Lessons learnt: Silvopastoral management of Mediterranean timber plantations

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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 agroforestry innovation for high value tree systems. This report contributes to Deliverable 4.11: Lessons learned from innovations in silvoarable agroforestry systems.

2. Background

The initial stakeholder report with innovations proposed for field testing (Moreno 2014), the research and development protocol (Bertomeu García and Moreno 2015; 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) describes the lack of knowledge on the management practices. It highlights that the costs and benefits of agroforestry also prevents wider adoption of agroforestry schemes for timber production under Mediterranean climate, where soil is usually maintained bare (periodical cultivation and/or herbicides) to reduce water competition with grass. To overcome these difficulties eight areas of innovation were identified and prioritized to evaluate agronomic, ecological and economic viability with cooperating farmers and companies. Among these innovations, stakeholders proposed the use of grazing animals for plantation management and the development of dynamic models of grazing throughout the year based on the environmental conditions.

2.1 A participative research program

The research protocol (Bertomeu García and Moreno 2015) reported that foresters wanted experimental confirmation that grazing timber plantations could reduce management costs and does not compete significantly the tree layer, and if there was a decrease in the tree growth would be outweighed by increased incomes from livestock production. In addition, livestock breeders asked for guidance of the best understory management to optimise forage resources availability, and both foresters and breeders asked for tree management practices to match timber and livestock production. Accordingly, four field trials were designed to convert intensive timber plantations, with high chemical and energy inputs to a low-input silvopastoral system grazed by sheep.

The private company Bosques Naturales that owns 1300 hectares in Spain for quality timber production agreed to join a participative research program. This company initiated in the 2000s intensive hardwood plantations across Spain managed intensively with chemical inputs and high levels of energy inputs to reduce the rotation length (details in the system description report;

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 (Babcok et al. 2003; World Bank, 2008). The company and other foresters expected that silvopastoral management could help to reduce the net financial costs of these plantations and improve the delivery of environmental services such as carbon sequestration and control of nutrient leaching (Rigueiro-Rodríguez et al. 2009; López-Díaz et al. 2011).

The field experiments agreed with the private company were:

1. Soil/understory management
    1.1. Control of grass understory to reduce competition with trees for soil resources
    1.2. Sown rich-legume pastures to increase the pastoral value of the system and to reduce cost of mineral fertilization
2. Tree management
    2.1. Tree thinning to reduce tree density in order to reduce tree-to-tree competition and to increase grass productivity
    2.2. Tree pollarding to reduce the risk of cavitation and to provide more light to pasture understory

2.2 Intensive timber plantations

In the last decade, hardwood plantations have substantially increased in southern Europe due to the high demand of this high-quality timber that often exceeds the supply (Hemery et al. 2008). In Spain, up to 90% of new afforestation for valuable timber production have been planted with *Juglans* hybrids (Aletà 2014). Hybrid walnut is an excellent compromise between growth rate, resistance to damaging agents and climatic uncertainties, while easing the management for valuable timber production. It needs a rather humid climate, preferable with a moderate or assent dry period, not too cold, as well as a deep soil, with balanced texture and well drained. (Coelho et al. 2008). In recent years in Spain, wild cherry (*Prunus avium* L.) has been also planted in former agricultural land with the objective of producing high quality timber.

In order to yield high quality timber in short rotations (around 25 years), an intensive management is applied such as control of understorey vegetation and ferti-irrigation until final cutting (Goodman et al. 2013). The main problem is these operations are very expensive. In fact, plantation management costs account for more than 45% of the total investment (Rigueiro-Rodríguez et al. 2009). Moreover, they can produce important environmental impacts similar to intensive agriculture, such as nitrate contamination and impoverishment of soil carbon (Babcock et al. 2003).

In these plantations of high quality timber with intensive management, the control of competing herbaceous vegetation is required for avoiding tree-herbage competition for soil resources and fire risk. The most used method is the application of herbicides in tree lines, in spite of its environmental and economic cost (McAdam and Sibbald 2000). The continued application of herbicides produces mineral soils, with increasing loss of nitrate by leaching (Davis 2014), low organic matter content and high dependence on fertilizers (Stoate et al. 2001). Agroforestry systems, especially silvopastoral systems, could reduce the economic costs due to control of understorey plant competition and optimize the environmental functions of hardwood plantations (López-Díaz et al. 2011; López-Díaz et al. 2017) as well as productivity.

2.3 Silvopastoralism for timber plantations

Agroforestry management, especially silvopastoral management could reduce the economic costs due to control of understorey plant competition and optimize the environmental functions of hardwood plantations, such as the reinforcement of the carbon sequestration and the control of nutrient leaching (López-Díaz et al. 2011; López-Díaz et al. 2017) as well as productivity. Silvopastoral systems are characterised by interactions among three components: trees, pasture and livestock that are changing with time, which poses management difficulties. Competition between trees and pasture for water and nutrients is high mainly in the early stages of the development of silvopastoral systems established through afforestation (Nair and Graetz 2004; Mead et al. 2010). With time, balance subsequently declines in favour of the trees (Jose et al. 2004; Pollock et al. 2009). In the case of mature trees, most studies have only considered tree effects on understorey crops and the question remains on the effect of management on these trees. Dube et al. (2012) noted enhancement in 18-year-old pine growth stablished in silvopastoral systems respect to pure plantations.

Most silvopastoral systems receive extensive management. A question is whether quality timber production, with very high annual production and short rotations, requires intensive management. Perhaps the relationship between the trees and pasture is different. It remains unclear whether different management techniques affect the main resources, such as water and nitrogen, and then tree growth that is the main output of these highly productive systems.

Implementation of forage legumes could be an alternative to mineral fertilisation as legume sowing enhances the N availability in soil (Lin et al. 2011; Dube et al. 2012; O'Dea et al. 2015). In addition, managing grasslands with less mineral N fertilizers can reduce costs of inputs, avoid greenhouse gas emissions caused by the industrial synthesis, avoid the release of mineral N fertilizers to the environment while they improve pasture production and quality (Mccartney and Fraser 2010; Soussana and Lemaire 2014; O'Dea et al. 2015). Nevertheless, a portion of the nitrogen fixed by legumes could be leached and result in water contamination (Masoni et al. 2015).

There is an important relationship between resource availability, such as nutrients and water, and growth patterns of the root system (Gautam et al. 2002; Chen et al. 2016; Weemstra et al. 2016). These findings indicate that knowledge of plant architecture and its relationship with management can help us understand the response of plants to different management regimes (Gautam et al. 2002). Patterns of aboveground biomass distribution in terrestrial ecosystems are reasonably well understood, whereas knowledge of belowground biomass is still limited due to methodological difficulties (Finér et al. 2011; Contador et al. 2015; Xu et al. 2017).

2.4 Managing timber trees in silvopastoral systems

Hybrid walnuts, wild cherries and other timber plantations are usually designed and planted at high tree densities. However, after several years of high diameter and height growth, hybrid walnut trees can show very low growth rates which compromises the future of these plantations. Also wild cherry trees, after several years of high diameter and height growth, show severe symptoms of cavitation and embolism and much slower growth rates.

Cavitation is the formation of vapour bubbles in a flowing liquid in a region where the pressure of the liquid falls below its vapour pressure. In vascular plants, this phenomenon can occur in the xylem when the tension of the sap within a vessel becomes high enough that dissolved air within the sap expands to fill vessels. As a consequence, vapour-filled (embolized) conduits no longer hold sap and xylem hydraulic conductance decreases, leading to stomatal closure, the abscission of leaves, shoot dieback and eventually to plant death (Tyree and Sperry 1989; Vilagrosa et al. 2012). There are several factors affecting xylem cavitation. Frequently cavitation, as well as loss of hydraulic conductivity, occurs when drought leads to water deficit in plant tissues. Drought related cavitation is commonly observed on trees from water-limited environments such as the Mediterranean region, even if they have developed mechanisms to tolerate stress.

Species differ considerably in their vulnerability to cavitation. The less vulnerable species are usually the more desiccation-tolerant (Lambers et al. 2008). A recent study has showed that *Prunus avium* was, among 10 *Prunus* species, the third more vulnerable to cavitation (Cochard et al. 2008). Therefore serious doubts have now been raised about the appropriateness and feasibility of producing high quality timber by growing wild cherry trees in intensively-managed plantations in harsh Mediterranean climatic conditions, even if water and fertilization is abundantly supplied.

Field observations of frequently pollarded trees have led us to think of pollarding as a management practice to enhance tree diameter growth. Pollarding has been practised by cherry fruit tree growers for many years to control the height of their trees and thus facilitate fruit harvest. It has also been a common practice on fodder trees, such as *Fraxinus angustifolia,* to provide livestock with fodder in times of scarcity. In both cases pollarded trees have continued to grow in diameter, with the oldest trees reaching up to almost 1 m in diameter despite having been pollarded many times during their lifetime. Therefore if pollarded, wild cherry timber trees may also continue to grow and produce a lower portion of the stem with the minimum length (about 3 m) and diameter required for sawn timber.

Thinning is also a management practice commonly used in timber plantation to reduce stand density, reducing thus the tree-to-tree competition and enhancing tree diameter growth (e.g. Gauthier and Jacobs 2009). In agroforestry plantations, thinning would also reduce tree competition with understorey crops and would result in higher tree and crop/pasture yields.

3. Objective, innovation and description

The aim of the present study was to assess the effect of alternative techniques to control competing vegetation and fertilise intensive quality timber plantations and the effect of these techniques on the nutrient and water cycle, the productivity of the system, root architecture and soil organic content (SOC). Specifically, we raise the following research questions:

1. What is the influence of the different treatments on nutrient availability? Implementation of forage legumes could be an alternative to mineral fertilisation as legume sowing enhances the N availability in soil.
2. Which treatments improve the water regime? Herbaceous vegetation reduces the water available for trees, mainly in shallow strata. Therefore perhaps treatments that remove herbaceous strata would increase the water availability to trees.
3. How does the type of management (traditional or alternative) modify the productivity of the system (quality timber production and pasture production) in the short and long term? The productivity of alternative techniques would be similar to or better than traditional (and more intensive) practices in the medium and long term.
4. Which is the influence of the different treatments on tree and pasture root architecture? Root development, and nutrient and water access are strongly related.
5. How does the type of technique (traditional or alternative) affect SOC? The management system with least disturbance was expected to maintain highest soil C storage.
6. How does management affect the nitrate leaching? The increment of nitrate leaching supposes a loss of N to depth strata, where plants are unable to use it and it poses an environmental risk.
7. How tree thinning and pollarding could help to increase tree growth at the time increase light available for pasture understory.

This study can contribute to the optimization of the positive relationships between both strata (trees and pasture) of silvopastoral systems with intensive management from the point of view of the productivity and the environment.

4. System and experiment description

4.1 System and site

The experiment was conducted from 2011-2017 in northern Extremadura, mid-west Spain (Madrigal de la Vera station, 40°9´14´´ N, 5° 22´ 24´´W), in a timber plantation with hybrid walnuts (*Juglans major* x *regia* mj 209xra) and clonal wild cherries (*Prunus avium* L., clone Eurocherry C-9).

Walnuts were planted at a 6 m x 5 m spacing from 1998 to 2000, and wild cherries in a 5 m x 5 m spacing in 2004. In both cases, during the first three years trees were pruned in winter. Afterwards branch pruning was conducted each spring until the year 2011. Before planting, the land use was agricultural (maize). Previously to the start of the treatments (2011), the vegetation understory was controlled by herbicides; afterwards they were managed by grazing. In summer, trees were irrigated by a drip irrigation system.

The area is in the Mediterranean biogeographic region, with dry and hot summers, and cool and rainy winters. The site is characterised by an annual precipitation of 952 mm and annual average temperature of 15.6°C. Drought usually occurs from June to September. The experiment was performed in a sandy loam soil more than 140 cm in depth with less than 5% slope. Initial soil analyses revealed an acidic pH (pH 5 in water) and medium SOC levels (2.6%). Soil characteristics and history are similar. More details are given in Table 1.

Table 1. Description of the site, with soil, tree, understorey, livestock, and climate characteristics

Site characteristics	
Area:	9.72 ha
Co-ordinates UTM:	ETRS89 huse 20: X:298.303 Y:4.442326
Altitude	309 m.a.s.l
Slope	<5 %
Site contact:	Gerardo Moreno
Site contact email address	gmoreno@unex.es

Soil characteristics	
Soil type (WRB classification)	Fluvisols
Soil depth	>140 cm
pH	5-6
Soil texture	Sandy loam

Tree characteristics			
Experiment	Fertilized walnut	Grazed walnut	Wild cherry
Tree species	*Juglans major* x *nigra*	*Juglans major* x *nigra*	*Prunus avium* L
Variety/rootstock	mj 209xra	mj 209xra	clone Eurocherry C-9
Tree density (spacing)	5 x 6 m	5 x 6 m	5 x 5 m
Mean height	8.33	8.33	7.4
Mean breast diameter	19,4	16,1	18.3
Tree protection	None	None	

Understorey characteristics		
Experiment	Fertilized walnut	Grazed walnut and wild cherry
Species	Grass except sown plots	Grass except cultivated plots
Coverage	Complete	Complete
Additional details	Grass managed by grazing in late Spring	Grass managed by mowing, clearing and grazing depending on treatments

Livestock characteristics		
Experiment	Fertilized walnut	Grazed walnut
Species	Sheep	Sheep
Stocking density	1 sheep ha^{-1}	

Climate data	
Mean monthly Temp	14.1°C
Mean annual rainfall	844 mm

4.2 Experiment 1: understory management

Two experiments were established: one experiment with three techniques to control competition from herbaceous strata beneath trees ("Grazed Walnut"), and the other to test alternatives to traditional inorganic fertilisation ("Fertilised Walnut").

Table 2. Description of the essays and treatments

Experiment	Treatments	Description
Experiment 2.1 Control of grass biomass (Grazed walnut)	Mowing	In early spring
	Cultivated (initially given the symbol P for ploughing)	Cultivation with a harrow in spring
	Grazing	Introducing a stock of 1 sheep ha^{-1}
Experiment 2.2 Sown of legume-rich pasture (Fertilized walnut)	Mineral fertilisation	Application of 40 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} in March 2012 and 2013
	Legume sowing	- Cultivation - Application of the same quantities of PK in March 2012 and 2013 - Sowing of 25 kg ha^{-1} *Trifolium michelanium* and 10 kg ha^{-1} *Ornithopus compressus* in November 2012
	Control	No fertilisation or sowing

Figure 1. Image of experiments 2.1 (left) with control of grass understory by grazing and 2.2 (right) with sown of legume-rich forage

Fertilization application rates were based on tree requirements. Plots that were mowed and cultivated were fenced to prevent grazing. In the Fertilised Walnut experiment, the whole area was fenced to prevent grazing until in late spring after the grass had dried.

Nine replicate blocks were used for each treatment in the experiment 1.1 and six replicated blocks in the experiment 1.2 in a completely randomised design. Each plot had three alleys and two rows of 20 and 30 trees, respectively (Figures 2 and 3).

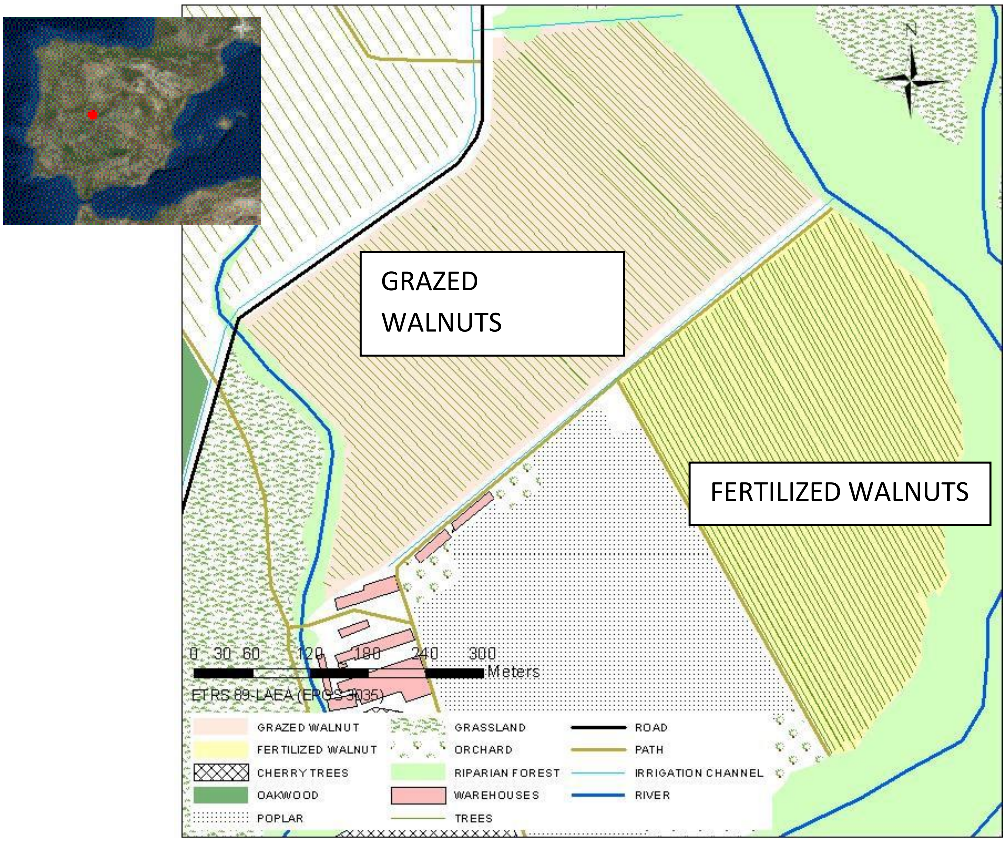

Figure 2. Map of location of the two field experiments for silvopastoral management of walnut plantations: sown legumes as alternative to mineral fertilization, and grazing to control of herbaceous vegetation

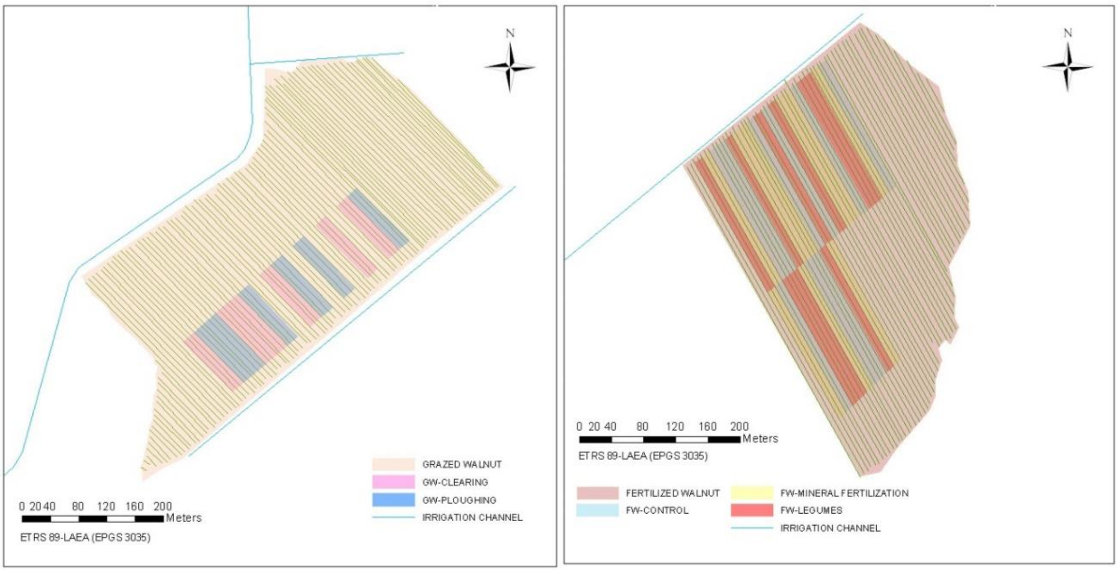

Figure 3. Map of location and distribution of plots in the grazed walnut experiment (with different treatments to control herbaceous vegetation; left) and fertilized walnut experiment (with different treatments of fertilization; right). Note: each plot is formed by 3 alleys and 2 tree rows of 20 and 30 trees each, respectively.

4.3 Experiment 2: Tree management

4.3.1 *Tree thinning*

In January 2014, we established an experiment at the hybrid walnut tree plantation to determine the effect of thinning on stem diameter increment. Removed trees were randomly selected, without any predefined scheme (e.g. those with a more defective trunk), producing a scattered gradient of thinning intensity. We defined the intensity of thinning that affected every remaining tree as the sum of the trees eliminated around the remaining tree, taking into account the stem diameter of the removed trees and their distance to the remaining tree.

$$\text{Thinning intensity} = \Sigma\ \text{DBH/distance};$$

(including at maximum the 8 trees at the perimeter of the remnant tree)

4.3.2 *Tree pollarding*

In January 2015, we established an experiment at the wild cherry plantations to determine whether pollarded cavitated wild cherry timber trees would exhibit the same or even higher diameter growth rate than unpollarded cavitated trees.

The experiment consists of five pairs of plots (total of 10 plots) randomly selected in the plantation. Each plot contains 3 rows of trees with 6 trees per row (i.e. 18 trees). The following treatments were randomly assigned to the plots: pollarding vs unpollarded trees (control).

In autumn 2014, before the trees shed their leaves a photograph was taken of each tree in order to be able to identify later on in winter, during the pollarding operation, the portion of the stem with live/death branches. Then in early February 2015, trees were pollarded using the photograph as a guide indicating the height at which the trees should be cut (Figure 3).

Tree height and dbh were measured the same day trees were pollarded. The length and the diameter at the base of the pollarded section of the tree were also measured (Table 4)

Table 4. Mean diameter at breast height (dbh) and height (H) of control and pollarded trees. The length and diameter at the base of pollarded section are also given.

Control plots			Pollarded trees				
						Pollarded stem	
Plot	Dbh (cm)	Height (m)	Plot	dbh (cm)	H (m)	Dbase (cm)	Length (m)
P1	17.5	6.2	P2	18.6	8.1	9.1	4.7
P4	18.7	7.6	P3	18.8	8.1	8.3	4.3
P5	19.7	8.0	P6	19.4	8.0	8.5	4.3
P7	17.0	6.9	P8	15.7	7.2	8.3	4.5
P9	19.6	6.1	P10	18.2	7.3	8.5	3.8

Figure 3. Pollarding of wild cherry timber trees, below the height of severe damage by cavitation (previously recorded autumn).

4.4 Sampling and measurements

In 2014, 54 soil cylinders (six per treatment; 6 cm diameter) were extracted every 10 cm to 1 m depth to assess root surface. Roots were separated into tree and pasture, and scanned (Epson Expression 10000XL). Images were analysed with WinRhizo TM software.

To determine SOC, soil samples were taken every 10 cm depth from the same cylinders used to measure roots. Soil samples were air dried and sifted through a 2 mm sieve. Carbon concentration was measured by the Walkley-Black method.

For determining nutrient (N, P, K and Ca) availability in soil, in May 2013, 12 ion exchange resins were installed at 15 cm depth in each plot (six for cations and six for anions). In June 2013 (one month later), they were taken out and analysed in laboratory. In July of three consecutive years, leaves were samples for further lab analysis of N, P, K and Ca.

Soil water content (SWC) was measured by means of Diviner 2000 (DV) (Sentek Pty Ltd) in permanent access tubes that were installed in March 2012 (one in each plot). This technique determines volumetric soil water content based on the measurement of changes in the dielectric constant of the soil. Measurements were usually taken each month since August 2012 to January 2014, at intervals of 10 cm depth until 1 m depth.

Nitrate leaching sampling was realized by ceramic cup samplers, those were installed in May 2012, at 30, 60 and 90 cm of depth. The sampling frequency depended on the precipitation. Finally, 12 samplings were realized since November 2012 until April 2014. Samples were stored at 6°C and were analysed in the next 24 h to avoid chemical transformations by direct reading with UV-VIS spectrophotometry at 220 nm.

Three herbage samples (50 cm x 50 cm) were taken from each plot using hand clippers at a height of 2.5 cm in June. Pasture biomass production was estimated after oven drying at 60°C (48 hours). Tree diameter at breast height was measured from 2011 to 2017 every January.

Table 5. List of measurements to be taken in the two treatments

Element	Parameter	Method
Tree growth	Diameter at breast height	One measurement per year. In 120 trees, dendrometers are installed
Pasture	Pasture production	Three herbage samples (50 cm x 50 cm) were taken from each plot using hand clippers at a height of 2.5 cm in June
Soil	Organic matter content	Soil samples are taken each 10 cm until 1 m depth and OM is analysed
Pasture and tree roots	Biomass, length and surface	Soil samples are taken each 10 cm until 1 m depth and roots are separated in tree and pasture. Samples are weighted and analysed with Winrrhizo program for determining length and surface
Tree leaf nutrients	N, P, K, Ca	Standard lab methods
Nutrient availability in soil	N, P, K and Ca	Ion exchange resins (50 cm^2) installed at 15-20 cm depth for one month in Spring
Nitrate leaching	$N\text{-}NO_3^-$	Two ceramic cup samplers were installed in each plot at 30, 60 and 90 cm Measurements depends on rain frequency
Soil moisture	%	72 Diviners are located in plots (Figure 10). Measurements are taken each 10 cm until 1 m each month
Carbon sequestration	% and Mg/ha	Variations in carbon sequestration are calculated based in OM in soil and biomass in tree trunk and herbaceous and tree roots

Figure 4. Image of walnut plantation in winter when tree height (left) and stem diameter (right) were measured

5. Results from four experiments

5.1 Experiments 1.1: Grazing to control grass understory

5.1.1 *Soil water content*

Treatments modified the mean soil moisture, though the response varied with the period of year. Regarding to the treatments of control of understorey, when the availability of water was high, i.e. in spring, the highest values of SWC were registered after cultivation, which supposed an increment of 7-11% respect to the other treatments (Figure 5). Summer is a key period for the system productivity, since there are usually three months of drought, the competition of both strata of vegetation by water is high, and trees need irrigation. In this period, cultivation reduced the SWC about 18-33% respect to the other treatments, which can affect tree growth. The maximum value of SWC in summer was observed under grazing.

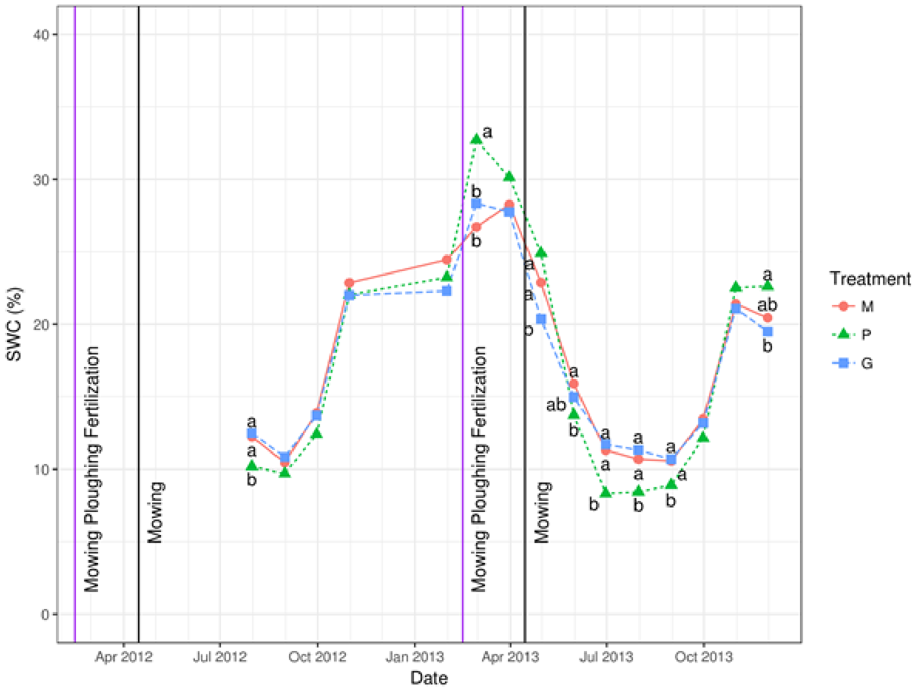

Figure 5. Evolution of soil water content (SWC, %) under different treatments of control of vegetation competence (Grazed Walnut). Vertical lines indicate treatment dates. Letters indicate significant differences between treatments in each sampling date. M: mowing; P: cultivation; G: grazing

The increment of SWC under cultivation was detected in the whole 1 m depth (Figure 6).

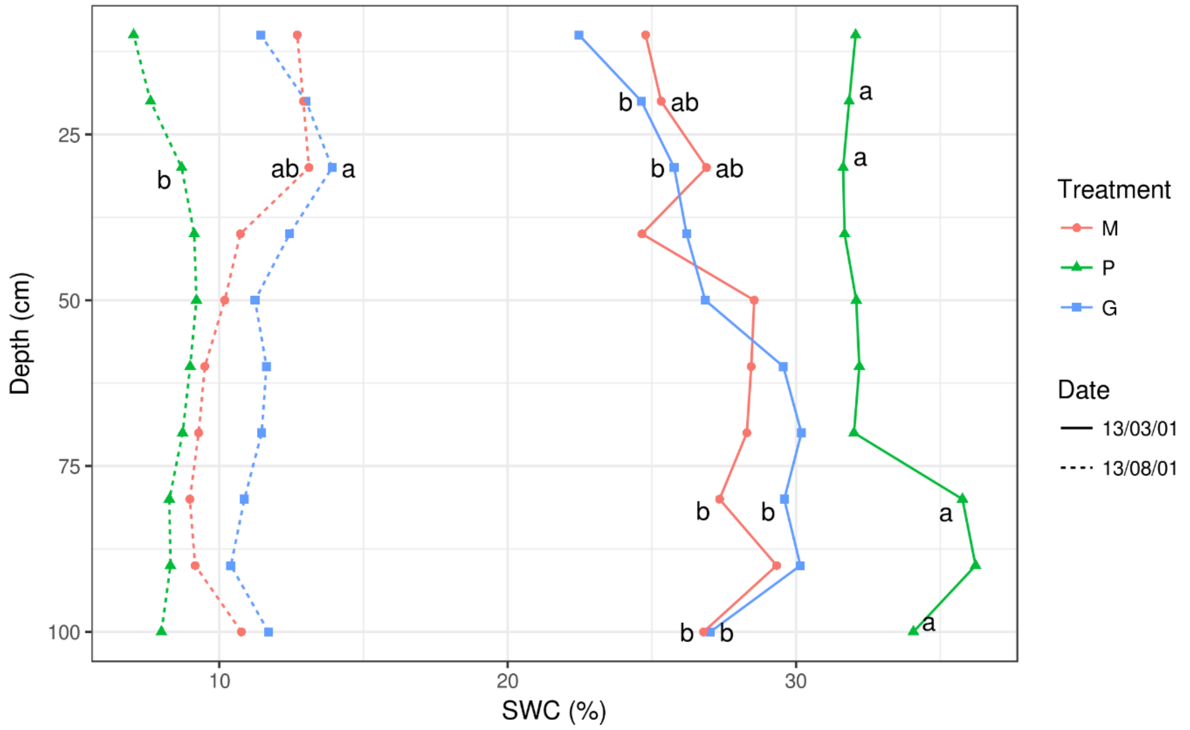

Figure 6. Soil water content (SWC, %) in spring (March 2013) and summer (August 2013) in the soil profile (0-100 cm depth) under different treatments of control of vegetation competence (Grazed Walnut). Letters indicate significant differences between treatments in each depth. M: mowing; P: cultivation; G: grazing

Finally, the question is, do understorey compete with trees by water? In our case, the response is not because no change in tree leaf water potential was noted with the different treatments (Ψpd > -0.5 MPa and Ψmd > -2 MPa). One possible reason for this absence of response is that trees can exploit deep water resources (Gyenge et al. 2002). Besides, the trees were irrigated in summer with drip irrigation system. However, in sites with reducing water availability, i.e. without irrigation or with less precipitation, as well as an actual change is the climate in which drought is more frequent, it could be an important handicap in these intensive systems. In any case, the silvopastoral management does not seem to compromise the water status of the trees in summer.

5.1.2 *Nutrient availability*

The analysis of the ion exchange resins indicate that the availability of N and Ca was improved by cultivation with respect to mowing, owing to the mineralization of soil organic matter. However, this treatment produced the lowest levels of available P. The best values for N and P were obtained with grazing. No differences among treatments were detected in K availability (Table 6). In addition, no differences for N, P and Ca content were found in the leaves of the trees managed with the three different treatments (Table 7).

Table 6. Soil nutrient (mineral N (N-nitrate + N-ammonium), available phosphate, K^+, Ca^{2+}; µg / 50 cm^2 of ion resin membrane/ month) availability and organic matter (OM, mg kg^{-1}). Standard errors are also given.

Nutrient	Mowing	Cultivation	Grazing	Significance
N	11.3 ± 1.7 b	19.3 ± 4.1 a	25.3 ± 16.1 a	**
P	3.6 ± 0.5 ab	1.7 ± 0.5 b	4.8 ± 0.9 a	***
K	39.8 ± 3.8	43.3 ± 3.1	39.7 ± 1.8	n.s.
Ca	46.7 ± 1.9 b	64.4 ± 3.7 a	52.7 ± 2.4 b	***
OM	42.4 ± 2.4 a	32.0 ± 1.8 b	35.6 ± 1.4 b	**

Table 7. Nutrient content in tree leaves (N, P, Ca; mg g^{-1}). Standard errors are also given.

Nutrient	Mowing	Cultivation	Grazing	Significance
N	20.0 ± 0.8	21.9 ± 0.7	22.1 ± 1.1	n.s.
P	2.65 ± 0.15	2.33 ± 0.18	2.20 ± 0.16	n.s
Ca	10.6 ± 0.5	10.0 ± 0.3	10.7 ± 0.4	n.s

5.1.3 *Soil carbon content*

Soil organic carbon was concentrated at the surface, with 43% to 51% of total SOC located at 0-25 cm soil depth (Figure 7). Mowing recorded the highest SOC values due to incorporation of debris, with slightly higher values in grazing compared to cultivation. The difference among treatments was maintained until 40-50 cm depth, even though the depth of cultivation was about 25 cm. It is important to highlight that soil C storage is important not only because of its role in the global C cycle, but also be because it affects forest productivity, as soil C is a principal source of energy for nutrient recycling (Nave et al. 2010).

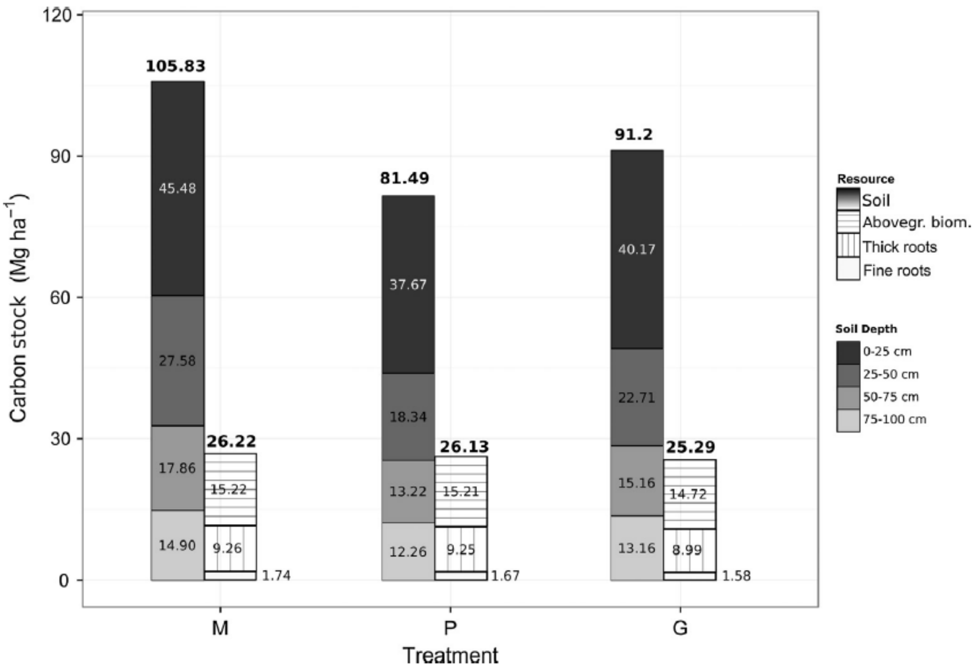

Figure 7. Carbon stock (Mg C ha^{-1}) in soil, aboveground (Tree trunk and branches), and belowground biomass (Fine roots of herbaceous and trees; and thick roots of trees) under treatments of control of herbaceous vegetation (Grazed Walnut). M: mowing; P: cultivation; G: grazing. Values above columns indicate total carbon stock of soil (0– 100 cm depth) (left) and vegetation (right). Adapted from López-Díaz et al (2017).

5.1.4 *Rooting profile*

The response of root surface density was different depending on the kind of plants (tree vs. pasture). The different treatments of control of understorey vegetation produced a sharp change in the pasture root architecture. Regarding to herbage roots, can be ranked as follows: grazing, mowing and cultivation. Differences between treatments were observed in the upper 70 cm of the soil. In contrast, the response of tree roots to the treatments were scarce though a positive response to graze was observed at 40-60 cm depth.

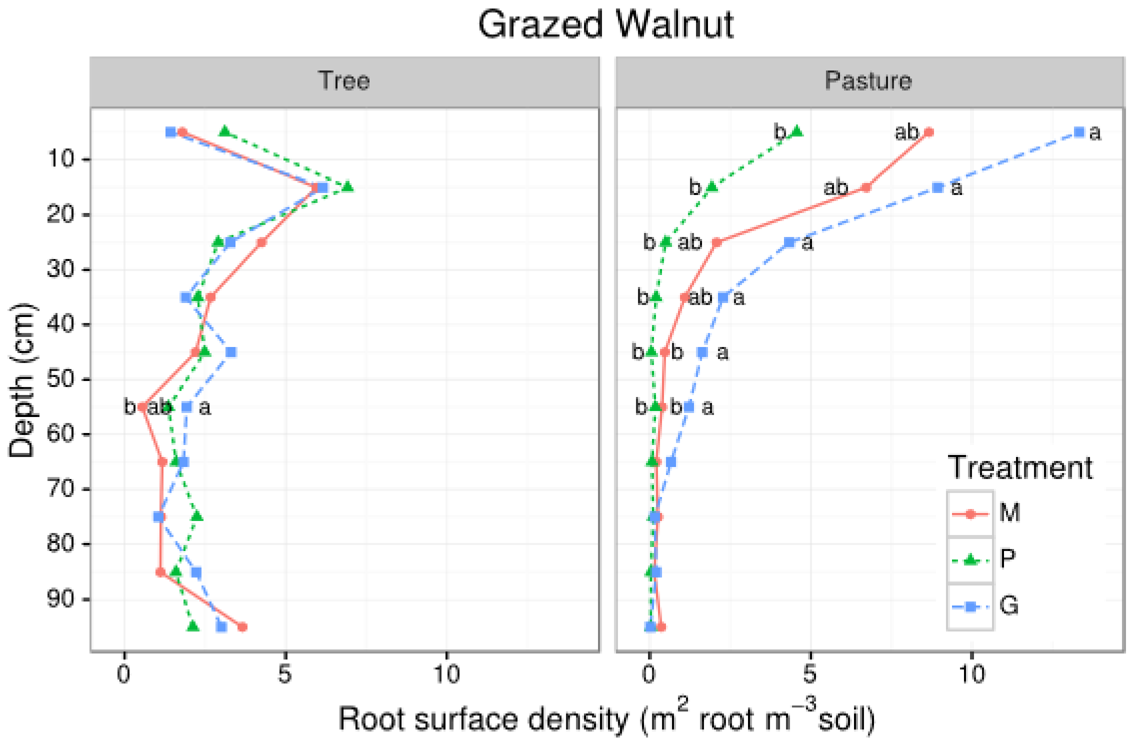

Figure 8. Root surface density (m^2 root m^{-3} soil) of pasture and tree under different treatments of control of vegetation competence (Grazed Walnut) and fertilization (Fertilized Walnut) in soil profile. M: mowing; P: cultivation; G: grazing; NF: no fertilization; F: inorganic fertilization; S: legume sowing

5.1.5 *Nitrate leaching*

Soil nitrate concentration in the uppermost soil layer is the result of the N mineralization and fertilization, of the N plant uptake, of ammonium oxidization and finally of nitrate leaching. The accumulation in deeper layers is normally consequence of nitrate leaching. The highest values were obtained with cultivation, mainly in autumn, when precipitation was high. However, the high concentrations observed with cultivation are only at shallow depths (0-30 cm) and not in deeper horizons, maybe because the tree roots that can use this nutrient. The results obtained with grazing and mowing are similar and lower than those with cultivation. In any case, overall we did not observed nitrate accumulation in deeper layers except once for the cultivation treatment (November 2012) and once for mowing (April 2014). This is one of the benefits of the presence of the trees in all of the systems, because they have a deep root system relative to the pasture, and they can efficiently use the nitrate before it leaches out of the soil.

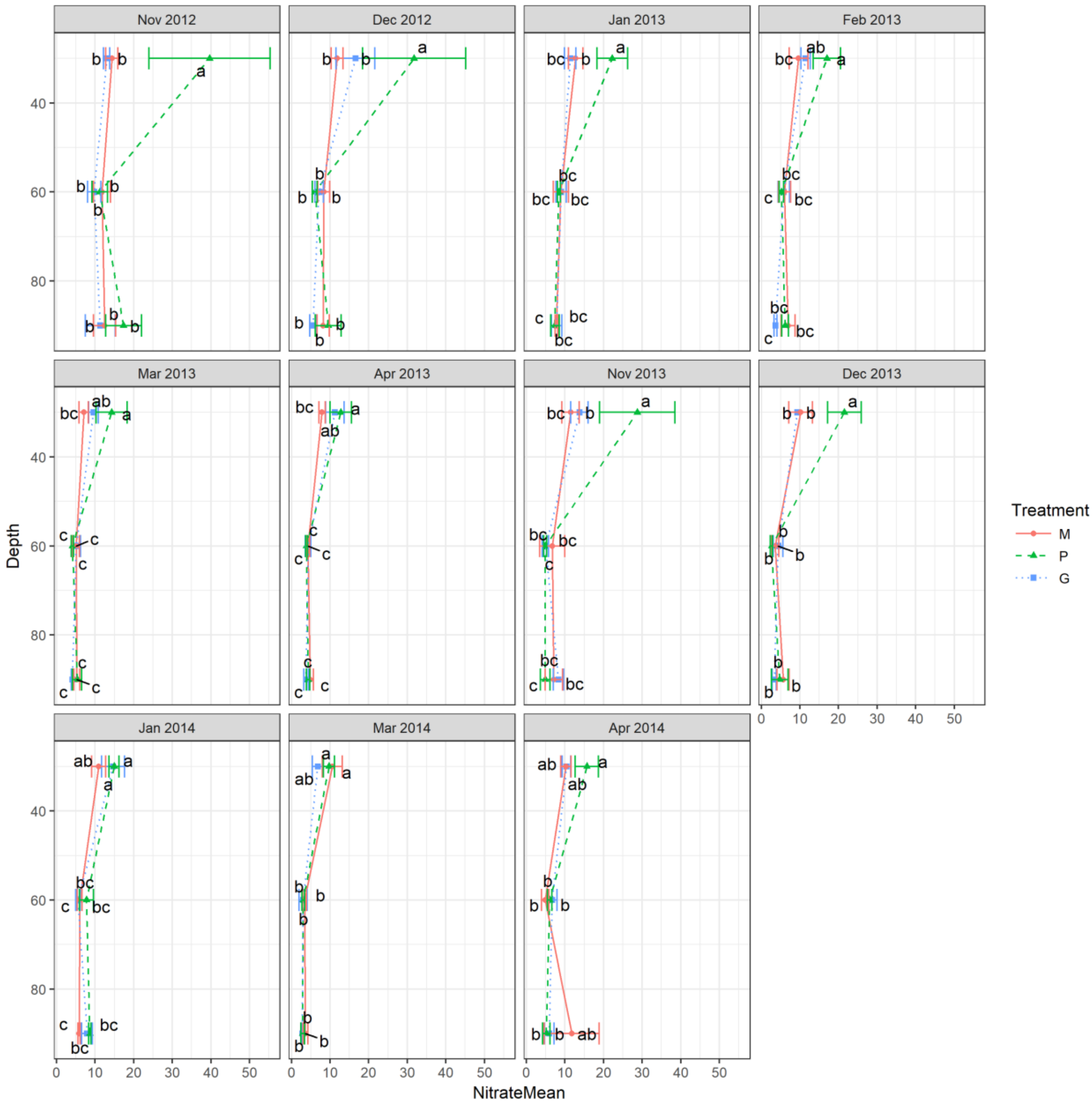

Figure 8. Nitrate concentration (mg NO_3^- l^{-1}) in lixiviated water in different dates in different treatments of control of vegetation competence (Grazed Walnut). M: mowing; P: cultivation; G: grazing

5.1.6 *Tree growth and pasture productivity.*

Maximum tree growth was observed in the cultivation treatment (7 ± 0.3 cm) with intermediate values for grazing treatment (6.6 ± 0.3 cm) treatments (Figure 9). Therefore, silvopastoral systems with high stocking rates are compatible with hardwood production. On average, in the grazing plots, where pasture was grazed by sheep, the forage production was of 3500 kg/ha/y.

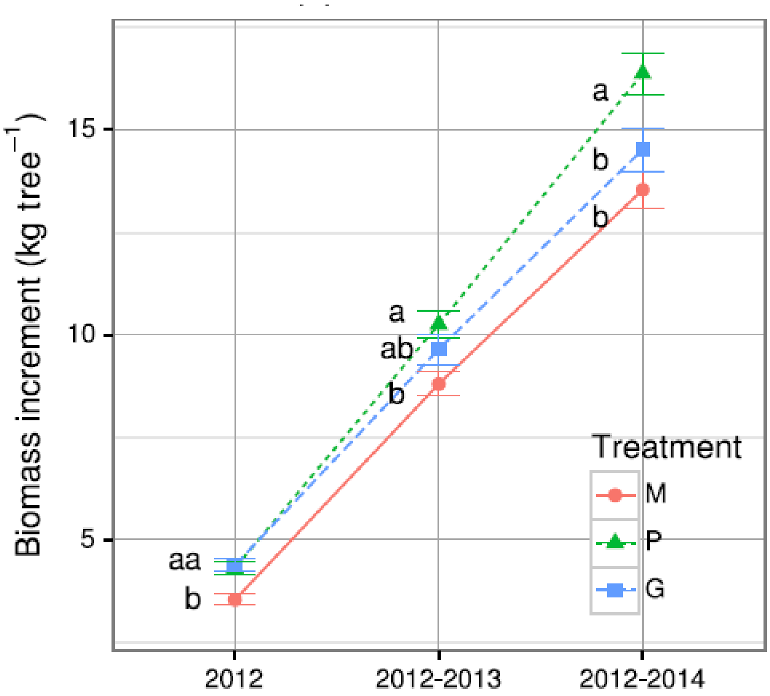

Figure 9. Mean values ± standard error of aboveground biomass increment (kg tree^{-1}) (a) under treatments of control of herbaceous vegetation M: mowing; P: cultivation; G: grazing. Different letters indicate significant differences ($p < 0.05$) between treatments in each period.

5.2 Experiments 1.2: Sown rich-legume pastures

5.2.1 *Soil water content*

In sowed plots water availability increases in spring (3-7% higher respect to the other two treatments). The increment of SWC in spring was detected in 40-80 cm layer (Figures 10 and 11). It is important to take into account that this treatment was cultivated before sowing and, then, the response is partially attributable to the working of the soil. By contrast, in spring in the upper soil layer (0-30 cm depth), where pasture roots are mainly developed, water availability with legumes was similar to that obtained with the other treatments. However, legume sowing reduced SWC in summer (8-15% respect to the no-fertilization), although in this period the results were similar to those obtained with mineral fertilization. These findings indicate that legumes (*Trifolium michelanium* and *Ornithopus compressus* mixture) and grass with inorganic fertilization, similarly competed with trees for water and this was related to their similar pasture production. Previous studies found that the productivity of the understorey varied depending on the legume-grass mixture supported, depending on root depth and production. Thereafter, it is important to select appropriate understorey species, especially when trees are young.

Anyway, the question is, do understorey compete with trees by water? Again, the response is not, because no change in tree leaf water potential was noted with the different treatments ($\Psi pd > -0.5$ MPa and $\Psi md > -2$ MPa). As commented before, one possible reason for this absence of response is that trees can exploit deep water resources (Gyenge et al. 2002). In any case, the improvement of pasture productivity, either with mineral fertilization or with sown of legume-rich forage, could introduce additional water stress to trees, and reduce their growth.

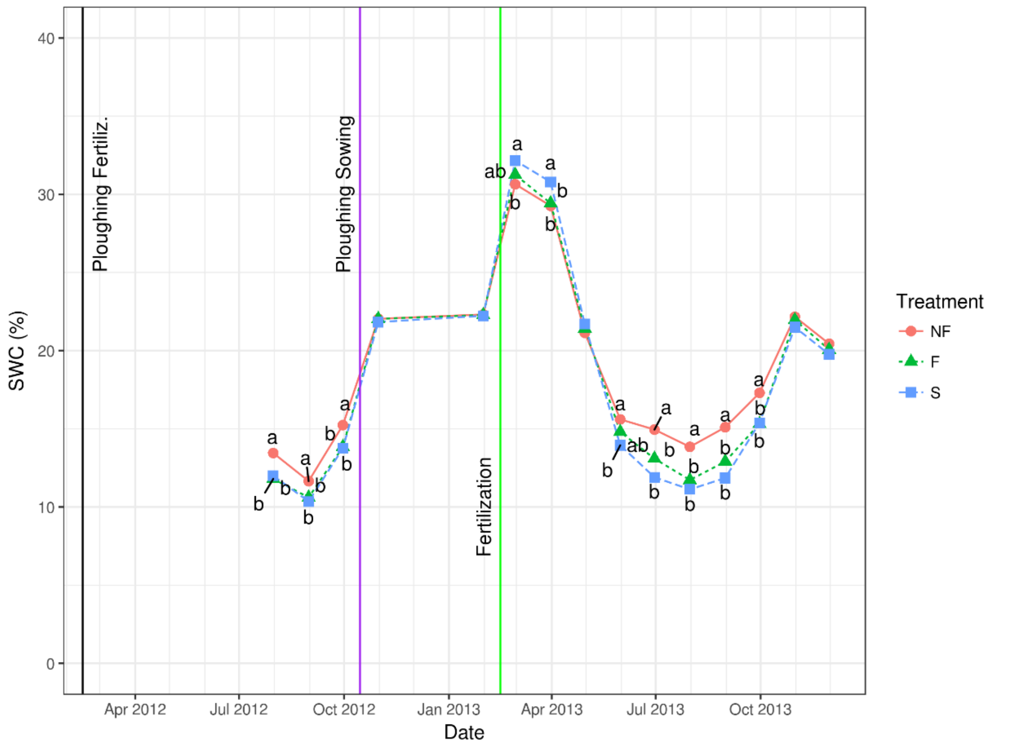

Figure 10. Evolution of soil water content (SWC, %) under different treatments of fertilization (Fertilized Walnut). Vertical lines indicate treatment dates. Letters indicate significant differences between treatments in each sampling date. NF: no fertilization; F: fertilization; S: legume sowing.

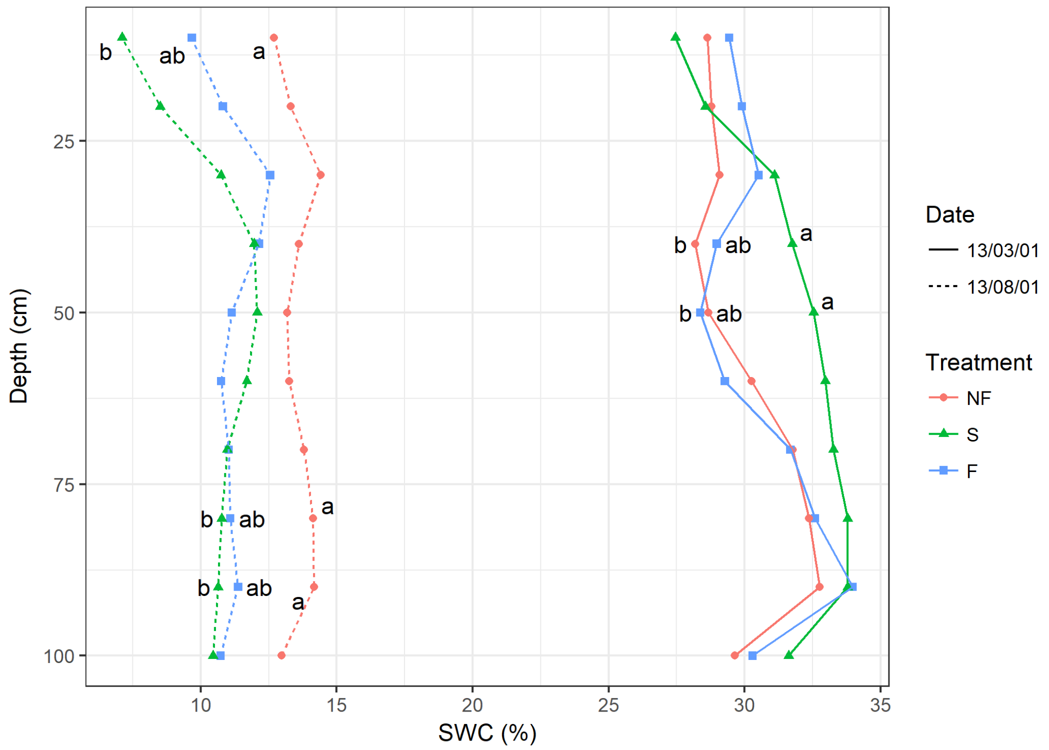

Figure 11. Soil water content (SWC, %) in spring (March 2013) and summer (August 2013) in the soil profile (0-100 cm depth) under different treatments of fertilization (Fertilized Walnut). Letters indicate significant differences between treatments in each depth. NF: no fertilization; F: fertilization; S: legume sowing

5.2.2 *Nutrient availability*

The analyses of the ion exchange resins indicate that the planting of legumes increased the available nutrients in soil, especially nitrogen, whose value increased by almost 200% compared to no-fertilization treatment (Table 8). This could be explained because of the contribution of N fixed by legumes. For P, the control plot showed the lowest values and the mineral fertilized treatment showed the highest, with intermediate values for the sown plot. For K, the sown plot reached similar values as the fertilized one, both with roughly double that of the control-unfertilized plot. However, these differences are not reflected in the tree nutrition, and trees growing in the legume-sown plots showed significantly lower leaf contents of P and Ca (Table 9).

Table 8. Soil nutrient (mineral N (N-nitrate + N-ammonium), available Phosphate, K^+, Ca^{2+}; µg / 50 cm^2 of ion resin membrane/ month) availability and organic matter content (OM, mg kg^{-1}). Standard errors are also given.

Nutrient	Control	Mineral fertilizer	Legumes	Significance
N	7.4 ± 0.8 b	9.6 ± 2.2 b	21.6 ± 3.1 a	***
P	1.7 ± 0.3 b	3.6 ± 0.8 a	2.3 ± 0.5 ab	*
K	29.5 ± 2.1 b	62.1 ± 8.1 a	65.3 ± 7.7 a	***.
Ca	37.0 ± 0.8	38.1 ± 0.9	39.1 ± 1.1	n.s.

Table 9. Nutrient content in tree leaves (N, P, Ca; mg g^{-1}). Standard errors are also given.

Nutrient	Control	Mineral fertilizer	Legumes	Significance
N	21.9 ± 0.6	22.7 ± 0.6	23.1 ± 0.7	n.s.
P	3.18 ± 0.21 a	3.44 ± 0.20 a	2.72 ± 0.13 b	*
Ca	9.0 ± 0.2 a	9.3 ± 0.2 a	8.6 ± 0.2 b	*

5.2.3 *Soil carbon content*

Soil organic carbon was concentrated at the surface, with around 50% of total SOC located at 0-25 cm soil depth. SOC increase with both mineral fertilization and legume sown (similar among them) respect to the control-unfertilized plots.

5.2.4 *Root architecture*

The response of root surface density was different depending on the kind of plants (tree vs. pasture). The different treatments of control of understorey vegetation produced a sharp change in the pasture root architecture. It seems that in the shallower layer (0-10 cm depth), the surface density of pasture roots was increased under sowing and no fertilisation but it was only a tendency. However, inorganic fertilization increased the deep where roots were developed. In fact, in this treatment, pasture root presence was detected until 70 cm while in the other treatments there were not roots under 40 cm depth. Legumes were recently sowing but, with time, it is expected that the root development subsequently would be similar or deeper than grass roots.

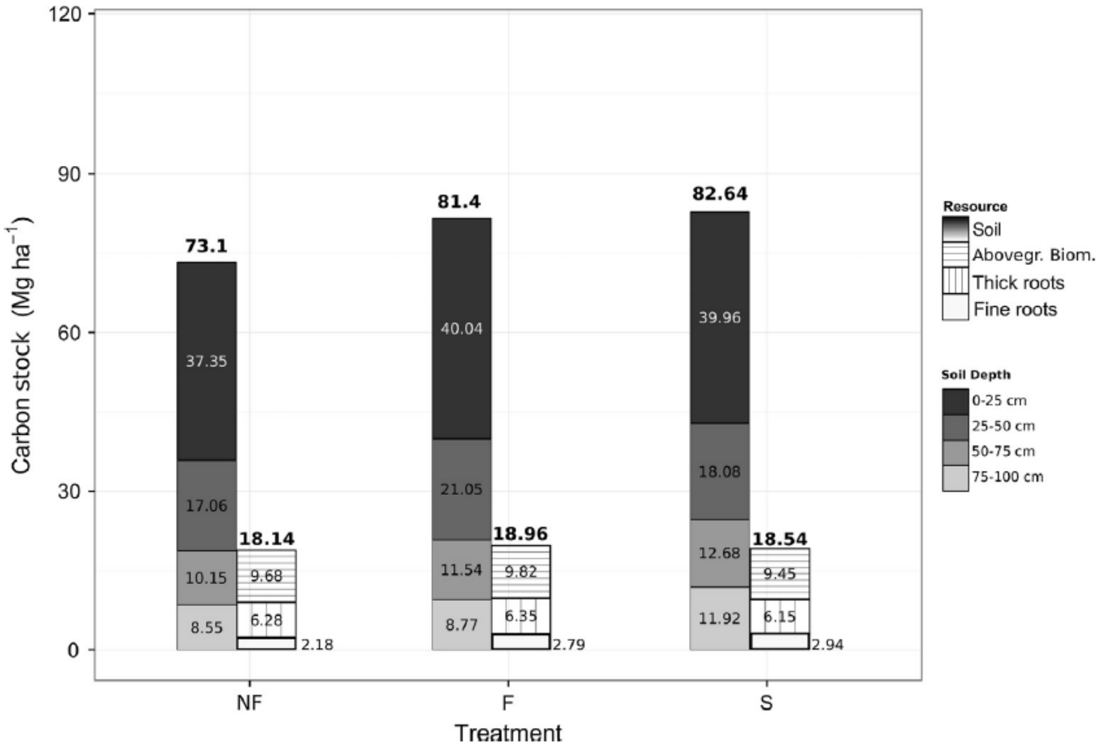

Figure 12. Carbon stock (Mg C ha^{-1}) in soil, aboveground (Tree trunk and branches), and belowground biomass (Fine roots of herbaceous and trees; and Thick roots of trees) under fertilisation treatments. NF: no fertilisation; F: inorganic fertilisation; S: legume sowing. Values above columns indicate total carbon stock of soil (0–100 cm depth) (left) and vegetation (right).

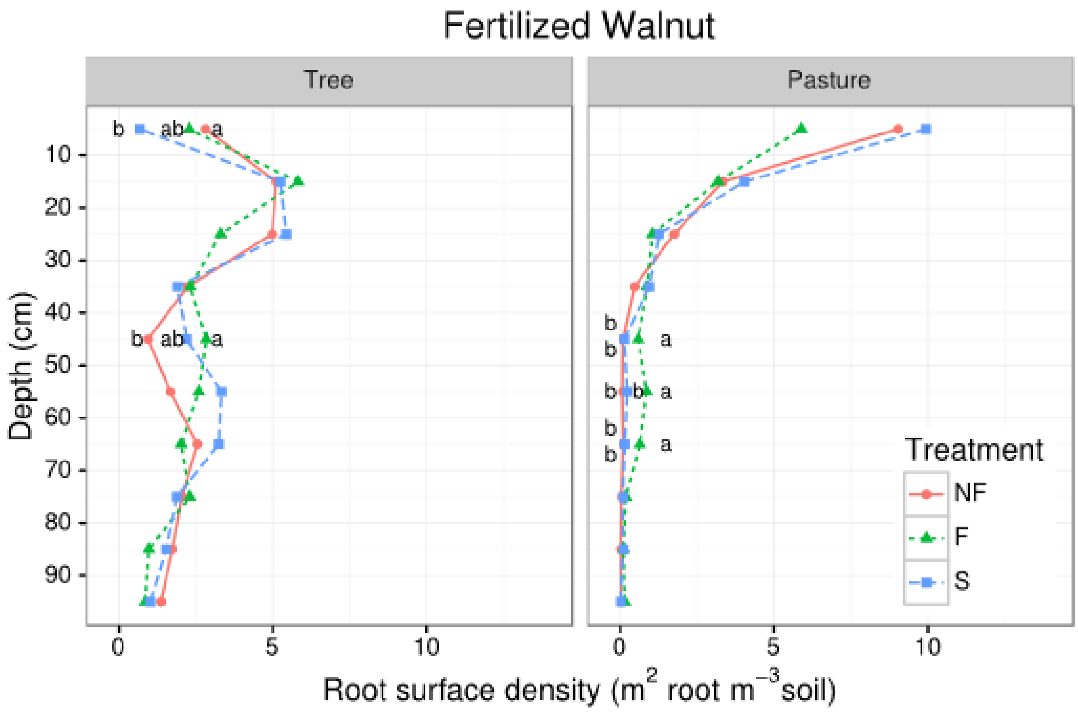

Figure 13. Root surface density (m^2 root m^{-3} soil) of pasture and tree under different treatments of control of vegetation competence (Grazed Walnut) and fertilization (Fertilized Walnut) in soil profile. M: mowing; P: cultivation; G: grazing; NF: no fertilization; F: inorganic fertilization; S: legume sowing.

5.2.5 *Nitrate leaching*

In a same way as the previous study, soil nitrate concentration in the uppermost soil layer is the result of the N mineralization and fertilization, of the N plant uptake, of ammonium oxidization and finally of nitrate leaching. The accumulation in deeper layers is normally consequence of nitrate leaching. The highest nitrate accumulations at the bottom soil layer deepest were found in the legume-sown plots, but only in November 2012, few months after sowing. Afterward, nitrate did not seem to be leached (Figure 14). Thus, it is important to highlight that these high values, caused by cultivation and sowing, were not maintained in time, after plant development. By contrast, in the following sampling dates, the control-unfertilized treatment, with the lowest pasture production, produced the highest nitrate concentration in soil deep layer (December 2012 and January 2014).

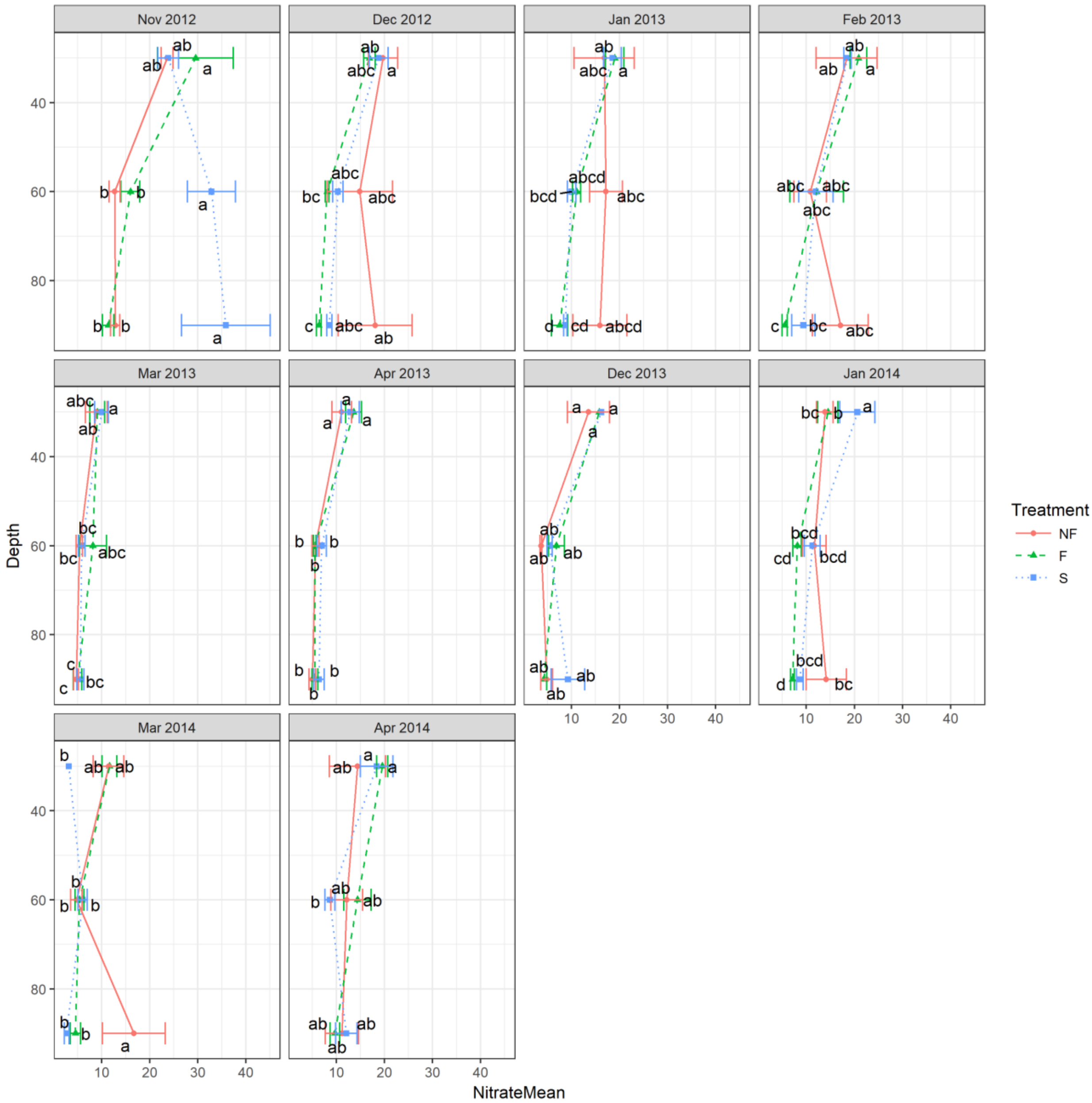

Figure 14. Nitrate concentration (mg NO_3^- l^{-1}) in lixiviated water in selected dates in different treatments of fertilization (Fertilized Walnut essay). NF: no fertilization; F: mineral fertilization; S: legume sowing.

5.2.6 *Tree and pasture productivity*

The application of mineral fertilizer produced the highest increment of tree diameter in 3 years (4.2 ± 0.1 cm) followed by legume sowing (3.7 ± 0.1) and control (3.3 ± 0.1 cm). In the case of pasture production, the yields of the legumes (6.4 ± 0.3 t $ha^{-1} y^{-1}$) and mineral fertilization treatments (5.9 ±0.3 t $ha^{-1} y^{-1}$) showed similar values, which were higher than the no-fertilizer plot (3.5 ± 0.3 t $ha^{-1} y^{-1}$).

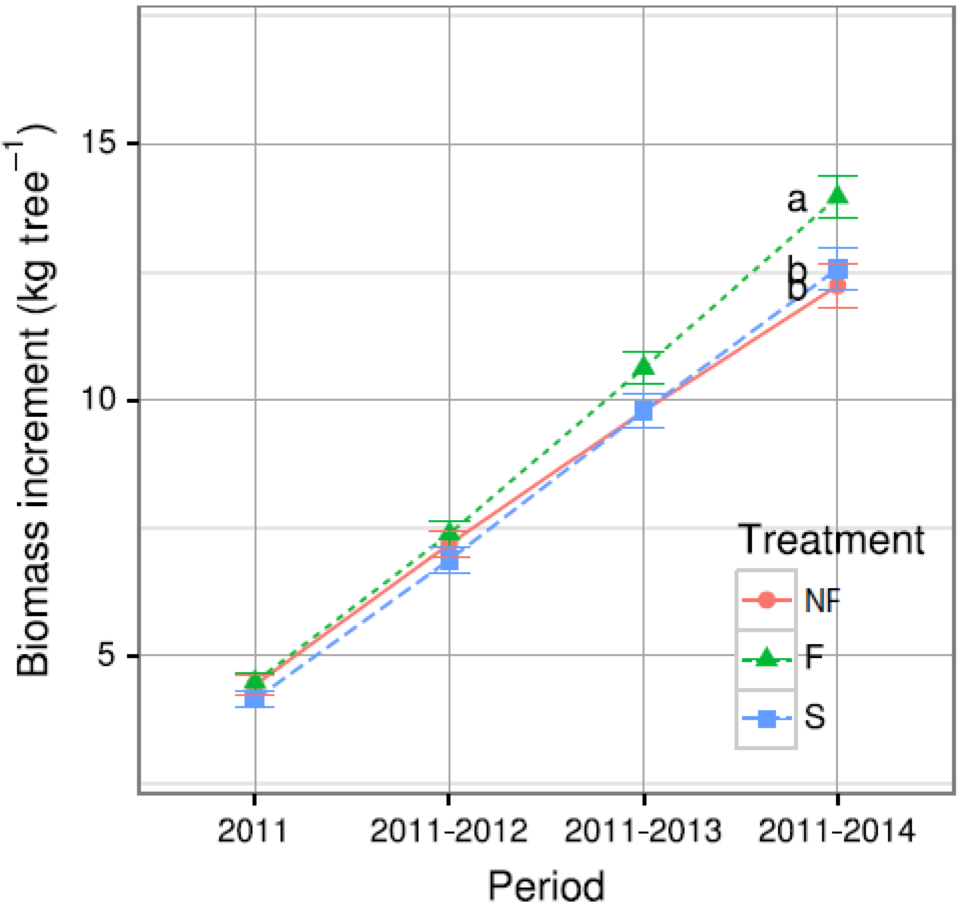

Figure 15. Mean values ± standard error of aboveground biomass increment (kg $tree^{-1}$) (a) under treatments of control of herbaceous vegetation NF: no fertilisation; F: mineral fertilisation; S: legume sowing. Different letters indicate significant differences ($p < 0.05$) between treatments in each period.

5.3 Tree thinning

Results show a slight positive effect of the thinning on the DBH growth over two years (Figure 16). The positive effect was not maintained for the third year.

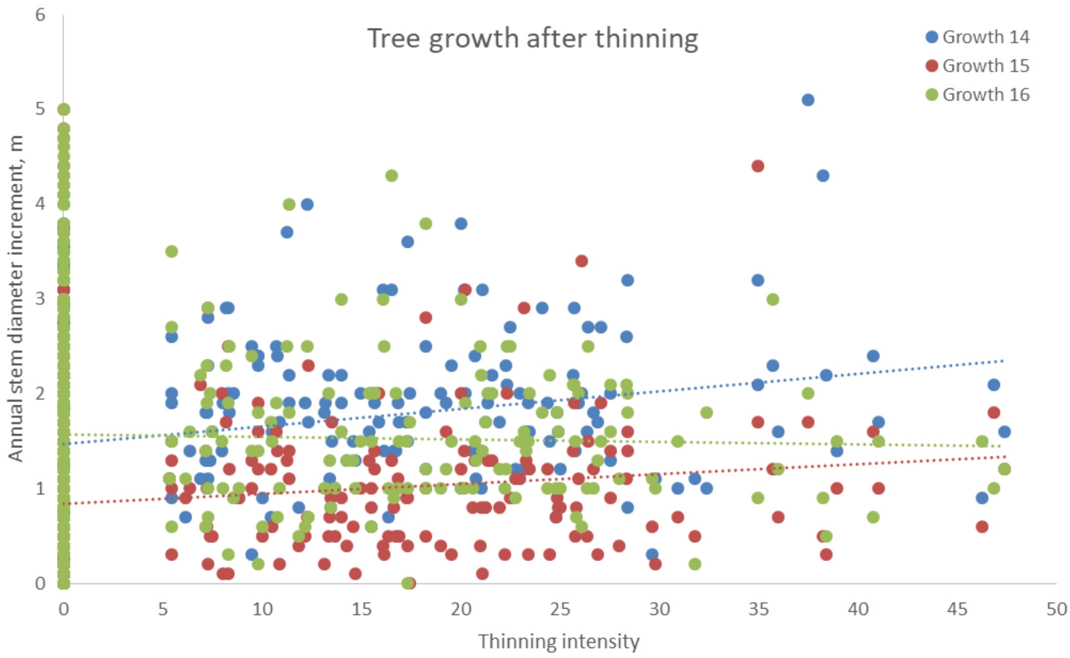

Figure 16. Response (stem diameter increment in two years) to intensity of tree thinning. Note that only the two years after thinning had a slight positive effect on tree growth.
Year 2014: Slope = 0.0181; r = 0.189; $p < 0.001$
Year 2015: Slope = 0.0114; r = 0.120; $p < 0.001$
Year 2016: Slope = 0.0044; r = 0.039; $p < 0.264$

5.4 Tree pollarding

Results of the first year (DBH increment) show not significant differences among pollarded and control trees ($F_{1,168} = 0.132$; p = 0.72), with very low growth for both groups of trees (0.35 ± 0.01 S.E. vs 0.37 ± 0.05 S.E., respectively Table 10). Trees will be followed over coming years to assess if the expected improved in the physiological status of pollarded trees lead to greater tree growth in terms of DBH increments.

Table 10. Diameter at breast height (DBH) incremental growth (cm y^{-1}) of pollarded *Prunus avium* as compared with unpollarded trees

Treatment	DBH increment (cm y^{-1})	Standard error	N
Control	0.369	0.052	90
Pollarded	0.350	0.015	90

6. Main lessons learnt

1. Cultivation increased water recharge of the soil in spring but reduced the soil moisture in summer, when the competition for water by the pastures and trees is high. The most favourable treatments for soil moisture in summer were those without fertilization. Any treatment to improve pasture yield, ether fertilization or sowing of legume forages, will decrease the water available for trees, but this did not have a significant effect on the water status of the trees.
2. Cultivation increased the immediate N and Ca availability, but reduced the P available in soil; the P was increased with grazing. The sowing of legume forage substantially increased the soil mineral N and K^+ but reduced significantly the available P. Again consequences for trees were barely significant, although a slight but significant decrease of tree leaf content of P and Ca was detected.
3. Unmanaged pasture yield was around 3.5 Mg ha^{-1} y^{-1}, what could support around 0.6 LU ha^{-1} y^{-1}. Sowing rich-legume pasture in the alleys could roughly double the stocking rate without compromise the tree growth.
4. Mineral fertilization also doubled the pasture understory yield, but the rooting profile of the pasture was deeper, which could increase the competition with trees for water and other soil resources. Unexpectedly, mowing and grazing, in particular, produced a deepening of the pasture root profile, which could explain why tree growth was reduced slightly with respect to the cultivated plots.
5. Silvopastoral management with high stocking rates seems compatible with timber production for high quality such as hybrid walnut and wild cherry. Improving pasture production and quality by sowing legume-rich forages did not reduce tree growth (that remained similar to that of the control unfertilized trees). Grazing did not favour the tree growth as much as cultivation but it gave better results than mowing.
6. Carbon sequestration was specially favoured by mowing the grass understory and by sown legume forage (even stronger that the effect of mineral fertilization). Grazing also had a slight positive effect on carbon sequestration.
7. The tree rooting profile seems unresponsive to the soil/understory management, and in all cases it was much deeper than the rooting profile of the pasture understorey.
8. Nitrate leaching seems negligible in the walnut plantations studied, presumably due to the deep rooting profile. Only in a few cases, when favourable conditions for organic matter mineralisation overlapped with inactive trees, a slight risk of nitrate leaching was observed in cultivated (mid-autumn) and mowed (early spring) plots. Unexpectedly, control unfertilized plots exhibited the highest risk for nitrate leaching (derived from the natural mineralisation of organic matter and presumably because the low pasture cover).
9. Thinning had slight but positive effects on walnut tree growth, but the effect disappeared after three years. Pollarding had neither positive nor negative effects on tree growth, but damage from cavitation was reduced and this should have a positive effect for medium-term plantation productivity.
10. Overall, managing of Mediterranean hybrid walnuts and wild cherry timber plantation under silvopastoral schemes seem a feasible way to reduce the high economical maintenance costs of these plantations and the ecological risks, without compromising their productivity.

7. Acknowledgements

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