Lessons learnt: Cereal crops within walnut plantations in Mediterranean Spain

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1 Context

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

This report contributes to Objective 2 in that it focuses on the field-testing of an innovation within the “agroforestry for arable farmers” participative research and development network. In particular, this report contributes to Deliverable 4.11 Lessons learnt from agroforestry innovations for arable farmers.

2 Background

The initial stakeholder report with innovations proposed for field testing (Moreno 2014), the research and development protocol (Moreno et al. 2015), and the system description report (Moreno et al. 2016) provide background data on intercropping cereal in Mediterranean walnuts plantations.

The stakeholder report (Moreno 2014) highlighted the lack of knowledge on the management practices and on the costs and benefits of agroforestry prevent wider adoption of agroforestry schemes for timber production and arable crops. To overcome these difficulties eight areas of innovation were identified and prioritized to evaluate agronomic, ecological and economic viability with cooperating farmers and companies.

2.1 Intercropping Mediterranean hardwood plantations

One of the proposed innovations was the field testing of intercrops under Mediterranean climate conditions. As the research protocol reported (Moreno et al. 2015), the foresters wanted experimental confirmation that the intercrop does not compete significantly with the tree rows, and if any decrease in the tree growth this could be overcompensated by the incomes from annual crop production. In addition, farmers wanted real-farm data that demonstrate that crop yields are not reduced by tree shade and by competition for soil resources. They also asked for a program to identify the best adapted cereal species and cultivars for agroforestry under Mediterranean conditions, where competition for water is usually a strong determinant of plant productivity. A replicated experimental trial was designed accordingly, where cereal yields and tree growth under silvoarable agroforestry were compared with an appropriate control (i.e. cereal yields in open fields and tree growth in monoculture tree plantations).

The private company Bosques Naturales that owns 1300 hectares in Spain for quality timber production agreed to support a participative research program. In the 2000s, this company initiated hardwood plantations managed intensively by using chemical inputs and high levels of energy inputs to reduce the rotation length (details in the system description report by Moreno et al. (2016)).

Periodical harrowing, irrigation and the use of herbicides and mineral fertilizers are controversial management practices because of the high costs and their impact on soil and water pollution (Babcock et al. 2003; World Bank, 2008). The company and other foresters expected that agroforestry could help to reduce the net financial costs of these plantations and improve the delivery of environmental services (Rigueiro-Rodríguez et al. 2009; López-Díaz et al. 2011).

Experiences with durum wheat (*Triticum durum* L.) combined with hybrid walnut (*Juglans* x *intermedia* Ng23xRa) have showed that the woodland captured part of the residual nitrogen washed below the area occupied by the wheat root system, showing that the hybrid walnut has root plasticity to extend its roots in an area not occupied by those of the herbaceous crop (Andrianarisoa et al. 2015). Furthermore, the walnut root system can be modified both vertically and horizontally by the presence of the crop, developing root systems deeper than in monospecific plantations (Cardinael et al. 2015). This shows that walnut species (and presumably other hardwood species) have properties that could make it suitable for agroforestry systems with winter cereals.

2.2 Intercrops to cope with climate change

Arable farmers worry about the consequences of climate change and more specifically of early warm/dry springs that reduce yields of annual crops like cereals in Spain. Indeed, throughout the second half of the twentieth century, crop yields grew up due to improved agronomic techniques, using of fertilizers, energy and pesticides and genetic selection and breeding (FAO, 1996). These advances, known as "green revolution", allowed an increase in the crop yield per unit of cultivated soil by using high inputs (chemical and energy) and a small selection of crop species and cultivars, most of them adapted to full light condictions.

Despite the need to double food production in this century to feed the increasing human population, yields have stagnated in recent years. Decreases in crop yield are increasingly reported as a result of climate change and recurrence of extreme weather events (e.g. heat waves and long droughts) (Brisson et al. 2010; Ray et al. 2012). Brisson et al. (2010) showed that although genetic improvements are still being made to crops, this has been partly counteracted since the 1990 by climate changes which are unfavorable to cereals in temperate climates due to heat-stress during the grain filling phase and drought during stem elongation. Therefore, there is a need to design more productive and sustainable production systems. One approach is ecological intensification where the aim is to increase yield through a better use of the land's own resources (Bommarco et al. 2013; Cassman 1999; Doré et al. 2011). Agroforestry is an ecological intensification approach (Carsan et al. 2013; Tittonell 2014). Cultivating crops in between trees ("Agroforestry") can help mitigate the effects of climate change and the increased frequency of extreme weather events. Trees regulate the climate beneath them, reducing extremes of temperature, sheltering against wind and reducing evaporation from the soil surface. Indeed, it is well documented that trees have a major role in Mediterranean wood-pastures in stabilizing grass production through the typically variable seasonal rainfall (De Miguel et al. 2013; Gea-Izquierdo et al. 2009).

Agroforestry systems have a greater capacity for carbon sequestration than arable monocultures, because of the additional contribution of the trees to carbon sequestration in biomass and in soil (Lorenz and Lal, 2014), thus contributing to the mitigation of climate change. The additional carbon sequestrated in the soil also increases water retention capacity. As already mentioned, the shade of the trees can also reduce water loss via crop transpiration, which increases water use efficiency, a key factor in adapting to climate change (FAO 2013; Lasco et al. 2014; Schoeneberger et al. 2012; Verchot et al. 2007).

Combinations of short-cycle cereals with late-flowering walnuts may increase grain yields over monocultures. The effects of the trees on the arable crop can be facilitative or competitive, depending on the cultivars of cereals. Most cultivars have been traditionally selected for full light conditions and that is why selection programs are needed to find cultivars adapted to partial shade. This can be an approach to adapt to climate change, in the way that the trees can stabilize the interannual variation in yields by minimising the effects of high temperatures and droughts. To advance in this strategy, it is necessary to study both the cereal cultivars, theoretically the precocious ones, and the walnut plant material, in theory, the late flowering cultivars, because it allows the cereal crop to complete most of its development when leaves are not present.

2.3 Walnut plantations in Spain

The role of silviculture has been reviewed in the European Strategy for Climate Change (EU 2014), the European Forestry Strategy (EU 2013) and the fifth report of the IPCC (2015) as a mechanism of adaptation to climate change and through which greenhouse gases will be reduced.

The plant material most used in Spain for the production of quality wood is composed of different species of *Juglans*, such as *J. nigra* L. and *J. regia* L. But currently the hybrids among species of black walnut are more used (mostly *J. major* Torr. and *J. hindsii* Jeps.). In particular, the hybrid progenies *Juglans* x *intermedia* Mj209xRa and *Juglans x intermedia* Ng23xRa, whose life span are between 25 and 30 years, are the most used (Aletá and Vilanova 2011). Both have good forest characteristics and resistance to harmful agents, making their management easier (Coello et al. 2009). The French hybrid walnut, *Juglans* x *intermedia* Mj209xRa, results from the pollination of *Juglans major* Torr. var. 209 (Mj209) with *Juglans regia* L. (Ra). It is not known for sure which species the female parent belongs to (Mj209), which although initially considered *J. nigra* L., was later classified as *J. major* Torr. and is now thought to be an hybrid with reproductive capacity. This hybrid stands out for its fast growth (hybrid vigor) and low fruit yield. Furthermore, it has a great capacity to adaptate to different soils and warm areas of the Iberian Peninsula. Its sprout is, usually, after April 15th (Aletá and Vilanova 2006).

In Spain, in 2000, imports of sawmill timber from non-coniferous species were more than fifteen times higher than exports. Nowadays, despite the decrease in imports as a consequence of the economic crisis, imports are still three times higher than exports (EUROSTAT 2016). This shows the importance of wood transformation sector in Spain, that is not comparable to the plantation surface. In fact, the White Book on Agriculture and Rural Development (MAPYA 2003) highlights the need to begin research on associated cropping systems that allow simultaneous high yields of arable and woody crops. The high ecological requirements of the quality wood species had restricted this kind of plantations to irrigated alluvial lands in Spain in the recent years (García et al., 2010).

3 Objective, innovation and description

The objectives of this participative research program were

1. To assess the productivity of the components (crop and trees) of the silvoarable combination compared to separate components (crops in open fields and pure tree plantations) under Mediterranean climate conditions (Experiment 1; field experiment).
2. To start a research program for the selection of best adapted cereal cultivars for the silvoarable agroforestry under Mediterranean climate conditions in Spain (Experiment 2; garden experiment).

The initial hypotheses were:

- There is no significant competition between trees and crops for soil water, because roots of both vegetation types are developed at different depths and their water requirements differ in time.
- Tree growth is not reduced by crops due to nutrient or water competition.
- Crop yields increase under silvoarable conditions compared to open fields, but this increase depends strongly on the crop species and cultivars.
- During heat waves, increasingly common in spring during grain formation or filling, the growth of many cereal cultivars improve under partial shade.
- Early-season crop cultivars are the best candidates to be used for silvorable agroforestry.

4 System and experiment description

4.1 System and site

The experiment was carried out in a hybrid walnut (*Mj209xRa*; *Juglans major* x *regia*) plantation planted in 2007 for the production of quality timber and owned by the company Bosques Naturales S.A. (Table 1 and 2). The company started an intercropping program in 2014 cultivating annual crops of winter cereals (barley and bread wheat) in the alleys in between tree rows.

Table 1. General description of cereal production beneath walnut

General description of system	
Geographical extent	Plantations of walnut for the production of quality timber are found in Europe, United States, China and Chile.
Estimated area	The company Bosques Naturales S.A owns 1300 hectares in Spain for quality timber production with forestry certification by FSC.
Typical soil types	Fluvisols
Description	Walnut is commonly planted on arable land in orchards or on borders of arable land with other trees. Growing walnut for timber production has become increasingly popular due to the high value of its timber and its fast growth. Currently several agroforestry systems have been established using walnut trees intercropped with cereal production and fodder crops (Pisanelli et al. 2006; Mohni et al. 2009). Its principal aspect is the diversity of products provided by the system. So, this system can increase growth and/or quality of the walnut trees or provide an early financial return to help offset the costs associated with establishing the walnut plantation (Cabanettes et al. 1999; Chiffot et al. 2006).
Tree species	Walnut: *Juglans regia*, *J. nigra* and *J. major* and hybrids.
Tree products	High value timber
Other provisioning services	Possibility of using tree prunings as livestock fodder or as biomass. Rural employment.

Regulating services	The trees increase carbon storage.
Habitat services and biodiversity	This system can give shelter to birds. The plantation has the forestry certification of FSC (Forest Stewardship Council).

Table 2. Description of the specific case study system.

Specific description of site	
Area	0.5 ha
Location Coordinates	Carpio del Tajo (Toledo, Spain) 39°50'56'' N 4°28'03''W (39,8488°, -4,4675°)
Example photograph	
 Figure 1. Cereals grown beneath walnut; the irrigation system for the trees can be seen in the tree row on the left hand side.	
Climate characteristics	
Mean monthly temperature	15.3°C
Mean annual precipitation	442 mm
Details of weather station (and data)	The climate data was obtained from Estación Vegas de San Antonio (La Pueblanueva) (coordinates ETRS 89 UTM 30 N = 354.803 W; 4.424.260 N), placed 18 km far from the plot and at the same altitude. The annual precipitation (Figure 2) of the years of study (2013-2014, 2014-2015 and 2015-2016), with 387 mm, 284 mm and 302.2 mm respectively, were lower than the 1999-2013 average (442 mm). The rainfall distribution showed great variation between the years. The spring

rainfall in the third year was almost triple and double than on the first and second years, respectively (Figure 2).

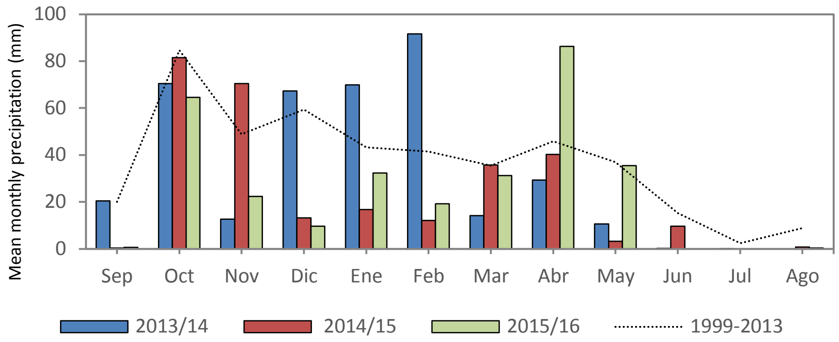

Figure 2. Monthly precipitation (mm) of 2013/14, 2014/15 and 2015/16 and average value for the period 1999-2013.

The occurrence of a long period with high temperatures in April was remarkable in the first and second years, when flowering has already started in the cereals (Figure 3).

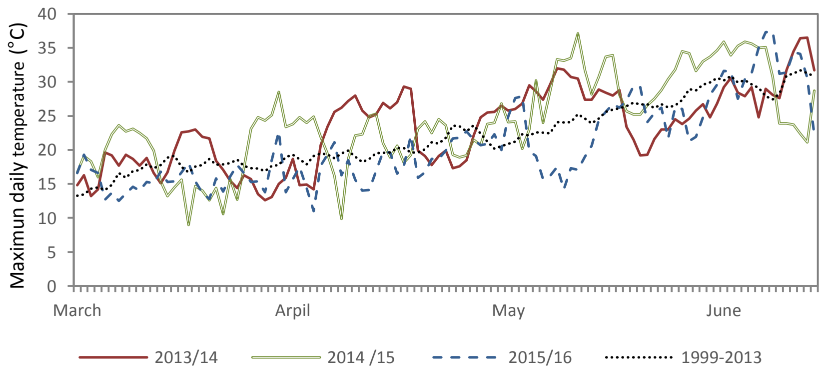

Figure 3. Maximum daily temperatures (° C) during the spring 2013/14, 2014/15 and 2015/16 and the mean value of the period 1999-2013.

Soil type	
Soil type	WRB classification: Fluvisol (stratified soils developed in alluvial deposits which are named from the Latin "*fluvius*" which means river; FAO 2015).
Soil depth	>140 cm
Soil texture	Sandy loam
Additional soil characteristics	pH 5-6 Slope < 5%
Tree characteristics	
Species and variety	Walnut (Nat7 clone - *Juglans x intermedia* Mj209xRa)
Date of planting	2007 (trees were 8, 9 and 10 years old in the three study years)
Tree size	Average height: 10-11 to 12-13 m from the first to the third study year. Average DBH: 15.3 -15.9 cm in January 2014 to 17.2 to 18.1 in January 2016.
Intra-row spacing	5 m
Inter-row spacing	6 m

Tree Management	Drip irrigation in two paralell lines Tree pruning in early summer
Crop/understorey characteristics	
Species	Different cultivars of wheat (*Triticum aestivum* L.) Different cultivars of of barley (*Hordeum vulgare* L.)
Proportion of area occupied by crop	66.7 % (cropped alleys are 4-m width, for 6-m inter-row spacing)
Management	Intensive management with irrigation and fertilization
Sowing date Harvest date	November Mid-June
Crop products	Cereal crops provide grain and straw as products. Additionally, cereal stovers are a source of nutrients and organic matter, which increases soil fertility and quality.
Regulating services	The crops increase carbon storage. The alley cropping system can also help to suppress weed species, reduce soil compaction, increase infiltration of rainwater and reduce erosion.
Fertiliser, pesticide, machinery and labour management	
Fertiliser	600 kg 8:12:12 (NPK) ha^{-1} in cereal sowing and 120 kg urea (46%) ha^{-1} in cereal tillering.
Pesticides	None
Machinery	Need for tractor access between trees for the fertilisation and the ploughing application.
Manure handling	Not necessary in field
Labour	The farm is ploughed once a year

4.2 Experimental design

Three vegetation systems are compared: the intercrop of cereal in the walnut plantation alleys (Agroforestry hereafter), and the two respective controls, the cereal cultivated in open fields (Monocrop hereafter) and the tree plantation alone, not intercropped (Forestry hereafter).

For the agroforestry treatment, five plots of 120 m^2 (20 m long x 6 m wide (of which 4 m were cultivated), including 5 trees in the line) were cultivated per cultivar of cereal. Furthermore, five plots of 2 m x 2 m were established per cereal variety without trees as a control of cereal production, setting spaces of 0.5 m wide between them. As forest control, three plots of trees without cereal sowing were used (45 trees each plot). The location of the plots varied between the 3-years study.

Shade tolerant varieties of wheat and barley that are adapted to agroforestry systems

Cereals grown beneath walnut; the irrigation system for the trees can be seen in the tree row on the left hand side.

Cereals grown in an open field; colours show different varieties of wheat and barley

Figure 4. View of the control and agroforestry plots with cereal

The cereal sowing was done manually in early November of each year and the species used were bread wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). The sowing rate was 180 kg ha^{-1} for barley and 220 kg ha^{-1} for wheat. The cultivars selected varied among years according to seed availability (Table 3).

Table 3. List of cereal species and cultivars tested in the Bosques Naturales silvoarable site in Central Spain (Carpio de Tajo, Toledo)

	2013-2014	2014-2015	2015-2016
Barley	Doña Pepa, Azara	Basic, Lukhas, Hispanic, Dulcinea	Hispanic, Graphic, Meseta, Pewter
Wheat	Kilopondio, Bologna	CCB Ingenio, Sublim, Nogal	CCB Ingenio, Nogal, Boticelli, Idalgo

4.3 Shading experiment

In 2016-2017, a greenhouse trial of winter cereal varieties was carried out at the Ecological and Mountain Agriculture Center (CAEM) in Plasencia (Cáceres, Spain). The trial included different cultivars of each cereal species (wheat and barley) to select those that showed a better behaviour under partial shade conditions for cropping in agroforestry systems. The seeds of these varieties were provided by the La Orden-Valdesequera Agricultural Research Institute, which collaborates with the Group for the Evaluation of New Varieties for Extensive Crops in Spain (GENVCE: http://www.genvce.org/). The nine varieties of each species were selected according to three categories of precocity (dates of sprout). These categories were: very early, early and medium (see Table 6).

Three treatments were established: full light with anti-bird net ("Light"), 10% shade ("Partial shade") and 50% shade ("Shade"). In each treatment a table was installed with six pots per variety, sowing four seeds in each pot (13 x 13 x 17 cm). On April 7, 2017 shading nets were introduced, coinciding with the leaf sprout of walnuts.

Three treatmets enclosed by nest of different light

“Light” treatment

“Partial shade” treatment

“Shade” treatment

Figure 5. View of the three treatments in the shading experiment

4.4 Measurements

4.4.1 Cereal yield, protein content and phenology

Cereal crops were sown on five plots per cultivar in each treatment (monocrops and agroforestry). The phenology was recorded in 16 plants per plot in three different dates in 2016 (4 May, 26 May, and 7 June) by Zadoks growth stages (Zadoks et al. 1974).

Samples were reaped (using hand clippers) in June 2014, 2015 and 2016 at ground-level in 50 x 50 cm squares, taking three samples per plot in the agroforestry system in central part and two samples per plot in monocrops.

After sampling, plants were dried at 60°C until constant weight. To determine the cereal yield, the following variables were measured: total biomass weight, total grain weight and weight of 1000 grains. The harvest index was then calculated as weight of total grain / weight of total biomass.

4.4.2 Tree growth

The diameter at breast height (DBH) of the trees was measured every year during the dormant period (January). From these data, the increase of diameter was calculated per year and treatment. This parameter was analyzed because it is the most determinant for the estimation of wood production, compared to the study of height growth, whose measurement is less accurate and of lower interest for timber producers. In the agroforestry system, four central trees per plot were measured and in the forestry system 45 control trees were randomly selected and measured.

4.4.3 Chemical analyses

Tree leaves were sampled in July 2014, 2015 and 2016 by selecting 12 random trees in each treatment (forestry and agroforestry). From each tree, a shoot was cut in the middle part of the crown with a telescopic scissor. North, South, East and West orientations allowed the sampling of 25% of the trees in each orientation). The terminal leaflets were collected from the leaves located in the middle part of the shoot (Hirzel 2008), stored in paper bags and dried at 60°C until constant weight. Then, an acid digestion was done in Kjeldahl tubes in the Gerhardt Bloc-Digest Model 20 to later determinate N, P and K content.

The P content was analyzed by the method G-189-97 with AA1 Auto Analyzer from Seal Analytical. The K content was analyzed with Flame Photometer Model 410 from Sherwood according to the method F-019G. The N content of cereal grain and tree leaves was determinated by combustión analysis according to the Dumas method (ISO 16634-1:2008(EN)) in two replicated analysis per sample with DUMATHERM® from Gerhardt.

For the soil, during the ripening of cereals (June), five random samples 20 cm deep and 5 cm diameter were taken from each treatment and stored cold in a plastic bag until analysis in laboratory. They were sieved to < 2 mm just before the chemical analysis. An aliquiot was at that time dried at 60°C to constant weight to estimate the soil moisture and included in later calculus.

Soil extractions were made with 1 M potassium chloride (KCl) (Rayment and Lyons 2011) to analyze the ammonium (NH_4^+) and nitrate (NO_3^-) contents. Extractions with Melich 1 (Sims 2000) were done to determine available phosphorus (P) and potassium (K).

The NH_4^+ content was analyzed by the ammonium protocol in 1M KCl soil extractions ISO 14256-2: 2005 and NO_3^- content was calculated according to the nitrate protocol in 1M KCl soil extractions ISO 14256-2:2005(E), both with AA1 Auto Analyzer from Seal Analytical.

Phosphorus determination was done following the G-103-93 protocol for the analysis of phosphate in water and soil extractions from AA1 Autoanalyzer. The potassium content was analyzed by Flame Photometer Model 410 from Sherwood, according to the method F-019G.

Relative Water Content (RWC) was measured 10 cm deep with a soil moisture meter in the central point per plot in the agroforestry and monocrops systems during grain filling (4 May). In the forestry system, 45 points were measured at 2 m from the plantation line (near the trees used for tree growth measurements).

5 Results from two experiments

5.1 Field experiment

5.1.1 Cereal growth and yield

The grain yields differed between years, species and systems. Over the first two years (2013-2014 and 2014-2015), barley yields were higher in the agroforestry system compared to monocropping system (Figure 6), being significantly higher the first year ($p < 0.001$, Table 4). The difference was more obvious for the cultivars Azara and Doña Pepa ($p < 0.05$, Table 5). For wheat, in the first year, the agroforestry system did not show significant differences for grain yields, but, in the second year, yields were significantly lower in the agroforestry system ($p < 0.001$, Figure 6), especially in the cultivars Sublim and Nogal ($p < 0.001$, Table 5). In the third year, the agroforestry system produced significantly lower yields of wheat ($p < 0.01$) and barley ($p < 0.001$) (Table 4), showing significant differences for the Hispanic cultivar of barley ($p < 0.01$) and in the cultivars Ingenio, Boticelli, Nogal and Idalgo of wheat ($p < 0.01$, Table 2).

In the first year (2013-2014), weather conditions were unfavourably for grain production, with low amount of spring precipitations (Figure 2). Furthermore, there was heat wave during the booting and preflowering period in the first days of April, and in the first days of May, when grains were starting to fill (Figure 3). This year was the worst in terms of grain yield, presumbaly by these climatic conditions. Both barley and wheat benefited from the presence of trees (Figure 6), with significantly higher yields in agroforestry system for barley ($p=0,003$).

In the second year (2014-2015), spring precipitation was greater than in the first year (Figure 2), and, consequently, so was the grain yields. There was also a heat wave during the preflowering period and grain filling, as it occurs in the first year (Figure 3). Barley grain yield was still higher in agroforestry system, but not in a significant way. Wheat, which had not been significantly benefited by the agroforestry system the first year, produced significantly less grain in agroforestry system in the second year.

In the third year, spring precipitation was almost a 200% greater compared to the two previous years (Figure 2). This year was the most productive year for monocropping. While for agroforestry, barley and wheat yields were significantly lower compared to monocrops.

In summary, in very productivie years, when climate constraints are low, cereal yields are reduced significantly by the presence of trees in the agroforestry system. By contrast in years with dry/hot climate events in spring that constraint cereal maturation, the shade provided by the trees works as a safeguard resulting in higher yields in agroforestry. The agroforestry combination appears more positive for barley than for wheat.

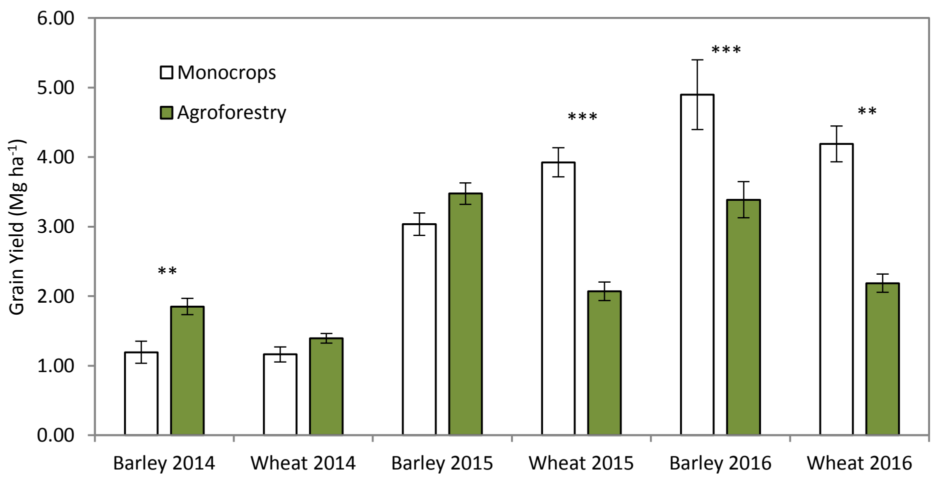

Figure 6. Grain yield (Mg ha^{-1}) in wheat and barley in the years of study in monocrop and agroforestry systems. Signification level (t-test): ** $p < 0.01$; *** $p < 0.001$.

Plant biomass was greater in the agroforestry system in barley the first and second year ($p < 0.01$, Table 4) and there was no difference for wheat. The barley cultivars which had significantly higher production were Azara the first year ($p < 0.05$, Table 5) and Hispanic the second year ($p < 0.01$). In the third year, when the climatic conditions were more favourable for cereal plants, monocrops showed a higher biomass in both species ($p < 0.001$, Table 4), being more evident in the cultivars of wheat (Ingenio, Boticelli, Nogal e Idalgo, $p < 0.001$) than in barley cultivars (Meseta and Hispanic, $p < 0.01$, Table 5).

Harvest index was significantly higher in agroforestry for barley and wheat the first year ($p < 0.05$, Table 4), especially the Bologna cultivar ($p < 0.05$, Table 5), and significantly lower in wheat the second year ($p < 0.001$), especially the cultivars Ingenio ($p < 0.01$), Sublim and Nogal ($p < 0.001$, Table 5). Grain size (weight of 1000 grains) of barley was significantly different between systems in the second year ($p < 0.01$), being greater in the agroforestry system, especially the cultivars Dulcinea and Basic ($p < 0.05$, Table 5).

Table 4. Grain and biomass yields (Mg ha^{-1} ± S.E.), harvest index and weight of 1000 grains (g *± S.E.)* of wheat and barley in the years of study in monocrop and agroforestry systems. Significance level (t-test): ** p < 0.05; ** p < 0.01; *** p < 0.001.* Significant differences are indicated in light blue.

Year	Species	**Grain yield (Mg ha^{-1})**		**Biomass yield (Mg ha^{-1})**		**Harvest index**		**Weight of 1000 grains (g)**	
		Monocrop	Agro-forestry	Monocrop	Agro-forestry	Monocrop	Agro-forestry	Monocrop	Agro-forestry
2014	Barley	1.19 ±0.16	1.85 ±0.12 **	6.32 ±0,36	7.71 ±0.27 **	0.19 ±0.02	0.24 ±0.01 *	29.78 ±1.01	29.62 ±0.64
	Wheat	1.16 ±0.11	1.40 ±0.07	8,23 ±0.26	8.29 ±0.29	0.14 ±0.01	0.17 ±0.01 *	24.82 ±1.16	22.34 ±0.66
2015	Barley	3.03 ±0.16	3.48 ±0.15	5.52 ±0.22	6.72 ±0.29 **	0.57 ±0.03	0.52 ±0.01	31.11 ±2.22	40.61 ±0.75 **
	Wheat	3.9 2±0.21	2.07 ±0.13 ***	6.83 ±0.16	7.18 ±0.32	0.57 ±0.03	0.28 ±0.01 ***	26.25 ±2.57	25.82 ±0.99
2016	Barley	4.90 ±0.50	3.39 ±0.26 **	11.58 ±0.87	7.94 ±0.33 ***	0.42 ±0.02	0.42 ±0.03	26.30 ±0.96	25.71 ±0.91
	Wheat	4.19 ±0.26	2.19 ±0.13 ***	17.1 0±0.53	8.79 ±0.40 ***	0.24 ±0.01	0.25 ±0.01	21.42 ±0.80	20.57 ±0.54

Table 5. Grain and biomass yields (Mg ha^{-1} ± *S.E.*), harvest index and weight of 1000 grains (g ± *S.E.)* of different wheat and barley cultivars tested in the years of study in monocrop and agroforestry systems. Significance level (t-test): ** p < 0.05; ** p < 0.01; *** p < 0.001.* Significant differences are indicated in light blue.

Year	Species	Cultivars	**Grain yield ($Mg\ ha^{-1}$)**		**Biomass yield ($Mg\ ha^{-1}$)**		**Harvest index**		**Weight of 1000 grains (g)**	
			Mono-crop	Agro-forestry	Mono-crop	Agro-forestry	Mono-crop	Agro-forestry	Mono-crop	Agro-forestry
2014	Barley	Azara	1.09 ±0.11	1.77 ±0.18*	6.14 ±0.49	7.60 ±0.37*	0.19 ±0.03	0.23 ±0.02	26.46 ±0.66	26.55 ±0.76
		Doña Pepa	1.30 ±0.30	1.94 ±0.15*	6.50 ±0.57	7.83 ±0.41	0.19 ±0.03	0.24 ±0.01	33.11 ±1.06	32.69 ±0.52
	Wheat	Kilopondio	1.20 ±0.19	1.33 ±0.08	7.92 ±0.29	8.43 ±0.39	0.15 ±0.02	0.16 ±0.01	29.19 ±0.80	24.56 ±1.01*
		Bologna	1.13 ±0.12	1.46 ±0.12	8.53 ±0.43	8.14 ±0.44	0.13 ±0.01	0.18 ±0.01*	20.46 ±0.54	20.13 ±0.56
2015	Barley	Basic	2.29 ±0.37	3.22 ±0.27	5.35 ±0.36	6.12 ±0.50	0.43 ±0.07	0.53 ±0.01	30.66 ±1.16	42.95 ±1.29*
		Lukhas	3.31 ±0.43	3.91 ±0.44	7.38 ±0.58	7.57 ±0.78	0.46 ±0.07	0.50 ±0.02	25.00 ±0.97	35.00 ±1.65
		Hispanic	3.24 ±0.22	3.68 ±0.25	4.79 ±0.12	7.24 ±0.53**	0.68 ±0.05	0.51 ±0.01***	34.70 ±1.34	43.21 ±1.19
		Dulcinea	3.19 ±0.28	3.08 ±0.17	5.25 ±0.25	5.96 ±0.39	0.62 ±0.06	0.52 ±0.01	34.07 ±1.26	41.28 ±0.78*
	Wheat	Ingenio	2.58 ±0.26	2.06 ±0.25	6.19 ±0.16	6.97 ±0.67	0.41 ±0.04	0.29 ±0.02**	30.38 ±0.87	30.17 ±1.50
		Sublim	5.25 ±0.20	2.36 ±0.26***	7.55 ±0.25	7.70 ±0.55	0.71 ±0.03	0.30 ±0.02***	30.06 ±1.24	26.30 ±1.89
		Nogal	2.94 ±0.21	1.81 ±0.17***	6.27 ±0.20	6.90 ±0.45	0.48 ±0.04	0.26 ±0.02***	18.48 ±0.64	21.31 ±0.77
2016	Barley	Meseta	5.13 ±0.72	4.17 ±0.33	11.94 ±1.07	8.37 ±0.50**	0.42 ±0.03	0.50 ±0.03	25.77 ±0.91	25.85 ±1.26
		Hispanic	4.67 ±0.77	2.60 ±0.19**	11.23 ±1.48	7.51 ±0.42**	0.41 ±0.02	0.35 ±0.02	26.83 ±1.78	25.57 ±1.39
	Wheat	Ingenio	3.67 ±0.56	1.96 ±0.19**	17.52 ±1.20	8.80 ±0.90***	0.21 ±0.02	0.23 ±0.02	23.45 ±1.36	20.57 ±0.69
		Boticelli	4.05 ±0.42	2.03 ±0.27 **	15.4 ±1.07	8.92 ±0.81***	0.26 ±0.02	0.22 ±0.02	20.73 ±1.69	21.00 ±1.36
		Nogal	4.20 ±0.31	2.54 ±0.26 **	17.17 ±0.84	8.78 ±0.72***	0.24 ±0.01	0.29 ±0.01	18.94 ±1.30	20.57 ±0.69
		Idalgo	4.85 ±0.70	2.21 ±0.31 **	18.29 ±1.00	8.67 ±0.85***	0.27 ±0.04	0.25 ±0.02	22.56 ±1.69	20.84 ±1.26

5.1.2 Crop phenology

Trees affected the phenology of the cereal plants recorded in 2016 according to the Zadoks phenophases (Zadoks et al. 1974). The monitoring period went from 4 May (just before walnut leafing) until 7 June (just after walnut leaves and cereal grains maturation were over).

Initially, during the early Zadoks growth stages 70-79 (milk grain development), the agroforestry system hastened barley growth compared to the barley plants growing in open fields (Figure 7). However, at more advanced stages, during the growth stages 80-89 (dough development), barley grain development was slower in the agroforestry system than in open fields. Finally, ripening of the grain (stage 90) was reached earlier in the monocrop than in the agroforestry (Figure 7).

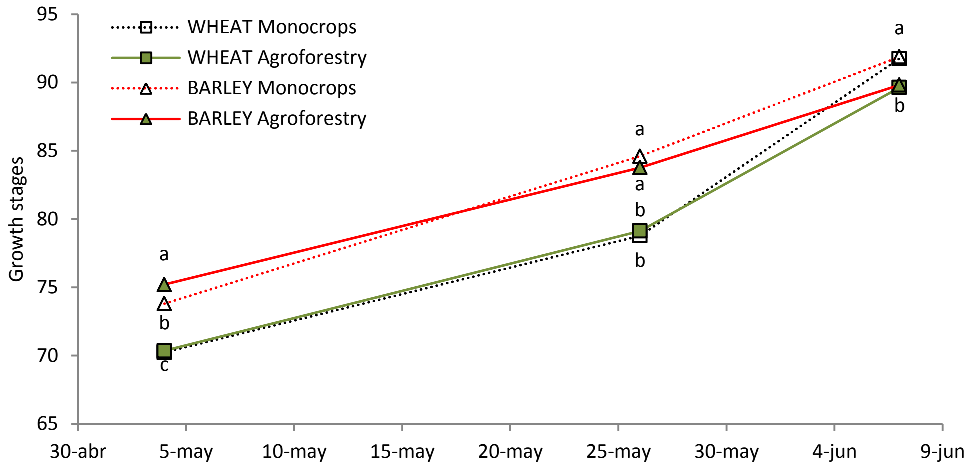

Figure 7. Growth stages according to Zadoks (1974) scale for wheat and barley in 2015-2016. Different letters show significant differences between treatments for the same period (t-test, $p < 0.05$). Tree leafing came about the first fortnight of May.

5.1.3 Grain protein

Grain protein content was assesed indirectly as N content in 2016. The conversion factor of total N to total protein in barley and wheat is 5.83 (FAO 1970). The average content of N in barley monoculture was 2.36 ± 0.24% and 2.07 ± 0.07% in the agroforestry treatment, so that their respective protein contents are 13.76 ± 1.40% and 12.06 ± 0.41% (Figure 8). These differences were not significant for barley. By contrast for wheat, significantly higher values were observed for agroforestry compared to the monocrops ($p < 0.01$). Nitrogen contents were of 2.50 ± 0.05% in monocrops and 2.76 ± 0.06 % in agroforestry, and protein contents were 14.58 ± 0.29 % and 16.10 ± 0.35 %, respectively.

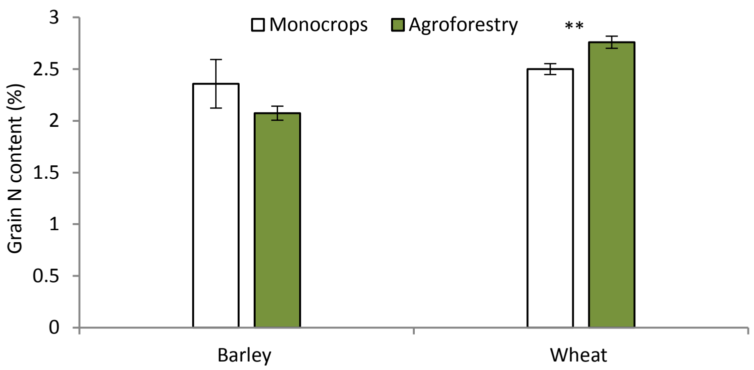

Figure 8. Grain N content (% N ± *S.E.*) of barley and wheat in monocrops and agroforestry system in year 2016. Significance level (t-test): *** p < 0.01.*

With regards to the grain potassium (K) content in crops, there was no difference beween systemsfor barley, but for wheat significantly higher K content was observed in agroforestry (Figure 9).

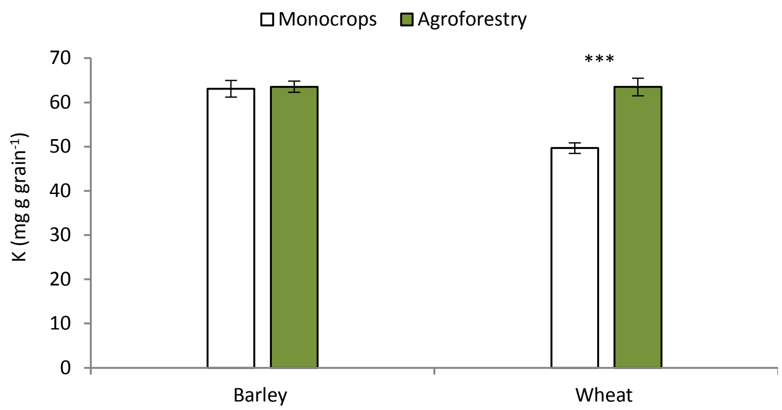

Figure 9. Grain K content (mg g grain^{-1} ± *S.E.*) of barley and wheat in monocrops and agroforestry system in year 2016. Significance level (t-test): *** $p < 0.001$.*

5.1.4 Tree growth

Figure 10 shows tree growth in terms of diameter (DBH) during the different years of the study. Initially, in 2013, DBH from both systems were similar. However during the study, trees in the forestry system grew faster than trees intercropped with cereals. This makes it clear than there was competition between the crops and trees in the agroforestry system (trees in both cases were planted under identical conditions). In the folowing section we explore some key results that inform us about the potential competition for soil nutrients and water.

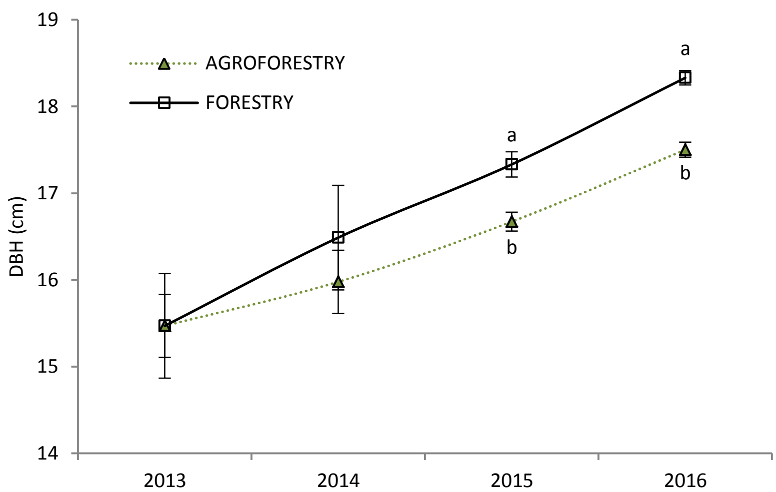

Figure 10. Means of diameter at breast height (DBH) of *Juglans* x *intermedia* Mj209xRa in the forestry and agroforestry systems in years 2013, 2014, 2015 and 2016. Different letters show significant differences between systems at different dates (t-test, $p < 0.05$).

5.1.5 Walnut leaf nutrient content

Walnut leaf N content did not show significant differences between systems and years of study and its mean value was 22.16 ± 0.51 mg / g leaf. Likewise P contents revealed no differences between systems and years and had a mean value of 1.34 ± 0.11 mg / g leaf. By contrast, K content in walnut leaveswas significantly lower in the agroforestry system than in the forestry system (Figure 11; $p < 0.001$ both in 2015 and 2016).

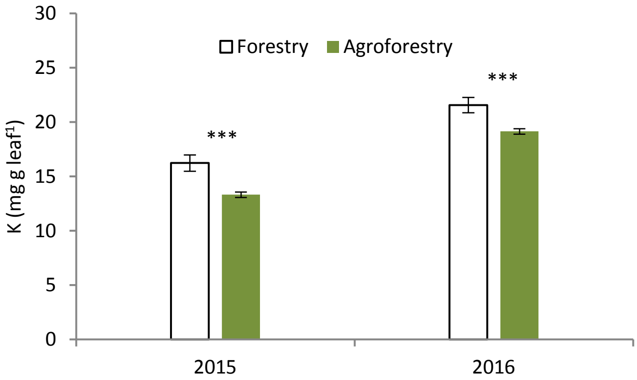

Figure 11. Walnut leaves K content (mg g leaf^{-1} ± S.E) in 2015 and 2016 in forestry and agroforestry systems. Significance level (t-test: **** p < 0.001*).

5.1.6 Soil resources

Soil K content showed higher values in monocrops, followed by forestry and lastly by agroforestry systems (Figure 12), being significantly higher in monocrops compared to agroforestry ($p < 0.05$). Differences for mineral N (nitrate and ammonium) and available P were not significant (data not shown). Relative Water Content (RWC) was significantly higher in forestry than in monocrops and agroforestry systems (Figure 13).

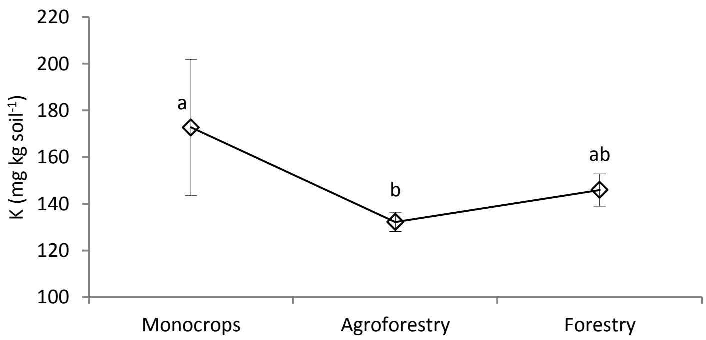

Figure 12. Soil K content in 0-20 cm soil layer(mg kg soil^{-1} *± S.E*) in 2015 in monocrops, agroforestry and forestry systems. Different letters show significant differences by ANOVA ($p < 0.05$).

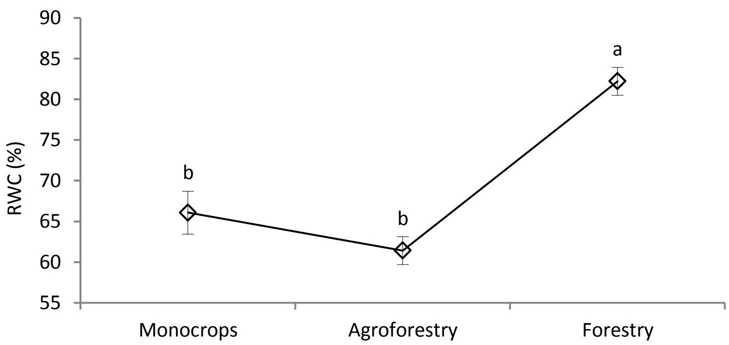

Figure 13. Relative Water Content (%*± S.E*) in 2015 in monocrops, agroforestry and forestry systems. Different letters show significant differencesby ANOVA ($p < 0.05$).

5.2 Shading experiment: selection of shade-adapted cultivars

In general, grain production (Figure 14) increased with shade. While barley did not show an increase at 10% shade, it showed a significant increase at 50% shade. By constrast, wheat grain yields increased significantly from full sunlight to 10% shade and kept the same grain yield at 50% shade. It is known that wheat is a full-light plant (Guerrero 1999), hence providing shade was not anticipated to improve the grain yield as it does in barley.

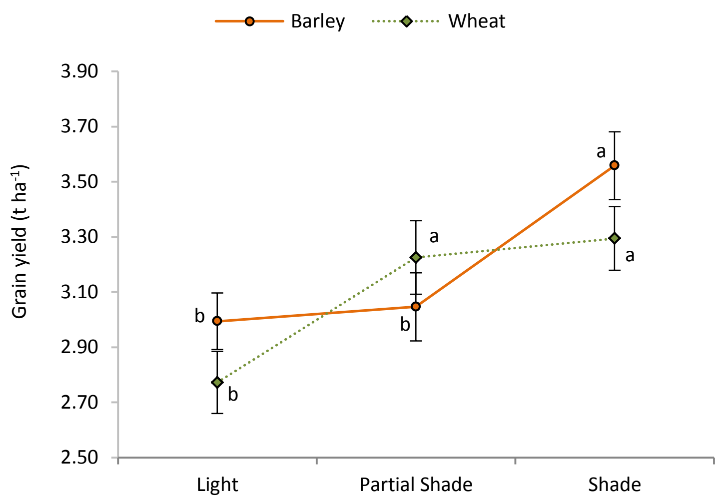

Figure 14. Grain yield (Mg/ha) of barley and wheat in the different treatments: full sunlight (Light), 10% shade (Partial shade) and 50% shade (Shade).

The biomass yield (Figure 15) show the same behaviour in wheat and barley. Plant biomass increased significantly from full sunlight to the 10% shade which was similar to the response in 50% shade.

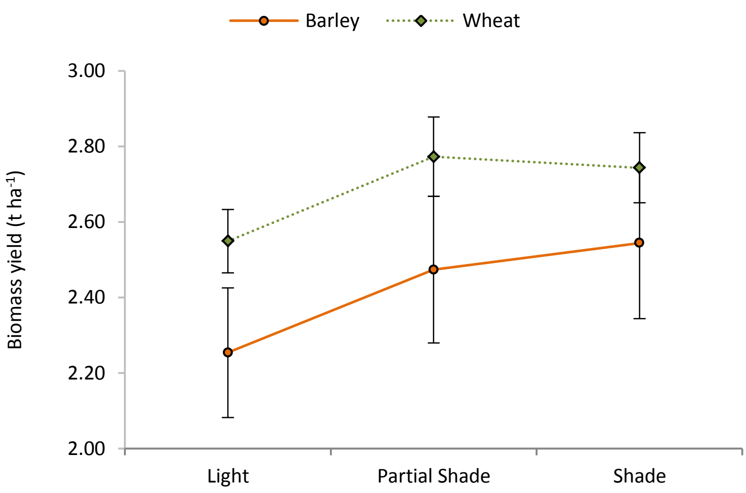

Figure 15. Biomass yield (Mg/ha) of barley and wheat in the different treatments: : full sunlight (Light), 10% shade (Partial shade) and 50% shade (Shade).

Grain size (weight of 1000 grains) is shown in Figure 16. For barley, grain size was similar in 10% shade and in full sunlight, and decreased significantly in 50% shade. For wheat, grain size was significantly higher in 10% shade compared to 50% shade and full sunlight.

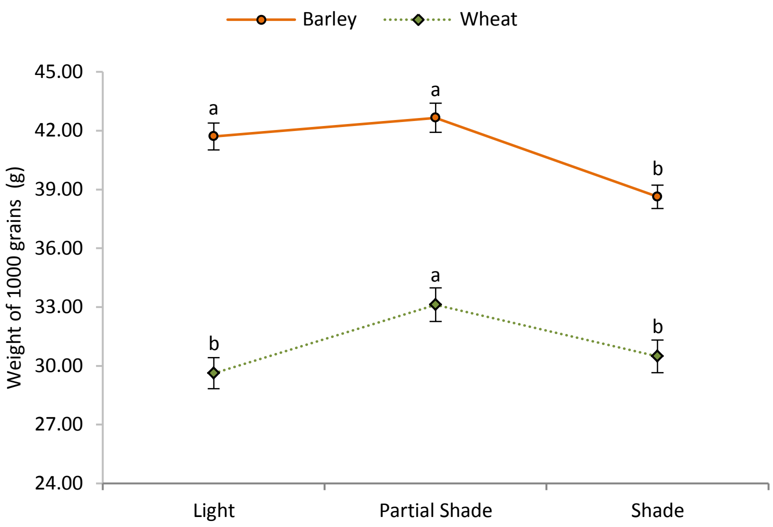

Figure 16. Weight of 1000 grains (g) of barley and wheat in the different treatments: : full sunlight (Light), 10% shade (Partial shade) and 50% shade (Shade).

The harvest index (Figure 17) was greater, in general, in barley than in wheat. The 10% shade treatment resulted in significantly lower harvest indices compared with full sunlight and 50% shade for barley. For wheat, the harvest index incease steadily with shade treatments, but differences were not significant.

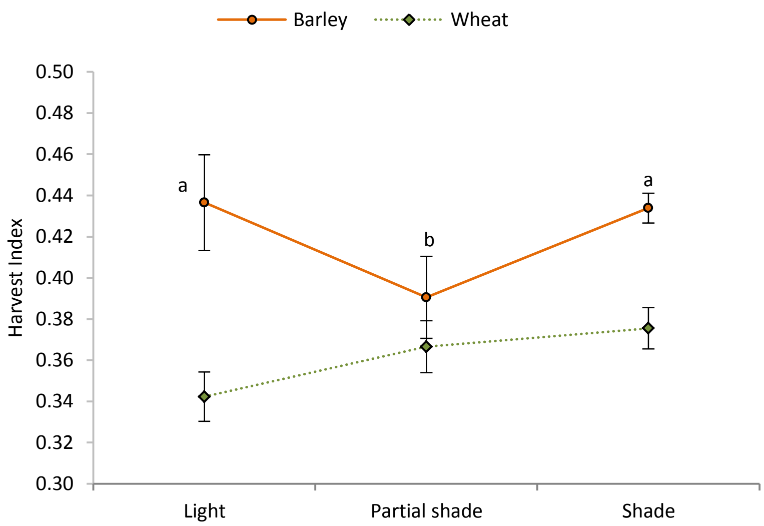

Figure 17. Harvest index of barley and wheat in the different treatments: : full sunlight (Light), 10% shade (Partial shade) and 50% shade (Shade).

Tables 6 to 9 show original data for different cultivars growing at different sinlight conditions (full sunlight, 10% shade, and 50% shade). Grain yield trend to be higher under 50% shade for most of the barley cultivars, being significant higher for “Lagalia” and “Meseta”. In wheat, the highest grain yields were mostly found for 10% shade, being significant for Sohelio. “Paledor” showed a better behaviour in 50% shade (Table 6). The biomass (Mg/ha) was usually higher in 10% shade for most of the barley and wheat cultivars, with significant differences for the barley cultivar Meseta and the wheat cultiva Nemos. For few cultivars, highest values were found in 50% shade, being significant for the wheat cultivar Solehio (Table 7). Grain size tended to be greater in 10% shade in both barley and wheat (Table 8). Harvest index rarely varied significantly, except for 3 out of 18 cultivars, for which harvest index was higher in 50% shade. Finally, we did not found signficant differences between the different precocity categories of cultivars.

Table 6. Grain yields (Mg/ha) for the cultivars tested

Species	Maturation	Cultivars	**Grain yield (Mg/ha)**		
			Full sunlight	10% Shade	50% Shade
Barley	Very early	Hispanic (T)	2.82	2.88	3.39
		Lavanda	3.48	2.90	3.49
		Luzia	2.89	3.34	3.38
	Early	Kalea	2.76	1.88 b	**2.90 a**
		Lagalia	3.14 b	3.43	**4.13 a**
		Carolina	2.78	3.54	3.57
	Medium	Meseta (T)	2.57 b	3.29	**4.02 a**
		Ibaiona	2.96	3.09	3.28
		Crescendo	3.53	3.08	3.85
Wheat	Very early	Nogal (T)	2.92	2.51	2.86
		Nudel	3.24	3.76	4.06
		Tocayo	3.33	4.18	3.89
	Early	Alogoritmo	2.95	3.30	2.75
		Paledor (T)	2.16 b	2.36 b	**3.40 a**
		Solehio	2.08 b	**3.33 a**	2.84
	Medium	Toskani	2.05	2.15	2.91
		Somontano	3.10	3.55	3.41
		Nemo	3.13	3.90	3.52

Significant differences ($p < 0.05$) are shown by different letters.

Table 7. Biomass yields (Mg/ha) for the cultivars tested

Species	Maturation	Cultivars	**Biomass yield (Mg/ha)**		
			Full sunlight	10% Shade	50% Shade
Barley	Very early	Hispanic (T)	7.93	8.60	8.64
		Lavanda	7.47	7.53	7.44
		Luzia	6.23	8.28	7.39
	Early	Kalea	6.95	6.90	7.18
		Lagalia	7.96	8.20	9.05
		Carolina	7.03	8.55	7.91
	Medium	Meseta (T)	5.28 b	**9.64 a**	**8.70 a**
		Ibaiona	7.00	7.83	7.56
		Crescendo	8.69	8.82	9.53
Wheat	Very early	Nogal (T)	6.76	9.59	7.53
		Nudel	9.03	9.32	9.78
		Tocayo	8.58	9.37	9.08
	Early	Alogoritmo	8.20	7.69	7.53
		Paledor (T)	7.97	7.99	8.67
		Solehio	7.15 b	**8.93 a**	**9.25 a**
	Medium	Toskani	9.69	8.27	9.22
		Somontano	8.24	9.39	9.05
		Nemo	7.92 b	**9.46 a**	9.03

Significant differences ($p < 0,05$) are shown by different letters.

Table 8. Weight of 1000 grains (Mg/ha) for the cultivars tested

Species	Maturation	Cultivars	Weight of 1000 grains (g)		
			Full sunlight	10% Shade	50% Shade
Barley	Very early	Hispanic (T)	44.12	43.47	39.86
		Lavanda	37.48	35.45	34.86
		Luzia	41.80	40.18	37.25
	Early	Kalea	41.89 b	**45.82 a**	35.31 c
		Lagalia	44.29	44.06	42.76
		Carolina	46.92	45.98	43.67
	Medium	Meseta (T)	35.98 b	**41.13 a**	35.09 b
		Ibaiona	41.79	42.77	39.09
		Crescendo	41.08 b	**45.07 a**	39.77 b
Wheat	Very early	Nogal (T)	**32.76 a**	26.69 b	30.00
		Nudel	28.97 b	**36.31 a**	33.56
		Tocayo	31.04 b	**37.66 a**	36.09
	Early	Alogoritmo	27.73	31.84	26.53
		Paledor (T)	25.52	27.52	28.24
		Solehio	33.01 b	**41.28 a**	37.00
	Medium	Toskani	25.10	31.72	26.94
		Somontano	31.04	30.96	28.13
		Nemo	31.41	34.09	27.89

Significant differences ($p < 0.05$) are shown by different letters.

Table 9. Harvest Index for the cultivars tested

Species	Maturation	Cultivars	Harvest index		
			Full sunlight	10% Shade	50% Shade
Barley	Very early	Hispanic (T)	0.34	0.33	0.38
		Lavanda	0.46	0.39	0.46
		Luzia	0.58	0.40	0.45
	Early	Kalea	0.40	0.26	0.40
		Lagalia	0.39 b	0.42	**0.45 a**
		Carolina	0.39	0.41	0.45
	Medium	Meseta (T)	0.55	0.58	0.47
		Ibaiona	0.42	0.38	0.43
		Crescendo	0.40	0.34	0.40
Wheat	Very early	Nogal (T)	0.43 a	0.30 b	0.39
		Nudel	0.35 b	0.41	**0.42 a**
		Tocayo	0.39	0.44	0.43
	Early	Alogoritmo	0.36	0.42	0.37
		Paledor (T)	0.27 b	0.29 b	**0.38 a**
		Solehio	0.29	0.37	0.32
	Medium	Toskani	0.21	0.26	0.32
		Somontano	0.38	0.38	0.37
		Nemo	0.39	0.42	0.38

Significant differences ($p < 0.05$) are shown by different letters.

6 Main lessons

1. In very productive years, without climate constraints for cereal growth, cereal yields were reduced significantly by the presence of trees in the agroforestry system.

2. While trees seem to enhance cereal growth in winter and early spring, after tree buds burst the growth of cereal plants slowed down and the last development stages can be negatively affected as demonstrated by a delay in crop development and/or competition with trees for soil resources.

3. In general terms, slight shade did not reduce the production of cereals. On the contrary, it increased grain yields especially in barley. Shade could be a way to mitigate excessive solar radiation in Mediterranean latitudes and high temperatures during the spike development and grain fill.

4. We did not find evidence of detrimental effects of tree competion for cereal nutrition.

5. Competition for soil moisture could happen, especially when grain filling and ripening (late season cereal cultivars) overlap with appearance of tree leaves (early bursting trees). So, under typical climate conditions, combinations of short-cycle cereals with late-bursting walnuts seem more favourable.

   Wheat has a later cycle than barley and grain filling starts when walnut leaves are already fully developed. It is known that wheat is a full-light plant (Guerrero 1999), so the solar radiation interception by trees, together with competition for water in a great demand period by both vegetation types, explain the stronger harmful effect of trees on wheat compared to barley. Similar results of decrease of grain yield have been observed in durum wheat yield (Triticum durum L.) in an agroforestry system with hybrid walnut Juglans x intermedia Ng23xRa (Dufour et al. 2013) and bread wheat with Juglans regia L. (He et al. 2012). These results underline the importance of competition for water between vegetative strata for wheat in Mediterranean climate conditions, where dry years are common.

6. In years with dry/warm climate events in spring that constrained cereal yields, tree shade can be a safeguard and cereal yields were higher in agroforestry than in the open fields.

   Several consecutive days with high temperatures (maximum daily > 25ºC) in the month of April and May, when the flowering and grain formation of the cereal take place could decrease the cereal yields. Romero and German (2001) indicated that at temperature above 25°C the translocation of the available carbohydrates towards the grain was constrained.

7. Trees can stabilize yield variability through the years in the current scenario of climate change by dampening the effects of the increasingly frequent extreme weather events.

   When the cereal yields were low, due to adverse climatic conditions such as those occurring in 2013-2014 (low spring rainfall and heat waves), production was higher in the agroforestry system in both cereal species, indicating that the trees minimised the effect of adverse conditions, in particularly in barley. In intermediate climatic conditions, such as those of 2014-2015 (similar temperatures but higher spring precipitation), for barley, the agroforestry system is still favourable but not for wheat. Finally, in very favourable climatic conditions for grain production, as in 2015-2016 (no heat waves and plentiful spring precipitation), the effect of trees is detrimental to both cereal species. Over the years, grain yields in the *agroforestry system remained in the same range of values, indicating its capacity to stabilize production in cereals under Mediterranean conditions, where a reduction in the cereal yields is expected by thermal stress and spring droughts (Brisson et al. 2010).*

8. The agroforestry combination appears to be more positive for barley than for wheat, presumably because of the earlier development of barley plants and better adaptation to water stress compared to wheat.

   In addition to being more premature, barley has a fast ripening and a short period of grain filling compared to wheat (Cossani et al. 2009). In fact, in Mediterranean agrosystems, under unfavourable conditions (arid and/or low fertility), barley is prioritized over other cereals (López-Bellido 1992), since its precocity and rapid ripening have advantages in the use of water by avoid the common terminal stresses. So when walnut has just developed its leaves, barley is in a more advanced phase in its grain filling process than wheat, thus suffering less competition with trees. In addition, the inclination angle of the leaves of barley and its foliage structure allows a greater interception of solar radiation (Muurinen and Peltonen-Sainio 2006), so it may be less sensitive than wheat to the possible negative effects of excessive tree shading. In addition, barley spike's edges increase the exchange of sensible heat and decrease the evapotranspiration, making it better tolerate drought in the ripening stage (Hoffman et al. 2011; Setter and Waters 2003). Consequently, barley could benefit more from the positive effects of the tree (during booting, flowering and grain formation stages) and being less affected by the competitive effect of the trees (during grain filling and ripening stages) than wheat in Mediterranean areas.

9. Agroforestry also favoured the protein content of wheat grain compared to open fields, but was unfavourable for barley grains.

   The grain protein content is a reference parameter of malting quality and generally should not exceed 12%, as it is established in the marketing standard (Arias, 1991). The agroforestry system tend to reduce the protein content of barley to the maximally allowed, which facilitates the barley production for beer. However, barley monocrops are not suitable for this purpose, showing too high protein content that would complicate the production process.

10. The facilitations generated in the agroforestry system depend on the cultivars of cereals, traditionally selected for light conditions. The cultivars which had a higher production and harvest index under intense shade (50% sunlight) were "Lagalia", "Carolina" and "Meseta" for barley and "Nudel", "Paledor" and "Solehio" for wheat.

11. Our results suggest the need of selection of cereal cultivars adapted to partial shade for implementation of silvoarable systems as strategy of adaptation to climate change. Besides, selection should not only be based on the optimal grain yield but also in functional traits indicative of important ecological procceses such as water use efficiency and pest resistence.

12. In consequence of the competition between trees and crops for water and nutrients, we observed a reduction in the increase of diameter of trees growing in the agroforestry system compared to tree plantation. Tree leaves of intercropped trees showed lower K content and soil moisture was much lower in agroforestry than in forestry plots at the beginning of tree growing season. This should be compensated with adapted fertilization and/or irrigation plans to minimise the loss of tree productivity.

7 Acknowledgements

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