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Using Tree Basal Area for Estimating Timber, Hay and Nut Productivity in a Silvoarable System with Common Walnut Tree (*Juglans regia* L.)

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Abstract: Agroforestry systems with multipurpose tree species, for the double production of timber and fruit, along with the intercropping with herbaceous crops, can be fundamental land use systems for multiple ecosystems services. Research was conducted in Italy, for one growing season, in 18 years old agroforestry experimental plots with common walnut (Juglans regia L.) trees, according to the previous agroforestry management (AFM) since tree planting. The aim is i) estimating trees growth and herbaceous yield in relation to increasing tree size, especially referring to the trees basal area (G); ii) evaluating the role of nut production as additional product to timber and food crops. Observations were run on tree growth and leaf phenology, total light transmittance (TTL) below tree canopy and hay yield with and without walnut intercropping. Nut yield was estimated from available literature and associated to G. At the end of the study year, representing two third of trees rotation, their height varied between 10 and 11 m, with much larger variation for tree diameter between 17 and 22 cm, according to the previous AFM, including tree mulching with plastic film. Hay yield varied between 4.5 and 3 Mg ha year^{-1} outside and under tree canopy, respectively. Negative regression were determined for G and TTL, and G and hay yield, with an annual reduction of 5% per G unit. Simulations were run on hay and nut yield, using G as main input parameter. The work points out the following key findings: i) the usefulness of plastic mulching, at tree planting, to increase the long-term timber productivity of the trees intercropped with herbaceous crops; ii) the negative linear relationship between hay productivity and walnut trees G; iii) G influences, in positive way, more markedly nut than hay yield. Suggestions are given on the optimum tree planting spacing and AFM for balancing timber, nut and hay yields.

Keywords: agroforestry; hay meadow; hemispherical photos; intercropping; plastic mulching

1. Introduction

Agroforestry is a land use combining, in spatial arrangements, trees with crops and/or grazing animals in agro or forest ecosystems. Traditional agroforestry systems, widely used in the past, had been strongly neglected by modernization of agricultural and forestry sciences of the Green Revolution period [1]. Agroforestry has been re-evaluated during the last decades for responding to the dramatic trilemma of wood-food security for the growing world population, and for environmental safeguard, both at global and local scale, especially concerning the mitigation and adaptation of Climate Change [2,3] and biodiversity conservation [4]. Agroforestry develops complex agroecosystems combining food production and tree multiple services. Multipurpose trees are often used both in traditional and innovative agroforestry systems. In Europe, agroforestry currently covers about 10 percent of the current agricultural area [5], and multipurpose trees such as oaks (*Quercus* spp.), chestnut tree (*Castanea sativa* L.), olive tree (*Olea europea* L.) and common walnut tree (*Juglans regia* L.) are highly appreciate species, for their ability of producing wood or timber, fruits for human or animal consumption, along with being able to be combined with arable crops or grazing animals [6,7]. Common walnut is the species combining very high quality timber production along with fruit with high nutritional values, and for these characteristics has been widely cultivated for at least two millennia in Europe [8,9]. In Italy, cultivation of common walnut for timber and fruit production, in combination with arable crops, peaked in the last century, and then decreased dramatically for the market globalization of the fruit, imported from Americas, and timber, with alternative hardwood timber imported from Africa and south east Asia [10–12]. Area of common walnut plantations for timber production increased in Italy during the last '90s and '10s, supported by the funds of the Common Agricultural Policy, for the reforestation of agricultural marginal lands [13]. Unfortunately, the great majority of these plantations failed in reaching the objective of producing timber for industrial uses, for the poor site characteristics of marginal agricultural land, along with the lack of the selected planting material, and poor plantation management [13]. The relaunching of common walnut cultivation in Italy, as well in other countries sharing the same site characteristics and socio-economic context, has to pass throughout innovative agroforestry systems, established on good agricultural soils, and combing timber and fruit production for both long term and annual incomes, and thus becoming more attractive for farmers.

In new silvoarable systems, with the intercropping of timber tree species with arable crops, the whole system profitability is strictly connected with the duration of the period of intercropping, with decreasing crops yield with increasing tree size and age [14–16]. It is therefore crucial to predict crops yield in relation to increasing tree size, according to simple tree parameters, such as the tree basal area (G), as was already tested for other tree species in several agroforestry systems [17,18]. In the juvenile stages of a silvoarable system, the herbaceous component grows with greater competitive strength compared to trees, for soil moisture and phytonutrients uptake [19,20]. On the contrary, in the adult phases of a silvoarable system, the trees canopy can significantly reduce the solar radiation available for agricultural cultivation, causing a decrease in the productivity of the associated herbaceous component [21,22]. In the case of common walnut tree species, the fruit production should represent an additional income. However, no research information on common walnut is available for optimizing tree density, and the combination of fruit and associated crop production [23–25].

The general objectives of this experimentation was to evaluate and quantify the main competitive relationships between the common walnut trees and associated crop component, represented by hay meadow, in an 18-year experimental area established by the CNR-IRET in 1992. In details, the research activity was focused in i) estimating intercrop yield in relation to increasing tree size, according to simple tree parameters, such as the tree basal area (G); ii) evaluating the role of nut production as additional product to timber and food crops. The experimental area was initially intended mostly for studying the common walnut tree for timber production in agroforestry systems, using a narrow tree planting density of 6 x 7 m. By the time of its establishment, with the current experience of the dramatic difficulties for farmers cultivating timber trees and relying solely on timber for profitability [26], it appears evident the necessity to evaluate the potentials of mixed systems combing food crops and trees for timber and fruit.

2. Materials and Methods

2.1. The Experimental area

The experimental area was located in central Italy, municipality of Orvieto, locality of Biagio (lat. N 42°40'15"'; long. E 12°02'33'', Figure 1). According to the climatic classification of Köppen [27], the area falls into the typology of "csa" climates, temperate climates from medium latitudes, characterized by very hot and dry summers. The area is in a hilly context, typical of the landscape of central Italy [28], on the south-eastern side of the Vulsini mountains, about 500 m above sea level, and about fifty kilometers from the coast of the Tyrrhenian Sea. Table 2 reports climatic data recorded by the meteorological station run by CNR IRET. Annual rainfall averages 830 mm, with

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an humid period during late autumn-early spring, and a dry period peaking during the months of July and August.

Previously to the experimental area set up, the land had been used for agricultural activity, mostly with rotation of winter cereals, legumes for hay production and sunflower. The agricultural soil has a good level of fertility, and details on soil physical and chemical characteristics are reported in a past study [29]. The soil has deep profile (>1 m). The texture is sandy-clayey, with slightly acid reaction (pH equal to 6.5), a general absence of carbonate of calcium ($CaCO_3$), a cation exchange capacity equal to 19 meq 100 g^{-1}, and an organic carbon content of 1.2%.

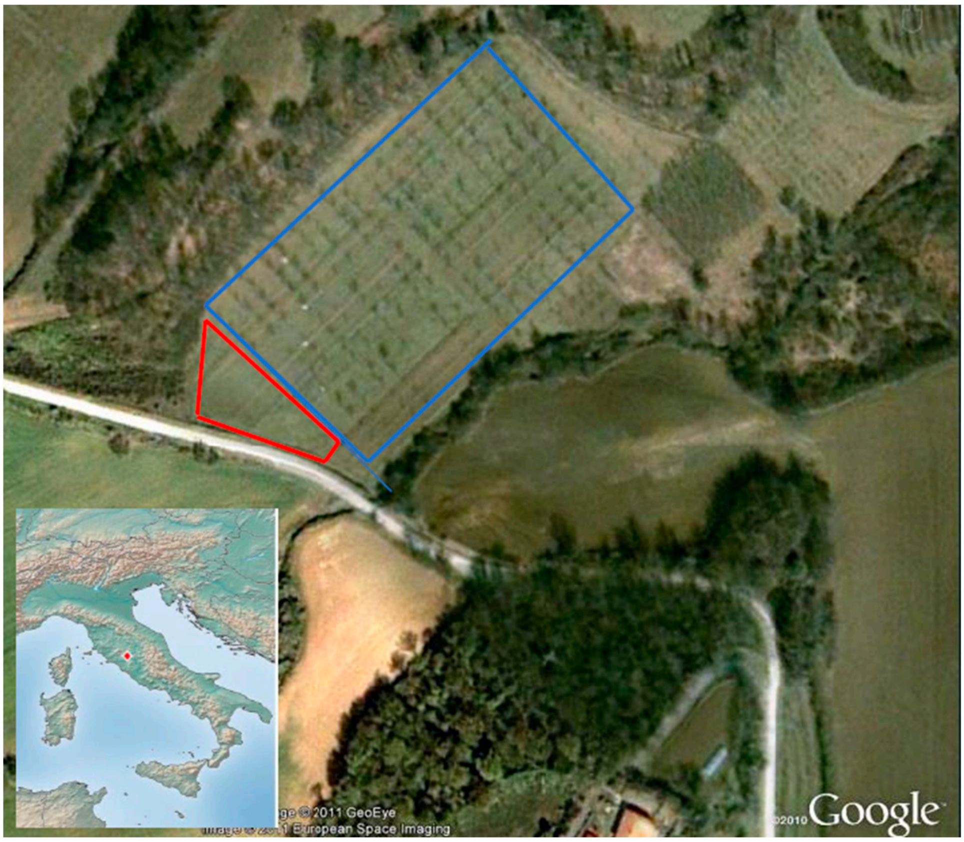

Figure 1. Aerial view (from Google Earth) of the experimental area, in Italy, in the year of the research. The experimental area with the common walnut agroforestry plots is in blue. The sampling area of the Sole Crop is in red.

The experimental area under study was initially set in February 1992, with tree planting, according to a planting spacing of 6 m x 7 m, equal to a density of 238 plants per ha^{-1}, with a tree line following a north-east /south-west orientation, in adaptation to the site slope (3%) and farm machinery circulation (Table 2).

A total of 12 plots of about 450 m^2 each were created, planting seedlings of common walnut species, as an half sib family of a plus tree of the cultivar *Feltrina* [30,31]. The original experimental lay-out was designed to study the effect of intercropping and plastic mulching of the growth and yield of walnut trees. We were comparing two level of intercropping: no intercropping, with periodical clean cultivation of the soil between tree lines, and intercropping with arable crops (see Table 2 for crops rotation throughout the years). Plastic mulching had also two levels: no plastic mulching and plastic mulching along tree lines. Details are provided in research papers published some years after the experiment set up [19].

Walnut tree plots were stratified into 3 blocks, each containing a replication of the following theses: i) Sole Walnut with plastic mulching (Sole+M); ii) Sole Walnut without plastic mulching (Sole

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-M); agroforestry walnut with plastic mulching (AF+M); iv) Agroforestry without plastic mulching (AF -M). Each plot was constituted by 8 walnut trees.

In the year 1999, and additional plot was added to the study area, with an approximately surface of 2500 m², as Sole Crop control, with crops without walnut trees. Additionally, all the walnut plots were divided into two parts, with and without intercropping, with 4 walnut trees per plot.

In the year 2004, the last crop sowed was white clover (*Trifolium repenes* L), used both in the agforestry and sole crop plots. After that year, all the study area was managed as an hay meadow, with one harvest per year, in late May-early June.

Throughout the years, cultivation was carried out in rainfed condition, without additional irrigation, both for crops and trees. Any product was used for pest and disease control regarding walnut trees.

Table 1. Experimental area information, common walnut tree management, experimental treatments, and crop rotations 1992-2010.

Geographic coordinates and elevation	42°40′15′′ N; 12°02′33′′E; 517 m a.s.l.
Koppen Climate Classification	Csa Type: Mediterranean hot summer climates
Tree establishment (year)	1992
Tree spacing	6 m x 7 m
Tree-row orientation	140°
Tree planting material	1 year old bare root seedlings of *Juglans regia* L., half sib family of plus tree of cultivar F*eltrina*
Agroforestry Plots	6 plots with plastic mulching along tree row (1992-1995) and 6 plots without plastic mulching
Intercrops	1992-1995: *Medica sativa* L. (alfalfa)
	1996: *Triticum aestivum* L. (common wheat)
	1997-1998: fallow
	1999-2002: alfalfa
	2003: common wheat
	2004: *Trifolium repens* L. (white clover) sowing
	2005-2010: hay meadow
Sole Tree Plots	6 plots with plastic mulching along tree row (1992-1995) and 6 plots without plastic mulching

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Intra row soil management	1992-2004: mechanical clean cultivation between May to September
	2005-2010: sward mowing
Sole Crop Plot	1992-2010: crops rotation as for walnut Agroforestry plots since 1999

Table 2. Climatic characteristics of the study site during the study period (2010) along with long term observations (1992-2009, own source).

Month	**1992-2009**		**2010**			
	Prec. (mm)	Ave. Temp.(°C)	Prec. (mm)	Ave. Temp. (C°)	Ave. Min. Temp. (°C)	Ave Max. Temp. (°C)
Jan.	69	3.9	144	2.8	-0,2	5.8
Feb.	53	4.4	109	5.1	1,5	8.7
Mar.	64	7.1	44	6.7	2,6	10.8
Apr.	67	10.0	75	10.9	5,5	16.0
May	63	14.8	181	13.4	8,2	18.5
June	57	18.4	23	18.1	11,8	24.4
Jul.	17	21.1	124	22.9	15,8	29.9
Aug.	40	21.5	21	20.8	14,4	27.7
Sept.	80	16.9	36	16.7	10,8	22.5
Oct.	95	13.1	68	11.7	7,1	16.2
Nov.	124	8.2	277	8.2	4,1	12.3
Dic.	109	4,9	125	3.9	0,5	7.3
Year	**838**	**12,0**	**1227**	**11.7**	**6.8**	**16.7**

2.2. Tree growth in the year 2010

During the study period, no tree thinning was carried out, while a progressive tree pruning was carried out, after the initial training pruning for the first 4 years after tree planting. Progressive pruning consisted in cutting all the branches having trunk insertion dimeter smaller them 5 cm.
In December 2010, the following measurements were performed on walnut trees:

- crown diameter (CC). Measurements were conducted through the use of a graduated rod on the crown project on the ground, with two orthogonal measurements;
- usable trunk height (Ht). This measurement was performed with a graduated rod, measuring the height between the soil surface and the lowest branch with a minimum diameter of 3 cm. The aim of this measurement is the definition of the trunk length, suitable for sowing or veneering;
- total stem height (H), with infrared hypsometer (Vertex III);

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- stem diameter at breast height (DBH). The measurement was performed using a precision metal calliper with an approximation to the millimeter, taking two orthogonal diameters on the stem section at 1,3 m from the soil surface.
- basal area of the walnut trees (G). In each plot of 4 walnut trees, G was determined using the following formula:

$$G = (\pi / 4 * DBH^2) * d; \quad \text{(eq. 1)}$$

with G is expressed in m^2ha^{-1}; d is tree density, as tree number per ha.

2.3. Tree leaf phenology.

In the period between March and May 2010, the tree leaf phenology measurements were conducted weekly by monitoring 4 trees for each replicate, equal to 12 plants per thesis. Observations concerned two phases of leaf phenology, the bud opening (bud break), and leaf extension, using a scoring system based on the following criterion for budbreak, according to a common protocol developed in the European research Project SAFE (Silvoarable Agroforestry for Europe, https://www1.montpellier.inra.fr/safe/english/index.htm):

Value 0: The plant has not yet opened the buds of the entire canopy.
Value 1: The plant has opened less than 50% of the buds of the entire canopy.
Value 2: The plant has opened more than 50% of the buds of the entire canopy.
Value 3: The plant has completed the opening of the buds of the entire canopy.

The same score and criterion was used for leaf expansion, evaluating the percentage of fully expanded leaves.

2.4. Meadow productivity.

Measurement of meadow productivity was carried out from March 31st to June 4th, both on Agroforestry and Sole Crop plots, with 1 m^2 sampling subplots. Cutting and specimen collection were done manually. Collected biomass was put in plastic bag after field sampling, and weighted in the laboratory few hours after sampling, with a scale with 1 g of precision. Dry matter weight was obtained calculating the percentage of humidity of the subsamples placed in paper bags in an oven at a temperature of 60 °C up to constant weight.

The final sampling measurement, before hay harvesting, was carried out on the July 1st identifying 3 different 1 m^2 subplots for each plot of 4 walnut trees, at the plot centre, one meter from the tree base, and in the middle of tree lines. Crop reference yield was calculated as the percentage difference of meadow yield in Agroforestry plots versus Sole Crop plot (CRY, in %). CRY was calculated just for meadow yield at hay harvesting of July 1st.

2.4. Hemispherical photos

From April to July, the total amount of solar radiation reaching the ground floor throughout the tree canopy, and available for the herbage vegetation, was determined with hemispherical photos, taken at the plot centre for the Agroforestry plots, and at three random position for the Sole Plot.

The photographs were taken with a digital camera (Nikon Coolpix 995) equipped with a hemispherical lens (fish-eye), mounted on a tripod at 0.8 m heigh from soil surface, operating at sunset condition of diffused sun radiation, and positioning the camera levelled and oriented towards the magnetic north using a compass. Photos were taken with the flash function turned off and using the highest camera resolution.

The obtained photos were then analysed with the free software GLA, Gap Light Analyzer [32], determining the total light transmittance (TLT%), as percentage of the full radiation available above tree canopy.

2.5. Estimation of fruit production from literature and scenarios of hay and fruit production

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Fruit production was not measured during the experimentation. A literature research was done on fruit production on multipurpose common walnut plantations in Italy, as well in other countries adopting the same cultural model. Very few literature was found suitable for the aim of identifying single tree production according to tree age and size, mostly because the double production cultural model has received very few research attention in the last decades. References were selected [25,33,34], by which it was possible to estimate the above data. Using the tree growth data of the experimental plantation, along with the data of fruit production from Table 3, two scenarios of planation management were compared for producing timber, hay and fruit, using two planting spacings. A fixed and fruit oriented planting spacing of 12 x 12 m, corresponding to 70 trees ha^{-1}, the best for full crown development and fruit production. A dynamic density, with initial planting spacing of 6 x 12 m (138 trees ha^{-1}), for timber production, determining the age of thinning for avoiding crown overlapping.

Table 3. Data for fruit production of common walnut for double cultural model of timber and fruit production, derived from a bibliographic research.

Reference and country	**Yield per ha (Mg ha^{-1})**	**Trees per ha**	**Yield per tree (kg)**
Minotta 1990, Italy [23]	2.5	70	35
Pergamo et al , 2017 Italy [34]	3	70	43
Rehnus et al 2017, Kyrgyzstan [25]	0.160	131	1.22

2.6. Statistical Analysis

Analysis of variance (ANOVA) was used to evaluate the intercropping and mulching treatments effects on walnut tree growth (H, Ht and DBH), using a full randomized design with intercropping and mulching treatments as fixed factors, and repetition as a random factor. ANOVA was also used for analysing the effect of sampling position on meadow yield. Post hoc Duncan's Test was used to detect significant differences. Those statistical tests were conducted using SigmaPlot 12.5 (Systat Software, Inc.). The dependence relationships between variables were analysed through correlation and regression analysis, determining the value of the determination coefficient (R^2) and its degree of significance. Correlations were run in Microsoft Excel, Microsoft 365 MSO (version 2010).

3. Results

3.1. Tree growth

Average values of tree growth parameters are presented in Table 4. After 18 years of growth the tree H varied between 10 and 11.2 m, respectively for the thesis of intercropped trees without plastic mulching and sole tree without plastic mulching, respectively. Tree that had been intercropped had a Ht lower than 2 m, while those trees without intercropping had Ht much higher than 2 m, with significant differences between mulched and unmulched trees. Mulching was applied in 1992, at the time of tree planting, and then removed at the end of the year 1995. Thus, mulching effect on tree growth are still evident after 15 years of its removal. DBH varied between a minimum of 16,9 and a maximum of 21,3 m, for intercropped and unmuched thesis and the sole tree with plastic mulching thesis, respectively. ANOVA results for tree growth parameters (DBH, Ht and H) are presented in Table 5. Total stem height (H) was not significantly affected by intercropping and mulching treatments. Trunk height (Ht) was significantly affected by the interaction between the two treatments. Stem diameter was affected significantly solely by the intercropping treatment.

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Figure 2 reports the high significant linear relationship between tree DBH and crown diameter at the end of the 18th growing season. The figure reports the individual data of all the trees in the study area, irrespectively of the experimental treatments.

Table 4. Tree growth (mean and s.e.m., in parenthesis) at the end of the year 2010, following experimental treatments applied for 18 years, and according to Table 2. Means followed by the same letters are not statistically different per p≤ 0.05, according to Ducan's Test; s.e.m: standard error of means; ns.: not significant; AF: Agroforestry; Sole: trees not intercropped; +/-M: trees with and without plastic mulching in the period 1992-1995. .

Thesis	H (m)	Ht (m)	DBH (cm)
AF +M	10.00 ns (0.760)	1.99 c (0.149)	17.75 b (1.41)
AF-M	10.20 (0.520)	1.86 bc (0.142)	16.87 b (0.798)
Sole +M	11.18 (0.315)	2.46 a (0.067)	21.29 a (0.647)
Sole -M	10.22 (0.468)	2.203 b (0.067)	18.99 ab (0.905)

Table 5. ANOVA p-values observed for tree growth in the year 2010, 18 years since tree planting. H, Ht, DBH are the total stem height, the height of the useful trunk and stem diameter at breast height (1.3 m), respectively. d.f.: degree of freedom.

Source	d.f.	H	Ht	DBH
ANOVA p-value				
Intercropping	1	0.219	<0.0001	0.002
Mulching	1	0.406	<0.017	0.061
Rep.	2	0.19	<0.0001	0.064
Int. x Mulch.	1	0.339	0.607	0.515

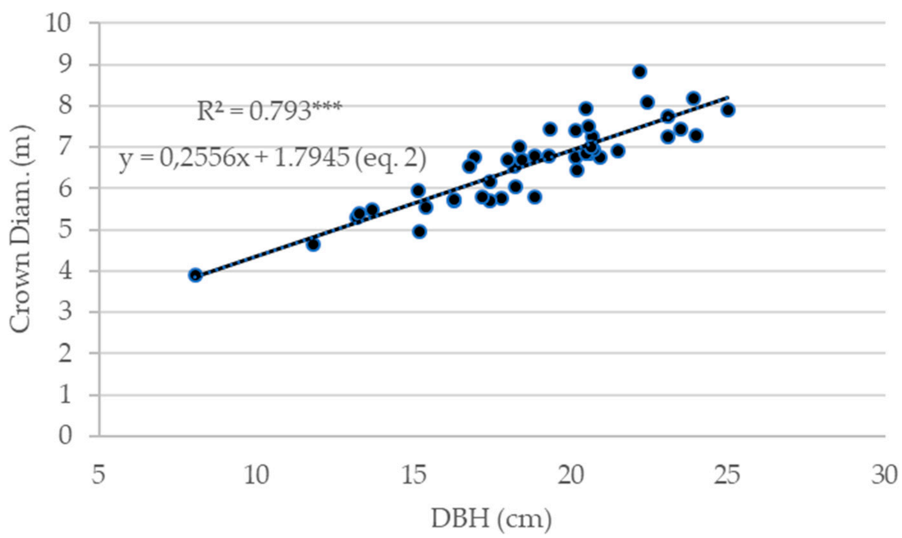

Figure 2. Relationship between tree diameter at breast height (DBH) and crown diameter of common walnut trees at the end of the 18th growing season. *** p≤0.001.

3.2. *Tree leaf phenology and Total light transmittance*

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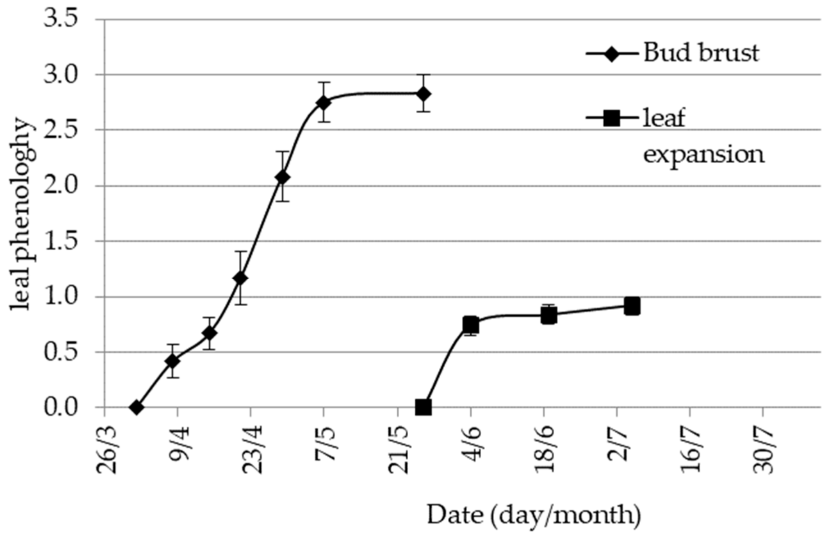
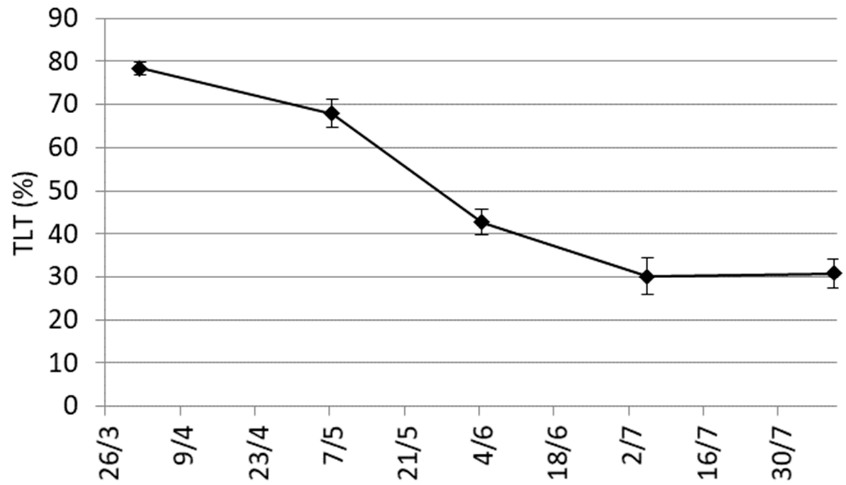
Figure 3 reports the seasonal development of tree leaf phenology for bud burst and leaf expansion at weekly interval during the beginning of the growing season of the year 2010. Data represents the leaf phenology indexes irrespectively of the experimental treatments. Bud burst started at the begging of April and lasted almost 1,5 months. Leaf expansion completed at the beginning of July, and was faster than completion of budburst. In parallel to leaf phenology observations, hemispherical phots were taken, and results are presented in Figure 3. Total light transmittance (TLT%) progressively decreased from late March to the beginning of July, reaching the minimum value of 30%, remaining stable after that date, due to the completion of leaf phenological phases.





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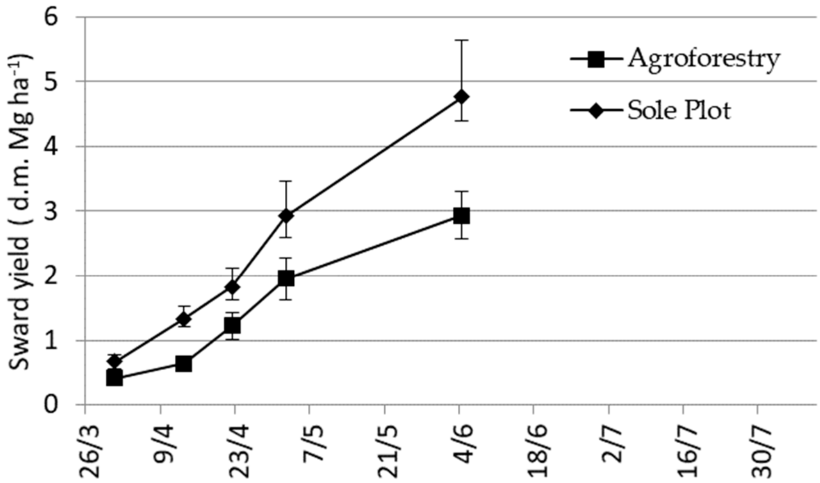

Figure 3. Leaf phenology indexes (bud burst and leaf expansion) of walnut trees (upper graph), Total light transmittance (TTL%) of solar radiation under the tree canopy (middle graph), and sward yield, in dry matter (bottom graph), during the 18th growing season. See the text for leaf phenology indexes. Vertical bars represent the s.e.m., and if not visible because lower than the symbol. .

3.3. *Meadow yield and correlation with G and TLT*

Figure 3, lower graph, present the evolution of the meadow yield in dry matter (Mg dm ha^{-1}) during the first part of the growing season from early April to early June, for the meadow yield under the walnut trees and for the meadow in the Sole Plot, without walnut trees. For the Sole plot, the sward yield is progressively higher than that for the tree Agroforestry plot, because of tree competition. ANOVA results (Table 6) doesn't show any significant effect of the sampling position (one in the Sole crop plot and 3 under the walnut tree canopy) on the meadow yield, at hay harvesting (beginning of July).The yield values are, however, highly different (Table 7), especially for the meadow yield without the walnut trees (4,3 Mg) and the values of yield for the meadow under trees (2.9-3.4 Mg dm ha^{-1}).

Table 6. ANOVA p-values observed for sward yield in the year 2010, 18 years since tree planting. d.f.: degree of freedom.

Source	**d.f.**	**Sward Yield**
Position	3	0.362
Rep.	3	0.996

Table 7. Sward yield, in dry matter (d.m.), according to the sampling position, in June 2010. Ns: not significant.

Sward Position	**Sward Yield (Mg d.m. ha^{-1})**
Sole Crop	4.35 (0.877) ^{ns}
Tree Canopy	2.91 (0.243)
Tree Canopy -Centre	3.021 (0.358)
Tree Canopy-Lateral	3.398 (0.541)

3.4. *Scenarios of hay and fruit production for two planting densities.*

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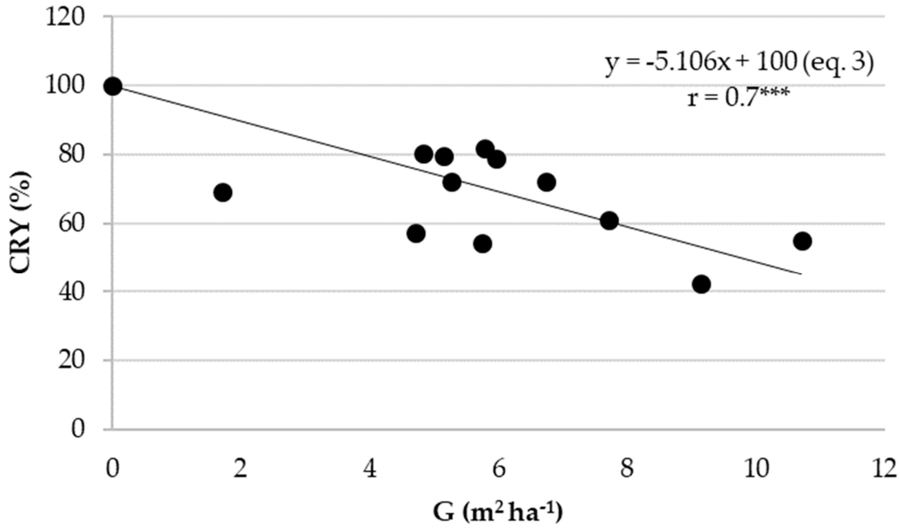
Table 3 reports the data of existing literature reporting fruit yield for common walnut in traditional multipurpose plantations. Yield data are very variable, according to the original reported data, and the site conditions, as well the cultivation intensity. Site condition and cultivation intensity in Kyrgyzstan are much more limiting than in Italy. According to those data, as well to the personal experience of the Authors, it was estimated that for a 35 year rotation, three yield phases are possible for nut production. From 0 to 10 years, with null fruit productivity. From 11 to 20 years, with 10 kg per tree, and from 21 to 35 years, with 15 kg per tree.

A spreadsheet calculator was developed in Excel, for comparing the two planting density (fixed, 70 trees ha^{-1}, dynamic 138 and 70 trees ha^{-1}) for comparing the total productivity of hay and fruit, additional to timber production. The scenarios are shown in Figure 5. DBH is set to 1 cm/ year. G was calculated according to equation [1] for the DBH 1 cm year-1 and the two compared tree densities. For the dynamic density, it was determined the age of thinning according to eq. 2 of Figure 2, with a DBH of 22 cm. Hay productivity under walnut trees was calculated according to eq. 3 of Figure 4. Figure 5 reports the cumulative productivity of 2 compared tree densities for fruit and hay.



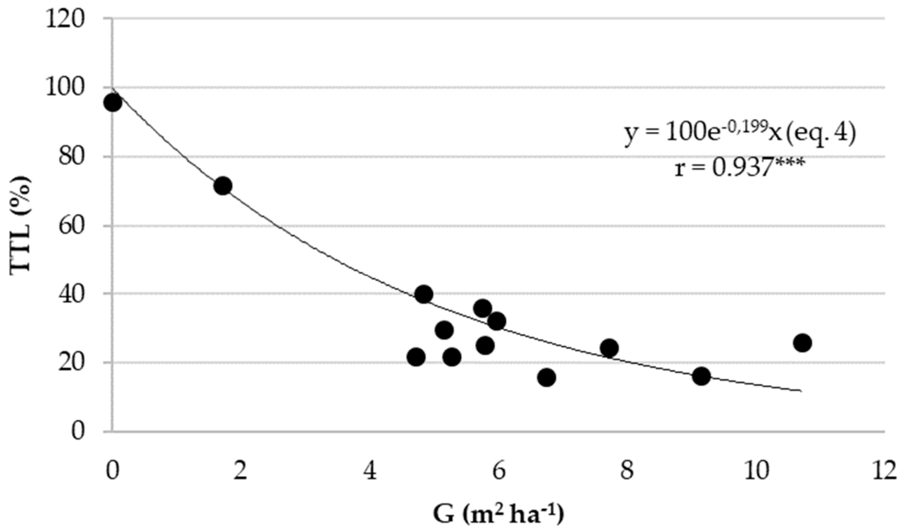


Figure 4. Relationships between tree basic area (G) and crop reference yield (CRY) (upper graph) and G and Total Light Transmittance (TTL) (lower graph) for walnut trees intercropped with hay meadow during the 18th tree growing season; r is the correlation coefficient of the regression; *** p≤0.01.

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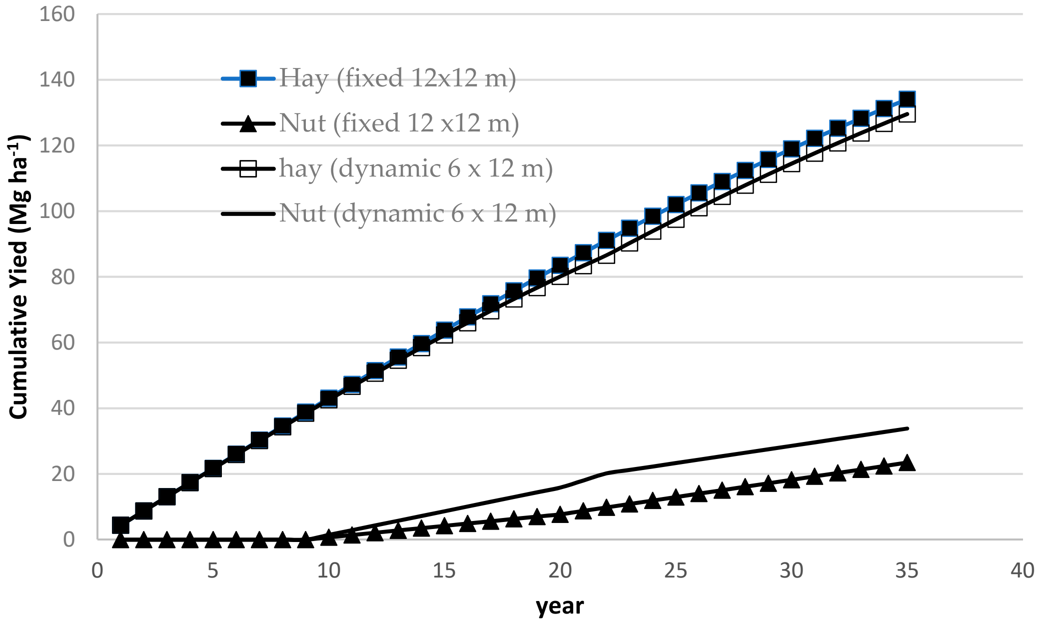

Figure 5. Simulation of cumulative productivity of nut fruit and hay for a common walnut plantation with two tree planting spacings: fixed at 12 x 12 m since planting time (year 0) up to end of tree rotation (35 years); dynamic, at 12 x 6 m at planting time, and 12 x 12 m after thinning, at year 22 up to year 35. See detail in paragraphs 2.5 and 3.4 for methods and results, respectively. .

4. Discussion

4.1. Trees growth

The growth of common walnut trees in the study area is consistent with data reported by literature in southern Europe. In 18 years, the DBH increase of c. walnut trees was 18.7 cm, as the average of the 4 theses (Table 4), corresponding to about 1 cm of average DBH increment per year. Eighteen years represent about a third of the rotation of c. walnut trees for timber production in Italy [35]. The above mentioned DBH increment corresponds to what reported on average for the timber plantations of c. walnut recently surveyed in Italy and Spain [36], for the 2nd fertility class of c. walnut plantations.

This paper does not report the average total height (H) of trees in the studied plantations. For total height (H) data we referred to a 2005 study [33] on 13 plantations of c. walnut trees in the Campania region (Italy) and to a 1996 article [37], both reporting an H at 18 years of about 10 m. H values of the trees in our study are in line with the available literature. The experimental treatments applied in the study over the 18 years showed significant effects on DBH and on the height of the usable trunk height (Ht), but not on H. These data are in partial agreement with previous studies [38,39], in early years of tree growth with intercropping and mulching treatments, with significant effects of both treatments on DBH and H. After 18 years from trees establishment, for the intercropping treatment there are significant differences on the DBH and on Ht. Initial mulching, at planting time, was also found to have significant effect on Ht. This is a very important data since it is directly connected to the quantity of high quality timber for veneering and/or sawing. According to [35], for the Italian market, c. walnut veneer logs must have a diameter > 30-35 cm and a length of 100-300 cm; for saw logs the diameter must be >25-30 cm and lengths of 200-300 cm. Especially for veneer logs, the greater the length of the log, the greater is its commercial value. In our study, the trunk length is approximately 2 m for intercropped trees, and higher than 2 m for non-intercropped ones, with significant differences for trees that have been mulched in the first 4 years after planting. Then the plastic mulch was removed, as had been degraded by agricultural practices, such as tillage and crops harvest. Thus plastic mulching at tree planting, on long-term effect, is capable to significantly influencing the amount of high quality timber of c. walnut trees. This study is, to our knowledge, the only one able of demonstrating the long-term utility of plastic mulching on timber productivity of the c. walnut tree in agroforestry systems with intercropping under the conditions of the study area, with medium site fertility class in southern Europe [40]. Mulching when planting c. walnut trees is an advisable practice to favour the production of quality timber, both for intercropped and non intercropped trees. Similar studies on intercropping of walnut trees were conducted in France and Spain [41,42], but on hybrid walnut trees (Juglans x intermedia Mj209xRa), which generally have a faster growth rate than c. walnut trees [30]. Those studies on walnut trees intercropping did not investigated on mulching.

4.2. Tree phenology, hay yield and TLT

The walnut trees began to open their buds at the end of March during the studied period, completing canopy development in early July (Figure 3). The walnut trees used in the experiment belong to *Feltrina* cultivar, originating from a more northern area of the study site. The *Feltrina* cultivar is in fact cultivated for double purpose (timber and nut) in the pre-Alpine area of the Veneto Region (46°01' N; 10° 50' E). Amongst the c. walnut cultivars, *Feltrina* is a medium late cultivar, as indicated by multisite studies conducted in Europe and Italy, comparing 20 genotypes from southern and northern Europe, between 35° and 52° latitude [30]. These studies have shown that in general the northern genotypes have a late leaf phenology, able to escape late spring frost damages, with apical shoots not killed by freezing. This positively affects the shape of the tree stem, which tends to grow with a rectilinear central axis, with strong apical dominance and less lateral branching. This has very important positive consequences on the qualities of the wood of the final trunk, which is longer, straighter and free of branches. In agroforestry systems, walnut tree genotypes with a late phenology therefore have the double advantage of delaying the leaf development and therefore the shading of the associated crops. Additionally, tree late leaf phenology favours the quality of the timber production due to a straight and long trunk.

The canopy development of the c. walnut trees progressively increased from the end of March until the end of June, reaching a maximum value of interception of light radiation of 70% in July and August (Figure 3, central plot). An accurate study on tree shading was conducted in southern France on hybrid walnut trees [43]. This study also produced a simulation model of tree shading as a function of latitude, tree row orientation, row spacing (17 and 35 m) and plantation age, from trees establishment to their harvesting. This study reports, at mid-latitudes (45°N), shading levels of 28 and 18% for row spacings of 17 and 35 m, respectively, at about two-thirds of tree rotation. Our study reports 70% shading level, which can be explained by lower distance between tree rows (7 m). This indicates that the chosen planting layout (6 x 7 m) is very narrow to maximize the production of associated herbaceous crops. Indeed, hay yields under the walnut trees were significantly lower than in the control hay plot (Table 7). These results are in full agreement with other studies indicating a significant reduction in the productivity of herbaceous crops due to tree shading, both as arable crops and forage crops. Ivezic (et al 2021) [44] reviewed the effect of trees on the productivity of associated crops in Europe, with a meta-analysis on numerous experimental sites of alley cropping and agrosilvopastoral systems (*dehesa* and *montados* of the Iberian Peninsula). For alley cropping, it was found a 2.6% of annual rate of intercrops yield for the first 21 years since tree establishment, attributing much of this reduction to solar radiation competition between trees and intercrops. In our study, the productivity reduction of herbaceous layer is already evident from the first phases of their growth during the studied period, with differences increasing during the growing season. This opens the hypothesis that the productivity reduction in herbaceous layer could not entirely related to trees shading, but also to other negative interactions of the c. walnut trees. It is well known that this species produces allelopathic substances capable of inhibiting the growth of other nearby plant species. A recent study by Zalac et al (2022) [45] confirms this hypothesis, suggesting appropriate removal of walnut litterfall form the soil for arable crops. In our study, the permanent soil cover with the meadow and without soil tillage for 5 years may had favoured the accumulation of allelopathic substances.

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4.3. Relationship between Basal Area (G) and Crop relative Yield (CRY)

An inverse linear relationship between trees basal area and CRY was found, with a -5.1% slope of the linear regression, indicating that for every unit increase in the basal area there is an approximately 5% decrease in hay productivity under the c. walnut trees (Figure 4, upper plot). In general, the available literature mostly reports inverse linear relationships between G and CRY [17,46]. Only [18] reports an inverse nonlinear relationship, in the case of gmelina and eucalypts at high planting densities, with 2000 and 1000 stems per hectare, respectively, in the Philippines. For eucalypt and *P. falcataria*, as evergreen tree species, research by Nissen et al [17] found inverse linear relationships with variable angular coefficients between a minimum of -7.8% and a maximum of -18.2%, linking the variations to the competitiveness of the tree species, able to more or less significantly shade the associated herbaceous crops. The same aforementioned paper, reprocessing data on paulownia [47], found lower angular coefficients, varying between -5.6 and -1.9%, respectively for the intercropping in the tree species with cotton and wheat. The lower values of paulownia, a deciduous tree species, compared to the evergreen species, are to be linked to the foliar phenology of the tree species, with very late foliation, shading the associated crops in their late phase of development. In the case of wheat, an autumn-winter crop, the shading of the crop by the paulownia trees occurs at a very advanced stage of wheat ripening. Angular coefficient differences as a function of associated crop were also found for hybrid walnut nut trees [46], associated with wheat, clover and pasture, with values of -6.2, -0.04 and 3, respectively. It is therefore not possible to make generalizations on the angular coefficient of the relationship between G and CRY, but it is necessary to identify the specific relation for each pair of tree species and associated herbaceous species, based on the leaf phenology and the production cycles of both components. It is also plausible that the relationship between G and CRY is also site specific, based on site characteristics of soil fertility and climatic conditions. In fact, it is possible that for each site fertility class, for the same DBH value, there may be different heights which can influence the shading of the tree on the associated crop. In this sense, it would be necessary to develop equations with 2 variables between CRY as a function of G and tree total height.

4.4. Scenarios of hay and nuts productivity

Figure 5 shows the cumulative production of hay and nuts for the two simulated scenarios with the fixed planting density of 12 x 12 m and the dynamic one with an initial layout of 6 x 12 m, then passing to 12 x 12 m from twelfth year. This simulation demonstrates that there are greater differences between the two scenarios for nut production than for hay production. It should be remembered that the production of nuts was estimated on the basis of the available bibliography, with 0 kg, 1 kg and 15 kg of nuts per tree, respectively for three tree age intervals (0 to 10 years, 11 to 20 years, and finally from 21 to 35 years). To our knowledge, the only study similar is one of Zalac et al, 2021 [24], in Croatia, for a semi-intensive system of fruit nut with yields per tree of 15-25 kg, and with 3 planting densities of 170, 135 and 100 trees per hectare, intercropped with grain maize, barley and rapeseed, for a 20-year rotation. The study compared the agronomic productivity and financial convenience of three cropping systems: monoculture walnut orchards, treeless arable crops and the same arable crops associated with walnut trees. The authors determined that the most financially advantageous option is the one with 175 trees per ha and intercropping with arable crops for the first 6 years. This study did not find any economic value for walnut wood, as in 20 years the size of the trees is not large enough to produce valuable timber. In our study, with a rotation of 35 years it is possible to produce walnut logs which theoretically have a commercial value, which on the Italian market can be estimated at around 140 €/Mg [26]. Our results indicate that for an extensive triple aptitude system (timber, nuts and hay) the choice of a dynamic layout is preferable, initially with 139 trees per hectare up to 12 years, to then move on to 70 trees per hectare, promoting nut production and without significantly reducing hay production.

5. Conclusions

Referring specifically to the agroforestry system of the common walnut tree for the production of timber, hay and nuts, the presented research results points to the following key findings:

- the usefulness of plastic mulching, at tree planting, to increase the long-term growth and timber productivity of the trees intercropped with herbaceous crops;
- the negative linear relationship between hay productivity and the trees basal area;
- the tree basal area influences, in positive way, more markedly nut production than the decrease in hay production.

Therefore, from an agronomic point of view, for the best combined productivity of the agroforestry system with walnut trees for the production of timber, hay and walnut fruits, it is advisable to mulch the trees, maintaining the plastic film for the first 4 years and using a planting density of 6 x 12 m, with thinning of the trees on the row at the age of 12, when the crowns would begin to overlap, passing to a planting spacing of 12 x 12 m. Based on our simulations, this seems to be the recommended crop model to maximize the quantity of the product that currently has the highest market value, i.e. walnuts, with a value of €2800/t, compared to hay (€200/t) (https://www.ismea.it/) and timber (140 €/Mg) [26]. For the continuation of research in this direction, it is necessary to have more accurate data on individual tree nut production according to trees age and size (DBH and/or crown area). Additionally, an accurate financial analysis with the crops costs is also needed for a full evaluation of the proposed model with triple production of timber, fruit and fodder.

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