Silvicultural guide to managing walnut plantations for timber production

This manual is a result of the project '**Second generation of planted hardwood forests in the EU — WOODnat**', financed by the European Commission

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All photos are from the company Bosques Naturales S.A. if the contrary is not stated.

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Contents

PREFACE

This book is a result of the project '***Second generation of planted hardwood forests in the EU — Woodnat***', financed by the European Commission, carried out by a companies' temporal consortium integrating Seistag Innovacion SL (Spain), Industrial Plants OOD (Bulgaria), ECM Ingenieria Ambiental SL (Spain), WAF Estructuras Digitales SL (Spain), Losan Romania SRL (Romania), Asimov Efficiency SL (Spain), Bosques Naturales SA(Spain), Consiglio per la ricerca In agricoltura e l'analisi dell'economia agraria (Italy) and Wale SAS (France).

The objective of this guide is to be a silvicultural manual analyzing the considered as the better practices to be applied for hybrid walnut (*Juglans x intermedia*) plantation management oriented to timber production, taking into account scientific literature and the experience in the sector of the companies who compound the Woodnat consortium.

This guide tentatively answers the questions any forest manager would have about walnut planted forests. Applied with common sense, combined with new information as available and modified when needed, these guidelines should be useful tools for the management of walnut planted forests under different cultivation systems and circumstances.

SECTION I. INTRODUCTION

1. Walnut trees

Walnut trees are species of the genus *Juglans* sp. L., traditionally characterized by their highly valued nuts and timber. The main walnut species are Persian walnut (*Juglans regia* L.), also known as European, English or Common walnut, and American or Black walnut (*Juglans nigra* L.) and different hybrids between them and/or other species. In addition, many clones have been selected during recent decades to improve timber production.

Common walnut has alternate imparipinnate leaves with 7-9 single leaves. The leaflets are oblong ovate and up to 12 cm long with smooth margin (Figure 1). Figure 2 shows some details about walnut general morphological characteristics.

Different Walnut species are used for timber production. The most common one is Persian walnut (*J. regia* L.), with origin in Central Asia and introduced in Europe centuries ago for nut production. Other very important species are the known as Black or American Walnuts (*J. nigra* L., *J. major* (Torr.) A. Heller, *J. cinerea* L., *J. hindsii* (Jeps.) Jeps. ex R.E. Sm.). However, several hybrids have been developed specifically for timber production by hybridation between Persian and American species, mainly: Mj-209xRa y Ng-23xRa (Coello et al. 2013).

Figure 1. Details of walnut (*Juglans* sp.) leaves

The relatively new forest plantations oriented for timber production and established with hybrid plant material are usually intensively managed and allow managers to sustain relatively high growth rates. To this respect, Mohini et al. (2009) expose these modern trends regarding walnut planted forests for timber which have been deeply discussed in the VALBRO COST Action (Growing valuable broadleaved tree species), financed by EU, as it is summarized in Hemery et al. (2008) [http://www.valbro.uni-freiburg.de/]. The silvicultural principles, goals and measures in growing valuable broadleaved tree species (discussed within the VALBRO project) are also analyzed in Oosterbaan et al. (2009).

Figure 2. Details about walnut (*Juglans* sp.) general morphological characteristics

2. Site requirements

Evaluating the species site requirements and matching species to site are keystones when investing in a commercial intensively managed productive planted forest such as a modern walnut plantation for timber production. This evaluation can be performed in a double way:

(1) Looking for a site for establishing a new planted forest matching the requirements of the species (walnut in this scenario) which was previously selected (e.g. a company dedicated to walnut timber production looking for expanding their plantations)

(2) Evaluating if a species (walnut in this scenario) is well suited for a determined site (e.g. a small or medium landowner who already owns a place and wants to establish a walnut plantation on it)

Forest productivity is mainly determined, without taking human management into consideration, by solar radiation, temperature and water and nutrients availability. Hence, climate and soils are considered the two main factors to take into account for matching species to site. Table 1 summarizes data from several authors regarding some limiting factors for walnut plantations and Figure 3 shows a summary of site requirements for hybrid walnut (*Juglans x intermedia* MJ 209) reported by Coello et al. (2013).

However, there are some other factors which should be considered when investing in a planted forest such as the presence of infrastructures, the access to the land, the legal issues regarding land property, the end-use for the timber that will be produced, the presence or absence of other nearby productive planted forests or the general characteristic of the region, among others.

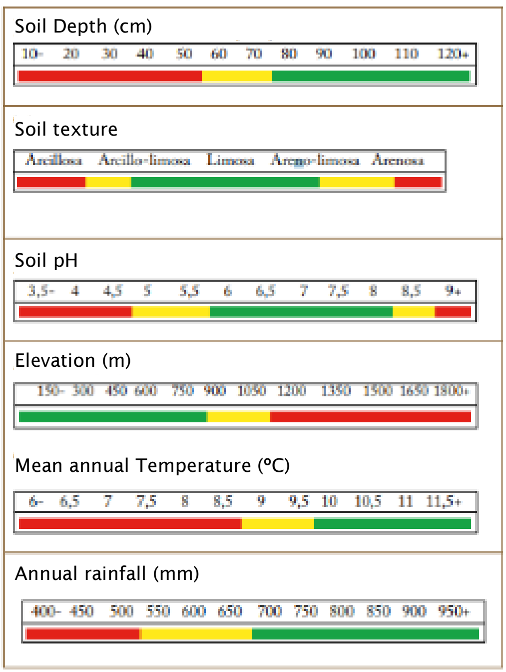


Figure 3. *Summary of site requirements for hybrid walnut (Juglans x intermedia MJ 209) modified from Coello et al. (2013)*

Table 1. Summary of climate and soil requirements for walnut (*Juglans* sp. L.) plantations published by several authors, considering the MJ209xRa provenance

Variable	Units	Lower level	Adequate	Optimum	Adequate	Upper limit
			Climate			
Annual solar radiation	$Kcal/cm^2$	<90 [1]				
Annual mean temperature	° C	< 10 [1]	> 8 / 10 (during 5 months) [2]	9.5 - 12 [3]	< 17 [2]	
Minimum winter temperature	° C	-20 [2]				
Cold hours	Hours			400-1000 [1]		
Summer temperature	°C					< 40 [2]
Vegetative period	Months			> 6 [1]		
No frost period	Months			> 6 [1]		
Annual rainfall	mm	<700 [2]		> 800 [1]		
Spring-summer rainfall	mm			100 - 150 [3]		
Elevation	m a.s.l.			< 900 [3]		
			Topography and soil physical properties			
Slope	%			0 - 15 [4]	> 15 [4]	> 30 [4]
Slope position		Lowlands with poor drainage [4]		Midslopes or lowlands with good drainage [4]		Summit [4]
Aspect		South [4]		North and East [4]		West [4]
Texture		Sandy [4]	Loam/ Silt loam [4]		Clay loam [4]	Clay [4]
Clay content	%			< 25 [3]		> 35 [3]
Silt content	%				30 - 50 [5]	
Sand content	%		30 - 50 [5]			
Effective depth	cm	< 60 [4]	60 - 90 [4]	> 90 [4]		
			Soil chemistry			
pH		< 5.4 [6]	> 6.5 [5]	7.0 - 7.5 [6]		8 [3]
Organic matter	%		> 0.7 [6]	1.5 - 2.0 [5]		
Active lime	%			5 - 6 [3]		
C/N				< 10 [6]		
K	mmolc/100g	< 0.35 [6]		> 0.4 [6]		
Ca	mmolc/100g		> 2 [6]	9.0 [6]	< 16 [6]	
Mg	mmolc/100g			> 0.7 [6]		

References: [1] Medel (1986) cited in Loewe et al. (2001) [2] Montero et al. (2003) [3] CESEFOR – INIA (2009) [4] Ponder (2004) [5] Luna (1990) [6] Technical experience from the company Bosques Naturales S.A. [7] Ibacache (2008) [8] Ayers and Wescot (1987)

Climate

The walnut is a relatively flexible species regarding climate, even though it is generally considered to require at least 700 mm of annual average rainfall (Figure 4), at least 100 – 150 mm during the vegetative period (Figure 5). Optimum precipitation would be 1000-1200 mm/year but it would also be enough with 500 mm/year if soil water reserves gives some help (e.g. sub superficial flows o high water retention) (Gonin et al. 2014).

Walnut requires warmth during the growing season, with at least 6 months of an average temperature > 10 ˚C, and it is sensitive to winter and late spring frosts, with the former being especially damaging for common walnut because the species often exhibits early initiation of vegetative activity (flushing). As the timing of spring flushing can vary greatly between provenances, provenance choice could affect propensity to frost damage (Mohni et al. 2009). Other authors consider that, for timber production, the average annual temperature should be higher than 8 ºC and it should be > 10 ºC during 5 months (Oliver et al. 2008). These temperature requirements can be associated to a general preference for altitudes lower than 900 m asl and tolerance up to 1100 m asl in Spain (Coello et al. 2013).

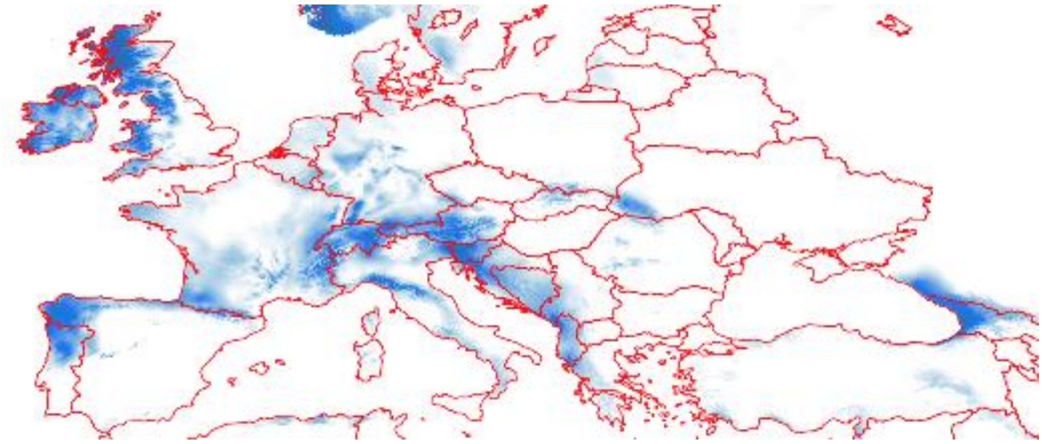


Figure 4. *Areas with mean annual precipitation over 700 mm, according to Worldclim [http://worldclim.org]*

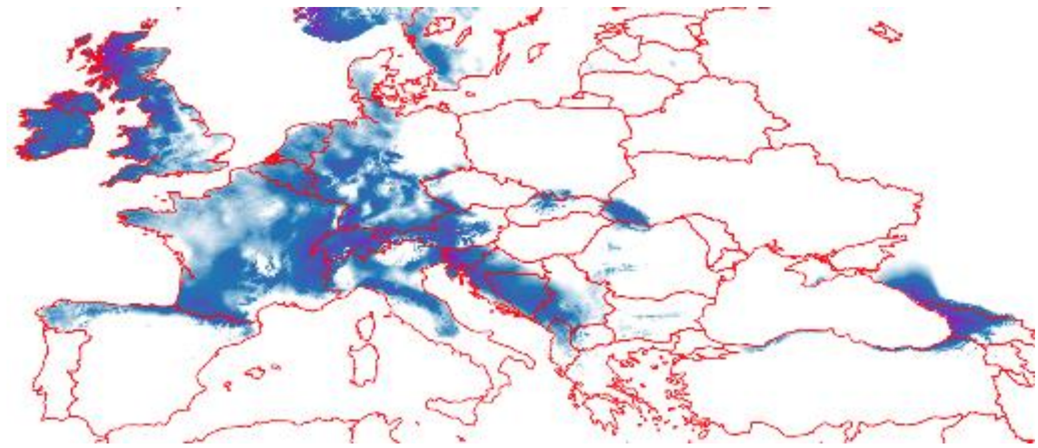


Figure 5. *Areas with mean summer precipitation over 125 mm, according to Worldclim [http://worldclim.org]*

Soil

On the contrary than climate, walnut is considered to have high requirements regarding soil fertility. Hence, deep, well drained soils with high fertility are usually considered as a requirement for walnut plantations. Some authors consider that the species should be planted in soils deeper than 80–100 cm (Figure 6) with a loamy texture (clay < 35 %, silt 30 - 50 % and sand 30 - 50 %). The clay content tolerance would be lower in relation to higher amount of rainfall (Oliver et al. 2008; Mohni et al. 2009), as it is considered to be a species with very low tolerance to bad drainage. To this respect, roots rotting is observed when floods and poor drainage conditions occurs during more than 3-4 days during the spring.

Optimum pH for the species has been considered to be between 6.0 and 7.5 and soil salinity should be evaluated as a limiting too, especially if watering is applied, which should not be done with water with an electric conductivity higher than 2.3 (Oliver et al. 2008; Mohni et al. 2009). However, it is considered to tolerate a wider pH range between 5.5 to 8.5 (Gonin et al. 2014) o even tolerate pH values near 5 (Coello et al. 2013). However, some problems have been detected in soils with high amounts of Calcium carbonates and high Ca active proportion.

Figure 6. Soil pit in walnut planted forests in Galicia (NW Spain)

Soil Nitrogen availability can be considered a limit to plant growth in many sites and N fertilization would be probably needed. Similarly, Magnesium and Zinc are usually considering as limiting walnut plantation growth in the experience of the company Bosques Naturales S.A. On the other hand, Phosphorus and Calcium are not commonly found as limiting Bosques Naturales' plantations.

Another relevant issue regarding soils in walnut plantations is the observed toxicity of some elements (e.g. Na, Cl, B), especially if watering is included in the management scheme. To this respect, Ibacache (2008) identifies some toxicity levels for the concentration of several elements in the soil water in the root zone which restricts walnut growth (Table 2). In addition, Ibacache (2008) also identifies some toxicity levels of electric conductivity which restricts walnut growth due to soil water salinity (Table 3).

The use of nitrate as N fertilizer has been regarded as a tool to control the Cl toxicity in several crops. Hence, the ratio between nitrate and chloride should be higher than 0.5 to avoid Cl toxicity.

Table 2. Toxicity levels for the concentration of several elements in the soil water in the root zone which restricts walnut (*Juglans* sp.) growth due to soil water salinity [from Ibacache (2008)]

Element concentration	Growth restrictions		
	No restriction	Medium	Severe
Na (SAR)	<5	5--15	>15
Cl (mmolc/L)	<5	5--10	>10
B (mg/L)	<0,5	0,5--3	>3

SAR: Sodium Adsorption Ratio

Table 3. Toxicity levels of electric conductivity which restricts walnut (*Juglans* sp.) growth due to soil water salinity [from Ibacache (2008)]

Electric conductivity [dS/m]	Growth restrictions		
	No restriction	Medium	Severe
Root zone	<1.5	1.5-4.8	>4.8
Irrigation water	<1.1	1.1-3.2	>3.2

3. Infrastructure

As previously stated, infrastructures should also be taken into account when analyzing the possibility of investment in a walnut planted forest for timber production. To that sense, there are some issues that should be evaluated:

Water infrastructures: Existence or not of a previous watering system and the possibility of establishing a new one in case there is no previous one. In the case of existence, the characteristics should be analyzed, taking into account the material and the conservation status, the possibility of changing the system, the location of the water input points to the system and the maximum amount of water available, among others.

Electric infrastructures: Existence or not of a previous electric system at the site.

Constructions: Existence or not of previous constructions at the site, as well as their dimensions and characteristics and feasibility for turning them into a warehouses or for other uses.

Roads: Existence or not of previous roads at the site, as well as their dimensions and conservation status.

Windbreaks: Existence or not of previous windbreaks at the site, as well as their dimensions and conservation status.

Fences: Existence or not of previous fences (Figure 7) at the site, as well as their dimensions and conservation status.

Figure 7. Detail of fences in a Bosques Naturales SA walnut plantation in Galicia (NW Spain)

4. Growth and site quality

Growth and site quality

Walnuts can live for 150–200 years and can reach 25–30 m in height and 1.5–2 m in diameter, whilst increased longevity (300–400 years) has been reported in natural stands (Mohni et al. 2009). In the planted forests established for timber production the rotations are considered to be between 20-25 and 50-80 years (du Cros 1987; Cisneros et al. 2008; Mohni et al. 2009; Coello et al. 2013)

Walnuts show a very different growth rate depending on site quality. To that sense, Mohni et al. (2009) and Cisneros et al. (2008) have summarized some published experiences, concluding that diameter growth rates varies from 1 cm in normal plantations to 2 cm in young low-density plantations situated on flood plains with deep soils rich in nutrients and well-fed with water. As an example, *"under the favorable conditions of Sibiflel-Hunedoara (in central Romania), at 60–70 years of age, walnuts can reach 80–90 cm in diameter, whereas walnuts of the same age but grown at upper elevations and on less fertile soils reach a maximum of 50–60 cm in diameter"* [Colpacci (1971) cited by Mohni et al. (2009)].

Montero and Cisneros (2006) have published site quality curves (Figure 8). The underlying idea is that a properly and intensively managed planted forests for timber production, established with clones and good plant material would be represented by the upper area of the site quality I curve.

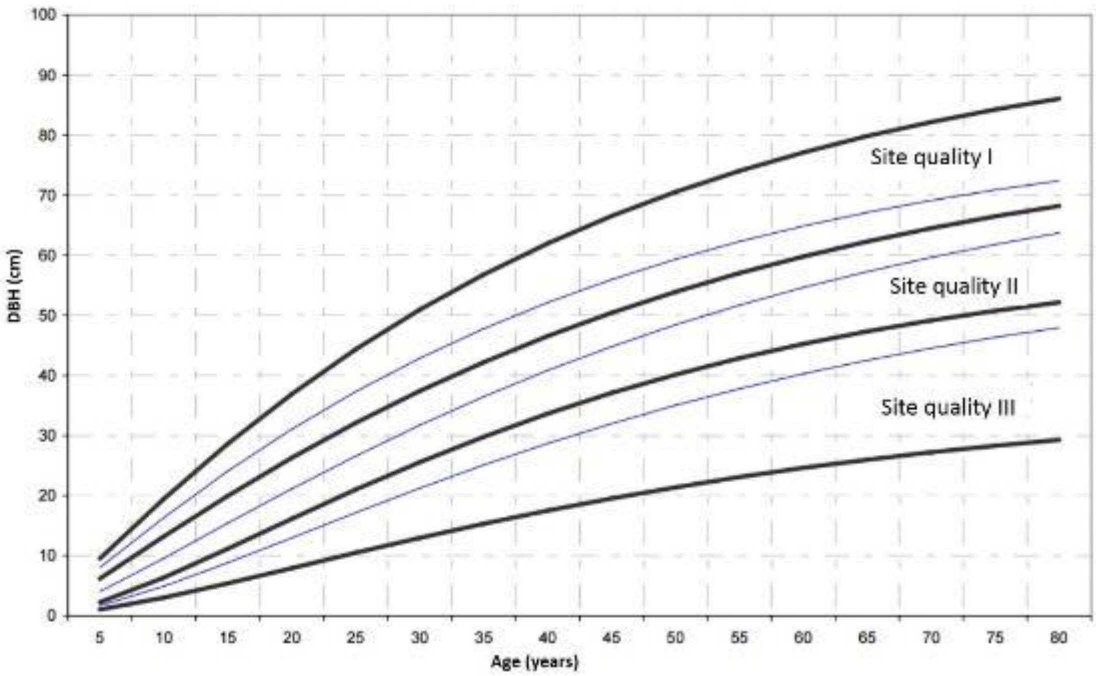


Figure 8. Site quality curves for walnut (*Juglans* sp. L.) planted forests (Montero and Cisneros 2006)

Growth estimations and modeling

Mohni et al. (2009) have also summarized some information about growth models for walnuts, which are included in this manual as Tables 4 and 5 in order to serve as a reference for managers to compare with the growth of their specific plantation.

Montero and Cisneros (2006) also propose a model to estimate DBH as a function of age and site quality:

$$DBH = a \cdot \exp\left(1 - b \cdot Age\right)^{\wedge(c)}$$

Where a, b and c are model parameters depending on Site quality (Table 6).

Table 4. Stand density and basal area for walnut (*Juglans* sp. L.) stands based on 100 % canopy closure and square planting DBH (diameter at breast height), CD (crown diameter), z (ratio between crown/stem diameter) [from Hemery et al. (2005)]

DBH (m)	CD (m)	Z (K/d ratio)	N (trees/ha)	G (m^2/ha)
0.10	4.47	44.70	500	3.9
0.15	5.35	35.67	349	6.2
0.20	6.23	31.15	258	8.1
0.25	7.11	28.44	198	9.7
0.30	7.99	26.63	157	11.1
0.35	8.87	25.34	127	12.2
0.40	9.75	24.38	105	13.2
0.45	10.63	23.62	88	14.1
0.50	11.51	23.02	75	14.8
0.55	12.39	22.53	65	15.5
0.60	13.27	22.12	57	16.1
0.65	14.15	21.77	50	16.6
0.70	15.03	21.47	44	17.0

Table 5. Mean expected value of merchantable tree volume, confidence intervals and mean tree height DBH classes in walnut (*Juglans* sp. L.) planted forests [from Bordin et al. (1977)]

DBH (cm)	Volume (dm^3)	Confidence intervals (dm^3)	Height (m)	Crown insertion (m)
5	6.1	± 0.1	4.6	2.7
10	27.5	± 0.2	7.1	3.0
15	65.2	± 0.6	9.3	3.8
20	119.0	± 1.3	11.2	3.9
25	189.0	± 2.3	12.8	3.6
30	275.2	± 3.6	14.1	xxx
35	377.5	± 5.3	15.2	xxx

Table 6. Model parameters [DBH = a · exp (1 - b · Age)^(c)] for the estimation of diameter as a function of age and site quality in walnut (*Juglans* sp. L.) planted forests (Montero and Cisneros 2006)

Site quality	Model parameters		
	a	b	c
I	82.9593	0.0272422	1.13268
II	79.4889	0.0237244	1.36059
III	60.1773	0.0259649	1.69596

5. Cultivation systems

Regarding the production of valuable broadleaved timber, a different approach has been defined from the traditional forestry schemes. Hence, valuable broadleaved silviculture a tree-oriented silviculture (as opposed to the traditional stand-oriented silviculture) aiming to produce a low number of big-diameter trees with high value timber, as it is deeply discussed in Oosterbaan et al. (2009).

Walnut has been planted in a very wide variety of systems from pure plantations to agro-silvo-pastoral systems. To this sense, Mohni et al. (2009) have reviewed several cultivation systems used in Europe, which we include in this manual.

Combined nut and wood production

Walnut has been traditionally planted as single tree crop or in linear plantations to produce nuts and wood, sometimes combined with hazel (*Corylus avellana* L.) for nut production. Later, specialized walnut plantations for nut production were adopted. In these type of plantations, able to produce both nuts and wood and in the specialized walnut seed orchard, it is possible to obtain valuable stem of 2 m height (Mohni et al. 2009).

Pure plantations

Prior to the 1990s the majority of walnut's timber came from multipurpose walnut plantations (nut and wood production). Specialized walnut plantations for wood production are relatively recent and many were established under CEE Reg. 2080/92. Early pure walnut plantations were designed with a stocking density of 300–400 trees per hectare. At this density the plantation required several thinnings and the spread of *Armillaria mellea*, a dangerous fungal disease, was favored. More recently, a stocking density of 150-200 trees per hectare was adopted. At this stocking density, it has been found difficult to maintain a constant diameter increment until a commercial dimension (40 cm) is attained. Currently, a low stocking density of 70-120 trees per hectare have been most widely adopted (Mohni et al. 2009).

In these low stocking density plantations, the cost of weeds control is very high, the height of stems is low and walnut trees present a heavy brunching. For these reason in these type of plantations, where the valuable trees are planted at a definitive distance, some companion trees or shrubs have been planted alternate to the walnut trees (Buresti et al. 2006). In Italy in the low density plantation the plantation of a couple of trees along the line, at the distance of 0.5-1 m instead a single tree, is recommended. This simple system permits to improve the quality of the valuable tree in particular if commercial seedling not improved are used. It is important to realize an early selection of the best tree of the couple after 3-5 years (Buresti Lattes et al. 2002). The use of the best provenance and especially of the best clones of hybrid walnut represent still now one of the best solution to produce interesting and profitable walnut monoculture.

Mixed plantations with companion trees

Mixed plantations (Figures 9 and 10) have been projected to reduce the planting and the management costs (especially pruning) and to obtain intermediate incomes, before the main walnut plantation reaches economic maturity. Many research programs indicate that the cultivation of walnuts in mixed plantations can support good diameter and height growth, and reduce the number and diameter of branches (for a revision see Mohni et al. 2009).

In particular, the use of N-fixing trees or shrubs can improve the diameter growth, stem form, shape of crown and branching (Tani et al. 2006 and 2007; Clark et al 2008, Bianchetto et al. 2013). The most suitable N-fixing tree to use intercropped with walnut are Italian alder (*Alnus cordata* Loisel) and Black alder (*Alnus glutinosa* (L) Gaertn.), while often Black locust (*Robinia pseudoacacia* L.) has been considered as too much aggressive and difficult to manage. These species can improve the soil fertility and increase the growth performance in low and medium site quality condition, while their effectiveness is less evident in very fertile soils.

Autumn olive (*Elaeagnus umbellata* Thumb.), a N-fixing shrub, has resulted as a very interesting species, increasing the walnuts' growth and shape (Clark et al 2008; Bianchetto et al. 2013). Other suitable companion shrubs for walnut, are: hazel and European elder (*Sambucus nigra* L). These shrubs can be planted near walnut at a distance of 1-2 m in order to rapidly cover the soil and reduce weed competition. However, they can restrict forest operations by making access more difficult, especially at the time of the last pruning and first thinning operations (Mohni et al. 2009).

There are sometimes problems associated to the commercialization of the wood of these companion species. To solve this problem, in particular where soil fertility in not a limiting factor, other nurse trees can be intercropped with walnut. Fast growing tree (as poplar, birch, plane, etc) characterized by a wood with a more stable market can be intercropped in a profitable way using a correct interplanting distance.

The use of mixed plantations can produce advantage from different points of view: environmental, landscape, more stability and resilience to adverse condition in comparison to monoculture, and economic. However, the use of mixture of different species can produce a high complexity in the plantations and needs of greater experience in the design and management.

Figure 9. Mixed planted forests with European walnut (*Juglans regia*) with companion trees: alder (*Alnus* sp.) and autumn olive (*Elaeagnus umbellata*). Photos from Italy by CREA

Figure 10. Mixed planted forests with European walnut (Juglans regia) with companion trees near Pesaro (Italy): (*Elaeagnus umbellata*; *Ulmus minor*, *Acer campestre*, *Salix alba*, *Alnus cordata*, *Platanus* sp.). Photos represents the state before (A) and after (B) of the removal of the competence from the companion trees to the walnuts. Photos from Italy by CREA

Polycyclic Plantations

Recently in Italy, France and North America mixed plantation with walnut and/or other valuable tree species and poplars clones have been implemented in tree farming plantation and in agroforestry (Zsuffa et al. 1977, Buresti-Lattes et al. 2008, Vidal and Becquey 2008, Paquette et al. 2008, Mohoni et al. 2009, Pelleri et al. 2013, Buresti-Lattes et al. 2014, Buresti-Lattes and Mori 2016, Buresti-Lattes et al. 2017). In this type of tree farming plantations, called in Italy "polycyclic plantations", different main crop trees, characterized by different rotation periods, coexist in the same plantation together with other types of trees:

- Very short rotation crop trees (5-7 years) for firewood or biomass production (i.e. Short Rotation Coppices);
- Short rotation crop trees (8-12 years) for peeler logs production (e.g. poplar clones);
- Medium-long rotation crop trees (20-30 years) for veneer production (e. g. walnut and other valuable broadleaved species).

The recent systems of planting design (Buresti-Lattes and Mori 2016) assign different surfaces (called blocks) to each types of crop trees considering their needs of space in relation to the length of rotation and type of assortment produced. The block is the unit surface in which it is possible to ideally divide the whole plantation (Table 7 and Figure 11).

Table 7. Main characteristics of main crop trees in polycyclic plantations (modified from Buresti-Lattes et al. 2017)

Type of trees	Species/clones	Rotation (years)	Block surface (m^2)	Tree density (trees/ha)	DBH (cm)
Very short rotation	PoplarAF2, plane, helm, hazel, hash, hornbeam, black locust	5-7	9-15	various-	5-19
Short rotation	Poplar clones I214, Lena, Neva, Villafranca	8-12	36-144	76-143	≥35
Medium-long rotation	walnut, hybrid walnut, oak, cherry	20-30	80-144	57-90	≥35

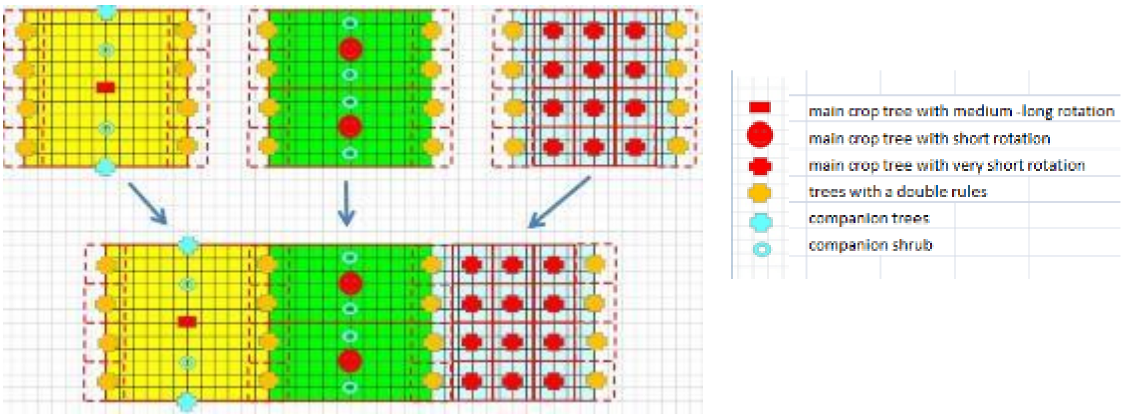


Figure 11. Example of blocks of different tree species in polycyclic plantations (modified from Buresti-Lattes et al. 2017)

The surfaces assigned to each crop trees can be temporary used with other different types of trees and shrubs. Trees with double rules are able to improve the shape and brunching of the crop trees but also to produce assortment requested from the local market. Companion trees and shrubs have to produce at least one of the following advantages: to educate the main trees, to fertilize the soil (e. g. N-fixing) and/or to control the weeds.

According to Buresti-Lattes and Mori (2016) the polycyclic plantation can be divided in the following types:

- Polycyclic plantation with end (plantation PT): formed only by blocks where are present main crop trees with the same rotation period, trees with a double rules and companion trees. At the end of the rotation period all the surface will be occupied by the crowns of the crop trees with longer rotation period and after their harvesting the plantation will be completely erased.
- Polycyclic plantation potentially permanent (plantation 3P): formed by blocks of different main crop trees with different rotation periods. These blocks can have all the tree types of trees (main crop trees, trees with double rules and companion trees). In the plantation 3P the whole surface of the plantation is never completely covered by the crowns of the main crop trees. In fact, the presences of trees with different rotation and the wide spacing permit to realize a new cycle after the harvesting using similar or different trees.

After nineteen years of experimental observations these plantations have shown that poplar and walnut can coexist in profitable way in mixture using appropriate minimum distance (Table 8, Figures 12 and 13).

In polycyclic plantations poplar clones grow faster considering the wider spacing (90-143 trees/ha vs. 278 trees/ha in monoculture) and the positive effect due to intercropping with trees and shrubs (about 600-700 trees/h) some of which are N-fixing. Diameter of 40-50 cm can be obtained in 10-12 years instead of 30-35 cm as in the traditional monoculture achieving, at the end of rotation period, similar production. These bigger logs have reached more high yields in terms of peeling and a reduction of production costs (Castro et al. 2013).

In addition, polycyclic plantations have a reduced cultivation's input and workload. A heavy reduction of cultural practices (-60%) was found between the two types of plantations, and specifically a strong pesticides and irrigation reduction (Pelleri et al. 2013, Chiarabaglio et al. 2014).

Common walnut intercropped with different poplar clones have obtained diameters from 13-14 cm and a total height of 12-13 m in 9 years, while hybrid walnut has showed superior DBH (14-16 cm) and height (13-15 m) in the same plantation (Pelleri et al 2013). In similar conditions but in an older plantation (19 years), no difference has been observed in walnut growth between a pure plantation and a polycyclic one (DBH 32 cm).

Table 8. Distance among different types of trees in polycyclic plantations (from Buresti-Lattes and Mori 2016)

Type of trees	Minimum distance among trees (m)	Other type of trees and shrubs
Main crop trees or tree with double rules	4	Companion trees or shrubs
Main crop trees with medium-long rotation	4	Tree with double rules with very short rotation (SRCs)
Main crop trees with medium-long rotation	7	Tree with double rules with short rotation (poplar)

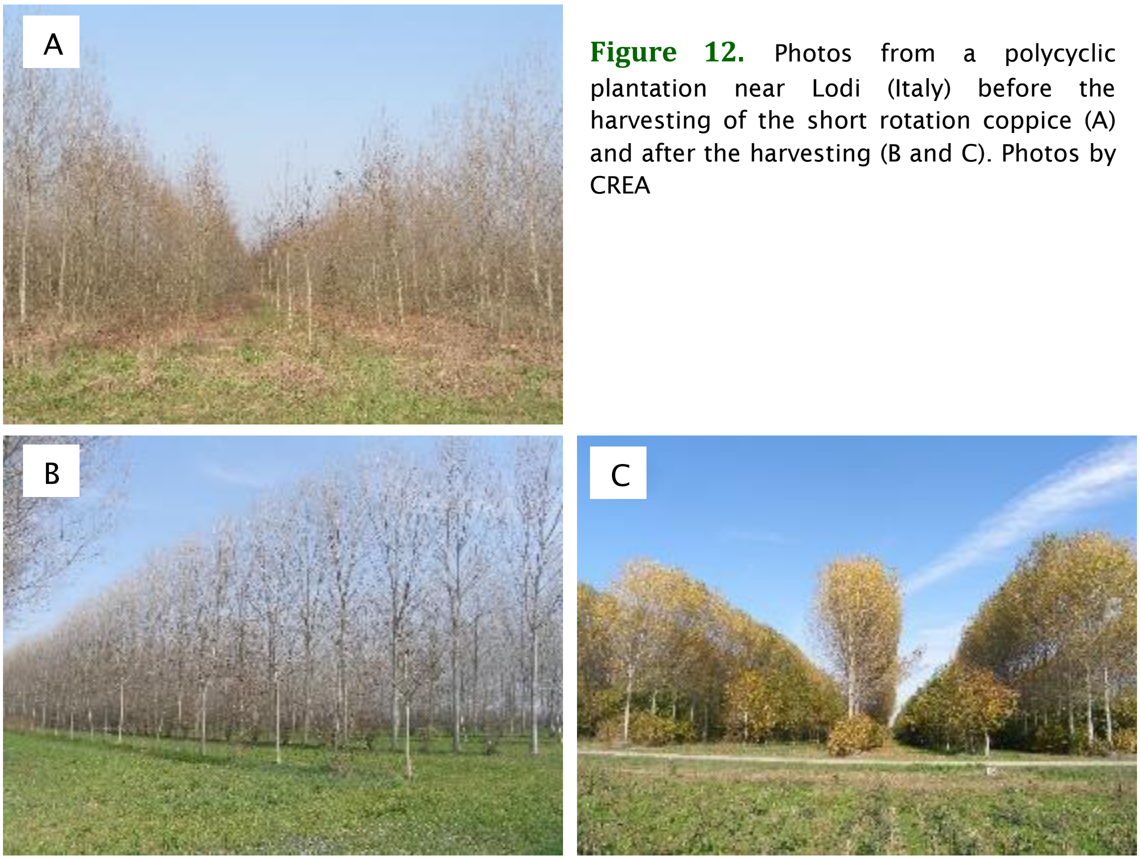


Figure 12. Photos from a polycyclic plantation near Lodi (Italy) before the harvesting of the short rotation coppice (A) and after the harvesting (B and C). Photos by CREA

Figure 13. Photo from a polycyclic plantation near Mantova (Italy). Photo by CREA

Agro-silvo-pastoral systems

Finally, several agro-silvo-pastoral systems have been established too using walnut in agricultural and/or pasture land intercropped with cereal production and fodder plants (for a revision see Mohni et al. 2009). Walnut can be planted in pure or mixed single line or in double line intercropped with agricultural crops (Figure 14). Wide spacing between the tree lines (10 m and more) should be used to maintain cereal production for longer time. Also in agroforestry system polycyclical linear block can be used to design line plantation using different trees with different rotation periods (Buresti-Lattes and Mori 2016).

Some research has been done regarding the use of walnut within agroforestry systems in Europe. To this respect, there have been some debate between the benefits and disadvantages of intercropping the trees with leguminous crops and grasses (e.g. Paris et al. 1995; Dupraz et al. 1999), mainly analyzing the balance between the benefits of increasing N nutrition and competing for the water resources, which would greatly depend on the site characteristics.

Figure 14. Agroforestry system intercropping maize within walnut planted forests in Galicia (NW Spain)

6. Wood properties in fast growing hardwood plantations

An important issue when thinking about to invest in a fast growing hardwood timber-producing planted forest is the doubts about the timber quality that would result from a forest with a much faster growth rate than "the traditional ones". Hence, the question arises, does the growth rate makes any difference for timber quality in temperate hardwoods? Coulson (2014) has done some research to this respect, which is included in this chapter.

It is generally understood that growth rate, in timber trees at least, has an influence on the usability and ultimately therefore on the commercial value. And that "understanding" seems to be that slow growth is good for quality, whereas fast growth is detrimental to good quality. That is certainly the case with softwoods (conifers) where fast growth leads to a preponderance of earlywood cells and proportionately fewer latewood cells. Thus, this wood is generally of lower density, possibly somewhat lower strength, and most probably poorer overall quality, since it consists mainly of "lightweight" earlywood tissue, which machines less well and gives wood with poorer texture and lesser surface hardness. That much is true: but only for softwoods!

With temperate hardwoods the situation is more complex and – in the case of one particular type of hardwoods – just the opposite. First of all, it needs to be understood that hardwoods can have one or other of two fundamentally different types of cell structure: ring-porous and diffuse-porous. In the former, the "pores" (those large, tube-like cells that conduct the sap around the tree) are mostly concentrated in the earlywood; and thus they form a very distinct band of growth in the tree's ring structure – hence the term "ring-porous". In the latter tree type, these wood cells are diffused (i.e. scattered) all across the growth ring, with no obvious accumulation of pores in any one part of the ring – hence the name "diffuse-porous". (In this type of hardwood tree, the growth rings are less distinct and are demarcated by a line of other tissue: it matters not what, in this short discussion). Figure 15 shows examples ring and diffuse porous structure.

The most important thing to realize about ring-porous hardwoods is that when they grow slowly, the rings are close together (just as with softwoods); but unlike the conifers, the latewood part of the growth ring does not dominate the timber: it is the earlywood which does. That is because the large earlywood pores still need to be accommodated within the narrow width of the ring; and this then leaves little or no room for the latewood – which is largely made up of the fibres which give wood its density and strength. Conversely, in ring-porous hardwoods that grow very fast, the much wider ring allows plenty of room for both the earlywood pores and the latewood fibres, resulting in a denser and stronger timber (quite the opposite to what happens in softwoods). With diffuse-porous timbers, the rate of growth has a negligible effect on density and strength, since the rings are formed quite differently and the pores are still scattered about in the wood, regardless of how and when they were formed.

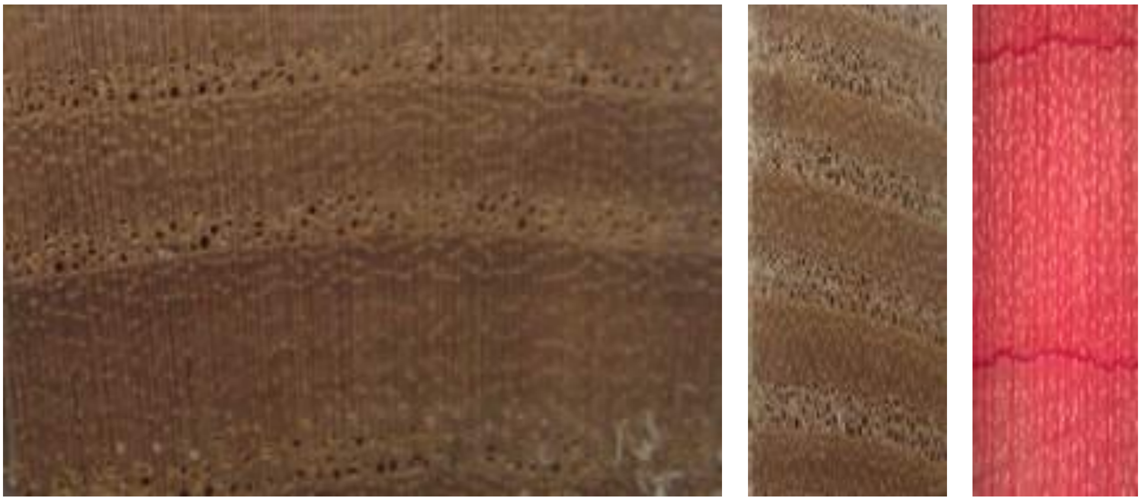


Figure 15. Examples of a ring porous species (ash) grown quickly (left) and slowly (center) and of a diffuse porous species (maple) grown quickly. From Coulson (2014)

Taking into account this theoretical work frame, the company Bosques Naturales S.A. and CIS MADEIRA have overcome some research analyzing the wood properties in their fast-growing walnut and cherry (*Prunus avium* L.) planted forests for timber production. Results from this research show how wood properties of these kind of forests are similar than the cited in literature for traditional forest systems (Table 9) (Merlo-Sánchez et al. 2009).

Table 9. Wood properties for traditional and fast-growing cherry (*Prunus avium* L.) and walnut (*Juglans* sp.)

Wood properties	Cherry		Walnut	
	Fast growing	Traditional*	Fast growing	Traditional*
Density (g/cm^3)	0.63	0.62	0.76	0.65
Contraction coefficient	0.50	0.45	0.56	0.34
Strength	3.19	4.30	4.90	3.80

* References from Vignote-Peña and Martínez-Rojas (2006)

SECTION II. ESTABLISHING THE PLANTATION

7. Plant quality and genetic material

Genetic material

The bases of the modern agriculture were established during the mid-XX century, being known as the Green Revolution. The Green Revolution implies the use of highly productive varieties (Borlaug 2002). The use of highly-engineered varieties has allowed the increase of yield at the same time that less land has to be dedicated to agriculture along with a better utilization of natural resources (water, soil, biological, etc.). Thus, several genetic improvement programs have been initiated at USA (Woeste y McKenna 2004) and Europe (Jay-Allemand *et al.* 1996).

Although great advances have been produced for most of the agricultural crops, less results have been obtained for forest species. In spite of walnuts being appreciated both for their edible nuts and timber, only varieties for fruit production have been obtained (Victory *et al*. 2004). With the purpose produce wood, several hybrids have been obtained during the last 100 years. Among them, the progeny of the mating between *J. major* var. 209 X *J. regia* (Mj209xRa) seems to be the most suitable for the European conditions. This seed progeny is characterized by its high vigour, a remarkable apical dominance and an outstanding growth (Aletà *et al*. 2003, Clark and Hemery 2010).

However, plantations with this seed progeny are accompanied by a high phenotypic variability that affect its industrial exploitation, being necessary the use of clonal plantations. Traditional vegetative methods are not suitable for massive reproduction of èlite genotypes; becoming tissue culture technologies the most important alternative for cloning, but the high recalcitrance of walnut species (Britton *et al.* 2007) hinder their commercial micropropagation.

In the framework of the improvement program that is functioning at Bosques Naturales S.A. since 1998, more than 100 trees from the Mj209xRa progeny have been selected for wood production. However, having refined genotypes does not assure by itself the success of a genetic improvement program; it is also necessary to have efficient propagation methodologies. Together with this selection program, an experimental micropropagation protocol was developed. As a result, the current in vitro germplasm pool is formed by 16 genotypes, from which 14 genotypes have been cloned successfully (Licea-Moreno *et al*. 2012, Licea-Moreno *et al*. 2015).

Various formats of micropropagated genotypes are available:

1. Acclimated plants in 200cm^3 pots. Vitroplants aged not more 6 months. It is the cheapest material but some loses may occur if appropriated conditions are not used to complete the hardening.
2. Acclimated plants in bigger pots (3,5 L in advance). Vitroplants aged more than 6 months. It is a more expensive material, however, few loses are expected under normal conditions (Figures 16 and 17).

3. Plants from field nurseries. Small trees that have passed at least a vegetative cycle under controlled conditions. This is the most expensive material, however, loses are unusual events.

Select the right plant source is one of the main issues once one has decided to establish a new walnut plantation in a site. Even though plenty of options could be available depending on the budget and dimensions, the plant quality and the genetic potential should be considered as one of the key investments when establishing a commercial planted forest.

Plant quality

Plant material should be healthy and without any visual symptoms of diseases or poor nutrition. It should match with the best characteristics according to the objective of the system, the site condition (climate and soil) and the available budget. In addition, it is importance to notice that plant material for afforestation must be in accordance with the European Union regulations to this respect.

Genetics and morphology are the two main issues to be taken into consideration when analyzing plant quality. Genetics is difficult to assess and it is usually useful to have the help of a well recommended and reliable nursery where to buy and check out information about the material. On the contrary, plant morphology is relatively easy to assess. It should have the right age (1 or 2 years), have a good balance between root and shoot, don't show any symptom of disease or damage and getting it in reasonable transport conditions. It is important to notice that plant quality should be homogeneous within the same buying order.

When a specific variety or clone is chosen, especial attention should be paid in the nurseries to avoid misunderstandings and confusion between the desired clone and the final obtained product.

Plant material is sometimes inoculated with mycorrhizas (a symbiotic fungus) which should be preferred when it would be possible as it usually increases the success in the plantations, improving water and nutrients availability for the trees.

Finally, hardening is one of the main issues regarding plant quality and survival in the field. Hence, even though plants in pots can be of good quality, bare rooted plants (0/1 or 0/2) are sometimes recommended as it is usually ensured a good hardening.

Figure 16. Bosques Naturales SA walnut nursery in Galicia (NW Spain)

Figure 17. Bosques Naturales SA walnut nursery in Galicia (NW Spain)

8. Plant density

Plant density and spacing would depend on the site conditions and on the plantation scheme and objectives. However, walnut is considered to be a species which do not grow well with the competence of high density. As a general pattern, plant density varies between 100 and 400 trees/ha, being 100 trees/ha a considered as good density for final felling.

Several approaches are possible in an agroforestry scheme, from regular to irregular spacing. Figure 18 shows a possible scheme for an agroforestry system with pairs of 2 plantation lines spaced 6 m (with 5 m distance between trees in the same line) separated by bigger clearances for agriculture of 12 m wide. In this system, the 6 m corridor between the plantation lines allow managers to work within the trees without make any disturbances to the agricultural fields.

In pure plantations (Figures 19 and 20), plant density can be determined based on site quality, plant genetic material and the desired or allowed management intensity and objectives (e.g. high spacing would favor agro-silvo-pastoral systems). Plants can be established at the considered as final spacing (i.e. no thinnings) at a density of around 100 trees/ha (e.g. 7x10 or 12x12). However, this is only recommended in optimum sites and with very high quality plant material. Hence, higher plant densities are usually recommended with associated thinning/s. This would allow to perform a tree selection for the final harvest and to obtain an intermediate economic input. An initial 5x5, 5x6 or 6x6 spacing can be chosen with this scheme, which can be slightly sparser (e.g. 7x7) with clones and good quality plant material.

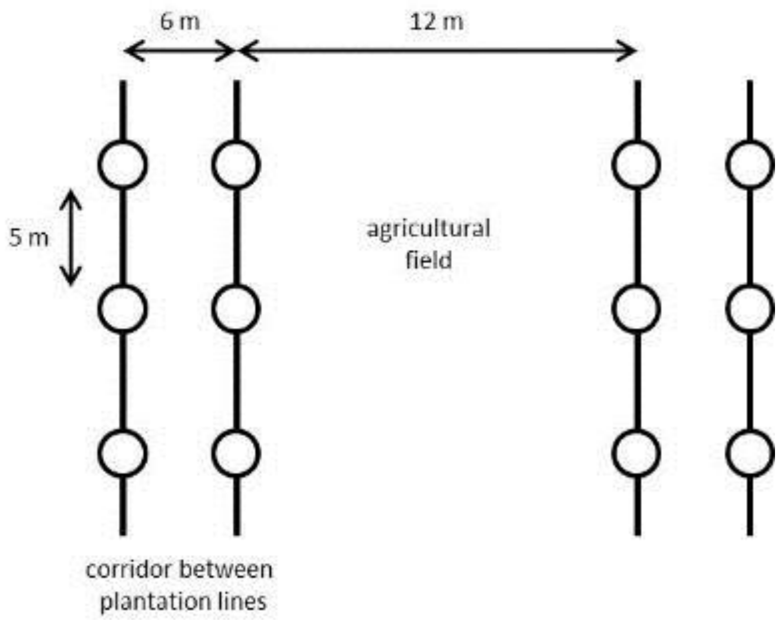


Figure 18. Scheme proposed for an agroforestry system including sparse walnut (*Juglans* sp.) planted forests

Figure 19. Bosques Naturales SA walnut planted forest in Cuenca (Central Spain) with a density of 333 trees/ha (5x6 m spacing)

Figure 20. Bosques Naturales SA walnut planted forest in Cáceres (Central Spain) with a density of 333 trees/ha (5x6 m spacing)

9. Site preparation

Site preparation before planting should be site and species specific as it should vary according to the species chosen, the systems chosen to establish and manage the species and the specific properties of the site. However, some general activities are described.

Vegetation control and clear of field

Controlling competition is very important for the first few years of the plantation. Vegetation control would avoid competition of the plantation trees with weeds or other woody vegetation previously stated in the field, which would be removed too. Vegetation control is usually done mechanically, even though it can be done by hand in small farms.

After clearing the vegetation at the field, soil tillage is commonly recommended. Depending on the specific characteristics of the field different tillage technique should be used but usually double cross tillage with a disc harrow can be recommended. Depending on the budget, this tillage can be done only along the future plantation lines.

Subsoiler tillage

A subsoiler is commonly recommended for deep tillage (down to 60 cm), with the aim of loosening and breaking up soil at depths below the levels worked by other ploughs (down to 60 cm). Subsoiler increase effective depth (allowing a better root growth) and improve drainage and infiltration soil properties.

It is recommended to do a double cross tillage following the future plantation lines with a 3-ripper subsoiler working to a depth at least of 50 cm. Best timing for subsoiler tillage would be around 2 months before plantation, taking into account that the soil needs to be wet but well drained at the moment. Usually it is done at the beginning of the autumn.

Liming

Liming is done with the objective to increase soil pH to the levels needed by the crop to be grown. As a result of increasing soil pH by liming, other benefits can be achieved:

- reduces the possibility of Mn^{2+} and Al^{3+} toxicity;
- improves microbial activity;
- improves physical condition (better structure);
- improves symbiotic nitrogen fixation by legumes;
- improves palatability of forages;
- provides an inexpensive source for Ca^{2+} and Mg^{2+} when these nutrients are included in the product used for liming;
- improves nutrient availability (availability of P and Mo increases as pH increases at 6-7, however, other micronutrients availability increases as pH decreases).

The need for liming should be analyzed on the basis of the soil analysis of the site, following the recommendation established in Table 10.

As it is summarized in Table 10, in slightly acidic soils or with some risk to be acidified during the rotation period, a conservation liming can be applied in order to ensure the actual soil status and avoid this acidification risk. On the other hand, in acid soils with low Ca contents, correction liming is recommended for solving the acidity problems present at the site. This kind of liming supposes a higher dosage of product to be applied and needs more time and money for achieving the objectives. Thus, when acidity problems are big enough at a site, the possibility of changing the species to a tolerant one should be taken into account.

A general recommendation can be considered to be 1 ton/ha of Magnesium calcite (20% MgO, 65% $CaCO_3$) to increase 1 unity the soil pH every 4 to 8 years. This dosage may be concentrated along plantation lines. Tillage with a disc harrow is recommended after liming to improve mixing the product and the soil. Best timing for liming would be in autumn, taking into account that the soil needs to be wet but well drained at the moment. More reactive products in high dosage can damage the plants.

Organic soil amendments

Organic soil amendments aim to increase (or at least maintain) soil organic matter content, improving soil physical, chemical and biological properties. Table 11 summarizes a classification to estimate the organic matter status of a field based on the organic matter content and the texture.

The amount of product to be applied to the field as part of the organic amendment would depend on the soil organic matter content and the product used. A relatively big application is usually recommended during the site preparation phase (before the plantation), followed by smaller applications during the rotation period, including some applications of earthworm humus (vermicompost) (around 5 kg/tree). However, Luna (1990) recommends 20-30 ton compost/ha (or 20-30 kg/tree).

Fertilization at establishment

Luna (1988) recommends the application of 100-150 kg P_2O5/ha and 150-200 kg K_2O/ha before the establishment of the plantation. On the other hand, Becquey (1997) recommends higher values, around 200 150 kg P_2O_5/ha and 300 kg K_2O/ha.

Stone removal

Even though sites with severe presence of stones might have been discarded during the site evaluation phase, there might be some stones (above or belowground) that should be removed. This operation widely depends on the specific field characteristics. It may be done manually with the help of machinery to remove the stones.

Table 10. Summary of the recommendations to evaluate the needs for liming in a site prior to the establishment of walnut (*Juglans* sp.) planted forests for timber production

Soil pH	Calcium content	Calcium status	Liming needs
pH ≥ 6.5	Any	Satisfactory	No need for liming (control each 2-3 years)
5.5 <pH< 6.5	≥ 100 mg/kg	Satisfactory	Conservation liming
	< 100 mg/kg	Unsatisfactory	Correction liming
pH ≤ 5.5	Any	Unsatisfactory	Correction liming

Table 11. Classification to estimate the organic matter status of a field based on the organic matter content and the texture. The classification is performed for irrigated sites in walnut (*Juglans* sp.) planted forests in Spain

Texture	Organic matter (%) levels				
	Very low	Low	Medium	High	Very high
Sand	> 0.4	0.4 - 1.0	1.1 - 1.5	1.6 - 2.0	> 2.0
Loam	> 0.6	0.6 - 1.5	1.6 – 2.0	2.1 - 2.5	> 2.5
Clay	> 0.8	0.8 - 1.8	1.9 - 2.5	2.6 – 3.0	> 3.0

Stands and sectors delineation

The site would be distributed in relatively homogeneous smaller areas (which may be similar or quite different between them) which later on could have a similar management between them or quite a different one, even more if they contain different species. This delineation should take into account the dimensions of the machinery that would be used in the future and the possible logistic issues needed for the management of the plantation.

Infrastructures

The plantation infrastructure should be completed before the establishment of the plantations. The workload of this activities would depend on the existence or not or on the conservation status of previous infrastructure at the site. Some infrastructures especially relevant are: Water and electric infrastructures, constructions, roads, windbreaks and fences. In addition to these, some areas should be kept clear in order to have an area for accumulate input and output products.

10. Plantation

This chapter describes the main activities to be carried out from the arriving of the plant material to the establishment at the site. The chapter is focused in bare rooted plants (at least one year in the nursery) as walnut plants for timber production planted forests are usually too big to be in container. However, most of the activities would be similar if container grown plants are used.

Receiving the plant material

It is usually recommended, if it would be possible, to receive the bare rooted plant material around one year before being finally planted and create a small nursery (planting them) in the field so the plants will get used to the site characteristics before establishing them in the final places. If this operation is done, plants should be carefully removed just before planting.

Mark the land

Mark the precise points in the land where the plants will be planted. Plantation lines would be delineated depending on the orientation, winds and shape of the site and taking into account the designed roads and cleared spaces. The result would be a grid in the field where the plants will be planted in the nodes.

Pit digging

Pit digging can be done manually or mechanically. Pits or holes should be of around 50-60 cm wide and 50 cm deep and should be done in nodes of the grid previously marked.

Planting

Plants are first distributed across the field and then established in each of the pits. Vermicompost should be mixed with the soil extracted during pit digging and the mix is placed in the pit with the plant carefully established.

Watering

Right after the plantation it is recommended to water it and repeat it after 15-30 days if there is not enough rainfall during that time.

Plant revision

After watering, every tree should be revised and correct any mistake during plantation.

Lime application to the trees

Besides liming (lime applied to the soil), lime can be also applied to the trees once they are established. This is done especially in areas where solar radiation is very high (especially in summer). This is done manually, “painting” the bark of the lower part of the trees with lime and repeating if it would be washed out by the rains. This results in a very expensive activity which is not recommended unless tree is in very poor conditions as a result of bad site selection.

Grow tubes and support stakes

Wild fauna causes common damages to newly established planted forests. Hence, if the presence of wild animals is noticed, plants should be protected with grow tubes to a height of around 60 cm. These should be from a sparse mesh to allow plant ventilation. Support stakes are also commonly used to guide the trees and ensure they grow up vertically.

Re-planting

Even if all the planting activities have gone well, there is going to be a small percentage (2-3%) of failure in plant establishment (planted plants who die). Hence, these dead plants should be replaced. This 2-3% extra plants should be taken into account when buying and receiving the plant.

SECTION III. PLANTATION MAINTENANCE

11. Forest inventory: growth measurement and control

It is highly recommended to monitor regularly the growth of the planted forests in order to keep a control of its status. This should be done by a series of periodic measurements, mainly the height and DBH (Diameter at Breast Height, 1.30 m), which will be used to estimate volume (Figure 21). Timber quality should be also estimated by means of a general evaluation of tree health and an evaluation of the shape.

Measurements should be done always in the same 500 m^2 permanent measurement plots which would be well marked in the field. The number of measurement plots would vary accordingly to the size of the plantation but should be higher than 3-5 (in very small plantations).

Figure 21. Measuring tree Diameter at Breast Height (1.3 m) with a caliper in the Bosques Naturales SA walnut planted forest in Girona (NE Spain)

12. Pests and diseases

Pests and diseases are among the main risks in a productive planted forest. West (2006) defines pests as damage of trees caused by a living organism (e.g. an insect), affecting its growth or development. On the other hand, the diseases cause impairment to the normal treatment of the trees and can be divided in biotic diseases (e.g. fungi or bacteria) or abiotic diseases (e.g. toxicity or absence of a nutrient). However, abiotic diseases are not considered in this manual as they are not very common in walnut plantations. Especially regarding walnut plantations, Table 12 summarize the main pests and diseases observed in walnut forest systems, respectively. In the following outlines, a brief description of the pathogens reported in Table 12 is given, focusing especially on the main symptoms in the field and with particular reference to the diseases reported in Italy.

Monitoring pests and diseases would be important in order to keep the risk and damage to a minimum. For example, the installation of traps is recommended for monitoring the populations of caterpillars (mainly *Zeuzera pyrina* and *Cossus cossus*) and evaluate when the application of products would be needed. To this sense, it is important to notice that the products used should be as much “selective” as possible in order to maintain the other organisms (e.g. insects and fungi) present in the ecosystem which are beneficial for the walnut. Similarly, toxic products for humans, mammals or birds should not be used, as well as products toxic for fish in places near rivers. As a general recommendation, legal issues should be taken into account when applying this kind of products in the field.

Goat moth (*Cossus cossus*)

The goat moth (Figure 22) is so called owing to the strong “goaty” smell of its caterpillar stage (i.e. larvae feeding in wood galleries). This lepidopter, polyphagous, is spread throughout Europe, Asia and North Africa and attacks orchard trees and especially declining trees of poplar, willow and walnut in arboricultural stands. The induced damage is a quality decrease of wood and a predisposition to attacks by weak parasites and rot fungi. The signs of infestation consist of about 1-cm wide holes on the trunk bark, from which a thick jelly exudate flows, dark brownish, composed of altered sap mixed with the caterpillar gnawdust, with a typical smell of rotten leather. The larvae (i.e. caterpillars), 8-10 cm long at maturity, with back form pink to dark red according to their age and creamy-yellow ventral strips, dark-headed, are born from brownish 1.0-1.5 mm-wide eggs layed down into bark fissures. Aggregated at first, they dig small tunnels around the trunk which destroy large portions of the cambium and then overwinter; in spring they wake and begin dipping dipper tunnels in vertical direction, both upwards and towards the roots. The whole second year is passed as larval stage, then in summer of the third year the emergence from the pupal case occur or, in colder climates, even during the fourth year. The adults are big moths with a wingspan of 7-10 cm, with anterior wings greyish-brown and dark-striped.

Figure 22. Goat moth (*Cossus cossus*) in walnut planted forest in Spain

Leopard moth (*Zeuzera pyrina*)

Polyphagous lepidopter like the carpenter moth, it is present above all in Europe from Scandinavia to the Mediterranean basin, including North Africa and the Middle East, more sporadic in Russia, Cina, Japan, and North America. The English walnut is reported as one of its main hosts and, differently from the carpenter moth, it affects twig distal portions digging tunnels inside the shoots; the most advanced larval stages may affect larger branches as well. The induced damage is a generalized crown decline and a predisposition to attacks by weak parasites and rot fungi. The caterpillars, 5-6 cm long at maturity, are yellow, dark-headed and pointed with black tubercles disposed in longitudinal stripes, whereas the adults (4-7 cm of wingspan) are bright moths with wings and body stained by black or bluish spots. According to the climate, one generation every year or every two years may occur: the adults are present especially in June and July and the just born larvae are able to enter in and escape from shoots many times, transferring to twigs of increasing diameter. The gnawdust is deposed on the ground or attached near the hole edges in form of ochreous pellets.

Leaf aphids: large walnut aphid (*Panaphis juglandis*) and small walnut aphid (*Chromaphis juglandicola*)

Both species are monophagous, i.e. they are only found on walnut, and occurring in Europe, Asia and North America (especially the western side where walnut cultivation for fruits is most spread). A main difference is that *P. juglandis* is observed only on the leaf upper side while *C. juglandicola* colonizes the bottom of the leaf blade. Sometimes, in case of high population levels, a darkening of the main veins may occur in association with a characteristic wrinkling of the leaf blade but this hardly can affect wood productivity.

Table 12. Summary of the main pests and diseases (with causal agents) observed in walnut (*Juglans* sp.)

Damage type	Affected tissue		
	Roots	Stem and branches	Leaves and shoots
Quality damage		Thousand cankers disease (*Geosmithia morbida*) Pustule canker (*Juglanconis juglandina*) Shallow bark canker (*Brenneria nigrifluens*) Deep bark canker (*Brenneria rubrifaciens*) Mechanical injuries Goat moth (*Cossus cossus*) Leopard moth (*Zeuzera pyrina*)	
Production damage	Armillaria root rot (*Armillaria mellea*) White root rot (*Rosellinia necatrix*) *Phytophthora* root and collar rot (*Phytophthora* spp.)		Anthracnose (*Ophiognomonia leptostyla*) Downy leaf spot (*Pseudomicrostroma juglandis*) Bacterial blight (*Xanthomonas arboricola* pv. *juglandis*) Abiotic stress Aphids (*Panaphis juglandis*, *Chromaphis juglandicola*)

Shallow bark canker (pathogenic agent: *Brenneria nigrifluens*)

The shallow bark canker by *B. nigrifluens*, an *Erwinia*-like bacterium, has been spreading in English walnut stands throughout Europe for the last twenty years (Figure 23). The factors that affect its appearance are not clear: probably the stand genotype and microecological parameters, like drought, have a role on the virulence of a parasite that may be present in latency among the cortical microbiota. The first symptoms, appearing mainly in plantations 15-year older, consist of small necrotic lesions oozing a typical brown exudate, localized from the base to the top of the trunk, often close to broader and desiccated canker wounds. The dead tissues gradually affect the whole trunk section, inducing a terminal stage characterized by large swellings composed of canker-connected callus reactions. The underlying wood, darkened and with tissue disorders, results useless at the final cutting (quality damage), while the most extended cankers impair tree mechanical stability exposing it to snow or wind breaks and to infections by decay fungal agents. The brown exudate, including active bacteria, is responsible for the spread of the parasite through penetration into fresh wounds after its transmission by insects or contaminated tools. There are no effective control measures to avoid or control such pathogen.

Figure 23. Deep bark canker (*Brenneria sp.*) in walnut planted forest in Italy (photos by CREA)

Deep bark canker (pathogenic agent: *Brenneria rubrifaciens*)

B. rubrifaciens host range, besides English walnut, includes Black walnut. Some features are similar to those of *B. nigrifluens*, described above, but its symptoms appear associated with higher temperatures and are more extensive, advancing slowly upward and affecting more and more branches which result weakened. Root system is generally not interested.

Thousand cankers disease (TCD; pathogenic agent: *Geosmithia morbida*)

This ascomycete pathogen, the first species of *Geosmithia* demonstrated to be phytopathogenic, is a wound parasite, i.e. it requires the intervention of a vector to penetrate into cortical tissues. Consequently, its presence is strictly associated with that of the so called walnut twig beetle (WTB), the scolytid *Pityophthorus juglandis*; for example, in Europe pathogen and pest were both recorded in Veneto plantations in 2013 for the first time, at first on black walnut and then on English walnut as well. They are now surely present in Lombardy too and, considering the quite thermophilic character of WTB, native to Mexico and South-Western USA, they will likely spread towards Southern Italy and other Mediterranean countries where the walnut is cultivated. Black walnut appears more susceptible to the disease than English walnut, but significant differences may exist among biotypes of the same species. Unfortunately, evident symptoms are not specific and only appear several years after the infections as yellowing and wilting of leaves and progressive dieback of twigs and branches. More specific TCD symptoms are detectable on small twigs as entrance and exit holes of infected WTB, that release mycelial propagules and allow fungal colonization of the subcortical tissues, thus inducing dark brown to black necroses elongated along the twigs and 10-20 cm as maximum in size. After repeated beetle infestations and the progression of necroses the tree decline advances, with WTB galleries and associated cankers occurring every 2 to 5 cm in the bark, and finally the cankers coalesce and girdle also the bigger branches; in this stage, the trees die within a few months. In bark galleries the WTB vector can be observed: it may have up to two generations during the vegetative season, so in the summer larve (white, C-shaped, legless, head reddish-brown) or adults (1.5-1.9 mm long, yellowish-brown) may be present, whereas in the winter only overwintering adults can be found. A control strategy for *Geosmithia* TCD is currently hard to be pursued.

Pustule canker (pathogenic agent: *Juglanconis juglandina*)

According to some reports, *Juglanconis juglandina* should be considered as a weak pathogen, inducing symptoms only on tissues already impaired by other adversities. In Italy, some damage is sometimes recorded in northern hill stands, as twig desiccations associated with foliage wilting; on the desiccated tissues long flat cankers can be observed, at first brown-reddish then blackish, on which several black pustules, i.e. pathogen fruiting bodies, are produced. Mature trees are more often affected, and English walnut is more susceptible than Black walnut.

Armillaria or fibrous root rot (pathogenic agent: *Armillaria mellea*)

The fungal pathogen is a primary parasite, i.e. not necessarily associated with previous conditions of weakness of the host, especially in soils rich of nutrients from previous agricultural crops. Conditions of water logging and root anoxy may predispose to the disease as well. The symptoms affect crown sectors connected with the infected roots and consist of wilting and desiccation of leaves and shoots; Armillaria epigeous symptoms can be recognized with respect to water stress since the latter induce a wilting spread on the whole crown instead to limited sectors. Once discovered, the bark of the infected roots is brownish to black, soft, and under it, after removal, parasitic mycelial mats creamy and fan-shaped can be observed (Figure 24). The underlying wood tissue results very pale and fibrous after the decomposition of cellulose, hemicellulose and lignin by the fungus. Under the bark, black string-like aggregating hyphae can be detected as well, i.e. the rhizomorphs, highly differentiated, with active apical growth, able to transport water and nutrients to long distances; they colonize other roots of the same host or can run free under the soil to infect new hosts. The fruiting bodies (basidiocarps) of the parasitic basidiomycete, commonly known as the “honey fungus”, appear in the autumn near the collar only once the rot has advanced for several years: always in clusters, they are honey-yellow to tan-brown in color, with gills attached to the stipe and this one showing a ring (armilla). While the basidiospores produced by basidiocarps are able to spread the fungus on a wide territorial scale, the rhizomorphs propagate it like wildfire on a local scale; root anastomoses can diffuse the mycelium as well. In any case, an infected plant is a main source of inoculum, so it has to be removed including the stump and the wood debris.

Figure 24. Armillaria or fibrous root rot (*Armillaria mellea*) in walnut planted forest in Italy (photo by CREA)

White root rot (pathogenic agent: *Rosellinia necatrix*)

This disease can rise in stands placed on soils with a fluctuating water table or which are anyhow conditioned by an irregular supply of water. The epigeous symptoms of the infections by *R. necatrix* are similar to those of *A. mellea* attacks, even if their appearance is generally more gradual: extensive yellowing of large crown sectors increases from one year to another, the foliage eventually withers and fall off. The terminal stage of the disease consists of the death of the main branches dependent on the infected roots. The infection almost never proceeds beyond the collar, therefore it can be diagnosed by exposing the roots and looking for a loose, cottony and embracing mycelium, whitish at first and turning to brown as the rot proceeds (Figure 25). Besides the cottony mycelium, mycelial strands, either white or black colored, can be detected on the infected roots or under the bark. The fruiting bodies of this ascomycete, named perithecia, are rarely observed in the field, enclosed in stromata large 1.2-2.0 mm at first reddish brown to dark brown and then black at maturity, single or in clumps, which erupt from the host bark. An imperfect stage, producing conidia disseminating the fungus, is much more frequent on the surface of infected roots as bundles of brown to reddish hyphae not longer than 1.5 mm. The propagation of the fungus in plantation, however, depends more on mycelial strands that run through the soil from the infected plants to susceptible hosts, and on mycelial fragments stuck to woody or herbaceous debris. As sources of inoculum, the infected plants therefore must be removed. Before planting, the pathogen presence in the soil may be assessed by sensitive PCR protocols.

Figure 25. White root rot (*Rosellinia necatrix*) in walnut planted forest in Italy (photo by CREA)

Phytophthora root and collar rot (pathogenic agents: *Phytophthora* spp.)

Several *Phytophthora* species are able to infect English or black walnut (*P. cambivora*, *P. citricola*, *P. cactorum*, *P. cryptogea*, *P. nicotianae*), but only *P. cinnamomi* and very recently *P. gonapodyides* were found as primary pathogens with high virulence. Apart of the last two species, the others may only act as predisposing factors to walnut decline, affecting the root system development and increasing the host vulnerability to environmental stress. The infections of *Phytophthora* are favored by soils water-saturated more than one day long, whereas a good drainage reduces the risk. The symptoms may range from a progressive decline to sudden death, particularly in summer time: crown dieback is often associated with brown to black wet patches at the collar level and up into the trunk, with abundant oozing; sometimes consequent cankers may reach two meters above the collar. The fungal agent, an oomycete, can leave as saprophyte in the soil and disseminates by zoospores in flowing water; thus, in plantations, also farm machinery may contribute to propagate the pathogen. The preventive and therapeutic treatments can hardly eradicate *P. cinnamomi* from infested tissues or soil, but some chemical control is obtained by fosetyl-Al, a systemic fungicide that induce a host defense response.

Bacterial blight (pathogenic agent: *Xanthomonas arboricola* pv. *juglandis*)

The bacterial blight (Figure 26) is known since the early 20th century and is now affecting the walnut wherever is cultivated, but its importance is indeed more marked in the orchards for nuts where it can induce hard damage to the production. Since only green tissues are involved, in timber oriented plantations its incidence is limited but it have to be monitored anyway. The symptoms affect buds, leaves, catkins, nuts and succulent twigs of the current season, whereas the lignified twigs are not susceptible: on leaf blades pale yellowish spots appear and enlarge up to a few millimeters, becoming angular and brown with yellow margins, most numerous near leaflet edges and often deforming them; the lesions on petioles and leaf rachises are dark brown to black as well. On flower or vegetative buds only tiny lesions develop, occasionally leading to their death.

On the catkins, soon after their elongation the infected florets droop and turn black, and lesions on the catkin rachis induce deformities; bacteria may also contaminate the pollen produced by catkin parts not damaged. The infected premature fruits can drop, and the infected nuts that remain on the tree exhibit a marked shell staining.

A chemical control is not suitable in the plantations for timber production, but it is strongly carried out in walnut orchards, mainly by copper-based biocides in combination with ethylene bisdithiocarbamate fungicides, and this caused the rise of *X. arboricola* pv. *Juglandis* resistant strains.

Figure 26. Bacterial blight (*Xanthomonas arboricola pv. juglandis*) in walnut planted forest in Italy (photos by CREA)

Anthracnose (pathogenic agent: *Ophiognomonia leptostyla*)

The anthracnose is a fungal disease most incident in climates characterized by wet growing season; at present, it is an adversity mainly remarked in eastern Europe. As for bacterial blight, green tissues are only affected and the damage in timber stands consists of a loss of production due to an early defoliation. On the leaves, circular brown spots appear at fist on the undersurfaces and then visible on both sides, up to a diameter of 5 mm and surrounded by a yellow edge. When they become numerous, the spots coalesce and lead whole blade portions to yellowing, curling and marginal browning; eventually a limited defoliation may ensue. Brown lesions can be observed on petioles, rachises and succulent twigs of the current season where they may be more elongated. The conidial propagating stage arises abundantly on the necrotic spot surfaces, particularly along the veins, and the conidia are dispersed by splashing and dripping water. The black fruiting bodies of the perfect stage are only produced in fallen leaflets on the ground, where they mature during winter and release the ascospores, responsible for the primary infections, in the spring rainy periods. The fungus, however, in some regions may also overwinter in twig lesions, from which the conidia are dispersed in the spring as well. No measure of control is economically suitable in timber-oriented plantations.

Downy leaf spot (pathogenic agent: *Pseudomicrostroma juglandis*)

This disease is not economically relevant, being its attacks never so incident to induce some detectable loss of production. Differently from the anthracnose agent, *P. juglandis* does not kill the infected leaf tissues before the sporulation, so a true foliar damage is not so frequent and may be observed only when the spots, pale yellow on the upper surface and downy white on the underside, occasionally coalesce to form large areas that eventually become brown and dry. In eastern Europe, the fungus is reported to overwinter as stromata in the fallen leaves, from which infectious spores are released in the air in spring.

13. Watering

Water is probably the most limiting factor in forest ecosystems and water requirements for walnut are high, especially if high growth is expected. Water balance would highly vary depending on climate and soils site's conditions. However, walnut water requirements (potential evapotranspiration) can be considered as relatively homogenous, even though it varies from site to site depending on Temperature and radiation conditions but in a percentage, that we do not consider relevant for management conditions. Hence, considering relatively standard water requirements, the differences from site to site would be basically the amount of precipitation and the water retention capacity, that would define the water balance in a site and, in consequence, would fulfill or not the water requirements from the plant.

Table 13 summaries a general estimation of water requirements (potential evapotranspiration) for walnut plantations during spring and summer in the Bosques Naturales planted forests in Spain. The rule of thumb would be: If weather would fulfill these requirements, watering might not be necessary; however, watering would be a keystone of profitability if weather does not fill these requirements. In the latter case, the difference between requirements and weather should be provided by irrigation. It is important to notice that watering (if necessary) represent a relatively very expensive practice in timber plantations and forest management should take this into consideration.

In the case of watering would be necessary, it might be done mainly by surface or by dripping. Manual irrigation is also done but it is very expensive and labor-demanding, only recommended in small scale plantations where the forest owner is the worker who would perform the activities.

Surface irrigation (furrow, flood, or level basin) needs that the field would be flat and well leveled and no fertilizer or phytosanitary products can be added to the water to be applied at the same time. On the other hand, drip irrigation can be done in slopes and fertilizer or phytosanitary products can be added to the water. In addition, dripping irrigation is considered as a much more water efficient practice. Two dripping lines (with dripping systems each 0.75-1 m) are recommended per plantation line, one at each side of the trees, in order to promote a more homogeneous tree growth.

Table 13. Estimated water requirements for walnut (*Juglans* sp.) planted forests in Spain

Month	Water requirements (L/m^2) by age				
	1 year	2 years	3 years	4 years	> 5 years
April	0.5	0.8	1	1.5	2
May	36	44	52	68	80
June	64	78.7	93	122	140
July	99	121	143	187	220
August	94.5	115.5	136	178.5	210
September	46	57	67.5	88	100
TOTAL	**340**	**417**	**492.5**	**645**	**752**

14. Nutrition and fertilization

Nutrient availability is another key factor which could limit the productivity of the plantation if it is not adequate. In addition to the detailed soil study that should be done before the establishment of the plantation, plant nutrition should be periodically monitored in order to manage the fertilization of the plantation. Two main tools can be used to this respect: soil and foliar analysis.

Foliar analysis

Nutrient foliar concentration is considered a useful tool to evaluate the nutritional status of a stand because (a) its variation is highly dependent on site and soil parameters; (b) it reflects the current nutrient supply; (c) it allows diagnosis of nutritional deficiencies when they are not severe enough to cause visually observable symptoms and, thus, it allows action to be taken before the effects on productivity are significant; and (d) deficiency symptoms are easily confused with other effects when visual guidelines are used (Mead 1984; Drechsel and Zech 1991; West 2006).

Foliar analysis has been used for diagnostic purposes, establishing critical levels or ranges within the simplified concept that a plant which has a nutrient concentration below the critical level will be less productive than plants with a higher concentration (see Richards and Bevege 1972). Table 14 summarizes some values reported by Muncharaz Pou (2001) as critical levels for the interpretation of foliar analysis in walnut forests.

Table 14. Summary of values reported by several authors as critical levels for the interpretation of foliar analysis in walnut (*Juglans* sp.) forests

Nutrient	Muncharaz Pou (2001)
N (%)	> 2.5-3.25
P (%)	> 0.12-0.13
K (%)	> 1.2-3
Ca (%)	> 1.25-2.5
Mg (%)	> 0.3-1
S (%)	> 40-170
B (mg/kg)	> 35-300
Fe (mg/kg)	> 75-155
Mn (mg/kg)	> 30-350
Cu (mg/kg)	> 4-20
Zn (mg/kg)	> 20-200
Mo (mg/kg)	> 0.7-1

Fertilization

The design of a specific fertilization plan should be done taking into account an as much detailed as possible soil and foliar analysis and an analysis of the nutrient cycling in the system, including an estimation of nutrient removal trough harvesting.

Fertilization of walnut production has been usually recommended as a consequence of the nut production (and consequent nutrient removal), which was usually the main purpose. As an example, Table 15 summarizes a yearly fertilization recommendation from Luna (1988) for walnuts oriented to nut production.

As nutrient requirements for a walnut plantation would be different depending on the main purpose (timber vs. nut), the fertilization is regarded to be different. Hence, Table 16 summarizes a general fertilization plan designed for walnut planted forests without any detected big soil deficiencies following the experience of Bosques Naturales S.A.

If a dripping irrigation system is installed in the plantation, fertilization and organic amendment can be done together with water (i.e. fertirrigation). Specific products can be selected for this purpose and a more detailed design should be drafted.

Table 15. Fertilization scheme recommended for walnut (*Juglans* sp.) planted forests oriented for nut production [from Luna (1988)]

	Yearly fertilization recommendation (kg/ha)		
	N	**P2O5**	**K2O**
Establishment		100-150	150-200
Young plantations	60-80	80-100	80-120
Mature plantations	60-80	80-100	120-180

Table 16. Fertilization scheme recommended for walnut (*Juglans* sp.) planted forests oriented for timber production from the Bosques Naturales S.A. experience

Age	**Yearly fertilization recommendation (kg/ha)**				
	N	**P_2O_5**	**K_2O**	**MgO**	**CaO**
1	20	12	24	5	4
2	40	24	48	10	8
3	60	36	72	15	12
4	80	48	96	20	16
5 a 8	100	60	120	25	20
9 a 17	50	30	60	13	10
18 a 25	25	15	30	6	5

15. Weeding and maintenance

A combination of weeding with specific machinery, herbicides application and tillage has been traditionally recommended in general as vegetation control to avoid competence, together with the use of livestock (mainly sheep) to control and get some profit from herbaceous vegetation, turning the planted forests into silvopastoral systems (Figure 27). In addition, a geotextile may be used for young plantations (younger than 5 years) to reduce the work-load.

The combination of these different techniques results in a program whose activities varies depending on the plantation age, which would vary depending on the desired or allowed management intensity and the occurrence or not of other activities such as watering. In this manual, a general weeding program is described for a plantation without irrigation.

Years 1-2

Periodic mechanical weedings should be done in spring-summer. If they are done double-crossed, they would be done into 2 different and elapsed times to improve effectiveness in the section crossed. This can be complemented with tillage in summer when hydric needs are higher than usual to avoid water competence and a localized weeding just around the trees (< 1 m^2/tree) manually or with herbicides.

When herbicide application is suggested in spring or autumn, 4 L/ha of Oxyfluorfen (24%) is generally recommended, except for sites near water sources (<20 m) where 8 L/ha of Oxadiazon (25%) is preferred aiming to reduce environmental impact. Similarly, when herbicide application is suggested in summer, 4 L/ha of Glyphosate (36%) and 0.4 L/ha of Oxyfluorfen (24%) is generally recommended, except for sites near water sources (<20 m) where 4 L/ha of Glufosinate (16%) and 75 mL/ha of Paraffin Oil (81 %) is preferred aiming to reduce environmental impact.

Years 3-4

The same operations are recommended than for years 1 and 2 but with a lower intensity and periodicity. Herbicides considerations are the same as proposed in years 1 and 2.

At the early spring of the third year, a grass land can be established between the plantation lines either using the natural seeds from the soil bank or introducing new ones (e.g. *Trifolium subterraneum*, *Lolium* sp., *Agrostis* sp. or a mix from them).

Years 5-7

The same operations are recommended than for early years but with a lower intensity and periodicity.

Weeding control with herbicides can also be done in a 1.5 buffer each side of the plantation lines during that stage of the plantation. This should be done once right at the end of the winter or early spring and 2 times during the spring. For late winter/early spring herbicide application, 4 L/ha of Oxyfluorfen (24%) is generally recommended, except for sites near water sources (<20 m) where 8 L/ha of Oxadiazon (25%) and 4 L/ha of Glyphosate (36%) is preferred aiming to reduce environmental impact. For spring and summer herbicide applications, 5 L/ha of Glyphosate (36%) and 300 mL/ha of Paraffin Oil (81 %) is generally recommended.

At this stage of the plantations the trees have usually reached enough dimensions to resist the possible damages from livestock (mainly sheep) and the establishment of a silvo-pastoral system could be recommended.

Years 8-20

During this period, the weeding control should be progressively reduced as the trees grow and inhibit the weed growth and no weeding should be necessary at the end of the rotation.

Figure 27. Silvopastoral system with sheep grazing (used for weed control) within walnut planted forest in Galicia (NW Spain)

16. Pruning

Considering that timber-oriented walnut planted forests are usually managed with an objective of quality timber, pruning is an important activity in plantation maintenance which would be directly reflected in final timber price and, hence, plantation profitability (Figure 28). Mohni et al. (2009) have reviewed several issues to be taken into account regarding pruning in walnut plantations, which are included in this manual.

Formative shaping

Walnuts do not have a strong central axis, their growing habit being sympodial, and formative pruning is normally required to ensure a single and straight stem of 1.5–3.0 m. Walnut terminal shoot sometimes shows reduced growth so it can be overtaken by one or two lateral shoots. In this case the defective terminal shoot should be substituted with the most vertical and tall lateral shoot.

Walnut formative shaping should be initiated from the second growing season when trees reach 1 m in height and demonstrate annual height increment of approximately 25 cm. Productive pruning should be started later, after 3–4 growing seasons, when trees are 2 m in height or when the diameter of branches reach approximately 3 cm at the basis of the crown.

Pruning

It is possible to define three types of formative pruning: “flagpole pruning” (termed “astone” pruning in Italy , and “élagage en queue du billard” in France) is the typical pruning method adopted in the South of Italy and in France for the production of wood and nuts, “progressive pruning” used in France and a new type, “reiterative pruning”, tested in Italy. These three types of pruning are described in more detail in Table 17 and Figure 29.

Pruning that is conducted too early and too brutally can have the following consequences: a lack of stem rigidity (cylindrical trunk rather than conical), an explosion in the production of epicormics, a hypertrophy of the pruning wounds (continual elimination of the epicormics which develop on the wounds of pruning) and a general reduction in growth. This type of pruning could initially encourage height growth but only for a few years, thereafter as a consequence, growth would slow down considerably, accompanied by a general weakening of the tree. On the contrary, if a good proportion between crown length and the length of the pruned stem is maintained (respectively ⅔ and ⅓ of the total tree length, and for isolated trees ½ and ½), pruning will permit the development of a clean trunk without epicormic growth.

Pruning that does not exceed 50 to 60 % of the total tree length is advised. The target pruning height would be 4 m for isolated trees and 6 m for stand trees. On isolated trees grown on less favorable sites, the pruning height could be as little as 2.5 m but this should be considered the minimum. Hence, in most plantations the target height should be between 2.5–4.0 m. The stem diameter should not exceed 10 cm at the height of the lowest pruned branch.

Pruning can be done at any time during the year in walnut plantations and Table 18 summarizes the effects of the different pruning seasons. The best time to prune to avoid development of epicormics, is June and August; although diameter growth was reduced (20 % less radial growth compared to unpruned trees) for three to four years after pruning in June and August. It is inadvisable to prune in November due to the development of a high number of epicormics and the detection of pathogenic fungi. However, pruning in summer produce negative effects on wood quality (wood discoloration). The presence and extent of wood discoloration depended mainly on branch dimension, indicating that a maximum branch diameter of 3 cm was desirable. To obtain a clean trunk without epicormics and other defects, it is advised to limit any pruning to small-diameter branches (less than 3 cm in diameter). Regarding the method, pruning can be done with a platform to reach higher heights (Figures 28 and 30) or manually (Figures 31 and 32 and).

Figure 28. Platform for pruning in a walnut planted forest in Caceres (CentralSpain)

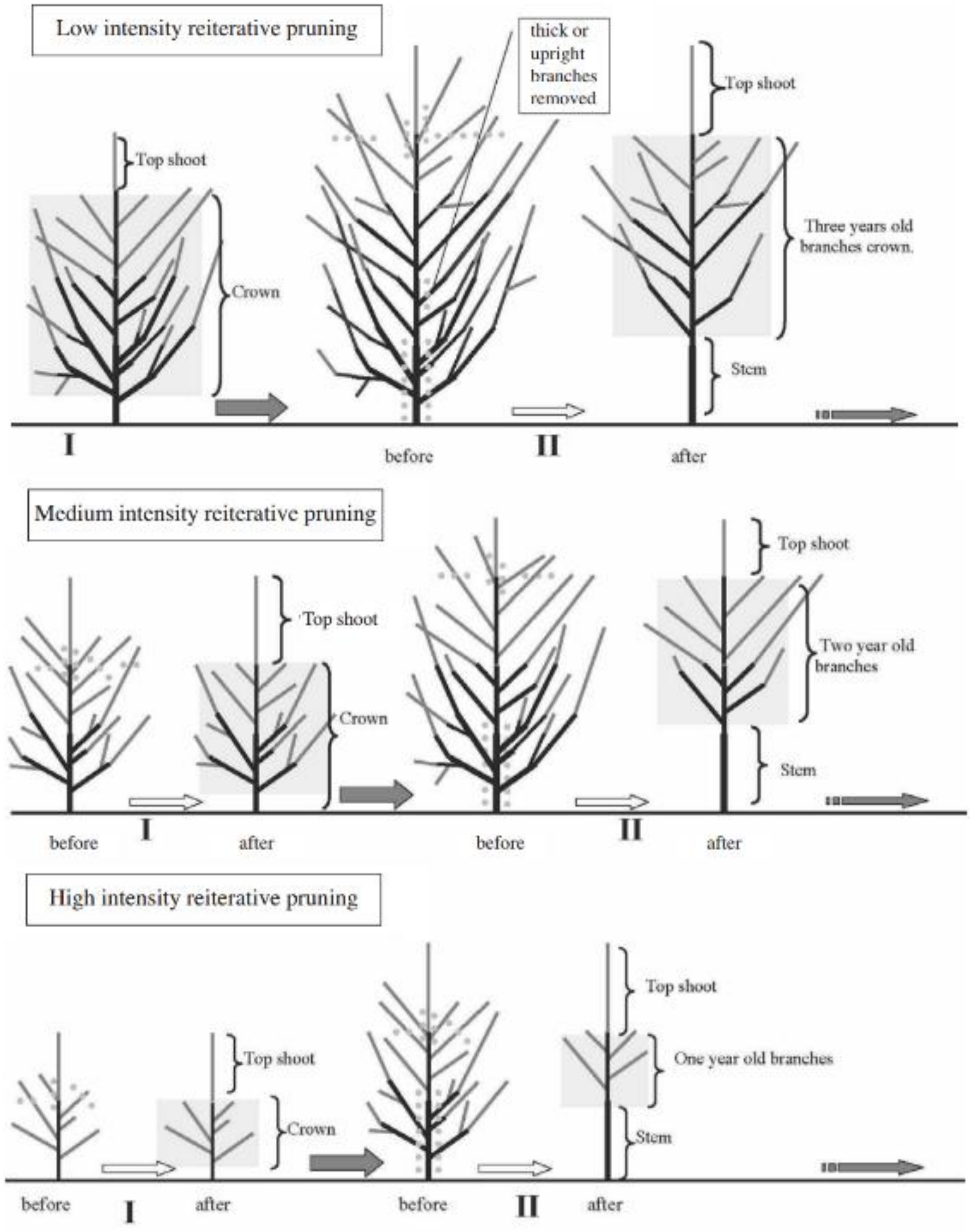


Figure 29. Different intensity levels of reiterative pruning for walnut (*Juglans* sp.) planted forests (Mohni et al. 2009)

Table 17. Summary of the three methods of pruning used for walnut trees (*Juglans* sp.): definitions, advantages and disadvantages (Mohni et al. 2009)

Pruning method	Advantages	Disadvantages
Flagpole pruning This technique is the most widely adopted for walnut in Italy. It is practical only with optimal site conditions where it is possible to obtain an annual height increment of at least 100-150 cm. Use of this pruning method provides effective control of tree architecture. It consists of systematic and repeated removal of all shoots along the stem. Only the apical shoot it is not controlled and grows freely. It is necessary to repeat this process every year until the trunk reaches 2.5-3.0 m in height. When this pruning method is adopted, more operations are necessary during the same growing season to control new shoots. In general, the pruning period extends from April to July.	Pruning produces rapid stem elongation and defects are absent from the central stem.	The stress due to this technique, that favors stem elongation rather than diameter growth, produces instable trees that need additional support.
Progressive pruning In this type of pruning trees initially grow without any intervention. Later, at least after two years, pruning is carried out to control and modify tree architecture. During formative cutting (shaping) only branches that are prone to become dominant or competitive with the apical shoot must be cut or controlled. The progressive pruning method focuses on increasing the crown height minimizing the stress on a tree in order to reach a minimum of 2.5 m of clean stem. This goal must be obtained progressively before stem diameter reaches 10 cm by removing all branches. Using this technique, larger knots and anomalous colors in the wood are avoided. Progressive pruning can be implemented in winter or spring but to favor rapid healing, vigorous branches (c. 3 cm) should to be cut in winter.	With this method of pruning it is not necessary to provide additional support because trees are generally stable. This technique is more suitable for medium and low fertility conditions.	This pruning technique requires a highly skilled workforce. In contrast with the other pruning methods, wood quality is lower due to the presence of knots and defects.
Reiterative pruning This pruning method is carried out in green (June-July). With this technique it is possible to stimulate trees to produce a particular crown structure that will be reiterate every year until a free stem 2.5 m long is produced. The typical crown structure consists in: (A) apical shoot without lateral branches; (B) intermediate stem of two or more years (according to pruning intensity) with many small branches able to develop freely and to produce a large photosynthetic surface; and (C) basal stem without branches. In relation to site conditions it is possible to distinguish three intensity levels: (1) Low intensity: used in non-optimal site conditions, trees have to demonstrate height increments at least 50-70 cm; (2) Medium intensity: used in medium-good site conditions, trees have to demonstrate height increments at least 70-100 cm; and (3) High intensity: good site conditions, trees have to show height increments at least 100-150 cm.	The trunk presents few defects in the central cylinder. Its dimension depends on pruning intensity.	Using high intensity pruning, trees are stressed and instable, similarly to flagpole pruning, and additional support is required.

Table 18. Summary of pruning season and their effects on walnut (*Juglans* sp.) trees [modified from Mohni et al. (2009)]

Pruning season	Epicormics	Radial growth	Callous margin	Discoloration	Fungi infection
June	0	++	(2)	+	0
August	0	++		+	0
November	++	0	(1)	+	+
February	+	0	(1)	0	0
Symbols legend	0=neglible +=moderate +=high	0=no reduction +=moderate ++=High reduction	(1)=medium (2)=best	0=very little +=normal	0=no infection +=infection

Figure 30. Platform for pruning in a walnut planted forest in Caceres (CentralSpain)

Figure 31. Photo of a manual operation of reiterative pruning in Italy (photo by CREA)

Figure 32. Photo of the crown shape after a manual operation of reiterative pruning in Italy (photo by CREA)

17. Thinnings

Different fashions have been around during last decades regarding walnut plantations and some of them were about planting the trees in low density, near or equal the final one, with consequently no need for thinning. However, in recent years, even though density is still recommended to be low, planting a bigger stock and perform one or two thinnings is suggested. Thinnings allow selecting the best trees in the plantations, removing the worse ones while maintaining a good density and concentrate the land productivity in a smaller number of bigger trees. In addition, thinnings may obtain an intermediate economic input. However, in order to attach this economical objective, certain dimensions (e.g. DBH 20 cm) needs to be reached depending on industry requirements.

Even though some research has been done regarding thinnings in walnut plantations, there is a general lack of information to this respect and plenty of research is being carried out at the moment.

Early thinnings in plantations from seeds

The plantation designs described in previous chapters as tentative spacing (e.g. 5 x 6 m or 7 x 7 m, etc.) might be exact when establishing clonal plantations with high quality plant material, where good performance of each tree is ensured by the selected genetic material.

On the other hand, when seed plant material is used, the performance of each tree is very variable and you can find well performing trees near to ones with poor growing rates or shape problems. Hence, an early thinning would be necessary in those cases to select the good performing trees and discard the bad ones. A nice solution which is being used in some plantations in Italy is to plant 2-4 plants spaced 1 m between them around each of the spots where the trees are marked following the designs detailed in the previous chapter. Hence, this would allow to select 1 of these group of 1-4 trees at an early age of around 3-5 years old, resulting afterwards in a design similar than the desired with slight modifications as a result of this selection (Figures 33, 34 and 35). Hence, this would require a much higher initial plant density (x 2, x 3 or x 4-fold) at establishment to allow this early thinning.

Taking into account that good clones are nowadays difficult to be found in the market, this option has been used to somehow overcome the problems with commercial seedlings either in pure, mixed and polycyclic plantations

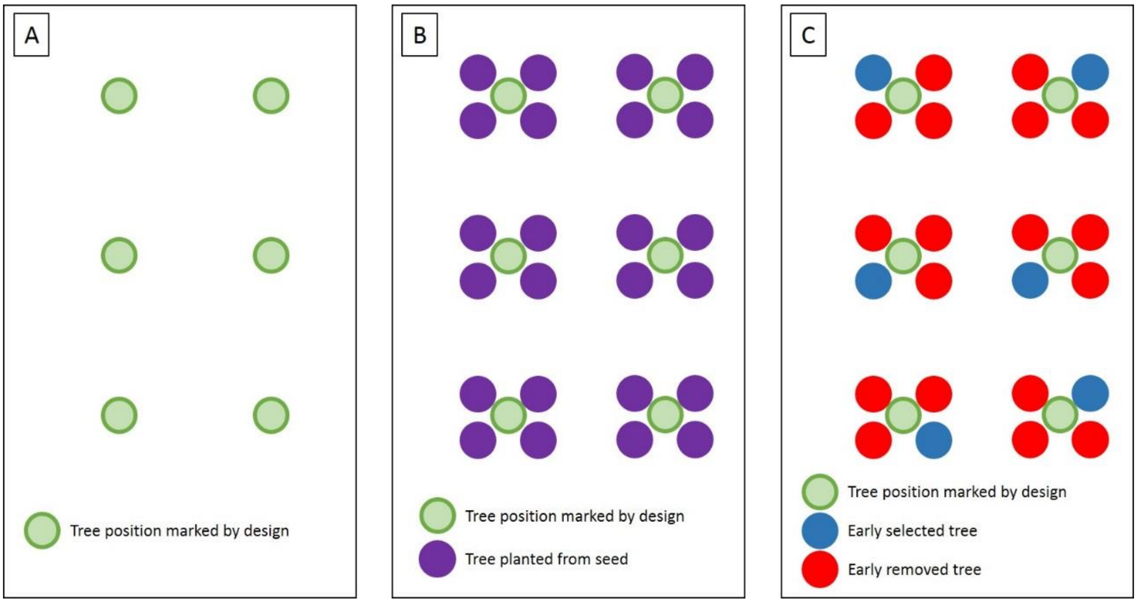


Figure 33. Example of an early thinning in an initially high-density walnut (*Juglans* sp.) planted forests using seed plant material. (A) Ideal position of the trees following the desired plantation design. (B) Planting 4 plants spaced 1 m between them around the ideal positions designed. (C) Early thinning selecting one tree of each group of 4 and removing the others, resulting in a plantation design slightly different than the designed one (A).

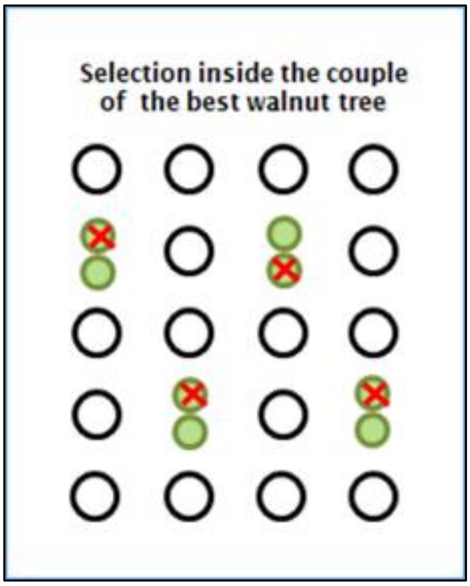


Figure 34. Example of an early thinning in an initially high-density walnut (*Juglans* sp.) planted forests using seed plant material, planting 2 plants spaced 1 m between them around the ideal positions designed and selection one of them in an early thinning.

Figure 35. Photo of two young walnut trees planted very close in order to perform an early thinning for selecting the best performing one in a plantation in Italy (photo by CREA)

Thinnings in mature stands

At the moment, based on information generated for black walnut (*Juglans nigra* L.) in USA, the method of crown competition factor (CCF) is proposed as a method for thinning design (USDA 1981; Mohni et al. 2009). CCF is the per cent ratio between Maximum Crown Area (MCA) and the surface (A) of land occupied by trees: $CCF = \Sigma\,(MCAi)/A \times 100$. This factor is an objective method to evaluate the optimal stocking density and to plan thinning regimes. In Italy, CCF has been applied in plantations with different stand density (from 4 × 4.5 to 7 × 7) and has shown good potential of application for walnuts plantations in Europe. When CCF has reached 110 %, the stand must be thinned reducing the factor to 70 %. Independently from the initial spacing, this aim is achieved by thinning approximately 30 - 40 % of trees.

Walnut does not readily react to canopy opening if it is grown in dense plantations where excessive lateral competition and reduction in a crown's functionality is already evident. In such situations, the tree demonstrates small diameter growth for many years after thinning (Marchino and Ravagni 2007). Therefore, thinning must be undertaken before lateral competition influences diameter growth, with the aim of maintaining trees with crowns free from competition and able to grow with large and constant diameter increments.

Table 19 shows a general recommendation about when to perform the first thinning depending on the initial plant density (Cisneros et al. 2008). Under this general framework it can be estimated that under a scheme with initial plant densities lower than 400 trees/ha the first thinning would correspond with mean DBH higher than 20 cm, considered to be a threshold differencing a profitable and a non-profitable thinning because of log dimensions and industry demands. Similarly, in plantations where initial plant densities are lower than 200 trees/ha, the first thinnings can be considered as final felling as the DBH would be higher than 35 cm, considered as a diameter big enough for the industry (Cisneros et al. 2008).

Table 19. General recommendation about when to perform the first thinning depending on the initial plant density in walnut (*Juglans* sp.) planted forests (Cisneros et al. 2008)

Initial plant density (trees/ha)	DBH (cm) indicating excessive competence	Recommended thinning (trees/ha)
100	53	36
150	41	55
200	34	73
250	29	91
300	26	109
350	23	127
400	21	145
500	18	182
600	16	218

DBH: Mean Diameter at Breast Height (1.30 m)

Montero and Cisneros (2006) propose an equation to estimate walnut crown diameter (Dc) as a function of DBH in order to evaluate tree competence:

$$Dc = 0.580511 \cdot DBH^{(0.759553)}$$ [Montero and Cisneros (2006)]

Based on the CCF system and the proposed estimation of Dc based on DBH, Cisneros et al (2008) propose a scheme with an initial plant density of 400 trees/ha and 4 thinnings, at different ages depending on the site quality, to obtain 66 trees/ha with 60 cm DBH at final felling with a rotation period between 50 – 70 years (Table 20).

Coello et al. (2013) proposed an adaptation from the model suggested by Cisneros et al. (2008) based on a lower initial walnut density (185 trees ha^{-1}), estimating a final harvest at 50 years of rotation period of around 55 trees ha^{-1} of 60 cm DBH (Table 21).

Table 20. Management scheme proposed by Cisneros et al. (2008) for walnut (*Juglans* sp.) planted forests with an initial plant density of 400 trees/ha and 4 thinnings, at different ages depending on the site quality, to obtain 66 trees/ha with 60 cm DBH at final felling with a rotation period between 50 – 70 years

	Plantation age		Before the thinning (CCF=110%)			After the thinning (CCF=70%)	Trees thinned
	Site class I	Site class II	DBH (cm)	Dc (cm)	N (trees/ha)	N (trees/ha)	N (trees/ha)
1st thinning	13	20	21	6	400	255	145
2nd thinning	19	27	29	7	255	162	93
3rd thinning	27	38	39	9	162	103	59
4th thinning	40	55	52	12	103	66	37
Harvest	51	70	60	13	66		66

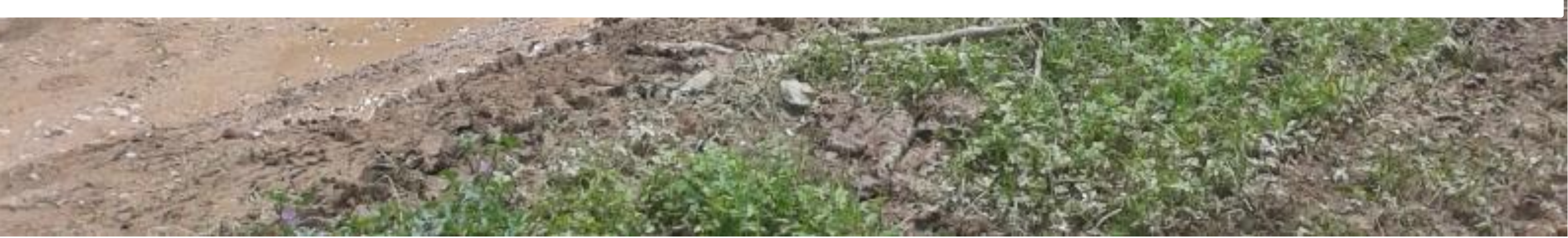
DBH: Mean Diameter at Breast Height (1.30 m). Dc: Crown diameter. CCF: Crown Competition Factor

Table 21. Thinning schedule proposed by Coello et al. (2013) for walnut (*Juglans* sp.) planted forests with an initial plant density of 185 trees ha^{-1} (9x6 m spacing) and 4 thinnings, taking into account an estimation of 5 trees ha^{-1} which are lost due to natural mortality or lack of vigor

	Age	DBH (cm)	Thinned trees (trees/ha)
1st thinning	18	20	45
2nd thinning	25	28	35
3rd thinning	35	41	25
4th thinning	43	50	20
Harvest	50	60	55

DBH: Mean Diameter at Breast Height (1.30 m).

SECTION IV. HARVESTING THE PLANTATION



18. Harvesting

Even though thinning may be considered as an intermediate harvest if economic profitability is obtained, the main harvest would be at the end of the rotation period. This depends on the cultivation systems, the silvicultural planning and management and the site conditions, varying between 20-30 years in intensively managed planted forests and longer and more traditional rotations of 50 years in good sites and 70 or more in worse sites.

Depending on these same described factors, the harvested volume is highly variable, from 1 to 6 m^3/ha/year, considering 1-2 m^3/ha/year as a conservative estimation of good quality harvest for furniture. In short rotation plantations. To this sense, Cisneros et al. (2008) summarize different models which allow to estimate volume as a function of DBH:

> V (dm3) = -11.6 + 0.336 · DBH + 0.2692 · DBH^2 [ICONA (1980) cited by Cisneros et al. (2008)]
>
> V (dm3) = -0.8508 – 0.5674 · DBH + 0.3237 · DBH^2 [Bordin et al. (1986) cited by Cisneros et. (2008)]

Cisneros et al. (2008) warn about a possible lowering bias in the first of the equations and recommend the second one.

Even though different harvesting techniques are possible, clear felling is usually used in this kind of planted forests, cutting and removing all the trees at the end of the rotation. Depending on the plantation characteristics and the availability in the region, harvesting would be as much mechanized as possible.

Depending on the financial situation, once the trees get to certain dimensions, rotation period can also be modified depending on market situations and owner's needs. Two possible examples of this can be: (1) A more "commercial plantation" which ends the rotation period but market prices at this time are lower than the average can evaluate the possibility of waiting until market prices rise up. However, in this scenario it would be necessary to evaluate the risks of letting the trees at the field would have (e.g. fire, pests …). (2) A "small owner plantation" can consider the plantation in some cases as a "bank deposit" and sell some (or all) trees if a cash input would be needed.

19. Log classification

Wood produced by planted forests must be classified according to the needs and demands from the forestry industry, which is an important keystone when designing and planning the establishment and management of the plantation. To this respect, walnut (Juglans sp.) planted forests are mostly oriented for the final production of wide slicing veneer logs, assuming the industries demand those and prices are relatively high. However, these wide logs (i.e. big diameter) are considered as the target production at the end of the rotation period. On the other hand, when considering the variety of products that can be obtained along the whole rotation period, it can be highlighted that smaller logs can also be obtained (e.g. thinnings, intermediate harvests, etc.) that might not be suitable for slicing veneer industry but definitively they might be used in peeling veneer industry or as saw logs. For some other species, the definition of the requirements from the industry are relatively clear, but the particular conditions of the walnut market have caused that the log classification for walnut (apart from the slicing veneer) are unclear. Hence, one of the objectives of the Woodnat project is to expose the experience of the partners to this respect and show a scheme regarding log classification for different uses of walnut wood.

Taking into account the high variability in walnut wood properties (mainly aesthetical) depending in the history and local conditions of each tree (genetic material, management, etc.), as well as the wide diversity of end-products, the big market interest and the relatively high prices of walnut wood, classifying the logs is a key process in the production chain when the "plantation phase" ends and the "industry phase" begins.

Hence, log classification is considered very relevant for the owners and managers of walnut planted forests and a specific deliverable of the WOODNAT project has been dedicated to this subject and it is published for public consultation (Fernández-Moya et al. 2019) while and the main issues regarding this topic are summarized in this chapter.

Classification by size

The log dimensions are key in order to evaluate and classify the logs from a forest harvesting. To this respect the European Standard EN 1315-1 establish a guideline for dimensional classification of hardwood round timber, summarized in Table 22.

According to this European Standard EN 1315-1, dimensional classification shall be made, irrespective of length, into classes according to the mid diameter under bark or over bark. The under bark classification is described by a D letter. The over bark classification is described by an R letter. The D or R letter shall specify the type of class. When the over bark classification is used, the seller shall specify the bark allowance used for the deduction of the bark. Bark allowance is expressed by the formula:

$$\text{Bark allowance} = (D^2 - d^2) \times 100 / D^2$$

Table 22. Summary of dimensional classification of hardwood round timber as described in European Standard EN 1315-1

Class	Mid diameter under bark (cm)*	Class	Mid diameter over bark (cm)*
D 0	< 10	R 0	< 10
D 1 a	10 – 14	R 1 a	10 – 14
D 1 b	15 – 19	R 1 b	15 – 19
D 2 a	20 – 24	R 2 a	20 – 24
D 2 b	25 – 29	R 2 b	25 – 29
D 3 a	30 – 34	R 3 a	30 – 34
D 3 b	35 – 39	R 3 b	35 – 39
D 4	40 – 49	R 4	40 – 49
D 5	50 – 59	R 5	50 – 59
D 6	≥ 60	R 6	≥ 60

* Mid diameter should be measured using the method stated in European Standard EN 1309

Classification by quality

This section specifies a qualitative classification and grade designations for standing walnut trees (derived from the European Standard EN 1316-1, relevant to Oak logs, and from the EN 1747, relevant to classification of standing trees – a project that has been abandoned). For the purposes of this document, the terms and definitions given in EN 844 apply.

The following referenced documents are indispensable for the application of this classification [for dated references, only the edition cited applies; for undated references, the latest edition of the referenced document (including any amendments) applies]:

- EN 844, Round and sawn timber - Terminology
- EN 1309-2, Round and sawn timber - Method of measurement of dimensions – Part 2: Round timber - Requirements for measurement and volume calculation rules
- EN 1310, Round and sawn timber - Method of measurement of features
- EN 1311, Round and sawn timber - Method of measurement of biological degradations

Grading principle: Each tree, or portion of tree individualized by a theoretical crosscut point, is qualified according to the presence, size and distribution of specific characteristics.

Designation of grades: Standardized designation of classes includes two characters, separated by a dash:

- the first character is the genus initial letter in Latin (i.e. “J” from Juglans);
- the second character indicates the quality class

Hence, the classification of walnut is divided in four quality classes:

- J-A is an exceptional quality class;
- J-B is a normal quality class;
- J-C is a less valuable quality class;
- J-D includes all trees and portions of trees which do not meet the requirements of the other quality classes, but not less than 40 % of the volume shall be useable.

Based on this grades, Table 23 gives the characteristics taken into account in this classification and these shall be measured according to EN 1309-2, EN 1310 and EN 1311. The presence of a single characteristic which does not meet the class requirement is sufficient to downgrade the tree or log that is being classified.

Table 23. Grading rules for standing walnut (Juglans sp.) trees

Characteristics	Class			
	J-A	J-B	J-C	J-D (3)
Sound knots/branches	<= 15mm/2.5m (1)		permitted	permitted
Unsound knots/dead branches	not permitted	(2)	<=50mm/2m	permitted
Marks on bark (pin knots, covered knots, burl) (number/m)	1/2.5m (1)		permitted	permitted
Ovality %	< 10	permitted	permitted	permitted
Sweep (cm/m)	<= 2	<= 4	<=10	permitted
Frost crack	not permitted	not permitted	not permitted	permitted
Insect attack, grub holes, rot	not permitted	not permitted	not permitted	permitted

(1) If there is no other singularity.
(2) Σ max = 100 mm of these singularities (sound branches, dead branches and pin knots) for a length of 2,5 m, with a diameter of a sound branch <= 60 mm and a diameter of a dead branch <= 20 mm. A pin knot is counted as a 5 mm diameter knot.
(3) For all the characteristics, in class J-D, > 40 % of the volume of the wood shall be useable.

Classification by end-product

In addition to log size and quality, the end-product is key in order to classify the logs accordingly to the main industries: mainly slicing veneer logs, peeling veneer logs and saw logs.

Classification for other species (e.g. oak, etc.) are relatively clear, but, the market conditions for walnut make their classification somewhat unclear. However, based on the experience of the authors, a classification system has been designed considering the previously described classifications according to size and quality (Table 24).

Table 24. Log classification by end-product for walnut (Juglans sp.) timber

Product	Minimum diameter (cm)	Minimum longitude (m)	Quality class*
Slicing veneer logs	35	2.5	A
Peeling veneer logs	20	0.6	A
Saw logs	15	1.2	A, B, C and D

* Quality classes as described in the previous section

20. Commercialization, industry and end-use

Timber is in most of the cases the main economic income in a walnut forest plantation such as the ones that have been treated along this manual. However, once the rotation cycle has been completed (or in an intermediate point of it) and the owner has decided to harvest it, a problem arises when trying to sell the timber.

Walnut timber traditionally has two main uses: wood veneer and sawn wood., Wood properties from hybrid walnuts are similar than from the common walnut (Merlo-Sánchez et al. 2009) (Table 9). However, there several relevant differences with respect the other species (Figure 36):

- More sapwood percentage for the same diameter (because a certain diameter is obtained with much younger hybrid walnuts compared with the common ones)
- Denser and more homogeneous sapwood in the hybrids
- Longer logs can be obtained, mainly because of pruning in the hybrids' intensively managed plantations
- Much lighter color in the hybrids, mainly because of the higher sapwood percentage. However, color is easily modified by the industry.

Figure 36. Wood from Black or American walnut (*Juglans nigra*) [left], Persian walnut (*Juglans regia*) [center] and hybrid walnut (*Juglans x intermedia*) [right] (Photo from Black walnut by www.wood-database.com)

The price a forest owner would receive for the timber would vary according to many factors, such as:

- Tree species: Different Walnut species (Black or American, European or Persian or Hybrid), for the present case
- Supply and demand
- Relation between the amount of timber and the total surface of the plantation

- Plantation topography
- Plantation roads infrastructure and access
- Quality, dimensions (long and diameter) and shape
- Distance between plantation and industry
- Market knowledge and owner's negotiation ability

The walnut timber end use is mainly for decoration and high quality and/or luxury furniture. This end use is independent of the walnut species. However, the market and the price may vary depending of them.

Black or American walnuts have an international, relatively stable and well-organized market with constant demand and supply which allow industry and owners to perform calculations and balances. Hence, a reference price for the American walnut timber can be relatively easy to consult from the industry (Tables 22 and 23).

On the other hand, the market of Common walnuts in Europe is local and very variable, with difficult products for the industry and, consequently, normally used by handcrafts carpenters. Hence, it is hard to make estimations about a reference price due to the small demand and the low amount of transactions in the market.

Finally, the timber from hybrid walnuts does not have a well-defined market yet and it is difficult to estimate a market price for that, because the amount of supply is still very low.

Table 25. Prices (with standard deviations) of Black Walnut (*Juglans nigra*) paid for delivered sawlogs by Indiana Sawmills (USA) depending on wood quality (Indiana Forest Products 2016)

Quality	October 2015		July 2016	
	$/m³	Std. dev.	$/m³	Std. dev.
Prime	722	185	700	70
N°1	554	81	476	28
N°2	405	71	332	38
N°3	243	52	200	35

Table 26. Prices (with standard deviations) of Black Walnut (*Juglans nigra*) paid for delivered veneer logs by Indiana Sawmills (USA) depending on wood quality and log diameter (Indiana Forest Products 2016)

Quality	Log diameter (cm)	October 2015		July 2016	
		$/m³	Std. dev.	$/m³	Std. dev.
Prime	1,248	203	1,488	154	1,248
	1,773	226	1,821	104	1,773
	2,337	196	2,434	103	2,337
	2,836	230	3,116	100	2,836
	3,601	291	3,908	226	3,601
	4,232	387	3,992	0	4,232
	4,149	699	4,202	0	4,149
Select	851	273	840	0	851
	1,187	320	1,471	0	1,187
	1,628	432	1,891	0	1,628
	1,996	369	2,129	392	1,996
	2,311	429	2,171	350	2,311
	2,626	504	2,381	350	2,626
	2,472	547	2,731	0	2,472

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