance of agroforestry systems by valuing the shade under trees better than cereals (Kato et al., 2019). In the long-term, the capacity of legumes to fix the atmospheric nitrogen can enhance soil nitrogen available (Dwivedi et al., 2015) for the olive trees, improve soil fertility, and hence have positive effects on olive production. Therefore, we highly recommend legumes to enhance and diversify the global productivity of olive groves and invite to consider an enlarged diversity of legume species. However, further studies on how crops modify water availability would be necessary to confirm the promising potential of olive agroforestry in the drier future of Mediterranean regions.

Our work finally reveals methodological difficulties to precisely determine LERs of fruitbased agroforestry, especially for alternate fruit species such as olive. Results of LER were highly variable from one year to another. However, we did not observe a clear trend with the water regime tested which might be due to the delay of water supply. Multiple factors can cause alternate yields, including climate variability, water stress (Haouari, 2013), and orchard management (Kour et al., 2018), making a definite diagnosis complicated. Consequently, we argue that the alternate behaviour of olive trees probably hindered our assessment of LER in cases of very low olive yields. Therefore, we suggest a careful interpretation of the extremely low or high LERs. Altogether, we stress the need to have more extended time series and/or spatial repetitions of yield data for consolidated conclusions about olive agroforestry systems. Implementing long-term experiments, capitalizing on experimental networks around the Mediterranean, and using modeling tools more extensively should together build promising approaches.

Conclusion

Olive agroforestry is gaining interest in the Mediterranean, but its relevance in a drier future remains uncertain. On the one hand, farmers fear the consequences of more intense negative tree-crop interactions under drought. On the other hand, ecological theory (SGH) predicts an increase in positive tree-crop interactions with increasing environmental stress. To move ahead, we evaluated a case of olive agroforestry along a water availability gradient, representative of most rainfed olive groves in the South Mediterranean. We show that olive trees limited crop growth during critical stages before flowering and caused a significant reduction in grain number per unit area and grain yield, whatever the water regime. In contrast, olive trees also improved grain filling and grain protein content, but not sufficiently to compensate for the negative effects on crop growth and yield. We concluded that in the case of olive agroforestry, the SGH needs a 'seasonal' reformulation to predict how the net balance in tree-crop interactions will change in a drier future. However, despite lower crop yield than sole crops, LERs > 1 reveal that olive agroforestry is a promising way of improving land and resource productivity, particularly with appropriate farming practices.

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CHAPTER V. Dynamic analysis of water flows in a wheat-olive system using the Biswat model

Abstract:

The introduction of an annual crop in olive orchards, especially in rainfed orchards, is a widespread farming practice in the southern Mediterranean. Tree crops association was established in order to increase land productivity and resources use efficiency. In order to understand water sharing in olive-based agroforestry, a field study was carried out in the Northern of Morocco. Biswat model is a 2D dimensions simple model allowing water balance components analysis. The model was adapted for a wide range of cropping systems and its advantageous thanks to the simplicity of inputs parameters requirements. The results showed that Biswat overestimated evaporation on the first 10 cm of the soil. In addition, depending on the soil layer, the model may over- or underestimate soil water content. However, it is possible that an adjustments between soil layers which may compensate the over- or underestimation of soil water content. Model evaluation through comparing measured and simulated water content showed a good estimation of soil water content in along 1 m deepth, particularly for sole olive trees (R^2 = 0.61) and for olive-wheat agroforestry (R^2 = 0.51). To conclude, the model allows simulating in a satisfactory way the soil water content as well as provides good description of the process describing the dynamics of water flows under ilivewheat agroforestry system. Overall, the results found showed that Biswat may be useful to describe the general behavior of crops which may be promoting to analyze olive-wheat system under different crop management.

1. Introduction :

Water is a determining factor of crop production in Mediterranean regions, where water deficit and heatwaves are more frequent at the end of crop cycle leading to yield losses (Zhang and Oweis, 1999). In these regions, most of farmers are completely dependent on rainfall. In order to enhance farms revenues, agroforestry is wide practices in dry lands (Krishnamurthy et al., 2019). Tree/crop combination is known to have an important role in improving water in the soil (Anderson et al., 2009), whereas the availability of this resource is mainly influenced by tree-crop interactions and orchard architecture (e.g. spatial arrangement of species and incident radiation). Competition for water and nutrient use occurs when tree and crop roots shares the same soil layers (Jose et al., 2004). As well, belowground competition becomes more important near the tree trunk and become more severe during crop growth (Luedeling et al., 2016). More efficient exploitation of water resources in semi-arid agroforestry can take place (Bai et al., 2016), through a complementary niche exploitation (Droppelmann et al., 2000) as a result of spatial separation of trees and crops rooting systems. In addition, cropping system management contributes to optimize the capture of water resources as well as reducing below-ground competition (Ong et al., 2007). For example, reducing water competition may be achieved through trees pruning leading to a decrease of tree root development (Peter and Lehmann, 2000). As a result, reducing competition between the two crops in arid Mediterranean regions, particularly for water, is a key success of the agroforestry system, which can be determined not only by resources availability but also by farmers' management choices.

A combination of experimental studies with modelling may enhance the understanding of spatial and temporal dynamics of tree-crop-soil interactions (Bayala et al., 2015), which include water sharing between agroforestry components. Modeling complex cropping system is still a big challenge for scientists and modelers (Burgess et al., 2008). Compared to monospecific models, few models were developed to analyze diversified cropping systems mainly due to the complexity of the processes and relationships between agro-system components (Matthews et al., 2004). According to (Burgess et al., 2019), the models evaluated in agroforestry covered several topics e.g. crop growth models, architecture models and others which describe the environmental impacts of crop tree associations, including farm scale or landscape models such as APSIM (Huth et al., 2002), WALNUCAS (Van Noordwijk and Lusiana, 1998) and Hi-safe (Dupraz et al., 2019). However, the majority of agroforestry models needs a lot of data for parameterization (Bertrand et al., 2018), and most can be used only by researchers (Ellis et al., 2004) (e.g. WIMISA, HYCAS…). Thus, there is a greater need for dynamic models able to predict agro-system resilience in face of climate change. As a main strategic crop, olive orchards occupies about 10 Mha in the Mediterranean basin (Angles, 2019), the majority still been rainfed and generally intercropped (Pantera et al., 2016; Bouhafa et al., 2015). However, the most productive and sustainable farming practices are not yet identified. Modelling may be a useful tool for analyzing and predicting the effect of management of intercropped olive orchards in dry condition. Water balance modeling in Mediterranean agroforestry was evaluated on olive/ potato and olive/ pea (Abid Karray et al., 2008) and olive/ cover crop (Abazi et al., 2013). Indeed, soil water availability, which varies with water supply (Liu et al., 2013), affects many plant functions, including transpiration (Livesley et al., 2004) and therefore photosynthesis (Monteith, 1966). Available water use is a complex concern particularly in agroforestry where water sharing includes both above-ground and below-ground processes (Abid Karray et al., 2008). Our objectives are (i) to describe crop response in sole and mixed cropping systems under contrasting water availability conditions; (ii) to evaluate if the Biswat model is a useful tool for analyzing and understanding the dynamics of soil moisture content in typical intercropped olive tree orchards in Mediterranean conditions. The study was conducted with data collected in a field experiment conducted in Morocco.

2. Materials & Methods:

2.1 BIS-Wat model description:

Biswat model (Bispecific Intercropped Systems – Water balance) was designed to simulate at a daily time step the water balance as well as the dynamics of a water stress indicator based on the fraction of transpirable soil moisture (FTSW) for tree and/or crop in the two-dimensional system pattern (2D) (Bertrand et al., 2018). In Biswat, soil profile is presented in the model as horizontal layers and vertical columns which were suitably defined by the user and should deal with root depth and soil structure. Biswat inputs were classified into three files and represented as an excel sheet to be entered by the user (1) the input variables file that includes daily climate data: rainfall, temperature, reference evapotranspiration ET_o according to Penman-Monteith equation, and radiation interception efficiency of both components A "tree" and component B "annual crop", which is based on leaf area index (LAI) and varies according to crop phenological stage (Fig.23); (2) the crop calendar file includes sowing date, irrigation (date, amount) and harvest; (3) the parameter file includes soil specific parameters (e. g., number of layers, soil moisture at field capacity (Fig.24)…), rooting system distribution (width and depth root growth), base temperature and the critical crop humidity of each crop.

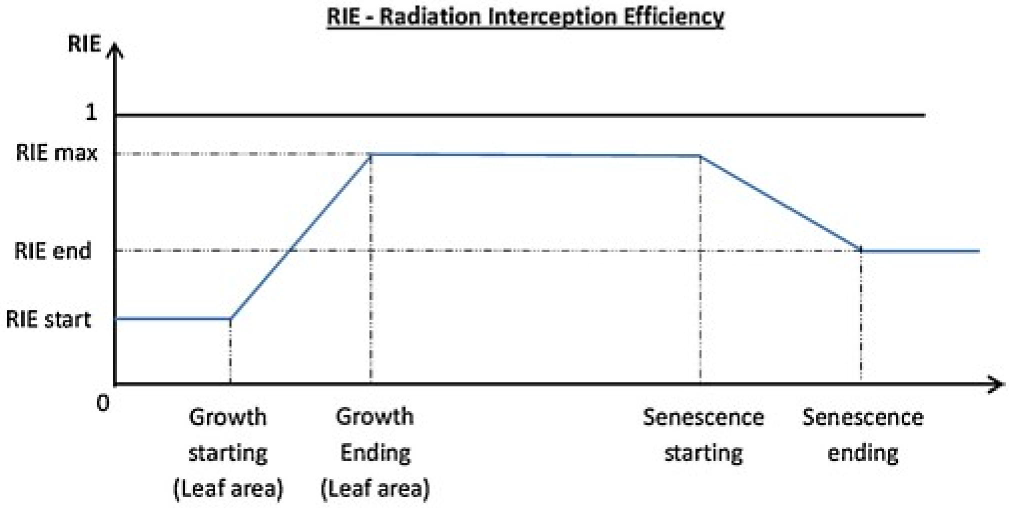


Figure 23: Estimation of the evolution of RIE, corresponding to the evolution of crop growth.

Plant transpiration and soil evaporation process occurs simultaneously (Katsoulas and Stanghellini, 2019), but soil evaporation is dominant at the beginning of growing season and transpiration becomes more important once plants are well developed (Katsoulas and Stanghellini, 2019). Biswat model simulate evaporation and transpiration (for trees 'A' Eq1., and for annual crop 'B' Eq2.) process, as driven by the reference evapotranspiration ETo and radiation use efficiency dynamics (Bertrand et al., 2018). Then, the water balance is calculated at daily time steps from the difference between the water entering in the system (irrigation and precipitation) and ouflows (transpiration, evaporation runoff and drainage).

Equation 1: $\boldsymbol{T_A(d) = RIE_A(d) \times min(1, \frac{FTSW_A\,(d-1)}{0.4}) \times ET_0(d)}$

Equation 2 : $\boldsymbol{T_B(d) = (1 - RIE_B(d))\,\frac{width_B(d)}{width_{AB}} \times \min(1, \frac{FTSW_B(d-1)}{0.4}) \times ET_0(d)}$

Biswat supposes (i) the symmetry on both sides of the tree line, which allows extrapolation of the results to the field scale for both crops in the intercropping system; (ii) soil evaporation occurs in the first 10 cm of soil; (iii) lateral water flux between adjacent soil samples are neglected (Roux et al., 2017).

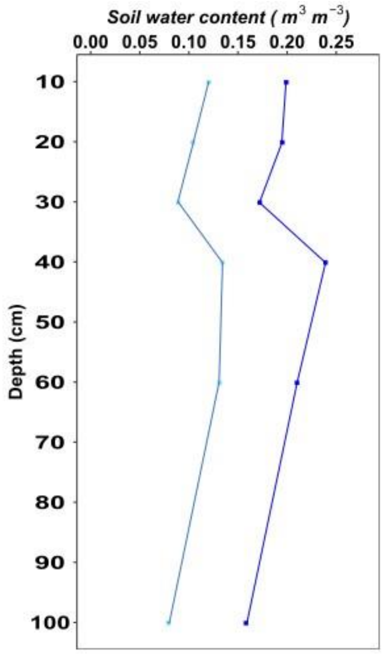


Figure 14: The evolution of field capacity (blue bold line) and wilting point profiles (blue light line) used in the simulation.

2.2 Data collection for modelling:

2.2.1. Biswat input data:

Tree and crop input parameters used to run the model were taken from the literature and field measurements. Olive trees root dimensions were considered equal to the depth with the highest concentration of roots (Abid Karray et al., 2008) and maximum lateral growth according to (Fernández et al., 1992) (Table 9). Wheat root system was considered to be at 30% of its maximum growth before tillering (Farahani and Bruggeman, 2008; Xue et al., 2003) and can reach its maximum at flowering (Supplementary Material). Radiation interception efficiency (RIE) was determined using (Eq.3) including the leaf area index which was measured for wheat at flowering using the leaf portable area meter (LICOR LI-3000C, Lincoln, Nebraska). The soil water contents at field capacity and wilting point were determined by measurements from soil samples taken at from an adjacent empty inter-row in agroforestry plot at different depths and then put in a pressure plate at 0.33 and 15 bar to estimate soil water content at field capacity and at wilting point respectively. The same values of field capacity and wilting point were used for all simulations in Biswat. The bulk density was measured by the cylinder method. The soil bulk density was 1.27 $g.cm^{-3}$, 1.32 $g.cm^{-3}$, 1.22 $g.cm^{-3}$, 1.28 $g.cm^{-3}$, 1.26 $g.cm^{-3}$ and 1.20 $g.cm^{-3}$ at 10, 20, 30 40 60 and 100 cm respectively. Tree and crop critical soil moisture at stomata closure was considered equal to soil wilting point due to the difficulty to determinate this parameter. The simulations began on 1st January which corresponds to the period marked by the return of the rainy season, filling soil reservoir. For these reason, we suggest that the initial values of soil water content were considered equal to field capacity.

Equation 3 : $\boldsymbol{RIE = 1 - e^{-K \times LAI}}$

With: k: the extinction coefficient ranging from 0 to 1; LAI: leaf area index

The meteorological data (rainfall, minimum and maximum temperature) during the experimental period were acquired from the mini meteorological station of the farm. These data were registered daily since 1988. Due to the difficulty in getting evapotranspiration data according to Penman-Monteith method, this parameter was estimated from the adjusted Thornthwaite equation (Trajkovic et al., 2019) (eq.4).

Equation 4 : $\boldsymbol{ET_{0Th,i} = \frac{16Ni}{360} \times \left(\frac{10Ti}{\sum_{i=1}^{12}(0.2\,Ti)^{1.514}}\right)^{0.016\sum_{i=1}^{12}(0.2Ti)^{1.514}+(0.5)}}$

With: ET_{0Th}: reference evapotranspiration estimated by the Thornthwaite equation (mm day^{-1}); Ni: The maximum possible duration of sunshine (h day^{-1}); Ti: mean air temperature in the i-th month (°C).

Table 9: Listing of Biswat input parameters.

Parameter	Parameter definition	Origin	Value
DistanceAB_mm	Width of the 2D pattern	Experiment	3500
ErdMax_B_mm	Maximum Effective Rooting Depth of a wheat	(Farahani and Bruggeman, 2008)	1400
ErwMax_B_mm	Maximum Effective Rooting Width of a wheat	(Farahani and Bruggeman, 2008)	2000
ErdMax_A_mm	Maximum Effective Rooting Depth of olive tree	(Abid Karray et al., 2008)	1000
ErdMax_A_mm	Maximum Effective Rooting Width of a olive tree	(Fernández et al., 1992)	2000
SoilZ_mm	Depth of each soil layer	Defined by user	0/100/200/300/400/600/1000/1800
$\boldsymbol{\theta_{FC}}$	Soil water content at field capacity for each soil layer ($m^3.m^{-3}$)	Measured	0.199/0.195/0.172/0.239/0.210/0.158/0.158
$\boldsymbol{\theta_{WP}}$	Soil water content at wilting point for each soil layer ($m^3.m^{-3}$)	Measured	0.120/0.104/0.089/0.134/0.131/0.079/0.079
θ-	Critical humidity for each soil layer for a plant ($m^3.m^{-3}$)	Equal to θ_{WP}	0.120/0.104/0.089/0.134/0.131/0.079/0.079

2.2.2. Study site and soil water measurements:

This study was part of a global field study aiming to assess olive-based agroforestry system performance along a water gradient. The experiment was conducted during two years (2017-2019), in Northern east Morocco in the “Providence Verte Farm” (33°53'48.26"N, 4°40'25.63"O, 615 m), where the climate is semi-arid. Rainfall was 429 mm and 345 mm in 2017/2018 and 2018/2019 respectively. The rainy period was recorded mainly between November and April. The soil was a sandy clay loam soil in the top 0-0.60 m. The cultivated olive trees (Olea europaea L., cv Moroccan picholine) are mature (65 years old) with a 7 m × 7 m plantation design. Three cropping systems were assessed: olive/durum wheat agroforestry system and sole durum wheat and sole olive, with three replication covering 18 plots. Intercropped durum wheat was sown at 1.5 m from the tree row and covered 4 m of the interrow. Three water modalities using drip irrigation were created to irrigate both trees and crops agroforestry; (1) high water regime received +159.3 mm and 100 mm respectively in 2018 and 2019; (2) medium water regime received +72.7 mm and 50 mm respectively in 2018 and 2019; (3) and rainfed regime. Model evaluation to simulate the soil water content for olive-wheat agroforestry systems, sole olive trees and sole wheat under three water regimes was done using 54 capacitance PR2 probe. Soil water content was measured with a capacitance profile probe (PR2/6, Delta-T Devices, Cambridge, UK) biweekly and weekly in 2018 and 2019 respectively. The PR2/6 probe used in the experiment measures soil moisture at 6 depths down to 100 cm at: 10, 20, 30, 40, 60 and 100 cm. The PR2 probe was combined with an HH2 moisture meter which displays the profile probe readings through a voltage output converted to the square root of permittivity. The adopted calibration equation is proposed by the manufacturer for the type of mineral soil such as our soil (for silty-sandy soils). In agroforestry, soil water content was the average of soil water content values from two distances from the tree row at 1.75 m and 3.5 m (where wheat grown under olive trees).

3. Results:

3.1 Effect of intercropping on measured soil water distribution:

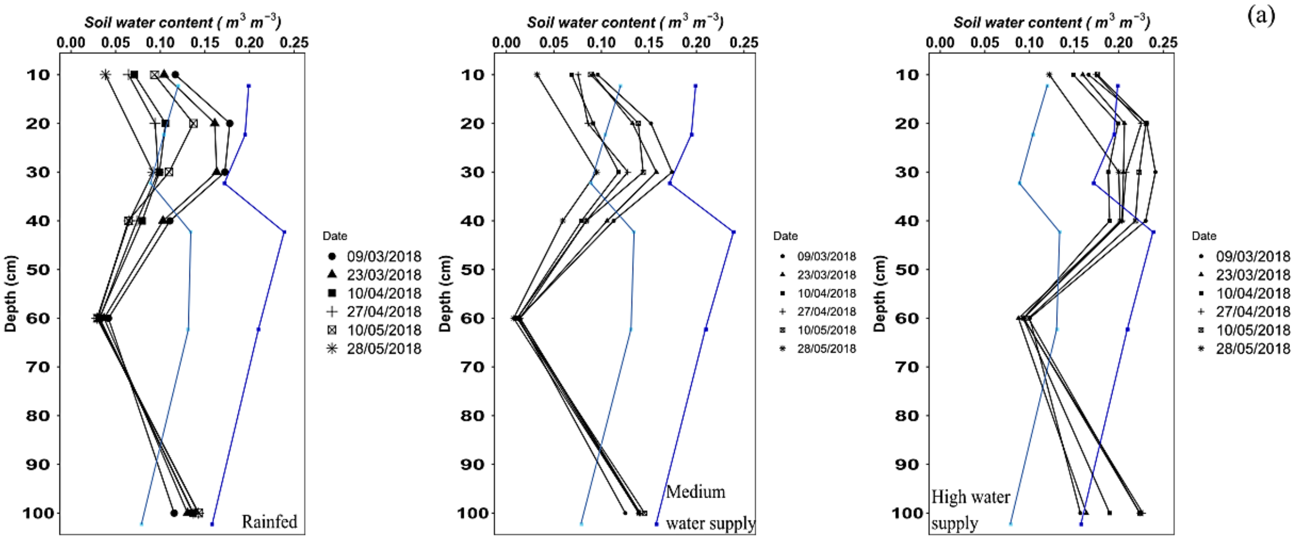
In 2018, soil moisture profiles measured with the PR2 probes are plotted every two weeks for the period 09/03 to 28/05 (Fig.25, 2018) and every week in 2019 from 04/04 to 26/06 (supplementary data). In 2018, soil water content in sole wheat system was high in 20-30 cm depth. Under rainfed sole wheat system, soil water content ranged from 0.094 to 0.177 $m^3.m^{-3}$ in 20 and from 0.091 to 0.172 $m^3.m^{-3}$ in 30 cm. Soil water content (Fig.25a) in deeper layer 60 cm was very low with an averaged value about 0.033 $m^3.m^{-3}$ under rainfed regime. However, under medium sole wheat, soil water content ranged from 0.085 to 0.152 $m^3.m^{-3}$ in 20 cm and from 0.095 to 0.174 $m^3.m^{-3}$ in 30 cm. Under medium water supply, soil water profile in sole wheat system showed a very low water content in 60 cm soil layer with a mean value of 0.012 $m^3.m^{-3}$ (Fig.25a). Soil water content under high water supply (Fig.25a) ranged from 0.199 to 0.231 $m^3.m^{-3}$ in 20 cm and from 0.188 to 0.241 $m^3.m^{-3}$ in 30 cm. In 60 cm depth, the mean soil water content was 0.094 $m^3.m^{-3}$ in sole wheat under high water supply. The soil water content under rainfed sole olive trees was high in 30-40 cm depth. In 30cm soil layer (Fig.25b), soil water content ranged from 0.157 to 0.189 $m^3.m^{-3}$, while in 40 cm soil water content ranged from 0.168 to 0.248 $m^3.m^{-3}$. Soil water content in sole olives trees under medium water supply ranged from 0.172 to 0.196 $m^3.m^{-3}$ in 20 and from 0.192 to 0.217 $m^3.m^3$ in 60 cm (Fig.25b), while in 100 cm soil water content was low with a mean value of 0.103 $m^3.m^{-3}$. Deeper soil layer showed a low water content under rainfed sole olive trees on average 0.110 $m^3.m^{-3}$ (Fig.25b). The average soil water content was high in 20 (0.225 $m^3.m^{-3}$) and 40 (0.238 $m^3.m^{-3}$) cm depth under high water supply sole olive trees. In 100 cm depth, the mean soil water content was low 0.124 $m^3.m^{-3}$ in sole olive trees under high water supply. In rainfed agroforestry (Fig.25c), the soil water content was low with an average values about 0.101 $m^3.m^{-3}$ in 10 and 60 cm depth. Under medium water supply (Fig.25c), agroforestry showed a high water content in 30 cm (0.246 $m^3.m^{-3}$) while deeper soil layer (100 cm) showed low water content (0.135 $m^3.m^{-3}$). Finally, soil water content under high water supply was high in 20-30 cm with average values of 0.200 $m^3.m^{-3}$ and 0.199 $m^3.m^{-3}$ respectively.

In 2019, soil water content in sole wheat system was high in 20 cm depth. Under rainfed sole wheat system, soil water content ranged from 0.092 to 0.195 $m^3.m^{-3}$. Soil water content (supplementary data) in top soil layer 10 cm was very low with an averaged value about 0.082 $m^3.m^{-3}$ under rainfed regime. In sole olive trees, soil water content was high in 20 cm (0.135 $m^3.m^{-3}$) under rainfed regime. In sole olive system, the mean soil water content values were high in 20 cm (0.184 $m^3.m^{-3}$) and 30 cm (0.200 $m^3.m^{-3}$) respectively for both high and medium water supply. In agroforestry, the mean soil water content was high in 20 cm (0.172 $m^3.m^{-3}$) and 0.165 $m^3.m^{-3}$ under medium and rainfed regime. The mean soil water content values were low in 60 cm (0.076 $m^3.m^{-3}$) under high water supply and in 100 cm for both high water supply (0.028 $m^3.m^{-3}$) and medium water supply (0.039 $m^3.m^{-3}$).

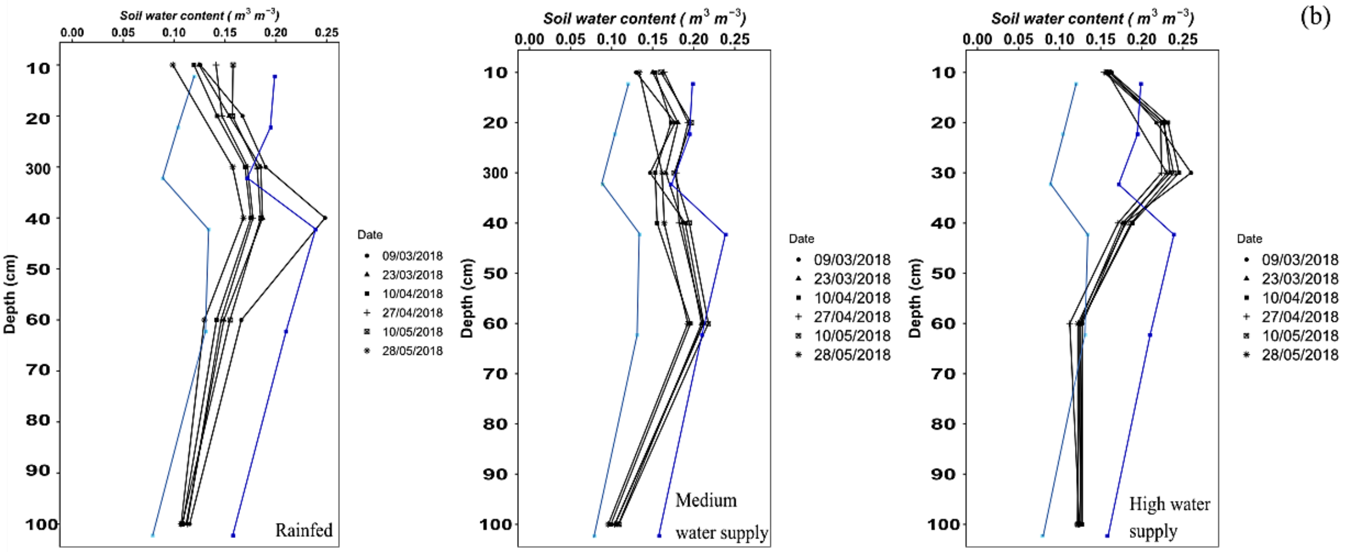
In 2019, date of water measurement had a significant impact on soil water content ($p<0.001$). Cropping system had a significant effect on soil water content in both 2018 ($p<0.001$)

and 2019 (p<0.001). Water supply was had a significant effect on soil water content in both 2018 (p<0.001) and 2019 (p<0.001).

(a)



(b)



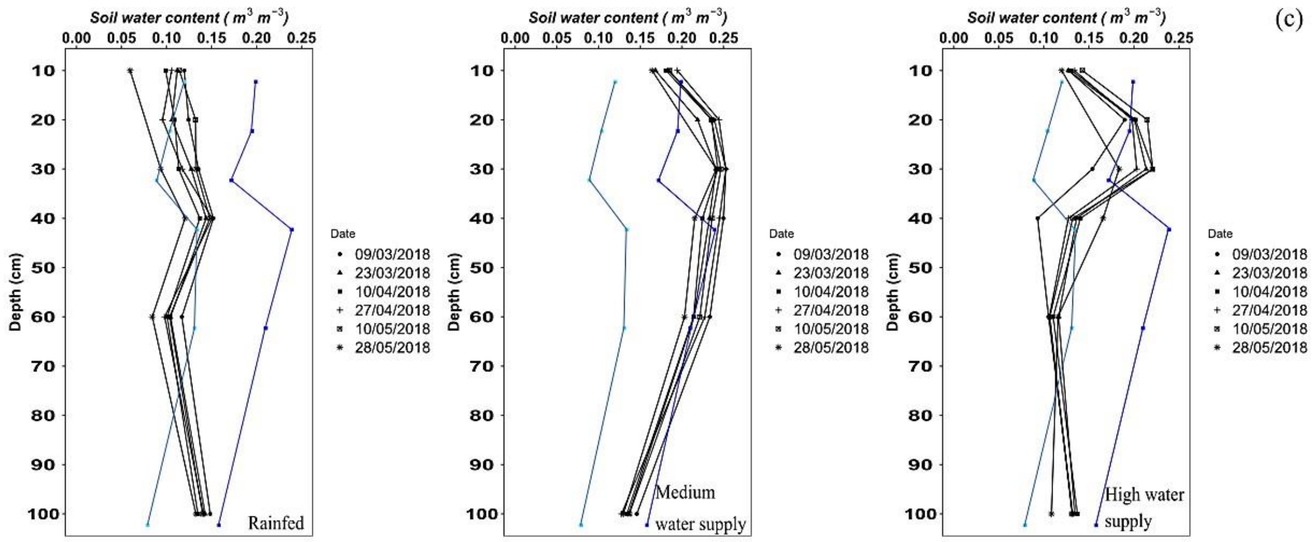


Figure 25: Soil water profile for three cropping systems sole wheat (a), sole olive trees (b) and agroforestry systems (c) according to three water regimes (High water supply, medium water supply and rainfed) from 09/03/2018 to 20/05/2018. The dark blue line corresponds to field capacity and the light blue line to wilting points measured in laboratory.

3.2 Evaluation of Biswat model with measurements:

The model showed a relatively good relationship between simulated and measured soil water content on the two top soil layers where the R^2 was 0.49 and 0.31 in 10 and 20 cm depth (Fig.26). The RMSE values ranged from 0.067 $m^3.m^{-3}$ to 0.037 $m^3.m^{-3}$ in the 10 and 20 first twenty soil centimeters. However, simulated and measured water content showed a small relation at 30 cm depth ($R^2 \approx 0.14$). We also highlighted a good accuracy of soil water content predictions in 100 cm depth ($R^2 = 0.43$). The RMSE values were 0.054, 0.071, 0.101 and 0.059 $m^3.m^{-3}$ for 30, 40 60 and 100 cm respectively. The bias was (-0.005 $m^3.m^{-3}$, 10 cm), (+ 0.001 $m^3.m^{-3}$, 20 cm), (+ 0.005 $m^3.m^{-3}$, 30 cm), (-0.007 $m^3.m^{-3}$, 40 cm), (- 0.009 $m^3.m^{-3}$, 60 cm) and (- 0.003 $m^3.m^{-3}$,100 cm).

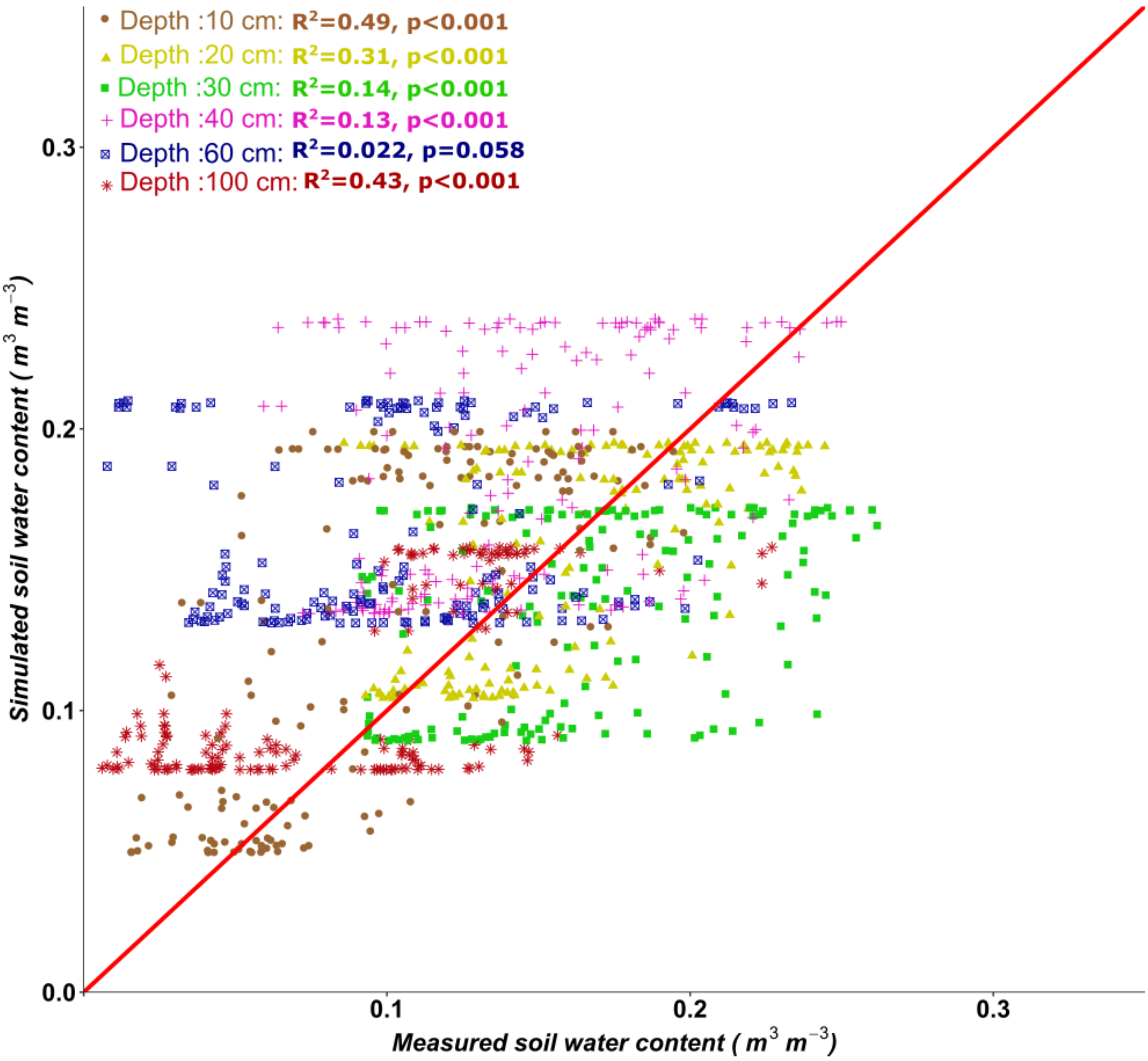
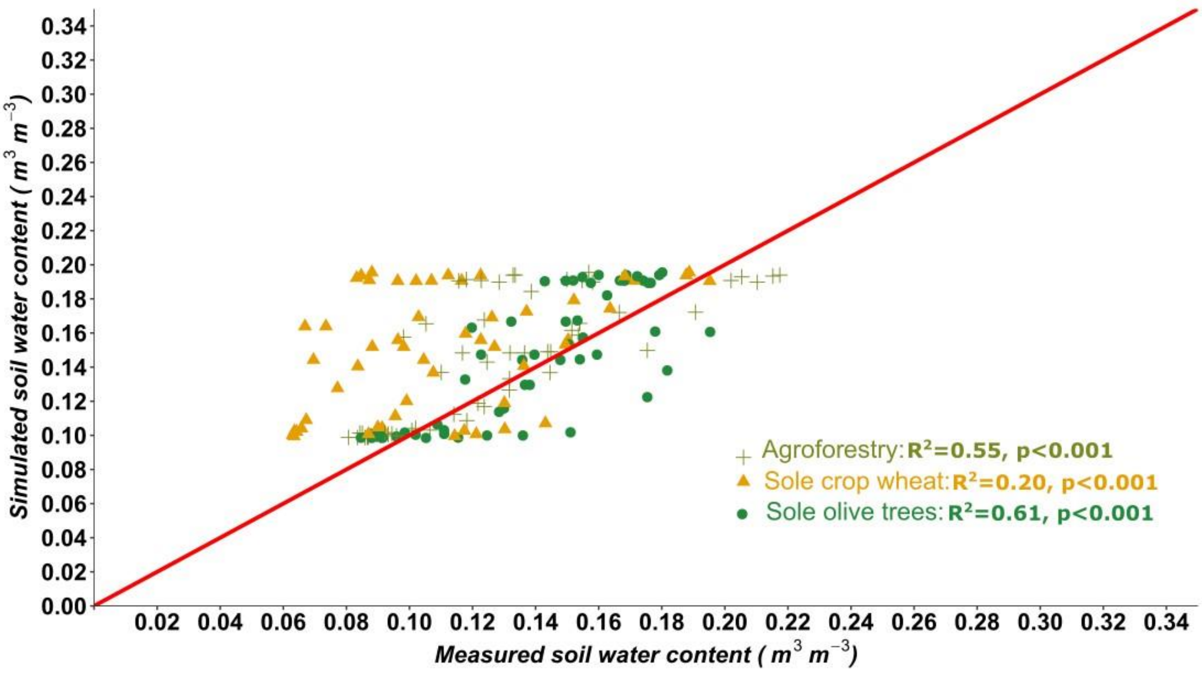


Figure 26: Comparison of soil water content estimated by Biswat model and measured values for the six soil layers: 10 cm layer (brown circle shape), 20 cm layer (yellow triangle shape), 30 cm layer (green rectangle shape), 40 cm layer (pink cross shape), 60 cm layer (blue rectangle shape), and 100 cm layer (red asterisk shape).

Better simulations were found considering the global water content down to 1m depth (Fig.27). Simulated soil water content was relatively acceptable for both agroforestry (R^2 = 0.55) and olive trees systems (R^2 = 0.61). The RMSE values were 0.049 $m^3.m^{-3}$, 0.036 $m^3.m^{-3}$ and 0.092 $m^3.m^{-3}$ for agroforestry, sole olive trees and sole wheat respectively. The bias was - 0.005 $m^3.m^{-3}$, - 0.001 $m^3.m^{-3}$, and - 0.012 $m^3.m^{-3}$ for agroforestry, sole olive trees and sole wheat. In both high water (R^2 = 0.77) and rainfed (R^2 = 0.31) regimes, soil water content was relatively well simulated by the model, with an RMSE of 0.038 $m^3.m^{-3}$ and 0.082 $m^3.m^{-3}$ respectively. The bias was - 0.005 $m^3.m^{-3}$, - 0.002 $m^3.m^{-3}$ and - 0.011 $m^3.m^{-3}$ for high water supply modality, medium water supply and rainfed regimes respectively showing a slight overestimation of soil moisture.



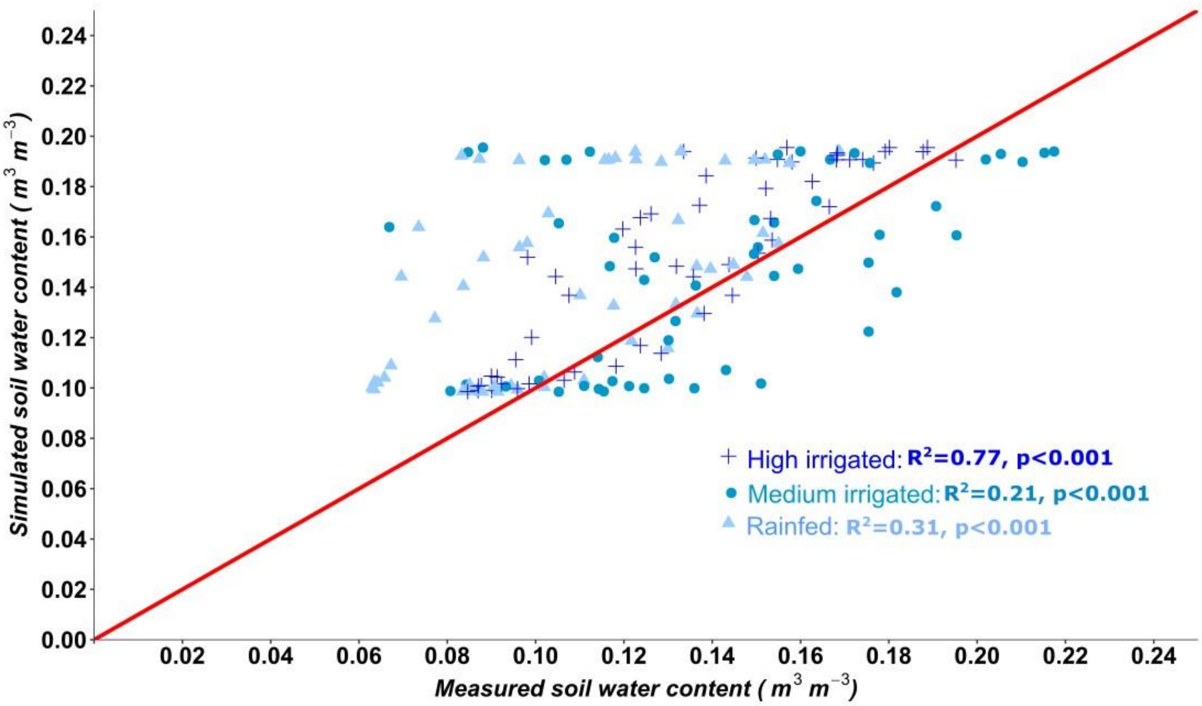


Figure 27: Comparison of soil water content estimated for 1 m depth by Biswat model and measured values. (A) For three cropping system: agroforestry (cross shape), sole olive trees (circle shape) and sole wheat (triangle shape). (B) Three water regimes were tested as follows: 'High supply' water supply (dark blue cross shape), 'Medium supply' water supply (mid-dark blue circle shape) and 'Rainfed' (clear blue triangle shape).

3.3 Simulated water balance components:

3.3.1 Rainfall and simulated drainage pattern:

Differences in the precipitation amount during the two simulation periods (01/01/2018 to 30/06/2018) and (01/01/2018 to 30/06/2018) resulted in differences in the amount of drainage water (Table 8). In 2018, simulated daily water percolation varied from 0 to 16.8 mm in rainfed sole-wheat (Fig.28a). In 2019 daily water percolation varied from 0 to 5.2 mm. Simulated daily water percolation in rainfed olive-wheat agroforestry varied from 0 to 13.6 mm in 2018 (Fig.28b), while daily water percolation ranged from 0 to 6.7 mm. Total simulated water percolation during the simulation period was 220.2 and 204.6 mm in both 2018 and 2019 respectively (Table 10).

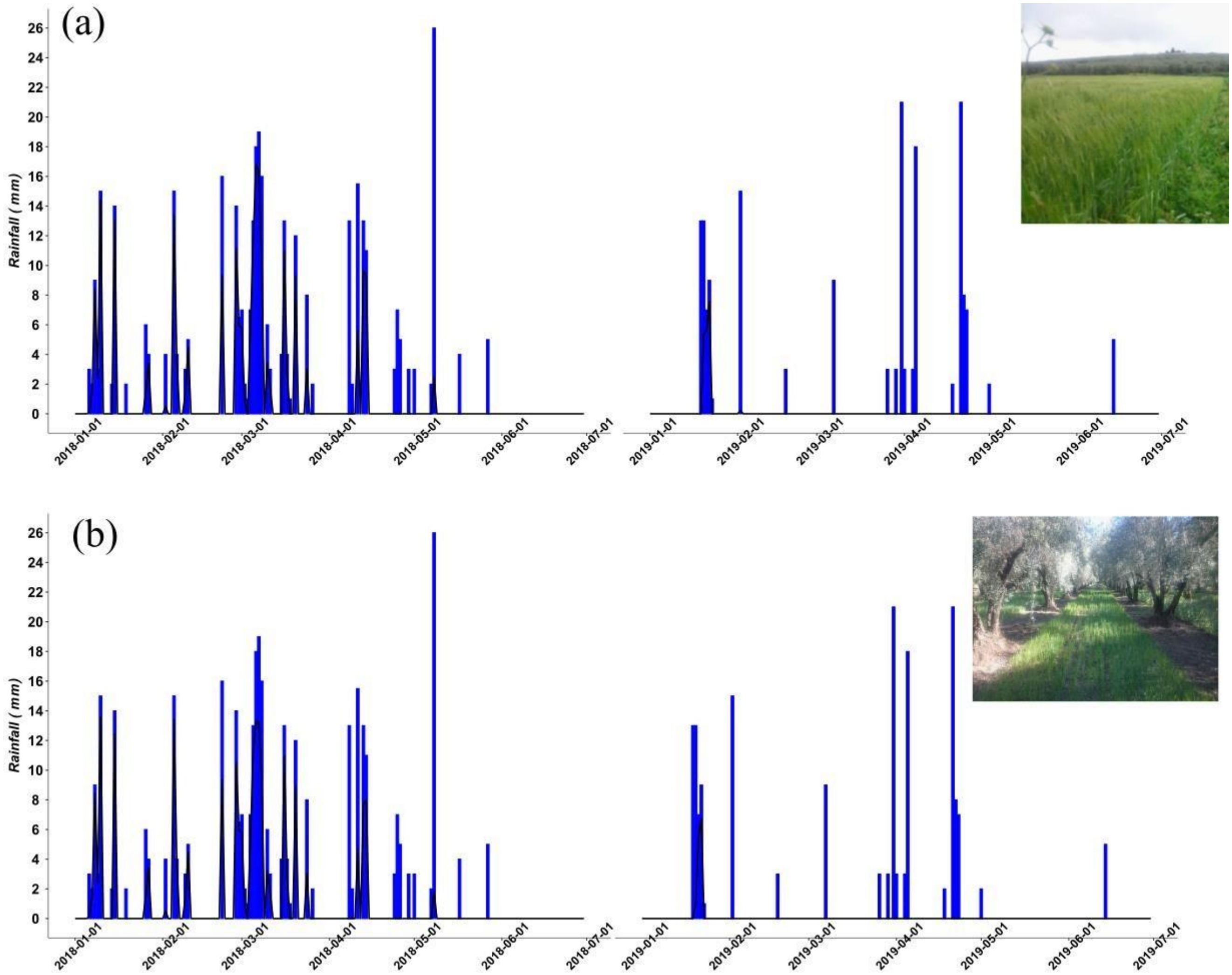


Figure 28: Rainfall (blue bars) and water percolation (black line) dynamic for two simulation periods (01/01/2018-30/06/2018) and (01/01/2019-30/06/2019) for (a) rainfed sole wheat and (b) rainfed olive-wheat agroforestry.

3.3.2 Soil evaporation and of crops water demand dynamic:

In the beginning of sole wheat growth (under rainfed water modality), water losses was mainly due to soil evaporation which ranged between 0 and 0.3 mm. Evaporation dynamic appeared as a relatively continual increase process. However, soil evaporation dynamic were more variable during 2019, and it increased up to 1.3 mm at 02/05/2019. Under high water supply, soil evaporation was more important and reached its maximum on 03/06/2018 (1.19 mm) and in 24/05/2019 (1.43 mm). In both water regimes, wheat water demand increased continuously during the growing season (Fig.29a, Fig.29b). Simulated transpiration for sole wheat varied from 184.79 mm under rainfed regime to 191.97 mm under the high water regime in 2018 (Table 10). In 2019, wheat canopy transpiration was higher by 13 % under high water regime.

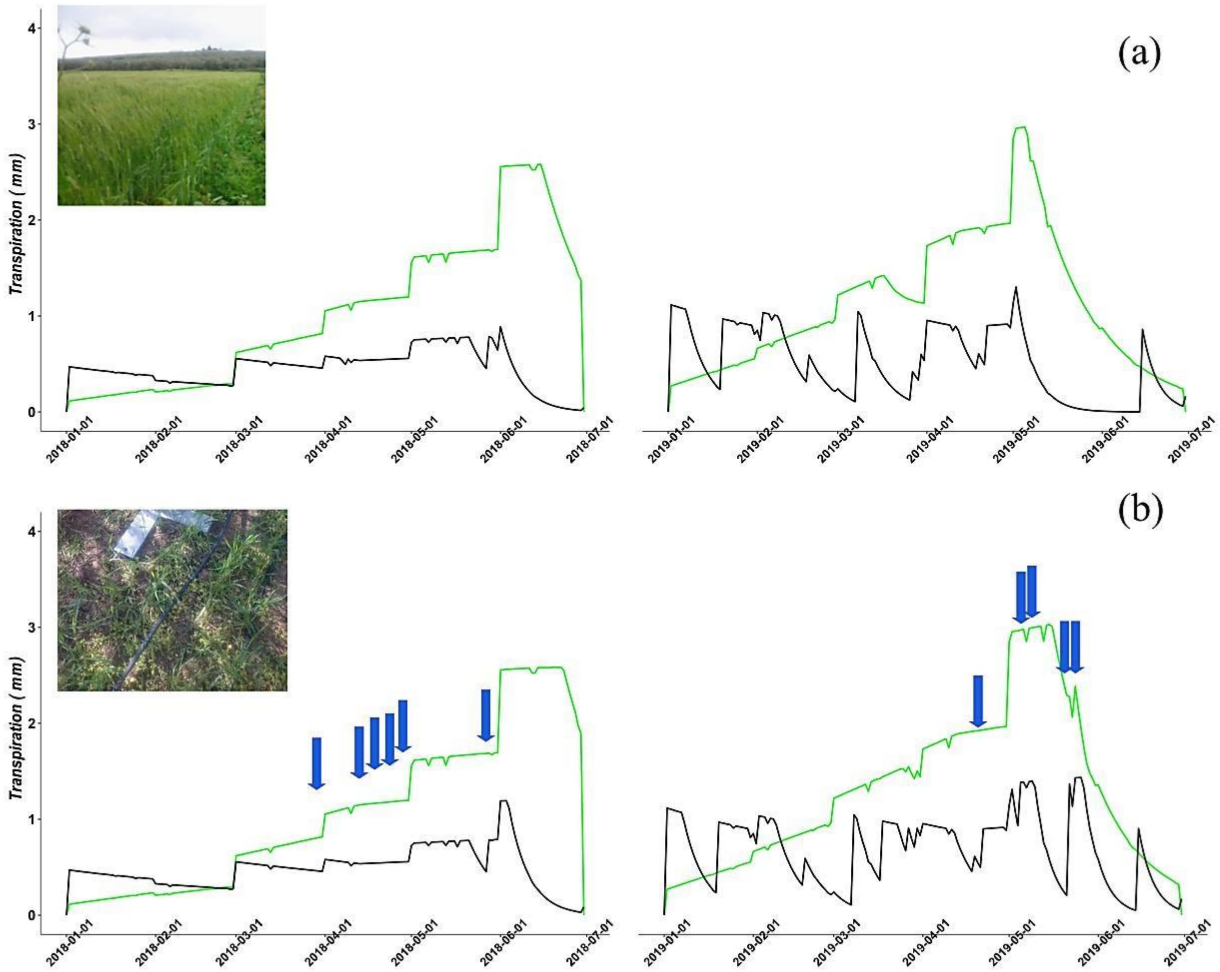


Figure 29: Transpiration (green line) and evaporation (black line) for two simulation periods (01/01/2018-30/06/2018) and (01/01/2019-30/06/2019) for rainfed sole wheat (a) and high water sole wheat (blue arrows correspond to water supply) (b).

Wheat transpiration increased continuously during the growing season. Simulated wheat water demand increased after irrigation to reach a maximum of 3 mm.day^{-1}. Under rainfed regime, wheat water demand reached its maximum in 10/06/2018 (2.57 mm) and in 05/05/2019 (2.97 mm). Under irrigated regime, wheat water demand reached its maximum in 14/06/2018 (2.58 mm) and in 14/05/2019 (3 mm). In 2019, wheat canopy transpiration was slightly higher by 5 % under high water regime than under rainfed regime, without significant differences. In 2018, simulated transpiration during the simulation period for wheat was 58.66 mm under rainfed regime to 60.22 mm under the high water regime in 2018 (Table 10). Wheat water demand increase in agroforestry for both rainfed and irrigated water regimes (Table 10).

Olive water demand is a continuously increase process during the simulation periods. The water demand of Olive tree was + 7 % and +13 % higher under high water supply than under rainfed regime (Table 10). Olive water demand reached its maximum in 01/06/2018 (1.66 mm.day^{-1}) and in 24/05/2019 (1.38 mm.day^{-1}). Under irrigated water (Fig.30 a), the olive water demand evolution showed that olive transpiration increase to reach a maximum of 1.93 mm.day^{-1} on 06/05/2019 (Fig.30 b). Olive water demand increase slightly in agroforestry than in sole olive trees (Table 10).

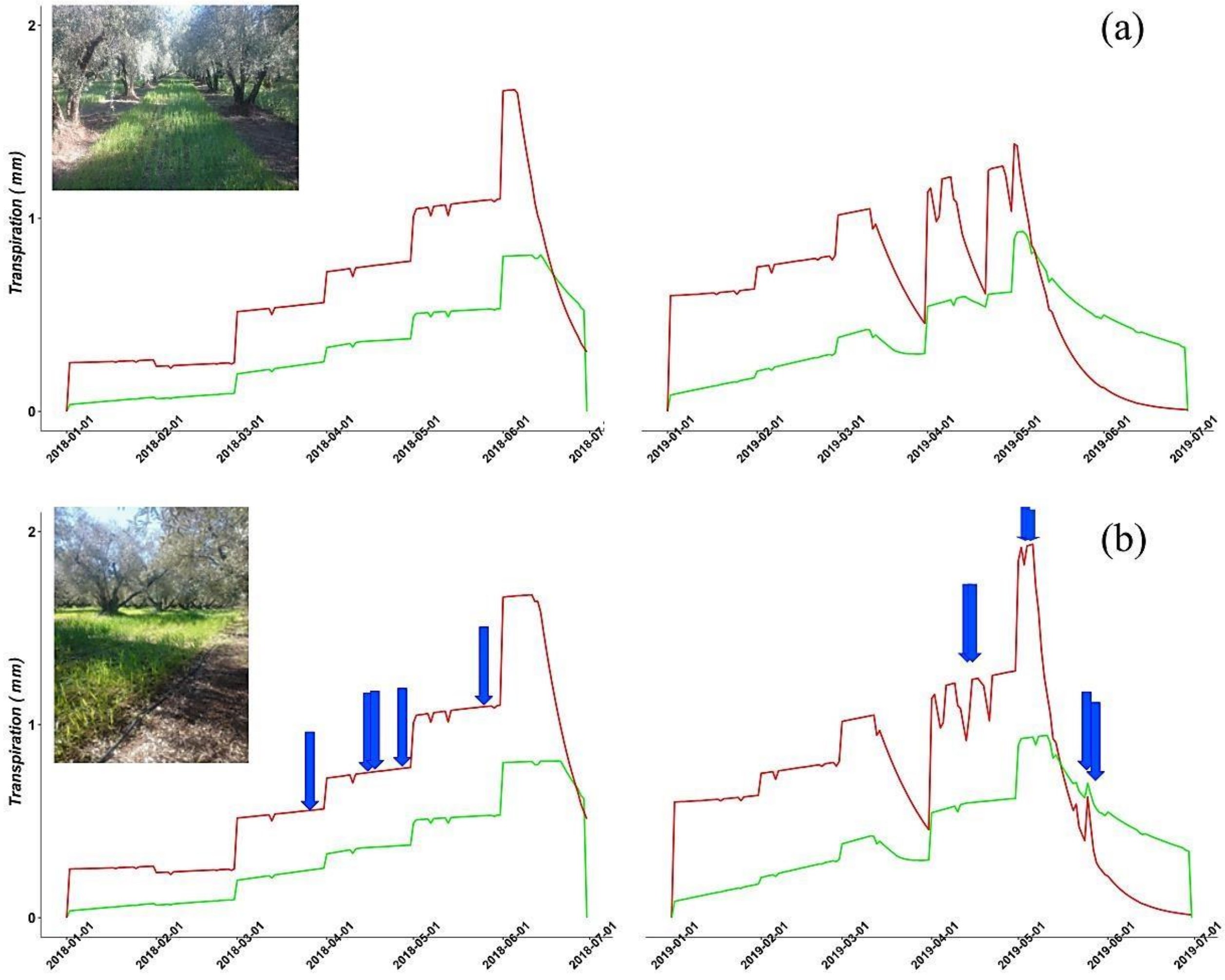


Figure 30: Transpiration of wheat (green line) and olive tree (red line) for two simulation periods (01/01/2018-30/06/2018) and (01/01/2019-30/06/2019) for (a) rainfed agroforestry and (b) agroforestry with high water regime (blue arrows correspond to water supply).

3.3.3. Stress indicator (FTSW) dynamic:

Simulated water stress indicator (FTSW) for rainfed sole wheat indicated late water stress in 2018 (from 15/06/2018, FTSW=0.38). However, the crop had earlier and longer stress periods in 2019 e.g. from 16/03/2019 to 30/03/2019 where FTSW<0.4, and 19/04/2019 (Fig.31).

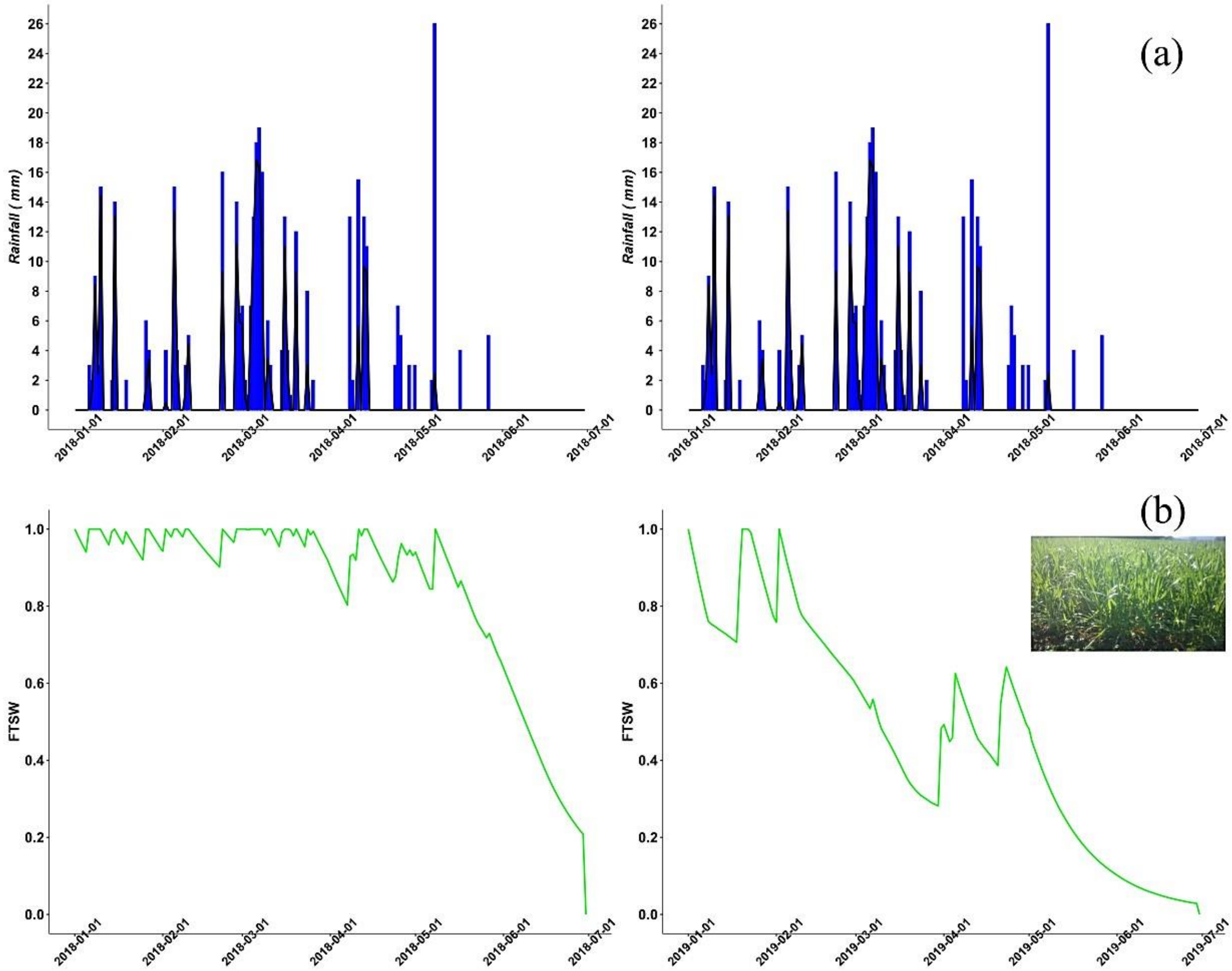


Figure 31: Rainfall and drainage dynamic for two simulation periods (01/01/201830/06/2018) and (01/01/2019-30/06/2019) (a) and (b) Sole wheat water stress indicator (green line).

Irrigation reduces wheat water stress. Simulated water stress indicator (FTSW) showed a delay of water stress period in 2018 (from 22/06/2018, FTSW=0.39). However, the crop had repeated stressful periods which occurred form 16/03 for15 days in 2019 where irrigation started in 17/04/2019(Fig.32). Despite, the water supply the FTSW was below 0.38 in the end of wheat growing season from 19/05/2019.

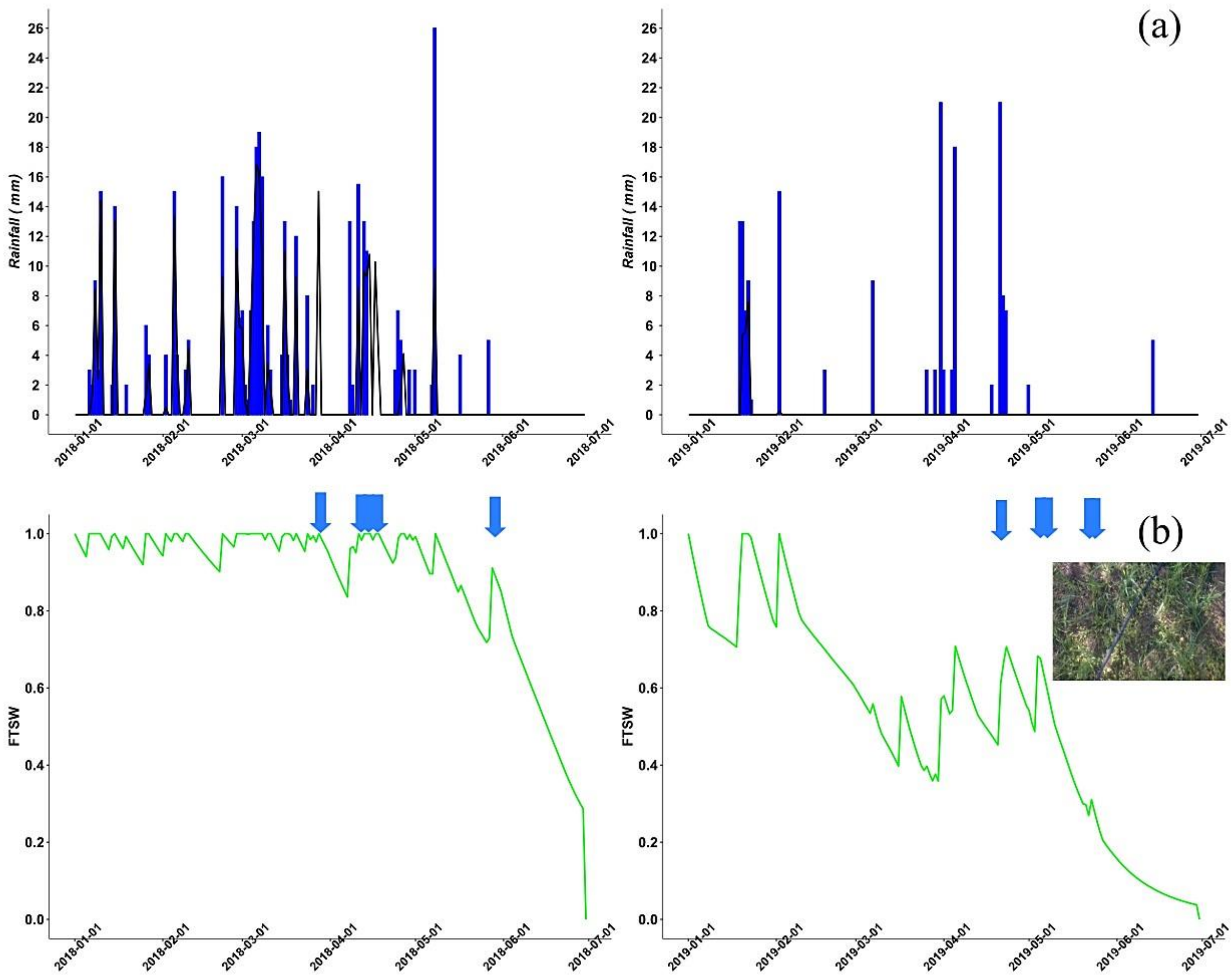


Figure 32: Rainfall and drainage dynamic in 2018 and 2019 (a) and the transpirable soil water fraction (b) (green line) (blue arrows correspond to water supply).

Simulated water stress indicator (FTSW) in rainfed agroforestry indicated that olive tree stress began from 05/06 in 2018 with FTSW=0.39, while that of the wheat crop started on 14/06 when FTSW was 0.38 (Fig.33). However, in 2019 wheat was more stressed at the beginning of the simulation period (FTSW=0.39) followed by olive which had a stress period of 12/03/2019 (FTSW=0.38). The rainy period (31/03/2019) helped to reduce the stress felt by crops from (31/03/2019) for wheat (FTSW=0.44), and 04/04/2019 for olive trees (0.50) (Fig. 33).

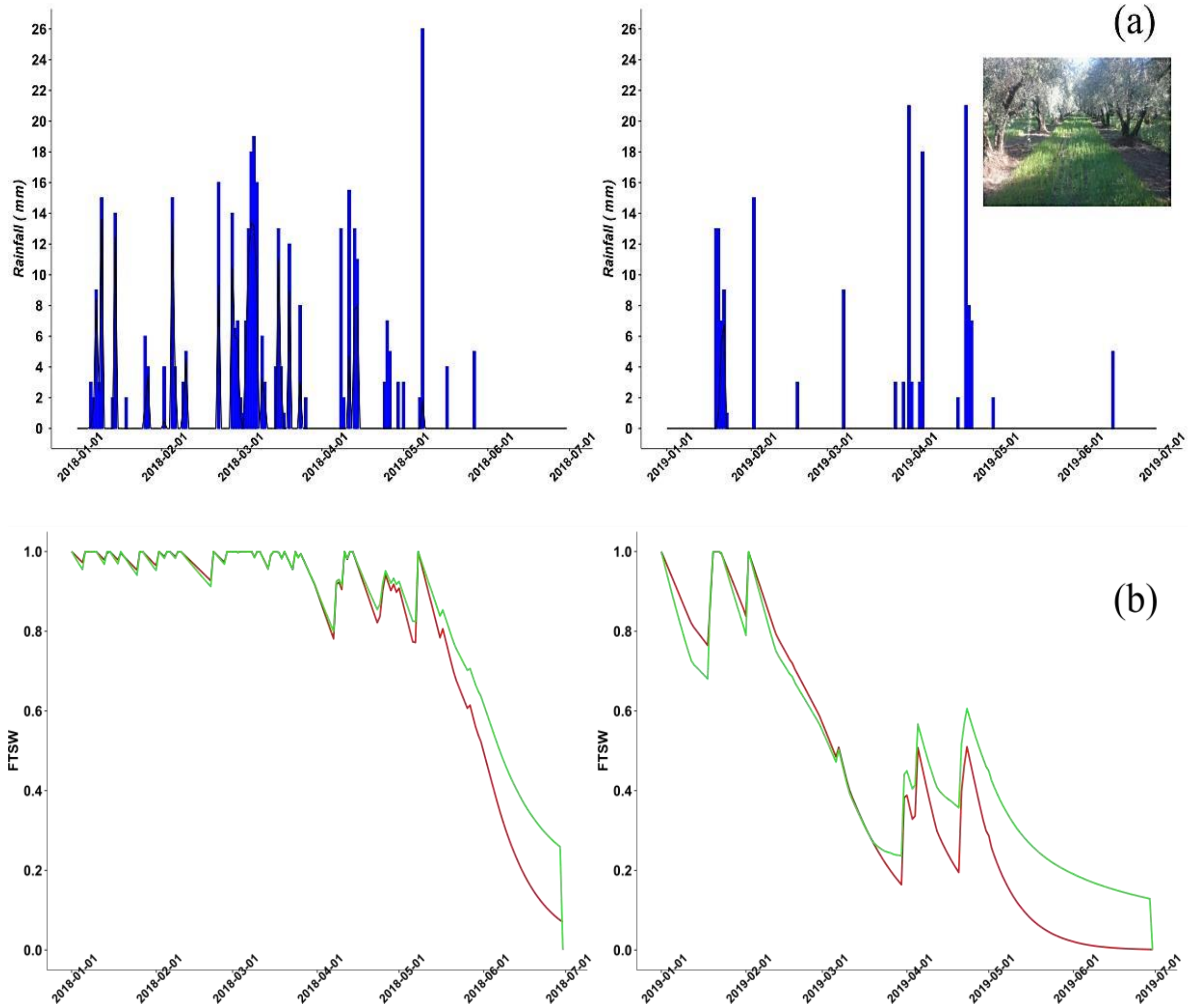


Figure 33: Rainfall and drainage dynamic for two simulation periods (01/01/2018-30/06/2018) and (01/01/2019-30/06/2019) (a) and (b) the transpirable soil water fraction in rainfed agroforestry of wheat (green line) and olive tree (red line).

At the beginning of the simulation period in 2018, the water stress indicator (FTSW) was around 1. Consequently, both olive trees and wheat were not stressed. Irrigation enhance transpirable soil water fraction in 2018. Crop stress was started on 13/06 for olive trees (FTSW=0.37) and on 21/06 for wheat (FTW=0.38). A greater variability of crop stress was noted in 2019 which was drier (total rain during the simulation period =166 mm). Wheat stress started slightly earlier on 11/03/2019 (FTSW = 0.39) than olive trees on 12/03/2019 (FTSW = 0.38). In 2019, irrigation reduces crops water stress (Fig.34).

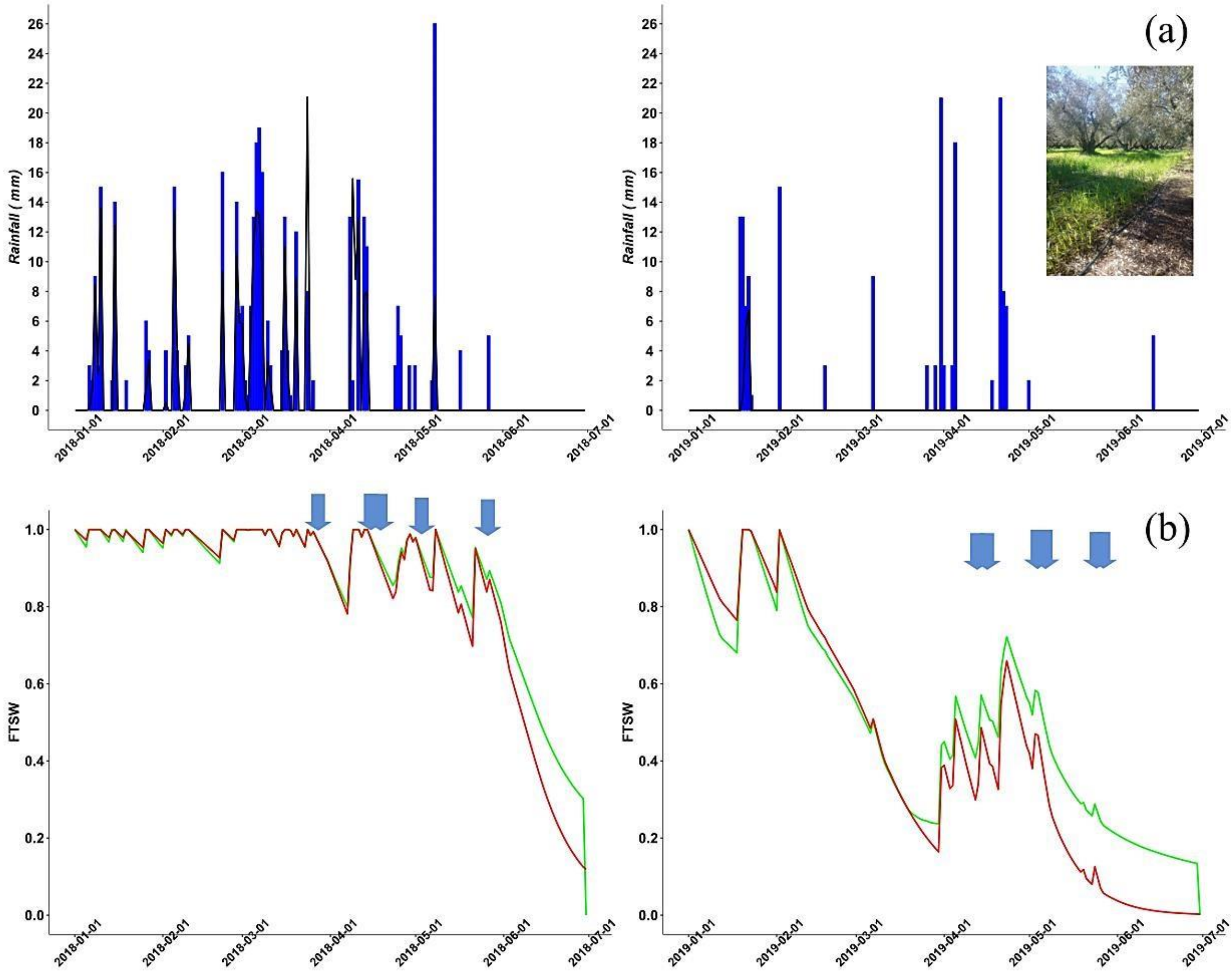


Figure 34: Rainfall and drainage dynamic in 2018 and 2019 (a) and the transpirable soil water fraction in irrigated agroforestry (b) green line corresponds FTSW-wheat and red line corresponds FTSW-olive tree (blue arrows correspond to water supply).

Table 10: Simulated total soil evaporation, transpiration and drainage of olive trees and wheat in each water treatment over the simulation period (over two simulation period from 01/01/2018 to 30/06/2018 & from 01/01/2019 to 30/06/2019) and total rainfall and iSimulated total soil evaporation, transpiration and drainage of olive trees and wheat in each water treatment over the simulation period (over two simulation period from 01/01/2018 to 30/06/2018 & from 01/01/2019 to 30/06/2019) and total rainfall and irrigation over the same period.

Year	**Cropping system**	**Water supply**	**Rain (mm)**	**Irrigation (mm)**	**Evaporation (mm)**	**Drainage (mm)**	**Transpiration olive tree (mm)**	**Transpiration Wheat (mm)**	**Soil water variation (mm)**
2018	Wheat Sole cropping	High water supply	376	159.36	87.41	276.7	-	191.9	-26.77
		Medium water supply	376	72.69	88.06	246.6	-	186.6	-78.65
		Rainfed	376	-	81.95	220.2	-	184.7	-116.9
2019		High water supply	166	99.99	123.9	18.82	-	233.9	-110.7
		Medium water supply	166	50	108.8	18.82	-	210.2	-121.8
		Rainfed	166	-	91.61	18.82	-	202.8	-147.2
2018	Sole olive trees	High water supply	376	159.2	84.10	239.9	170.7	-	-2.76
		Medium water supply	376	72.7	84.05	209.7	160.3	-	-48.61
		Rainfed	376	-	76.43	183.4	158.3	-	-85.36
2019		High water supply	166	99.99	112.67	10.63	174.2	-	-39.97
		Medium water supply	166	50	101.8	10.63	160.1	-	-65.01
		Rainfed	166	-	83.49	10.63	153.5	-	-90.02
2018	Agroforestry (Olive trees and wheat)	High water supply	376	159.2	82.18	261.1	125.	60.22	-15.28
		Medium water supply	376	72.7	81.33	231	118.1	59.10	-62.87
		Rainfed	376	-	75.50	204.6	115.7	58.66	-100.4
2019		High water supply	166	99.99	112.4	13.30	133	76.41	-72.75
		Medium water supply	166	50	102.6	13.30	121.2	73.75	-98.51
		Rainfed	166	-	85.04	13.30	115.4	72.49	-123.8

4. Discussion

4.1 Evaluation of tree-crop water uptake:

Crop root distribution depends on soil depth spatial heterogeneity of soil properties e.g. mechanical soil obstacles (Bécel, 2010; Forey, 2016), leading a variability in water distribution in the soil (Moroke et al., 2005). Experimental results showed that soil water content in the first 10 cm is lower than soil moisture in 20 cm throughout the growing crop cycle. This results may be explained by a high soil evaporation which occurs on the top soil layers (Li et al., 2020), crop water uptake can also reduce the amount of soil water (Moroke et al., 2005). Our experimental results show higher water uptake at a depth of 0.6 m under all water regimes, which can be explained by a high root concentration in the top 0.6 m (Moroke et al., 2005). During 2019, sole wheat water uptake under the three water treatment was important at 1m depth this can be explained by a better root plasticity under dry conditions (Ehdaie et al., 2012) allowing wheat to reach deeper water resources mainly that total water supply (rainfall and irrigation supply see Chapter2) was lower during the second year of experiment. In addition, we highlighted the presence of deep water uptake at 1m depth under the three cropping systems which may be a result of a deep root growth notably in agroforestry where low water content may be the results of tree-crop competition for water (Rao et al., 1998). The response to the water supply in 2018 did not change much the evolution of soil water profile which may be due to the measuring time scale (15 days) during which water absorption is continuous and may not reduce the visibility of water supply.

4.2 Performance of Biswat Model:

In this section, we will discuss the ability of Biswat model to describe some crop processes e.g. transpiration in mono and bispecific cropping system that contribute to impact soil water balance using available data describing crop growth. Our approach is based on the estimation of tree/crop parameters with literature data and some measured variables for wheat and olive to describe the water dynamics of sole wheat and wheat-olive agroforestry system under two water regimes (rainfed and high water supply (see chapter 2)). At the beginning of the crop cycle, soil water losses are mainly due to evaporation from the soil, which is closely related to the radiation intercepted by the soil under the crop canopy (Wang and Liu, 2007). The largest rates of water evaporation occur when the top soil layer is wet (Klocke et al., 2009) which may explains evaporation increase after water supply. For sole and agroforestry systems, trees and/or crop transpiration was at its maximum during most of the growing season, while soil evaporation was below its potential during crop development as the soil surface dries out towards the summer season. However, transpiration decline during a relatively short dry period (Fig.1) suggesting that the reduction of soil water content in dry season lead to stoma closure and hence transpiration reduction (van Wesemael et al., 2019). Consequently, the exceed crop water demand under dry season lead to reduce the transpirable soil water fraction (FTSW) (Luquet et al., 2008). Simulated transpiration increase in the growing season after irrigation (Silvestre and Ferreira, 2000). The main differences were consistent from one year to another due to low water supply (rain and irrigation) during the second year. In addition, simulated wheat transpiration in agroforestry was reduced in agroforestry where crop transpiration takes into account the radiation use efficiency of olive tree (Bertrand et al., 2018). This finding may be explained by the understory light interception due to the olive tree shade (Artru et al., 2017) leading to crop transpiration decrease (Campi et al., 2009). For both cropping systems, simulated drainage was high in 2018 which may be explained by rainy periods in rainfed system and the coincidence between irrigation and water addition (Wang et al., 2018). According to Abid Karray et al.(2008), soil water drainage in olive-spring pea was around 113 mm suggesting an overestimated of soil drainage by Biswat model (>200mm in 2018). This finding showed a high loss of water through drainage which is not useful by crop. Consequently, a slight deficit (water deficit < 20 mm in 2018) was found under high water supply for both cropping systems, while deficit water balance was higher in 2019 (Table 2) leading to crop water stress. This analysis showed that the used process in Biswat model are coherent and allows a good description of the functioning of the cropping system. However, slight differences on water balance were found between cropping systems. Simulated soil water distribution showed that the model appears to underestimate/ overestimate water content depending on soil layer. Particularly in the top 10 cm, model evaluation showed that Biswat tended to underestimate the soil water content in the top 10 cm (See Appendix). This finding may be explained by an overestimation of evaporation flows which modeled to occur only in the top 10 cm leading to a dry top soil layer. For deep soil layers, an overestimation of crop transpiration may lead to underestimate soil water content, while it still difficult to determine the causes of simulation errors. In addition, methodological limitations linked to used parameters may be the origin of these differences such us the critical humidity of the crops is defined as the soil moisture when stomatal conductance is the critical humidity of the crops is defined as the soil moisture when stomatal conductance is null and only epidermal conductance occurs (Ritchie, 1981) and it is dependent on the soil and the plant according to its anisohydric or isohydric character (Guinet, 2015).

Conclusion:

The use of a simple water model such as Biswat showed that the model may be a first step to better understand the functioning of the cropping systems. Biswat appears to be a useful tool to predict water balance process in the olive-based agroforestry system and sole durum wheat. However, the main advantage of Biswat was linked to the relative simplicity of the needed database for simulation compared to other more complex models, but which is accessible only through experimental study. Therefore, Biswat may be a useful tool to understand the evolution of diverse process affecting the water balance during a growing season. Finally, it would be interesting to evaluate the ability of the model to describe water flows at large time scale in order to understand the impact of climate change system functioning.

CHAPTER VI. Discussion

1. Main result summary:

Interspecific interactions between crops are highly dependent on specific plant characteristics, such as growth habits and local resource availability. In natural habitats, the Stress-Gradient Hypothesis (SGH) suggests that positive interactions increase with increasing environmental stress (Holmgren and Scheffer, 2010). In order to understand interspecific interactions effect on system outcome along water availability gradient, our study aimed to evaluate the relevance of the stress gradient hypothesis on cultivated agroforestry systems. For that, the effect of olive trees on barley performance in agroforestry system was assessed at plot scale according to an aridity gradient in Northern Morocco (chapter 3). This section reveals that (i) agroforestry reduced crop yield whatever the aridity level (ii) the lowest grain yield differences between AF an SC was at the driest site (ii) the number of grains per unit area was the most impacted yield component.

The second step was to analyze the stress gradient hypothesis through an experimental approach (chapter 4) aiming to zoom on two annual crops (durum wheat and faba bean) performance in olive agroforestry system as well as the global system productivity according to a water availability gradient. This section showed that olive trees limited crop growth at critical stages before flowering leading to a significant grain yield reduction, regardless the water modality. This study allows proposing a new vision of the stress gradient hypothesis where tree-crop interactions will be strongly negative during winter/spring and then become positive during hot summer. A final step (chapter 5) was built around the assessment of water dynamic within wheat-olive agroforestry as a simplistic tool which allow to understand crop responses to e.g. water supply, association…This chapter allowed us to conclude that the model provides a good description of crop process e.g. transpiration.

2. Methodological limits of this work:

Our study allows evaluating the outcome of olive-based agroforestry system along an aridity gradient. However, it is necessary to identify some methodological limitations to better understand these results. The following points were identified.

2.1 Limitations related to water gradient: in the surveys

Limits due to driest chosen site: It was not possible to cover the whole gradient where agroforestry may be found in particular (Fig.35)(Haouane, 2012), the extreme dry site. In reality, considering Taza as the most dry limit of our assessed gradient which did not sufficiently different from the medium arid site ‘Meknes’ (rainfall difference <100mm), may not be sufficient to show notable differences in the net effect of agroforestry on crop performance. In this sense, (LÓpez et al., 2016) suggest that positives interactions appears under extreme stress conditions e.g. aridity. However, there is no indication of the minimum and maximum dimensions of the abiotic stress gradient, from which positives interactions may occur (Maestre et al., 2006). The choice of the most extreme arid point of the gradient was limited by the introduction of irrigation by farmers, which is a very common practice during dry seasons e.g. in Guersif which located in Northeast Morocco (mean annual rainfall 222mm) (personal discussion with Agricultural consultants).

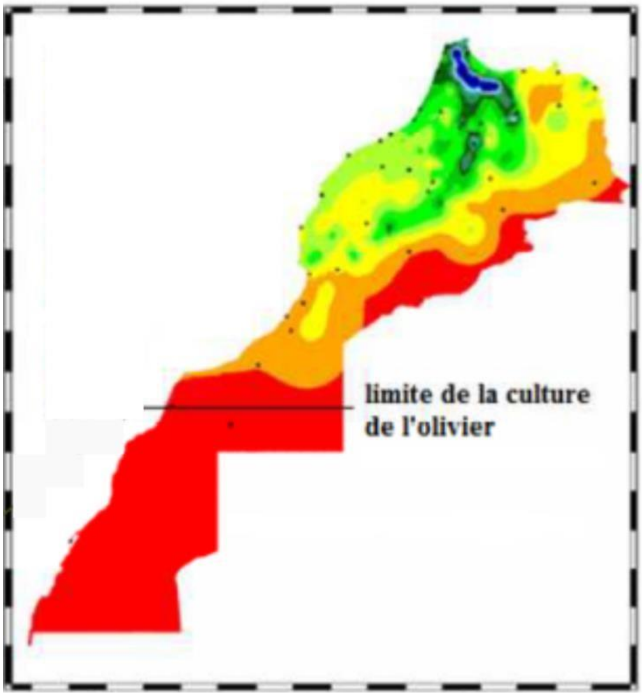


Figure 35: Presentation of the limit of olive tree cropping area in Morocco (the line corresponds to the limit of olive tree cultivation under irrigation) (Haouane, 2012).

2.2 Experimental limitations:

The experiment was designed to create a water availability gradient. Due to technical problems, it was not possible to apply the water supply during the beginning of the crop growing cycle but rather post-anthesis during the two years of experimentation. Consequently, the crop response may be limited since all yield components (e.g. pods, spikes…) are already determined.

3. Trees limit understory crop performance and enhance system performance

The results found in chapters 3 and 4 showed that olive trees reduced significantly the crop yields. The magnitude of reduction varied from 50% (chapter 4) to 55% (chapter 3). Similar results were found for wheat by Artru et al., 2017 under extreme levels of shade, while Dufour et al., 2013 reported only 20% of wheat yield reduction in walnut-based agroforestry system under sub-humid Mediterranean climate. According to Daniel et al., 1991, the negative effect of trees on the understory crop started in the beginning of the growing season which confirms our second sun-hypothesis. Several studies have explained the decrease of crop growth at the beginning of the growing cycle to competition for light (Chirko et al., 1996; Arenas-Corraliza et al., 2018), which is more probable under Mediterranean climate. The negative effects of trees on crop growth depend on trees density, in this context (Singh et al., 2007) reported higher trees density more than 200 trees.ha^{-1} in a mature orchard lead to crop growth reduction.

In both chapters 3 and 4, our results showed that the number of grains per unit area in agroforestry is the most impacted yield component which might be explained by the reduction of tillers for cereals (Inurreta-Aguirre et al., 2018; Gill et al., 2009; Xie et al., 2016; Kimura et al., 2018). Positive effect of trees may enhance grain filling (Campanha et al., 2004; ArenasCorraliza et al., 2018; Qiao et al. 2019) e.g. through microclimate modification (Mugunga et al., 2017) during summer. However, according to our study this result is not always obvious e.g. contrary to Chapter 3 result, our experimental evaluation (Chapter 4) showed that olive trees improved grain filling.

One of the biggest challenges in adopting agroforestry is the land use efficiency which was introduced by (Mead and Willey, 1980). A complementary result about the overall system performance were provided in chapter 4 showing that olive-based agroforestry allows a more efficient land use (LER) more than 1 compared to sole crop. Similar results were found in a Mediterranean olive based agroforestry (Panozzo et al., 2019). In addition, other fruit-based agroforestry systems found to be an effective mean of optimizing system productivity (Bai et al., 2016; Zhang et al., 2013; Hasan et al., 2020).

4. The stress gradient hypothesis is not appropriate for agroforestry systems

As currently proposed, our study reveals that the stress gradient hypothesis is not relevant for cultivated agroforestry systems. However, our observations confirm the fourth subhypothesis, which predict that tree-crop interactions is strongly negative during rainy winter when water availability was high leading to a crop growth reduction e.g. wheat in Paulownia based agroforestry system (Li et al., 2008) and wheat-jujube agroforestry (Zhang et al., 2018). Positive relationships may occur during warm seasons trees negatively affect crop growth before flowering but improve grain filling after flowering under water-limiting conditions, similar results were found in jujube tree-winter wheat agroforestry (Yang et al., 2016). Grain filling improvement was explained by the a facilitative effect of tree shade which buffer microclimate e.g. terminal heat (Lott et al., 2009; Mugunga et al., 2017 ; Peng et al., 2015; Campi et al., 2009; Coussement et al., 2018; Niether et al., 2018).

5. Perspectives

Our study was limited to the study of aerial performance, leaving aside root growth, which plays an essential role in the successful operation of associations in agroforestry (Forey et al., 2017). This is particularly the case when the two species have very contrasted depths or rooting dynamics, such as the case of olive trees that develop superficial roots (Fernández et al., 1991) and annuals that can explore a wide soil profile. In addition, the ideal is to have a root complementarity (Celette et al., 2008) with respect to the separation of roots (Bouttier et al., 2014; Cardinael et al., 2015) allowing to optimize the use of water and nutrient resources.

Moreover, the experimental assessment is based on an excellent layout, which allows evaluating the performances of two agroforestry systems that are wide spread in the Morocco (Razouk et al., 2016; Amassaghrou et al., 2014; Daoui and Fatemi, 2014). It will be therefore necessary to go further than the measurements carried out in Chapter 4 and those introduced in Chapter 5. We agree that radiation measurements would have provided complementary information to the analysis and we recognized that such measurements would be necessary in a following study.

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Supplementary data

Figure 36: mapping of radiation intercepted at different times of the day: (A) 10 am, (B) 12 pm and (C) 14 pm. Shaded areas in very light yellow corresponds to radiation values below 100 (w m-^{2}), medium shaded areas in light yellow corresponds to radiation values between 100 and 800 (w m^{-2}), and unshaded areas in dark yellow corresponds to radiation values upper to 800 (w m^{-2}). Green circles correspond to olive trees.

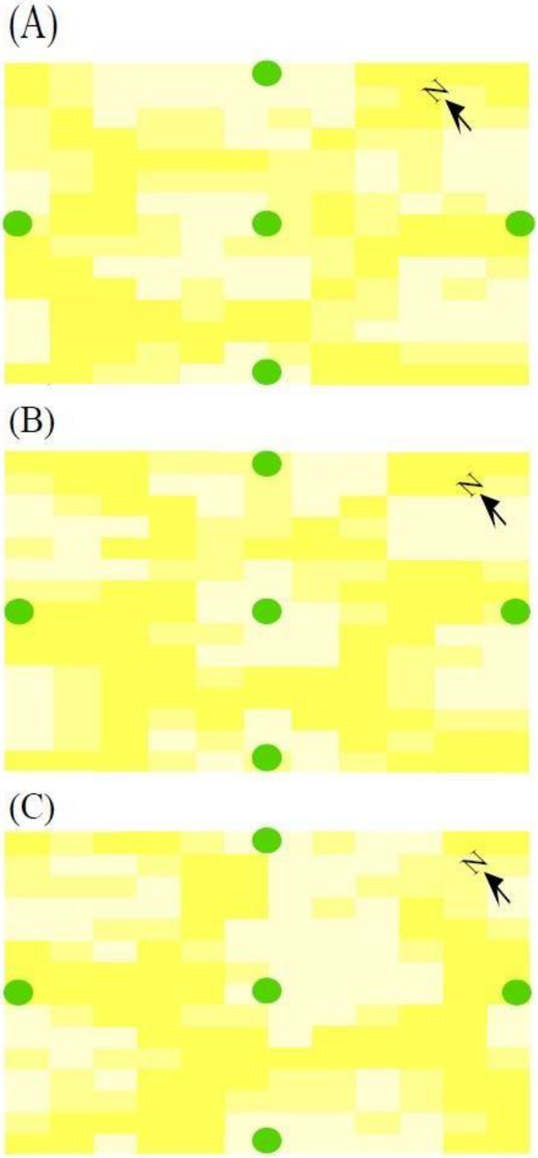


Figure 37: Experimental plots were: Olive-wheat agroforestry system (A), Olive-bean agroforestry system (B), sole olive trees (C) and sole annual crops (wheat and faba bean sole). The spacing between the rows of olive trees was 700 cm, 15cm between the wheat lines and 50cm between the faba bean lines. The spacing between the olive rows and the cultivated strip was 150 cm.

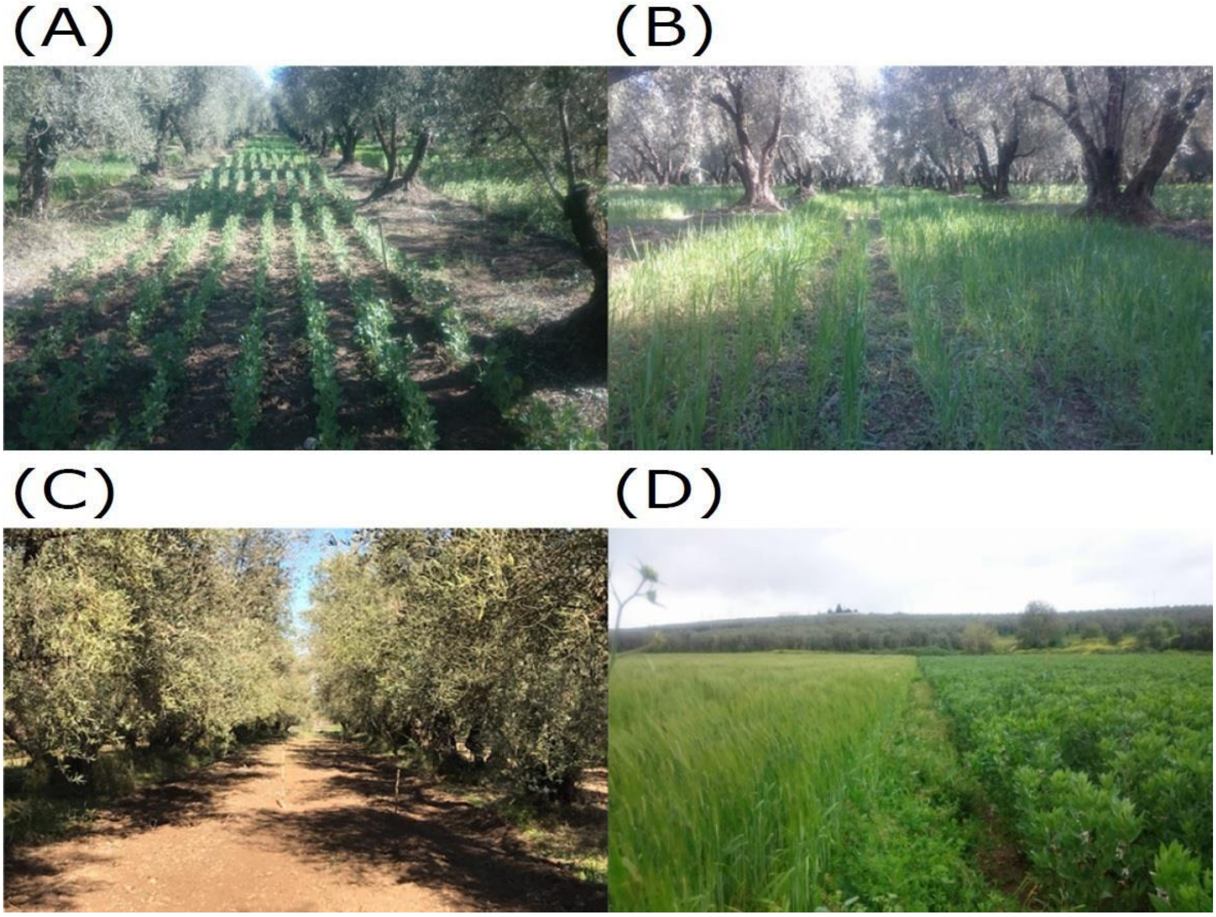
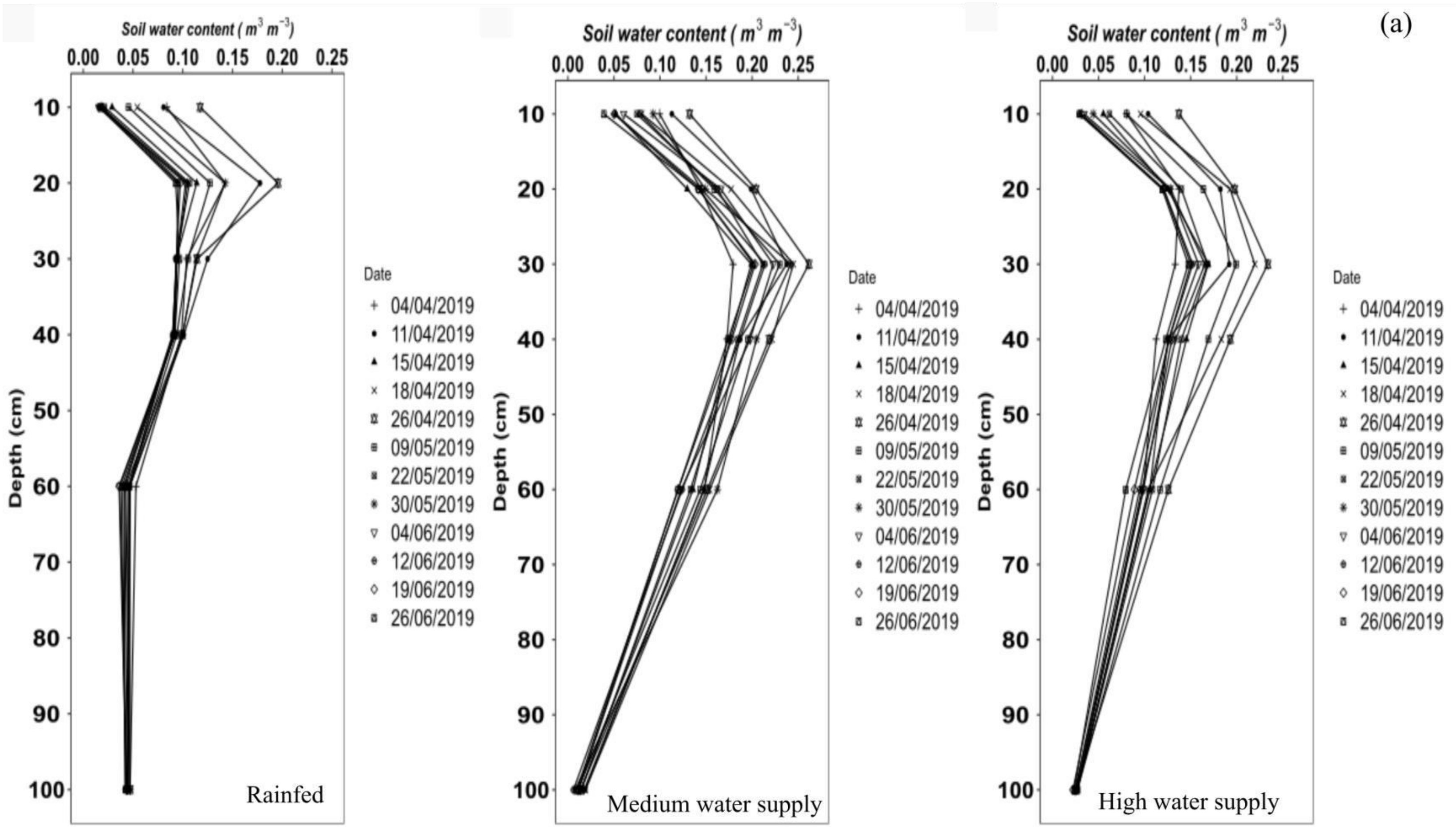


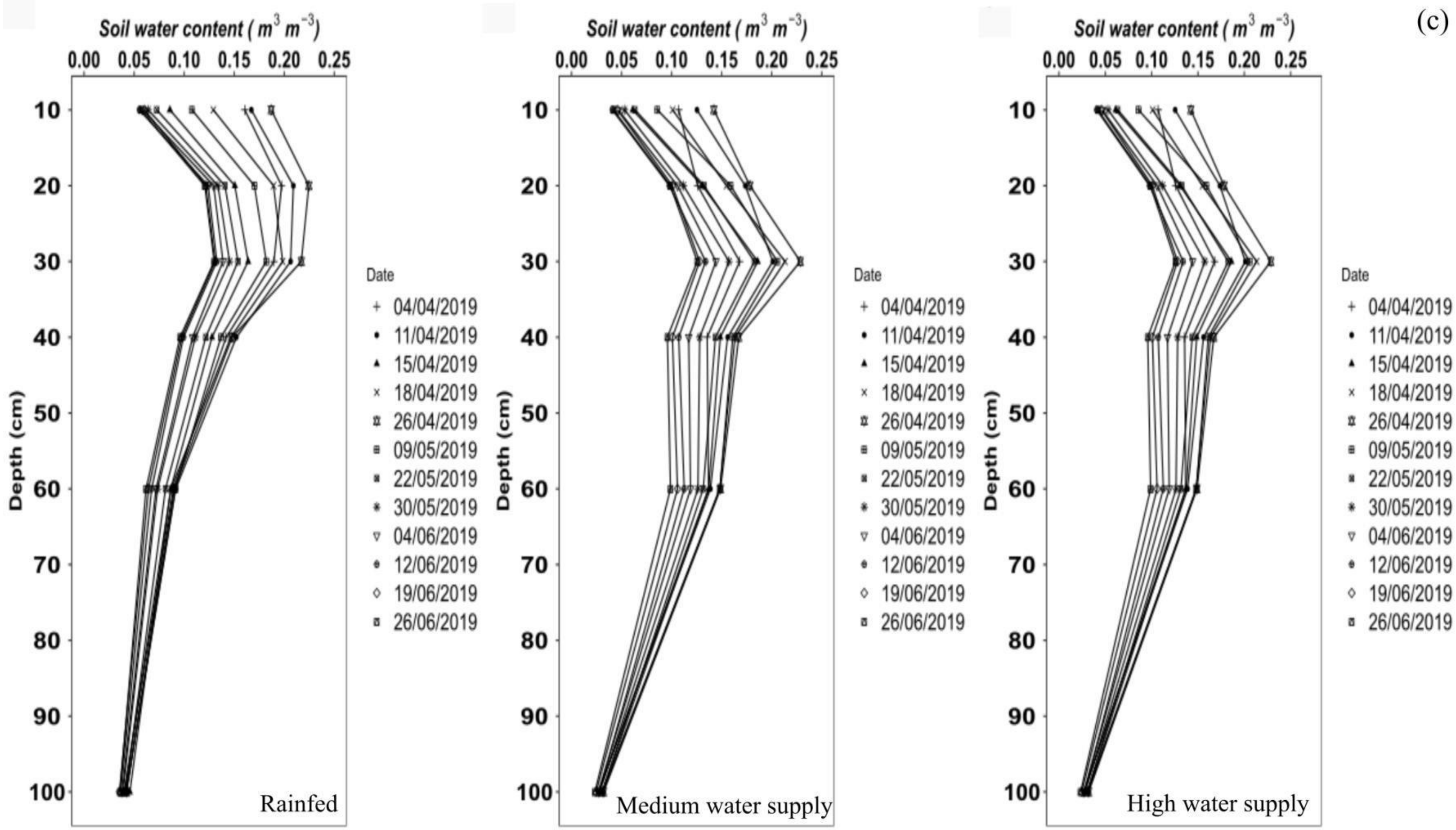
Table 11: Some soils characteristics of the experimental field Louata, Morocco (Source: Labomag).

	Agroforestry plot	Sole cropping plot
	0-60	0-60
Granulometry (%)		
Clay	28	28
Silt	21	17
Sand	52	55
Soil fertility		
Organic matter (%)	1.72	1.53
Total N (%)	0.10	0.08
C/N ratio	10.31	10.53
CEC meq/100g	12.27	9.93
pH	8.98	9.02
calcaire total (%)	64.78	72.07
Calcaire active (%)	12.75	13.12
Majors component (mg/Kg)		
CaO	10292.50	10322.17
P-olsen	23.33	50.83
K2O	158.33	177
MgO	1108.67	876
Soil Salinity		
Cl (Extrait1/5, mg/100g)	4.92	2.82
Electrical conductivity (Extrait 1/5, mS/cm à 25°C)	0.18	0.16
NaO2 meq/100g	158.17	91.67

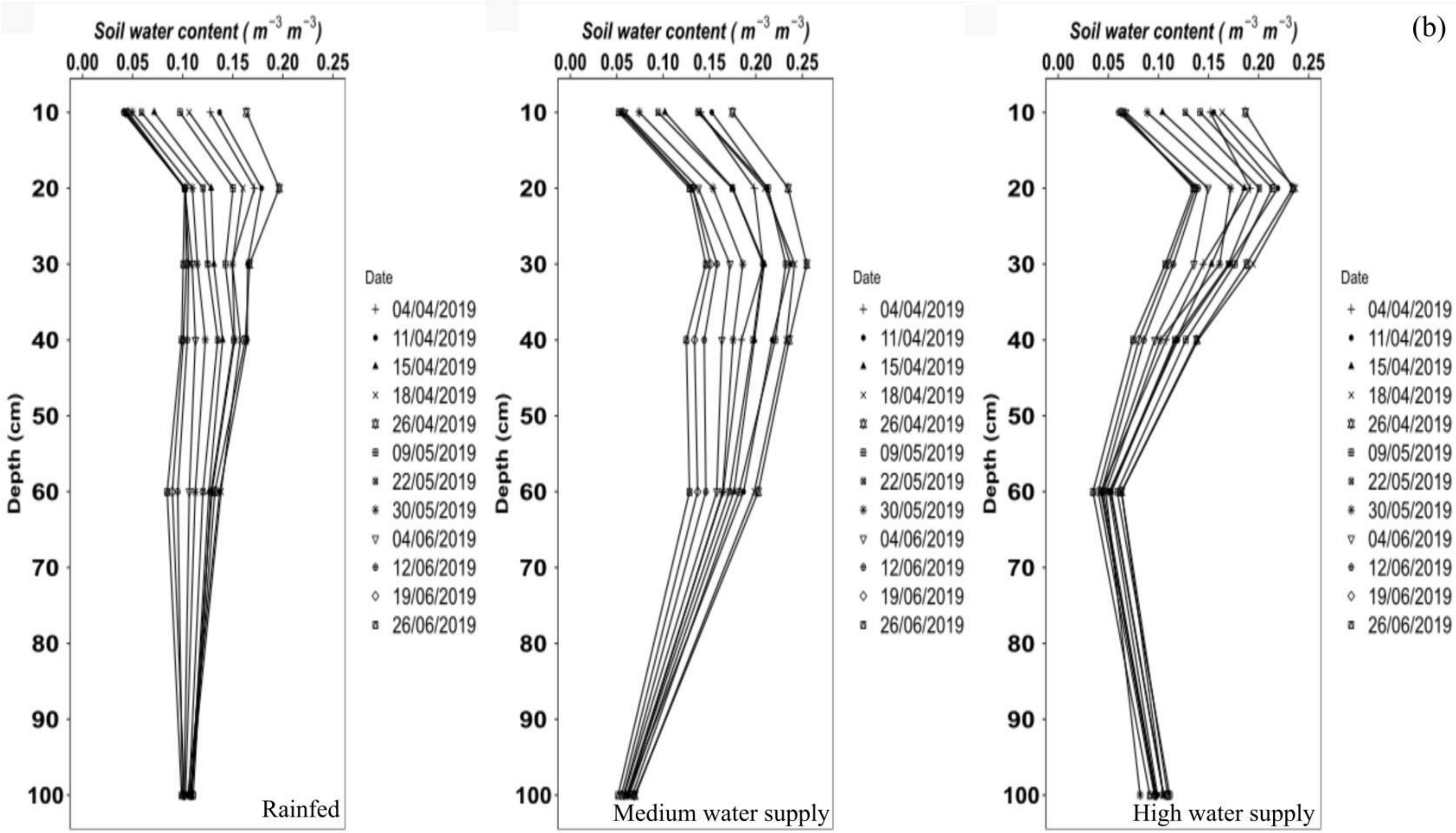
Figure 38 Soil water profile for sole wheat (a), sole olive trees (b) and agroforestry (c) during the growing season in 2019



(c)


Soil water content (m3 m-3)
0.00 0.05 0.10 0.15 0.20 0.25
Depth (cm)
10 20 30 40 50 60 70 80 90 100
Date
04/04/2019
11/04/2019
15/04/2019
18/04/2019
26/04/2019
09/05/2019
22/05/2019
30/05/2019
04/06/2019
12/06/2019
19/06/2019
26/06/2019
Rainfed
Medium water supply
High water supply

(b)



Soil water content (m^-3 m^-3)
0.00 0.05 0.10 0.15 0.20 0.25
Depth (cm)
10 20 30 40 50 60 70 80 90 100
Rainfed
Medium water supply
High water supply
Date
04/04/2019
11/04/2019
15/04/2019
18/04/2019
26/04/2019
09/05/2019
22/05/2019
30/05/2019
04/06/2019
12/06/2019
19/06/2019
26/06/2019

Figure 39: Simulated "Black line" and measured "Blue circle" water dynamic for sole wheat.

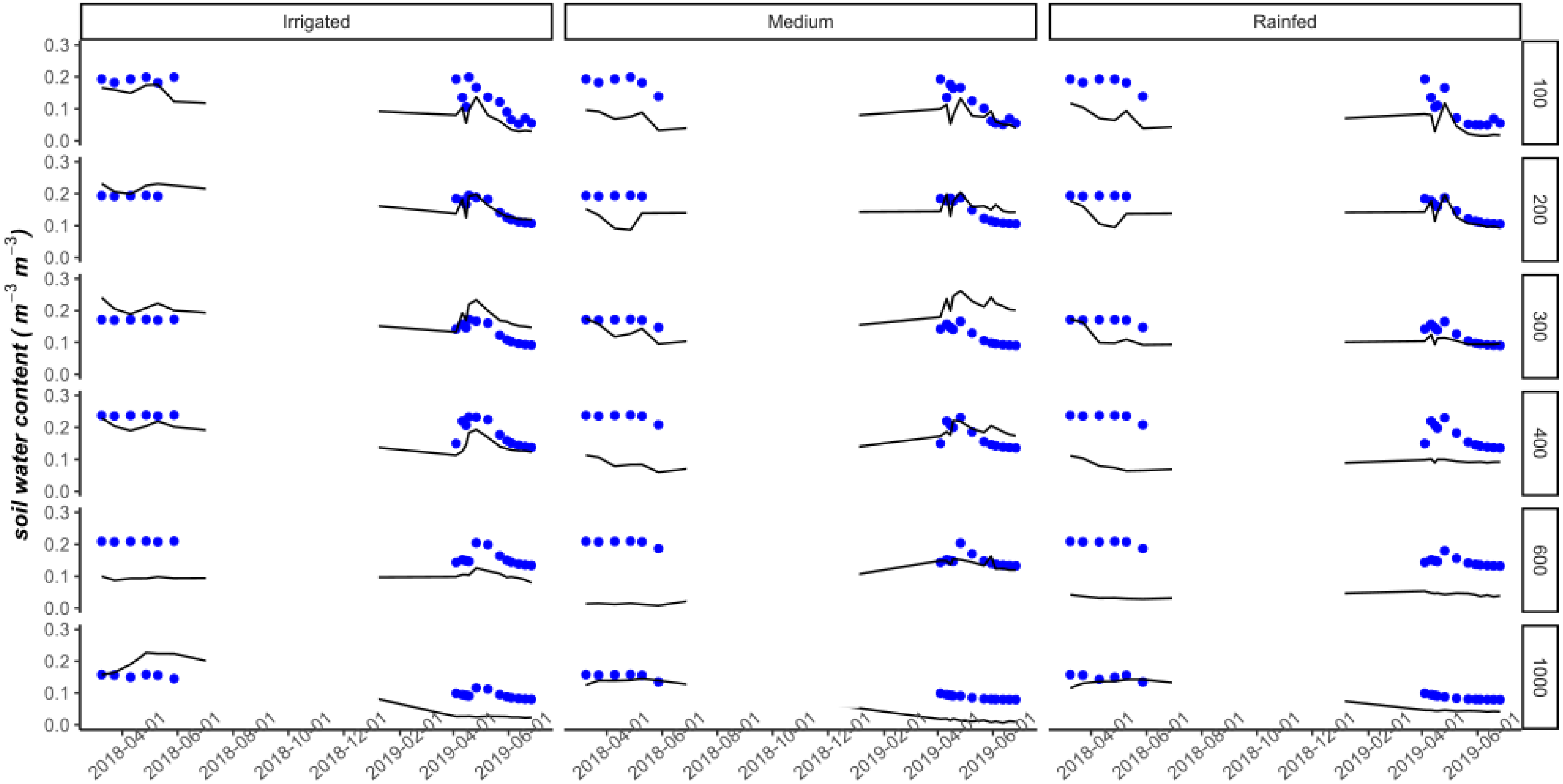


Figure 40: Simulated "Black line" and measured "Blue circle" water dynamic for sole trees.

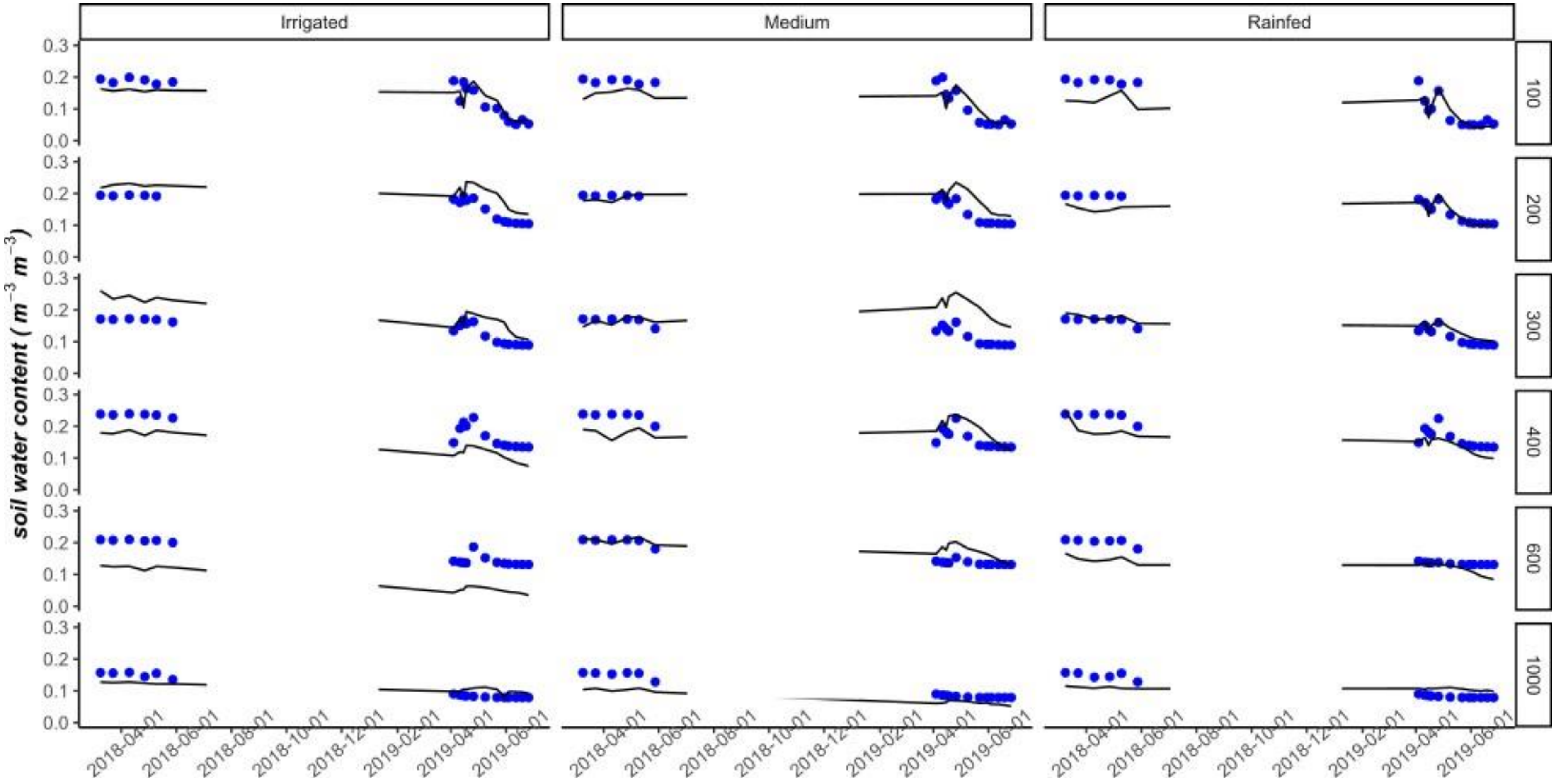


Figure 41: Simulated "Black line" and measured "Blue circle" water dynamic for agroforestry system.

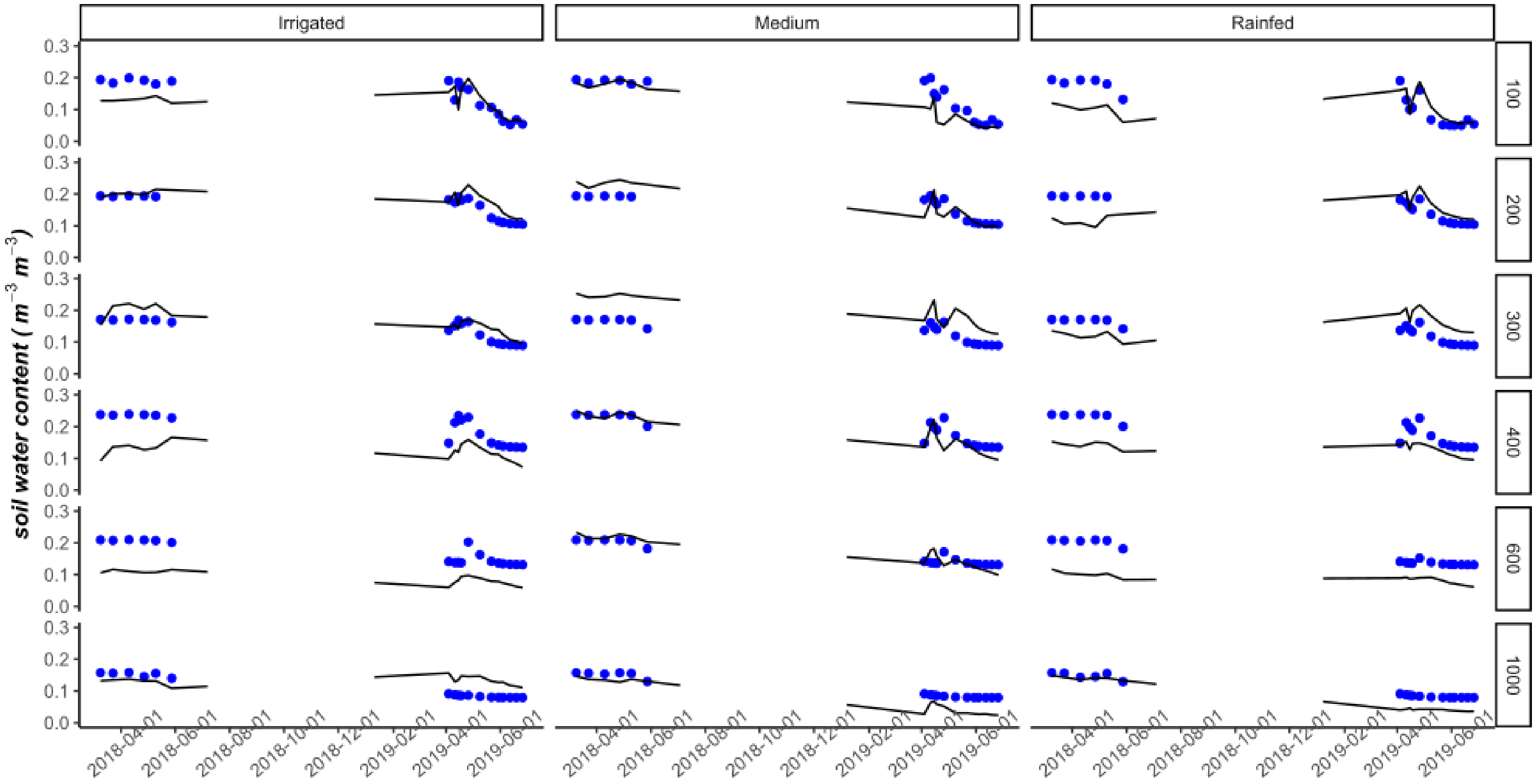


Figure 42: Simulated FTSW (transpirable soil water fraction) from 01/01/2018 to 30/06/2018 & from 01/01/2019 to 30/06/2019 for agroforestry under rainfed regime (a) and high water supply (b).

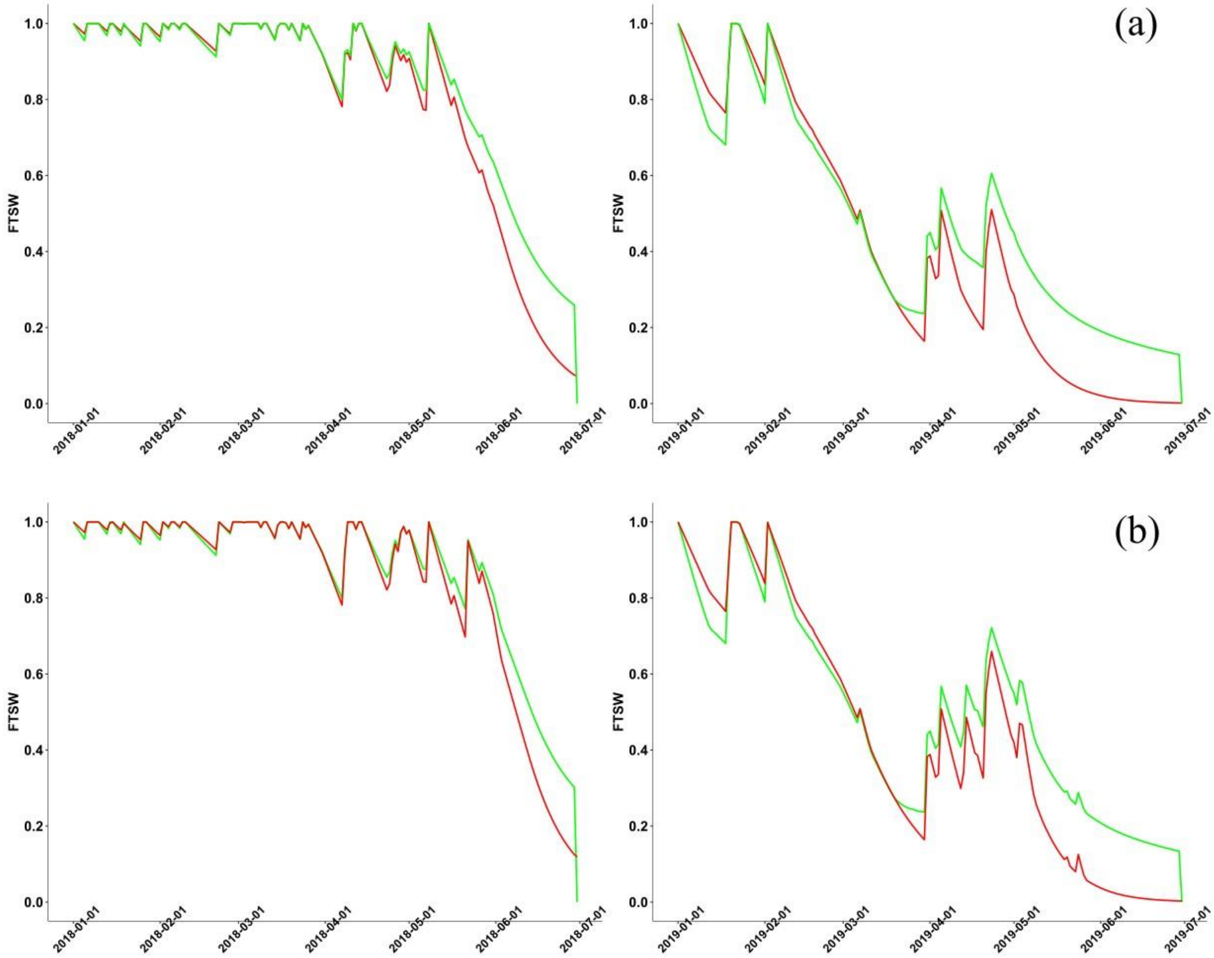
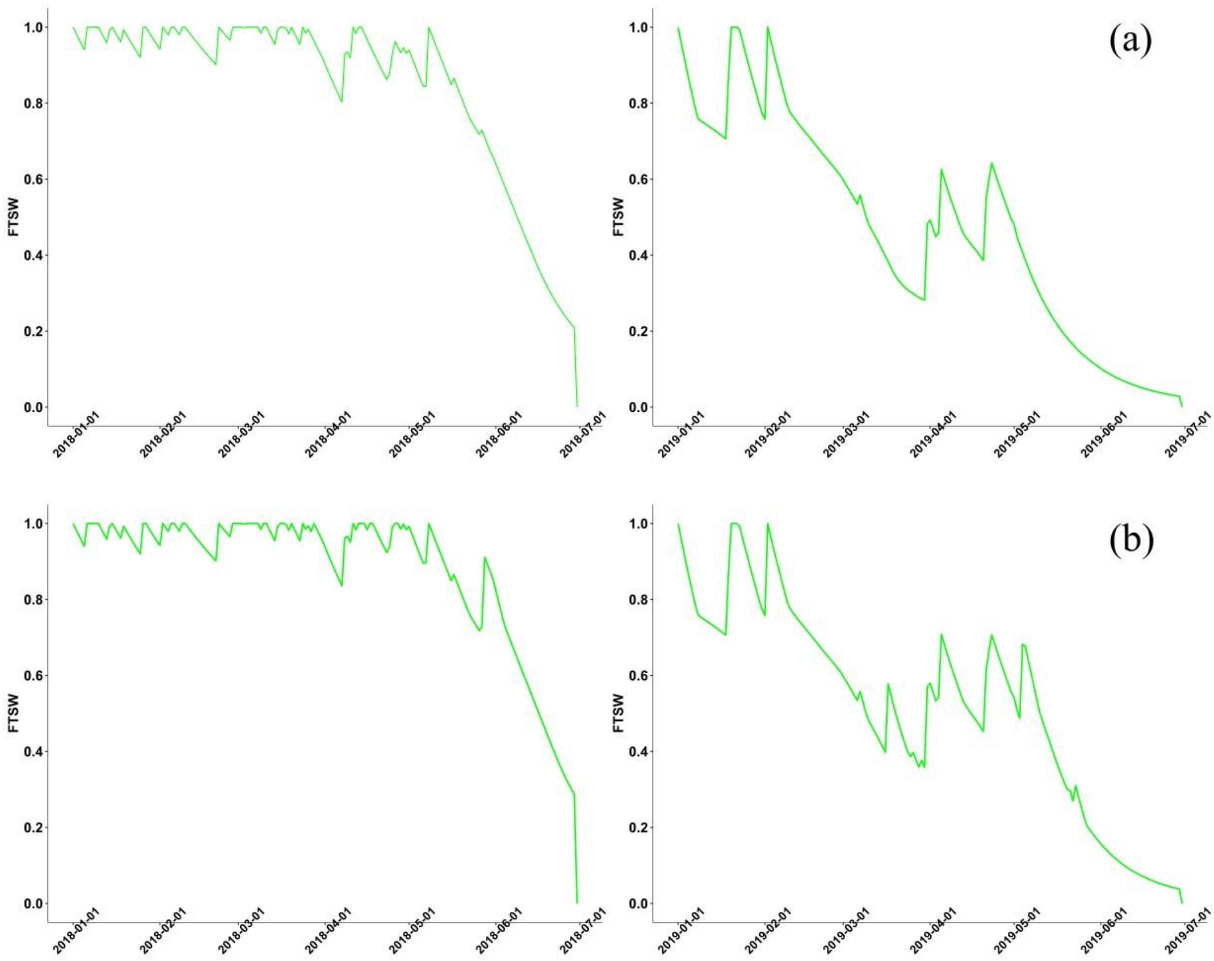


Figure 43: Simulated FTSW (transpirable soil water fraction) from 01/01/2018 to 30/06/2018 & from 01/01/2019 to 30/06/2019 for sole wheat under rainfed regime (a) and high water supply (b).



Résumé chapitre III

Titre : Comment varie les performances de l'orge en intercalaire selon un gradient d'aridité ? Évaluation de la réponse des interactions entre oliviers-orge aux facteurs pédoclimatiques et aux pratiques des petits exploitants dans le nord du Maroc

Dans le contexte du changement climatique, les systèmes agroforestiers peuvent être un moyen efficace de maintenir ou même d'améliorer les rendements des cultures dans les zones arides. En agroforesterie, les arbres sont en concurrence avec les cultures sur les ressources du sol, en revanche ils peuvent également améliorer les conditions de croissance des cultures associée en cas de sécheresse en leur fournissant de l'ombre. Inspirée de la théorie écologique, l'hypothèse du gradient de stress (SGH) suggère que les interactions positives deviennent plus importantes que les interactions négatives entre les arbres et les cultures lors d'une augmentation du stress environnemental (par exemple l'aridité). Pour tester les prévisions du SGH en agroforesterie, nous avons évalué et comparé les variations de la biomasse de l'orge et du rendement en grain à la récolte dans un système agroforestier à base d'oliviers (AF) et des cultures de seules (SC) suivant un gradient d'aridité régional dans le nord du Maroc. Nous avons enquêté 42 parcelles (21 en agroforesterie, 21 en cultures seules) qui décrivent les pratiques agricoles des agriculteurs, et nous avons prélevé des échantillons de sol et de plantes dans 9 et 3 cadrats respectivement en "AF" et "SC" dans chacune des parcelles sélectionnées. Le déficit hydrique climatique varie de - 467,32 mm à - 793,63 mm entre les sites les plus humides (Ouezzane) et les plus secs (Taza). Nous avons constaté que les pratiques agricoles les plus intensives sont sur les sites les plus secs et les moins intensives sont dans les sites les plus humides, aussi bien en agroforesterie des olives qu'en culture seule. Dans ce contexte, les rendements de l'orge en agroforesterie ont été réduits de 55 % par rapport aux cultures seules. Les différences des rendements en grain en fonction du gradient d'aridité étaient de 0,474 g.m-2 mais l'écart de rendement en grain entre l'agroforesterie de l'olivier et les cultures seules était plus faible sur le site le plus sec. Le nombre de grains par unité de surface a été la composante du rendement la plus impactée. En revanche, l'intensification n'a pas amélioré les rendements. Nos résultats suggèrent que les interactions entre les oliviers et les cultures peuvent gagner en importance en cas de sécheresse de plus en plus importante, ce qui rend

l'impact de la concurrence moins important. Ils montrent la pertinence du SGH à guider les nouveaux systèmes agroforestiers à base des fruitiers, par exemple les oliviers, dans un avenir plus sec.

Résumé chapitre IV

Titre: L'agroforesterie des olives améliore la productivité des terres même en cas de faible disponibilité en eau dans le sud de la Méditerranée

Les systèmes agroforestiers peuvent être un moyen efficace de stabiliser ou même d'améliorer le rendement des cultures dans le cadre du changement climatique. En agroforesterie, les arbres sont en concurrence avec les cultures sur les ressources du sol, mais ils peuvent également améliorer les conditions de croissance des cultures en cas de sécheresse en leur fournissant de l'ombre. Ils peuvent favoriser un meilleur rendement et une meilleure qualité des récoltes. Cependant, l'effet bénéfique de l'ombre des arbres peut dépendre du régime saisonnier des précipitations, qui détermine la compensation entre les composantes du rendement. Dans cette étude, nous avons évalué la production de deux cultures annuelles (blé dur et fève) dans l'agroforesterie des olives du nord du Maroc. Nous avons manipulé l'approvisionnement en eau dans le cadre d'une expérience sur le terrain pour couvrir la forte variabilité interannuelle des précipitations sur le site et nous avons testé si les oliviers réduisent ou améliorent le rendement des cultures. Nous avons évalué l'effet de ces apports en eau sur la croissance des cultures, les composantes du rendement et la productivité globale de système. Et, nous avons estimé l'équivalent de surface assolé en agroforesterie à base d'oliviers. L'agroforesterie a limité la croissance et le rendement des cultures quel que soit le régime hydrique. La réduction du rendement grain était d'environ 50 % en moyenne pour les deux cultures. Le nombre de grains par unité de surface a été la composante du rendement la plus impactée. L'apport d'eau a eu des effets limités sur le rendement de la fèverole, par contre, un apport moyen améliore le rendement des grains de blé de 11 % et le nombre d'épis par unité de surface de 13 %. L'agroforesterie a amélioré le poids individuel des grains de 39 % pour le blé et de 17 % pour la fèverole, tout en augmentant la teneur en protéines des grains de blé et de la paille, respectivement, de 4 % et 9 %. Toutefois, les améliorations n'ont pas été suffisantes pour compenser la perte de rendement. Dans l'ensemble, nous montrons que les systèmes agroforestiers sont généralement plus productifs que les cultures et arbres seuls. Nous avons montré comment les changements dans l'approvisionnement en eau peuvent avoir un impact sur les performances de l'agroforesterie des olives dans un avenir plus sec.

Résumé chapitre V

Titre : Analyse dynamique des flux hydrique dans un système blé-oliviers à l'aide du modèle Biswat

L'introduction d'une culture annuelle dans les champs d'oliviers, en particulier dans les champs pluviaux, est une pratique agricole répandue dans le sud de la Méditerranée.

L'association des cultures a été créée afin d'accroître la productivité des terres et l'efficacité de l'utilisation des ressources. Afin de comprendre l'utilisation de l'eau par les cultures en agroforesterie à base d'oliviers, une étude de terrain a été réalisée dans le Nord du Maroc. Le modèle Biswat est un modèle simple à deux dimensions permettant l'analyse des composantes du bilan hydrique. Le modèle a été adapté à une large gamme de systèmes de culture mono et bispecifique. Son point fort est lié à la simplicité des paramètres d'entrée. Le modèle permet de bien représenter la dynamique de la transpiration des cultures en système irrigué et non irrigué. En plus le modèle a permis de bien présenter l'effet des associations où les cultures avait une tendance de transpirer moins. Les résultats ont montré aussi que Biswat surestime l'évaporation sur les 10 premiers cm du sol. . Selon l'horizon en question, le modèle peut surestimer ou sous-estimer la teneur en eau dans certains cas. Cependant, il est possible qu'il y ait des ajustements entre horizons permettant de compenser que ce soit la surestimation ou la sous-estimation de la teneur en eau. L'évaluation de modèle via la confrontation des humidités mesurés et celles simulés a montré une bonne estimation de la teneur en eau du sol dans un profil de 1 m de profondeur en particulier pour les oliviers seuls (R^2 = 0,61) et pour l'agroforesterie oliviers-blé (R^2 = 0,51). Pour conclure, le modèle permet de simuler d'une manière satisfaisante la teneur en eau de sol ainsi qu'une bonne description du processus décrivant la dynamique des flux d'eau dans les systèmes de culture.

Rapport : résumé de la thèse en Français :

Face au changement climatique, l'agroforesterie est une approche promotrice permettant de rendre les agrosystèmes plus résistants. L'agroforesterie présente de nombreux avantages agronomiques et environnementaux, comme l'amélioration de la productivité des terres et de la qualité des récoltes. Cependant, la réussite des systèmes agroforestiers dépend de leur capacité d'établir des interactions positives entre les cultures associées. Toutefois, les interactions interspécifiques entre les cultures dépendent fortement de plusieurs facteurs tels que la disponibilité des ressources. Prévoir le résultat des interactions et la performance des systèmes agroforestiers est donc un défi dans le contexte du changement climatique. Couramment testée dans les systèmes naturels, l'hypothèse du gradient de stress (SGH) suggère que les interactions positives (la facilitation) entre les espèces deviennent plus importantes que les interactions négatives (la compétition) avec un stress environnemental croissant (par exemple, la sécheresse). Bien encourageante, une telle hypothèse n'a pas encore été testée ni adaptée aux agrosystèmes. Au Maroc, les systèmes agroforestiers à base d'olivier sont très répandus et existent dans une large gamme climatique. Ces systèmes forment un excellent cas d'étude pour tester la pertinence de SGH pour le développement des systèmes agroforestiers dans le sud de la Méditerranée. Le cadre méthodologique de ce travail est réparti en trois volets complémentaires, combinant enquête sur le terrain, expérimentation et modélisation. Tout d'abord, des enquêtes de terrain ont été menées (42 parcelles) dans le nord du Maroc pour évaluer l'impact des oliviers sur une céréale tout le long d'un gradient d'aridité. Cette évaluation a été réalisée à l'échelle de la parcelle, en tenant compte de la diversité des pratiques agricoles. Ensuite, une évaluation expérimentale des effets positifs et négatifs des oliviers sur la croissance et le rendement d'une céréale et une légumineuse au nord du Maroc. L'eau a été manipulée afin de simuler des régimes hydriques contrastés. La productivité globale de système a été aussi évaluée en prenant en compte le rendement olive. Finalement, le modèle de bilan hydrique BISWAT (Bispecific Intercrop System Water Stress dynamic model) a été utilisé afin de pouvoir évaluer la dynamique hydrique de système oliviers-blé à travers la description de différents processus (par exemple Transpiration). Les principaux résultats ont révélé que l'agroforesterie réduisait les rendements des cultures annuelles de plus de 50 % par rapport à la culture seule, quel que soit le régime hydrique. Les résultats ont remis en question la validité et les prédictions émises de SGH qui ont révélé que la saisonnalité de la disponibilité de l'eau détermine les interactions entre les arbres et les

cultures. Les interactions entre les arbres et les cultures étaient fortement négatives pendant l'hiver/le printemps (croissance des cultures) lorsque la disponibilité de l'eau était élevée. En revanche, les interactions positives sont devenues plus importantes au cours du printemps/été (remplissage des grains) pendant la période sèche, en particulier dans les conditions les plus sèches. Ces travaux présentent des exemples de comment le changement d'eau peut impacter les performances en agroforesterie pour un avenir plus sec de la région Méditerranéenne.

Problématique de la thèse :

La population mondiale est en constante augmentation, elle devrait atteindre 9,7 milliards vers l'horizon 2050 (Mouël et al., 2018). Ce qui va être accompagné par une augmentation de la demande alimentaire qui peut allait jusqu'à 98% vers l'horizon 2050 (Valin et al., 2014). Afin de répondre à cette demande, la production agricole devrait doubler dans les prochaines décennies (Waldron et al., 2017). Cependant, la durabilité des systèmes agricoles et leur capacité à répondre la demande est soumise à des divers challenges suite aux changements climatiques. Ces changements se manifestent principalement par l'augmentation des températures (Akompab et al., 2013) ainsi que les périodes de sécheresse (Myers et al., 2017) et de la variabilité des précipitations (Olayide et al., 2016). L'impact du changement climatique sur l'agriculture diffère d'une région à l'autre, en particulier, les régions méditerranéennes semblent très vulnérable à ces changements (Gilmont, 2015) (Hallett et al., 2018) mettant en cause la durabilité de ses systèmes de cultures. Actuellement, la plupart des régions de bassin méditerranéen notamment celle de sud de la méditerranée souffrent d'une insuffisance alimentaire et des dépendances céréalières les plus élevés au monde (Marty et al., 2017). Face à ces menaces, de nouvelles stratégies agricoles doivent être mise en place afin de pouvoir garder une durabilité de production. L'agroforesterie, qui consiste à combiner des arbres et des cultures annuelles sur la même unité de surface, peut être une approche prometteuse de l'intensification écologique (Jose, 2009). L'agroforesterie a montré un large spectre d'adaptation (Blanco Sepúlveda and Aguilar Carrillo, 2015;Chirwa, W. and Quinion F., 2012;Paningbatan et al., 1995; Jiang et al., 2017; Béliveau et al., 2017;Cardinael et al., 2015; Cannell et al., 1996; Isaac et al., 2014 ; Mthembu et al., 2018). L'amélioration de la performance des systèmes via la diversification des espèces est l'un des résultats les plus importants et les plus attendus de l'agroforesterie (Montagnini et Metzel, 2017), qui représente aujourd'hui le plus grand défi de l'adoption d'un tel system (Patel et al., 2015). La capacité de l'agroforesterie à base des fruitiers en particulier à améliorer la productivité globale des systèmes a été démontré dans plusieurs études (Bai et al., 2016; Zhang et al., 2013 ; Panozzo et al., 2019;Hasan et al., 2020). Cependant, pour réussir les associations en agroforesterie il est important que les espèces associées arrivent à établir des interactions positives qui doivent en quelque sorte minimiser les interactions négatives. En effet, les interactions interspécifiques dépendent de plusieurs facteurs comme l'eau en particulier dans les zones sèches. La compétition pour la lumière se manifeste par une réduction de la lumière interceptée par les cultures suite à la présence des arbres (Dufour et al., 2013). L'ombrage des arbres réduit la croissance des culture (Sgarbossa et al., 2020) à travers la réduction de rayonnement photosynthétique (PAR) (Dufour et al., 2013 ce qui entraine une réduction de rendement des rendements des cultures (Zhang et al., 2018). Toutefois, cet effet négatif peut être partiellement compensé en modifiant le microclimat sous les arbres pendant les climats chauds et secs (Massetti et al., 2019). En effet, l'ombre crée par les arbres permet de tamponner les températures extrêmes (Rigal et al., 2020) ce qui entraîne une réduction de l'évapotranspiration (Coussement et al., 2018). D'un autre côté, la compétition pour l'eau et les nutriments se produit quand les systèmes racinaires de deux cultures colonisent les mêmes horizons de sol (Jose et al., 2004). Cependant, il est difficile de pouvoir séparer les interactions aériennes des interactions souterraines qui varient à leur tour en fonction des ressources, par exemple les précipitations (Latiri et al., 2010).

Objectifs & hypothèses de la thèse :

Dans ce contexte, l'objectif principal de ce travail est d'évaluer la performance des systèmes agroforestiers et leur capacité à faire face aux défis actuels via l'optimisation de la productivité, en particulier sous un contexte d'aridité croissante. Basé sur un cadre théorique fourni par l'hypothèse de gradient de stress 'SGH', qui prédit la prédominance des interactions positives vis-à-vis les interactions négatives au sein des associations et sous conditions d'aridité croissante. Notre étude se concentre sur l'évaluation des systèmes agroforestiers basés sur l'olivier en analysant les effets des arbres sur la performance des cultures annuelles associées, et aussi de la productivité du système comparativement à des témoins agricoles. L'approche adoptée comprenait une évaluation quantitative des performances des annuelles comme le résultat des différentes interactions (positives et négatives) en fonction du gradient de disponibilité en eau. Très répondus en méditerrané, les systèmes agroforestiers à base d'olivier présentent un excellent cas d'étude pour répondre aux enjeux de la région. L'hypothèse principale et les sous-hypothèses de ce travail peut être formulée comme suit : Inspirée de cadre théorique de l'hypothèse du gradient de stress, la diversification des cultures en agroforesterie module les interactions négatives dans les zones sèches, et inversement sous des conditions humides.

Sous-hypothèse 1 : La performance en terme de productivité (rendement et composants) des cultures annuelles dépend de niveau des interactions positives entre les cultures.

Sous-hypothèse 2 : Le développement d'interactions négatives commence à des stades précoces de croissance des cultures.

Sous-hypothèse 3 : Les composantes du rendement ne seront pas affectées de la même manière par les interactions entre les arbres et les cultures.

Sous-hypothèse 4 : La validité de l'hypothèse du gradient de stress "SGH" est partielle, où des relations positives se produisent pendant les saisons chaudes lorsque les oliviers ont un effet négatif sur la croissance de la culture avant la floraison mais en contre partie améliorent le remplissage des grains après la floraison dans des conditions de limitation de l'eau.

Plan de la thèse :

Ce travail est structuré en 6 chapitres. Le premier chapitre porte sur une introduction générale de contexte de l'étude ainsi que les enjeux actuels de l'agroforesterie particulièrement en Méditerranée. Le deuxième chapitre présente le matériel et méthodes générales : les sites des enquêtes et des expériences ainsi que les méthodes utilisées pour répondre à nos objectifs de recherche. Le troisième chapitre analyse les systèmes agroforestiers par rapport aux témoins agricoles selon un gradient d'aridité répartis sur trois sites du nord du Maroc, dans le but d'évaluer l'hypothèse du gradient de stress et d'identifier les facteurs pédoclimatiques ainsi que les pratiques agricoles affectant le rendement des cultures en agroforesterie. Le chapitre suivant (4) est présenté sous la forme d'un article soumis pour publication à la revue Agriculture, Ecosystems & Environment. Le cinquième chapitre vise à réaliser une modélisation conceptuelle par l'évaluation dynamique des flux d'eau dans un système agroforesterie (oliviers-blé). Le sixième et dernier chapitre correspond à une discussion générale des résultats obtenus, clarifiant les biais de recherche et le champ de validité des résultats ainsi que les perspectives scientifiques.

Les principaux résultats de chapitre 3 : Enquêtes

Dans cette partie, nous avons examiné la manière dont les facteurs environnementaux en particulier la pluviométrie et de gestion peuvent modifier les interactions entre les arbres et les cultures ainsi que leur influence sur les rendements des cultures le long d'un gradient d'aridité. L'évaluation a été réalisée sur de l'orge cultivée en intercalaire dans les oliveraies dans des trois sites ayant des niveaux d'aridité contrastés au le nord du Maroc. Nos hypothèses ont été reformulés autour de l'hypothèse de gradient de "SGH" : (i) les oliviers améliorent le rendement des cultures dans la situation la plus sèche où l'intensification agricole devrait être réduite ; (ii) les oliviers peuvent réduire les différences des rendement et améliorer la stabilité du rendement des cultures en association sous des conditions arides; et (iii) l'intensification du système de culture par l'application d'engrais et le désherbage devrait améliorer le rendement des cultures sous les arbres et minimiser les différences des rendement (entre l'agroforesterie et les témoins agricole) dans les conditions les plus humides.

Présentation des sites d'études

Notre étude a permis de couvrir un large spectre climatique où l'agroforestier à base d'oliviers existe dans le nord du Maroc (Fig. 1). Nous avons étudié trois sites connus pour leur grande diversité de systèmes agroforestiers ainsi que leurs pratiques agricoles : Ouezzane (34°47'43.25 "N, 5°34'02.34 "O, 614 m), Meknès (34°03'33.14 "N, 5°31'35.62 "O, 504 m) et Taza (34°13'12.20 "N, 4°01'02.72 "O, 513 m). Le climat est semi-aride avec une forte influence méditerranéenne, alternant des étés chauds et secs avec des hivers froids et humides. Les périodes pluvieuses se situent entre octobre et avril. La température et les précipitations annuelles moyennes varient de 17,8 °C et 707 mm à Ouezzane, 18,4 °C et 484 mm à Meknès et à 20 °C et 461 mm à Taza. L'aridité des sites a été évaluée sur la base de l'indice de déficit hydrique (CWD), calculé comme étant la différence entre les précipitations annuelles (P) et la demande évaporative cumulée (ET0). Le déficit hydrique climatique a varié de - 467,32 mm à - 793,63 mm entre les sites les plus humides (Ouezzane) et les plus secs (Taza).

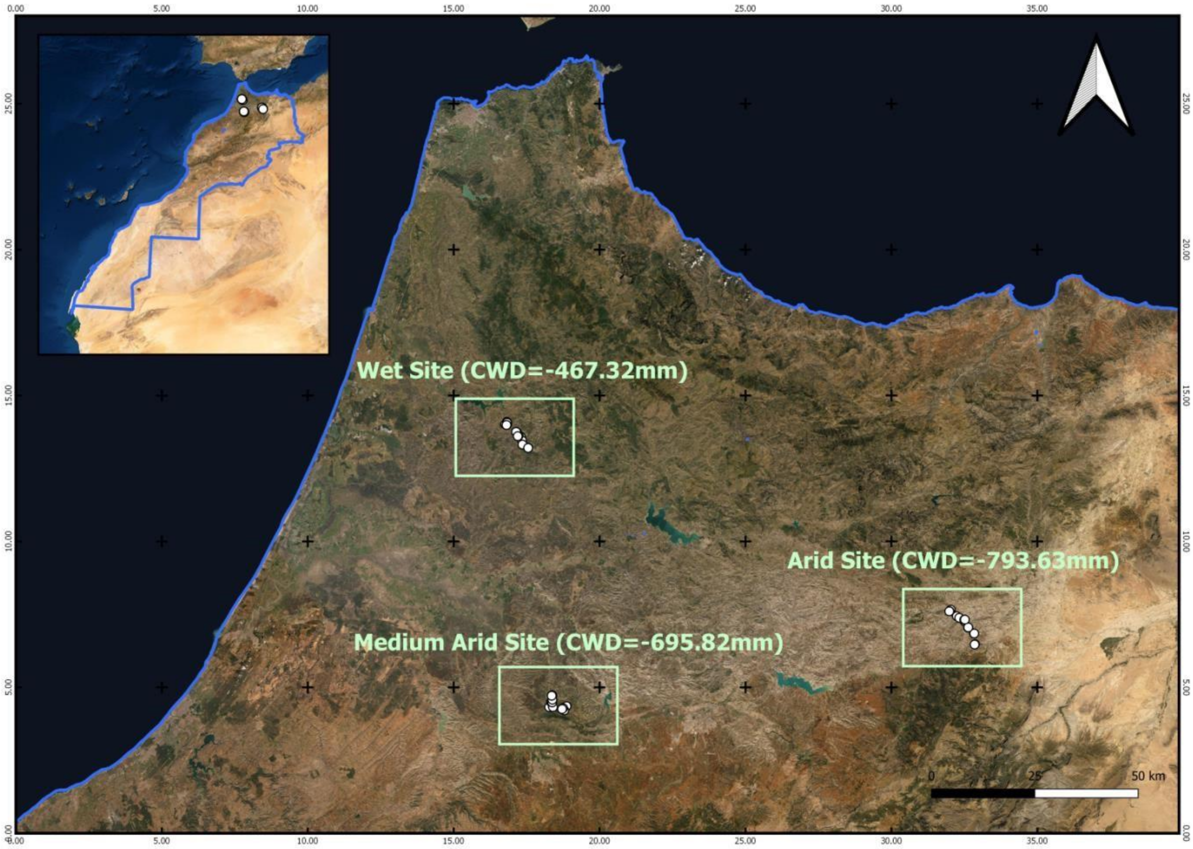


Figure 13: Localisation des trois sites etudiés au Nord du Maroc

Les principaux résultats

Sur la base de 42 parcelles enquêtées dont 21 en agroforesterie et 21 en cultures seules, la description des pratiques agricoles via des entretiens avec les agriculteurs, ainsi que la prise des échantillons de plantes (9 et 3 quadrats respectivement en agroforesterie et culture seule) et de sol. Nous avons constaté que les pratiques agricoles les plus intensives ont été soulignées dans le site le plus sec et que les pratiques le moins intensives dans les sites les plus humides en agroforesterie qu'en culture seule. Dans l'ensemble, l'agroforesterie réduit les rendements de plus que 55 % par rapport aux cultures seules. Les différences de rendement en grains le long du gradient d'aridité étaient de 0,474 $g.m^{-2}$, mais les différences de rendement en grains entre l'agroforesterie et les cultures seules étaient plus faibles sur le site aride. Le nombre de grains par unité de surface a été la composante du rendement la plus touchée. En revanche, l'intensification n'a pas amélioré les rendements. Finalement, nos résultats suggèrent que les interactions positives entre les oliviers et les cultures associées peuvent gagner en importance en cas de sécheresse croissante, réduisant l'impact de la compétition. Ces résultats peuvent servir à mieux comprendre le comportement des systèmes associées vis-à-vis un avenir plus sec.

Les principaux résultats de chapitre 4 : Evaluation expérimentale des systèmes agroforestiers à base d'oliviers

En effet cette partie vient pour apporter plus de précisions sur l'étude de plus prés des associations à l'échelle de l'expérimentation. Pour se faire, nous avons évalué les performances de deux cultures annuelles (blé dur et fèverole) dans l'agroforesterie à base d'oliviers au nord du Maroc. Nous avons manipulé l'eau afin de pouvoir un gradient de disponibilité d'eau permettant de simuler des situations hydriques. Nous avons évalué l'effet de l'ajout d'eau sur la croissance des cultures, les composantes du rendement et sur la performance globale des systèmes via l'estimation de l'indice de surface assolée.

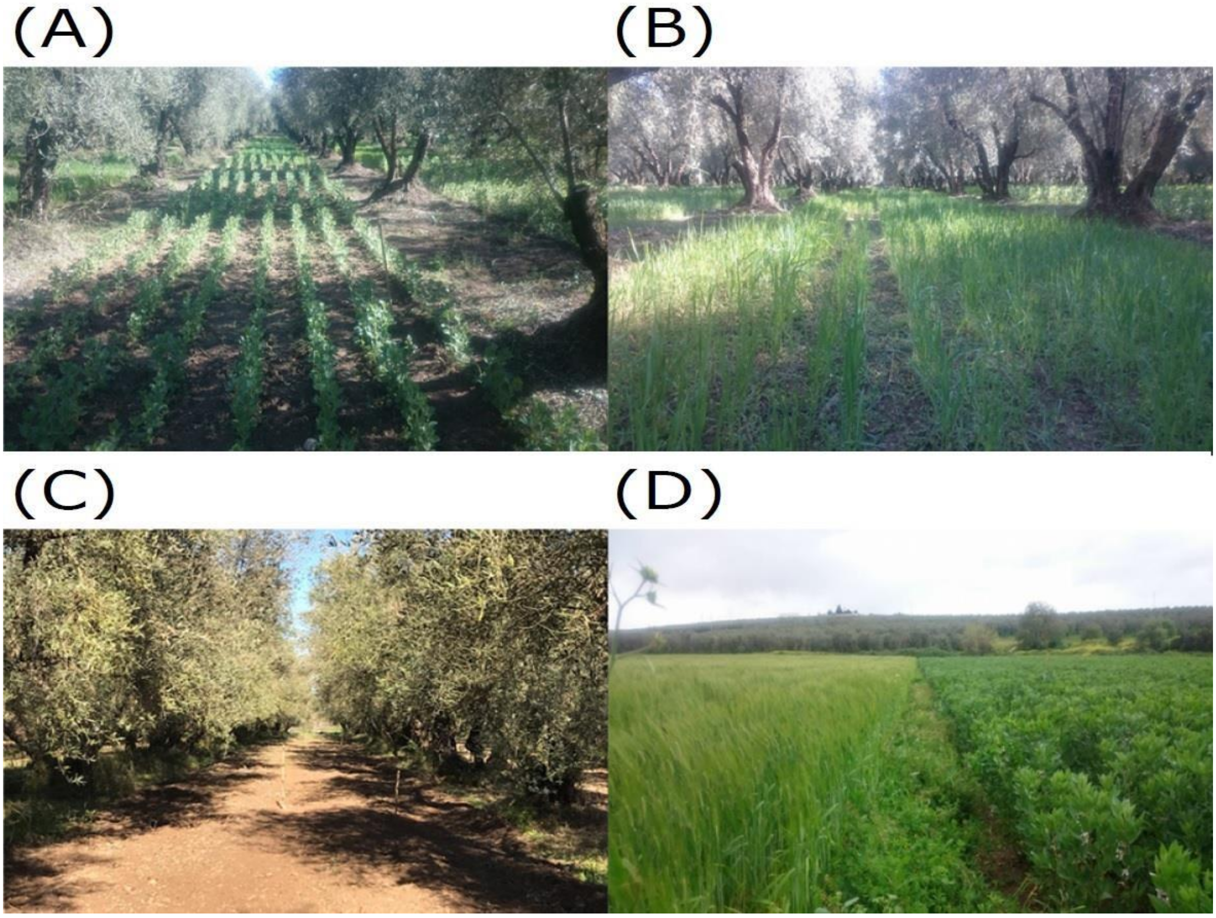


Figure 14 : Présentation des parcelles expérimentales: (A) le système agroforestier olivierfèverole, (B) le système agroforestier olivier-blé, (C) le système oliviers seuls et cultures annuelles seules (blé et fèverole). L'espacement entre les rangs d'oliviers était de 700

cm, 15 cm entre les lignes de blé et 50 cm entre les lignes de fèverole. L'espacement entre les rangs d'oliviers et la bande cultivée était de 150 cm.

Les principaux résultats :

Notre étude a montré que l'agroforesterie a limité les rendements des cultures quel que soit le régime hydrique (Fig.3).

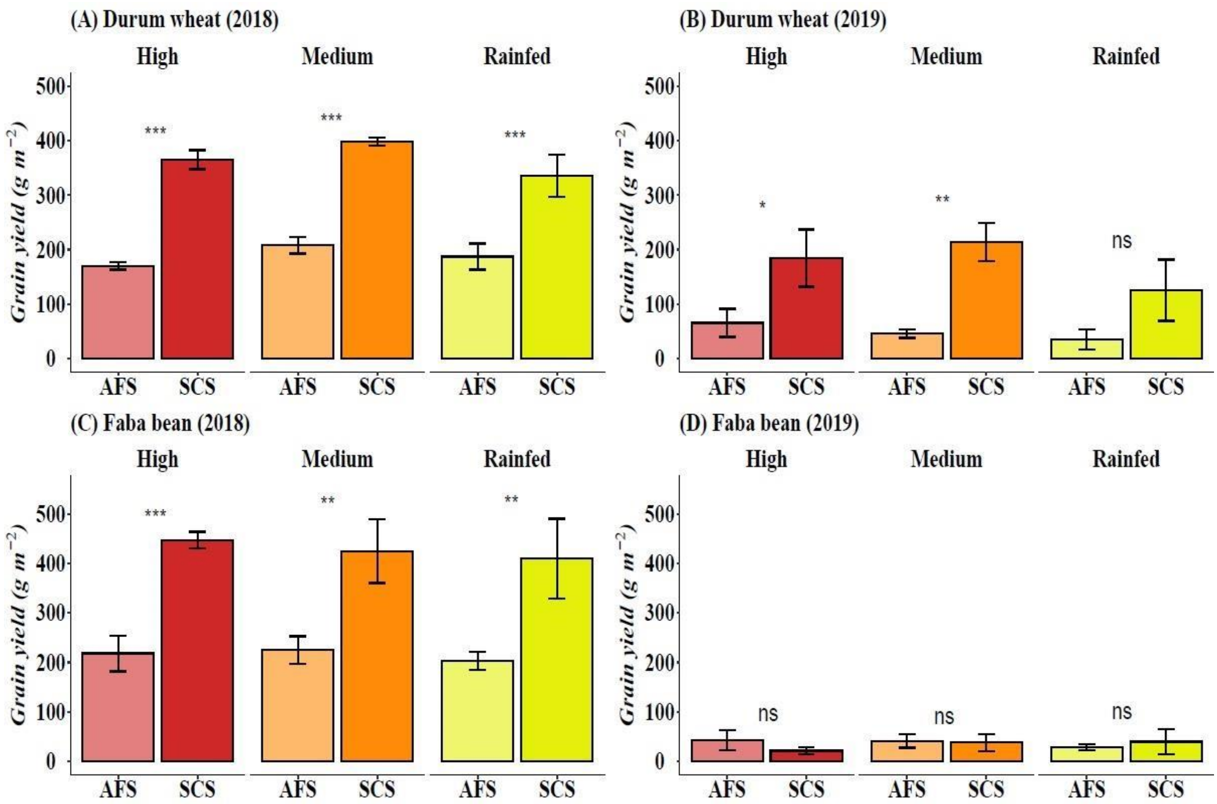


Figure 3 : Le rendement grain (g.m^{-2} ± sd) à la récolte en agroforesterie (AF) et en cultures seules (SC) pour le blé dur (A : 2018 ; B : 2019) et la fèverole (C : 2018. D : 2019). La couleur des barres indique le régime hydrique (rouge : "High" indique un bonne apport d'eau ; orange : "Moyenne" apport d'eau ; jaune : "Pluvial"). Niveau de signification (différences entre AF et SC) : * p< 0,05 ; ** p< 0,01 ; *** p< 0,001.

-Nos résultats ont montré que la perte de rendement été de l'ordre de 50 % en moyenne pour les deux cultures en 2018. De plus, notre étude montre que le nombre de grains par unité de surface a été la composante du rendement la plus touchée durant les deux ans d'expérimentations 2018 et 2019. L'ajout d'eau a eu des effets limités sur le rendement des féveroles, mais un apport moyen améliore le rendement en grains de blé de 11 % ainsi que le nombre d’épis par unité de surface. On peut constater que l’agroforesterie améliore le poids individuel des grains de 39 % pour le blé et de 17 % pour la féverole. Toutefois, La légère amélioration de la teneur en protéines n’a pas permis de compenser la perte de rendement.

Dans l'ensemble, nous montrons que les systèmes agroforestiers sont généralement plus productifs que les seules cultures et les seuls arbres, même dans des conditions arides. Nous montrons comment la modification de l'approvisionnement en eau peut avoir un impact sur les performances de l'agroforesterie oléicole dans un avenir plus sec.

Les principaux points à retenir de chapitre 5: Evaluation de la dynamique hydrique en agroforesterie via le modèle BISWAT

Présentation de modèle

Le modèle Biswat est un modèle hydrique de type réservoir à deux dimensions (2D). Ce modèle permet d’analyse à pas de temps journalier pour les systèmes mono-spécifique comme pour les systèmes bispécifique les composantes du bilan hydrique (par exemple : l’évaporation, transpiration (pour chaque espèce s’il s’agit d’un système bispécifique, la percolation…). Le modèle a été adapté à une large gamme des systèmes de culture et dont l’avantage réside à la simplicité des paramètres d'entrée requis. Les simulations s’effectuent suivant une scène ou motif de simulations prend en considération la scène jusqu’à la moitié de l’inter-rang (Fig.4) où le sol est limité en profondeur par le nombre de couches qui le constitue mais également par un nombre de colonnes qui permet d’évaluer l’apport d’eau via une irrigation localisée.

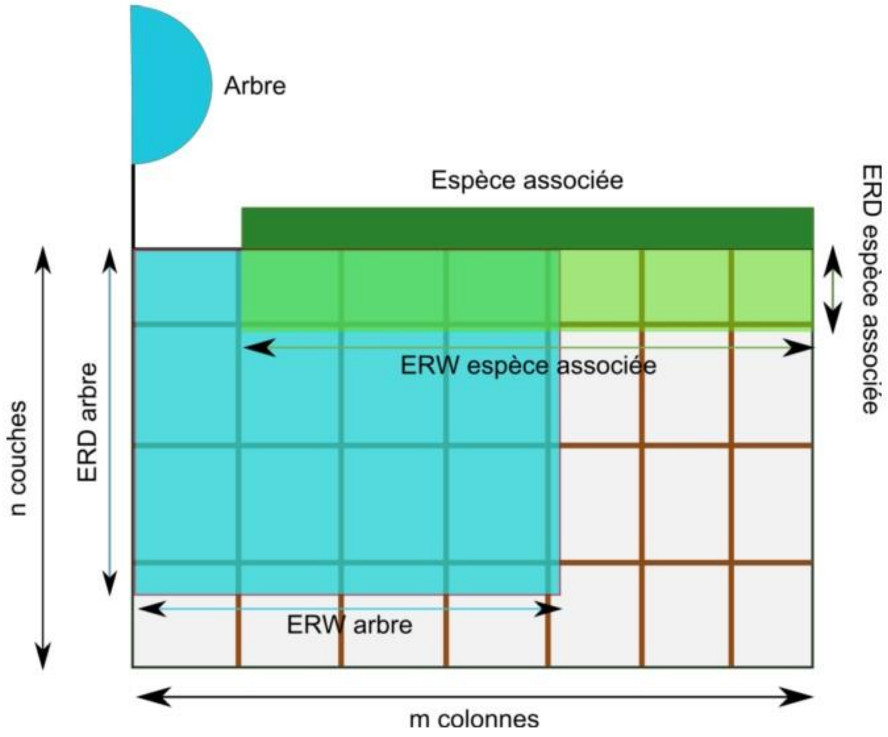


Figure 4 : La présentation de la scène modélisée par BISWAT. Les dimensions des systèmes racines de chaque espèce sont représentées en profondeur par (ERD) et en largeur (ERW)(Forey, 2016).

Les principaux résultats de ce chapitre

Le modèle permet de bien représenter la dynamique de la transpiration des cultures en système irrigué et non irrigué. En plus le modèle a permis de bien présenter l'effet des associations où les cultures avait une tendance de transpirer moins. Les résultats ont montré aussi que Biswat surestime l'évaporation sur les 10 premiers cm du sol. . Selon l'horizon en question, le modèle peut surestimer ou sous-estimer la teneur en eau dans certains cas. Cependant, il est possible qu'il y ait des ajustements entre horizons permettant de compenser que ce soit la surestimation ou la sous-estimation de la teneur en eau. L'évaluation de modèle via la confrontation des humidités mesurés et celles simulés a montré une bonne estimation de la teneur en eau du sol dans un profil de 1 m de profondeur en particulier pour les oliviers seuls (R^2 = 0,61) et pour l'agroforesterie oliviers-blé (R^2 = 0,51). Pour conclure, le modèle permet de simuler d'une manière satisfaisante la teneur en eau de sol ainsi qu'une bonne description du processus décrivant la dynamique des flux d'eau dans les systèmes de culture.

Discussion générale

Les résultats présentés aux chapitres 3 et 4 ont montré que les oliviers réduisaient considérablement le rendement des cultures. La réduction variait de 50 % (chapitre 4) à 55 % (chapitre 3). Des résultats similaires ont été trouvés pour le blé sous des niveaux d'ombre extrêmes (Artru et al., 2017), des réductions relativement inférieur (20%) ce qu'on a pu trouver ont été rapporté par (Dufour et al., 2013) chez le blé dans le système agroforestier méditerranéen à base de noyers. Nos résultats ont permis de montrer la deuxième sous l'hypothèse, qui prédit que l'effet négative des arbres sur la culture commence à un stade précoce de la culture conformément à ce qui a été trouvé par (Daniel et al., 1991). Plusieurs études ont expliqué la diminution de la croissance des cultures au début du cycle de croissance par la compétition pour la lumière (Dufour et al., 2013 ;Chirko et al., 1996 ; Arenas-Corraliza et al., 2018) ce qui est plus probable sous le climat méditerranéen caractérisé par de hiver plutôt pluvieux. En effet, d'autres facteurs liées à l'arrangement spatiale des cultures peuvent induire la réduction de croissance et des cultures des oliviers tel que la densité et l'âge des arbres (Singh et al., 2007).

Sur sa formulation actuelle, notre étude révèle que l'hypothèse du gradient de stress n'est pas pertinente pour les systèmes agroforestiers cultivés. Cependant, nos observations confirment la sous-hypothèse 4, qui prévoit que les interactions entre les arbres et les cultures sont plutôt négatives pendant l'hiver pluvieux, lorsque la disponibilité en eau était élevée, entraînant ainsi une réduction de la croissance des cultures, par exemple l'association blé-Paulownia (Li et al., 2008). Des relations positives peuvent se produire pendant les saisons chaudes en particulier en été, dans ce cas les arbres affectent négativement la croissance des cultures avant la floraison mais améliorent le remplissage des grains après la floraison dans des conditions de limitation de l'eau. L'amélioration du remplissage des grains a été expliquée par l'effet de facilitation via l'ombre des arbres qui tamponnent le microclimat, par exemple en réduisant la chaleur terminale (Lott et al., 2009 ; Peng et al., 2015 ; Niether et al., 2018).

Conclusion et perspectives

Notre étude s'est limitée à l'étude des performances aériennes, malheureusement la croissance des racines n'a pas été évaluée malgré qu'il joue un rôle essentiel dans le bon fonctionnement des associations en agroforesterie (Forey et al., 2017). Le chevauchements des racines des deux espèces via la colonisation des même horizons peut induire des interactions négatives pour l’eau et les nutriments surtout pour des espèces d’arbres qui ont tendance à développer des racines superficiels le cas des oliviers par exemple (Fernández et al., 1991) al., 1991).

L'idéal est d’avoir des cultures qui peuvent élaborer des interactions de complémentarité une racinaire (Bouttier et al., 2014 ; Cardinael et al., 2015). Ça sera intéressant dans une étape qui suit d’analyser la distribution des racines afin de pouvoir mieux comprendre le fonctionnement des systèmes complexes. De plus, un excellent dispositif expérimental a été utilisée dans l'évaluation expérimentale cependant il manque une donnée aussi important pour bien pouvoir interpréter les résultats et qui consistent à l’évaluation de rayonnement et sa distribution.