Forest Systems
31 (1), eSC02, 7 pages (2022)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2022311-18200
INIA-CSIC

SHORT COMMUNICATION

OPEN ACCESS

A study case on polycyclic plantations (PP) as innovative models for sustainable combined production of noble hardwood and biomass

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Abstract

Aim of study: To verify the short rotation coppices (SRC) aboveground biomass production; to define the best planting intra-row spacing for walnut and poplar growth and wood production, with the last goal to assess the possibility of obtaining competitive yields in comparison to those produced by traditional monocultures.

Area of study: Po Valley, municipality of Meleti (Northern Italy).

Materials and methods: A randomized block design with three replications was applied for the experimental design. The growth-monitoring activities started in 2009 and have continued for 5 years on the SRC, 10 years on poplar clone 'I-214', whereas on common walnut they are still going on but only data concerning the twelfth year are reported in this work. The normality of distribution was evaluated for growth and yield data of species in the SRC model; all data were analysed with ANOVA; growth data were included in a linear mixed model analysis to evaluate the effect of age, spacing and their interaction, and the effect of SRC rows on growth and yield of poplar and walnut.

Main results: After 5 years of cultivation under SRC system, biomass yields obtained from the poplar clone 'AF2' were 39.9 Mg ha^{-1}, from the elm 31.9 Mg ha^{-1} and from the plane 14.8 Mg ha^{-1}. After 10 years high timber production was obtained from poplar clone 'I-214' (average volume 98.2 m^3 ha^{-1}). After 12 years, walnut trees reached a diameter at breast height (DBH) of 17.8±0.2, 18.9±0.2 and 18.7±0.3 cm, respectively, for planting distances of 6, 7 and 8 m, and showed diameter increments of 1.5-2.0 cm yr^{-1}. With these growth rates, walnut can reach a merchantable dimension within 25-30-years.

Research highlights: Polycyclic wood plantations are a recent arboriculture model able to produce, on the same site, different assortments using various crop trees characterized by different growth rates and turnovers. This new type of mixed plantation is more environmentally sustainable compared to monoculture and allows diversification of production, obtaining continuous wood yields over the years (5, 10, 20, 30 years).

Additional key words: walnut; poplar; alley coppice; sustainable tree farming; short rotation coppices.

Abbreviations used: DBH (Diameter at Breast Height); H (Total Height); LMM (Linear Mixed Model); PP (Polycyclic Plantation); SRC (Short Rotation Coppice)

Authors' contributions: Conceived and designed the experiments: FP. Performed the experiments: CB, DS, FP, MP, AV, EB. Analysed the data: SB, MP, AV and FP. Statistical analysis: GF, MP, SB. Contributed analysis tools equally: EB, MCM and PMC. Supervising the work: FP. Drafting of the paper: MP, SB and FP.

Citation: Plutino, M; Bergante, S; Facciotto, G; Vitone, A; Bianchetto, E; Sansone, D; Manetti, MC; Chiarabaglio, PM; Bidini, C; Pelleri, F (2022). Short communication: A study case on polycyclic plantations (PP) as innovative models for sustainable combined production of noble hardwood and biomass. Forest Systems, Volume 31, Issue 1, eSC02. https://doi.org/10.5424/fs/2022311-18200.

Supplementary material (Tables S1, S2, S3, S4) accompanies the paper on SJAR's website

Received: 07 Apr 2021. **Accepted:** 07 Mar 2022.

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Funding agencies/institutions	Project / Grant
The European Commission (last part of the monitoring)	HORIZON 2020 'WOODnat' project

Competing interests: The authors have declared that no competing interests exist.

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Introduction

Planted forests represent about 7% of the world forest area (FAO, 2020) and provide for about 46% of total needs for roundwood for industry (Carle *et al.*, 2020), reducing the pressure on natural forest ecosystems. Almost all planted forests are monocultures (Liu *et al.*, 2018) and only about 0.2% are mixed forest plantations (Cateau *et al.*, 2018). In Europe, in 2012, there were 55,000-60,000 ha of mixed forest plantation, mainly composed of poplars (*Populus* spp.) and willows (*Salix* spp.) (Mola-Yudego *et al.*, 2017). Recently, some authors have stressed the potential benefits of mixed-species production forests with respect to monocultures (Paquette & Messier, 2010; Liu *et al.*, 2018). Potential benefits include: improved habitats for biodiversity (Carnus *et al.*, 2006; Le *et al.*, 2021); increased recreational value (Norman *et al.* 2010); improved soil organic carbon stocks (Gong *et al.*, 2021), soil conditions (Thomas *et al.*, 2020) and CO_2 sequestration (Forrester *et al.*, 2005; Gong *et al.*, 2021); reduced damage to main tree species by pests and pathogens (Jactel & Brockerhoff, 2007); reduced risk of damage from wind and fire (Gonzalez *et al.*, 2006); enhanced environmental and societal advantages at both local and global scales (Buresti *et al.*, 2014); reduced cost and increased benefit for farmers (Pra *et al.*, 2019; Ludvichak *et al.*, 2021).

In recent decades, in some European countries (Italy, France, Spain) and North America, many mixed-tree farming plantations have been established with walnut (*Juglans* spp.), poplar (*Populus* spp.) and other valuable broadleaved species combined with nurse species, mainly N-fixing trees or shrubs (*e.g. Alnus* spp., *Robinia pseudoacacia* L. and *Elaeagnus* spp.) (Rivest *et al.*, 2010; Pelleri *et al.*, 2013). With the introduction of short rotation coppice (SRC) models in such mixed plantations (Morhart *et al.*, 2014) it is possible to grow noble hardwood species for high quality timber production with fast growing species for energy purposes, having the advantage of a periodical income from the harvest of SRC.

In Italy, these so called "polycyclic plantations" (PP) cover about 400 ha, mainly in northern Italy, and have been defined as tree farming plantations where main crop trees with different cultivation cycles coexist in the same plantation (Buresti *et al.*, 2014). In such plantations, at least two types of the following kinds of crop trees must be present: (1) very-short-rotation crop trees for biomass and energy production, with the advantage of a periodical income (SRCs); (2) short-rotation crop trees for plywood production (poplar clones); and (3) medium-long-rotation crop trees for valuable timber production (walnut, oak or other valuable broadleaved species).

Crop trees are intercropped with nurse trees or shrubs (often N-fixing species) and with tree species playing a double role of nurse for main crop trees and production of biomass for energy purposes. Significant benefits, in terms of productivity and ecosystem services, have been shown by using N-fixing trees and non-N-fixing trees (Paula *et al.*, 2020).

This paper reports the first results obtained in a PP where common walnut (*Juglans regia* L.) and the poplar clone 'I-214' (*Populus ×canadensis Mönch*) are placed at different spacing and in alternate rows with different fast-growing species in a SRC model. The specific goals were to: (1) verify the SRC aboveground biomass production, (2) define the best planting intra-row spacing for the growing of walnut and poplar, (3) maximize poplar and walnut timber production in this type of plantation, and (4) improve timber quality (stem shape, reduced number and size of branches, and wind protection).

Material and methods

Site description and plantation management

The investigated plantation is located in a floodplain of the Po Valley in the municipality of Meleti (45°7'44.483" N, 9°49'28.998" E, Lodi Province, northern Italy). The soil was previously used for corn (*Zea mays* L.) cultivation. The main farm production target is animal husbandry. The area is characterized by deep, silty-sandy and moderately alkaline soils and by a sub-continental climate with hot, wet summers and cold winters. The mean annual temperature (average of 12 years) is 13.1 °C, and the mean annual rainfall is 800 mm with a maximum in autumn (288 mm) and a minimum in winter (149 mm). The plantation, which extends over 4.5 ha, was established in January 2006. A different type of planting material was used for each different species or production target: 2-yr old poplar poles (about 6 m high, without roots and branches) for clone 'I-214'; unrooted cuttings (22 cm long, obtained from stem) for the poplar clone 'AF2' (*P. ×canadensis Mönch*) in SRC; bare root seedlings for common walnut; while other species were planted using 1-yr old vegetative material in pots.

The randomized block design included three replications. Walnut and the poplar clone 'I-214' were planted in alternating lines, 11 m apart from each other, and three planting distances were used within the respective lines: for walnut these were 6, 7, and 8 m corresponding respectively to a density of 75, 65 and 57 trees ha^{-1} and for poplar these were 4, 5 and 6 m corresponding respectively to a density of 114, 91 and 76 trees ha^{-1}. Along the rows, nurse trees and shrubs were alternated: black alder (*Alnus glutinosa* (L.) Gaertn.) with walnut, and common hazel (*Corylus avellana* L.) with poplar (see Fig. 1). Between the poplar and walnut rows, seven species were tested in the SRC model to determine those with the best performance in such an environment: the poplar 'AF2' clone, field elm (*Ulmus minor* L.), hybrid plane (*Platanus hybrida* Brot.), common hornbeam (*Carpinus betulus* L.), European hop-hornbeam (*Ostrya carpinifolia* Scop.), common hazel and narrow-leafed ash (*Fraxinus angustifolia* Vahl.). The biomass lines were located at a distance of 4 m from the main crop trees (poplar and walnut) in double lines (with a 3 m distance between the rows), with the biomass trees planted every 2 m along the lines corresponding to a density of 900 trees ha^{-1}.

Mechanical weed control was carried out during the first three years. Walnut trees were pruned to a height of 3.0-3.5 m, and poplar trees to a height of 5.5-6 m. No chemical fertilizers were applied and some digestate, derived from

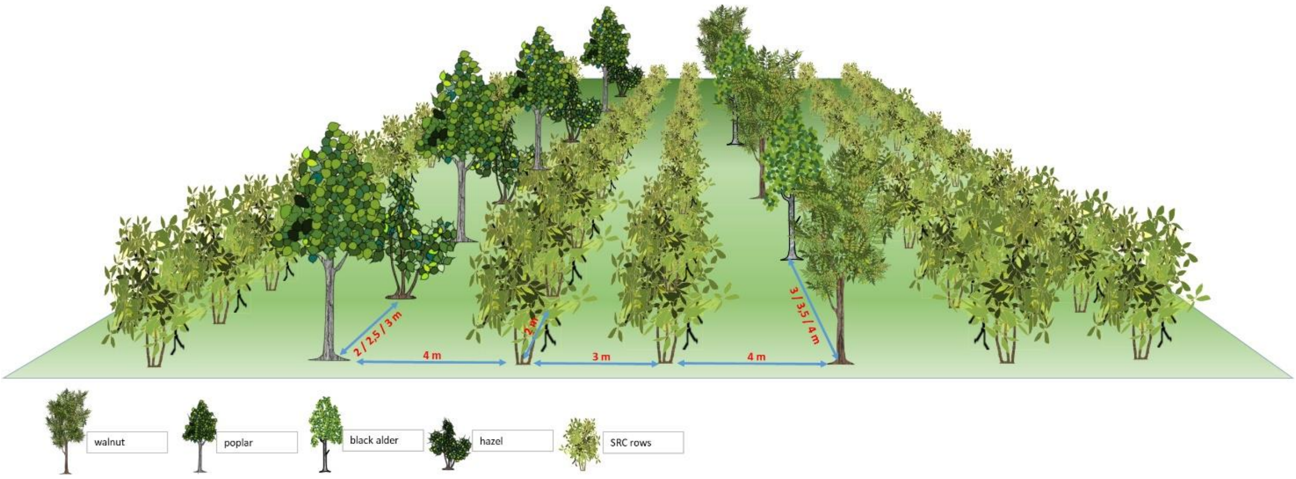

Figure 1. Adopted planting design. Distance between poplar 'I-214': 4, 5 and 6 m. Distance between common walnut: 6, 7 and 8 m. Distance between poplar 'I-214' and common walnut: 11 m.

bio-gas directly produced on the farm (from corn and animal sewage: average of 3 kg t^{-1} of total N, 50% of ammoniacal N, 70% of organic matter), was spread two times over the whole plantation after SRC harvesting, considering a total amount of about 120 kg t^{-1} of total N per hectare, defined as the limit by Lombardy regional law. No replanting of poplar, walnut and other tree species was necessary due to a very low mortality. As regards to water supply, only one irrigation in summer was applied during the first four years. In spring 2011, after 5 years, the SRCs were harvested and chipped. Finally, in spring 2016, 10 years after planting, 'I-214' poplar trees were harvested for timber. The stumps of SRC were eradicated while the stumps of 'I-214' were allowed to resprout and give rise to a new row, together with field elm, potentially useful for a second production of biomass for energy (not measured). The final harvest of walnut is expected to take place 25-30 years after planting.

The monitoring activities started in 2009 with data collection of diameter at breast height (DBH) and total height (H). The DBH monitoring was performed annually on main crop trees (poplar 'I-214' and walnut). At the end of the tenth year (2016), corresponding to poplar harvest, the volume of each poplar tree was estimated by using a specific allometric equation performed by CREA for 'I-214' clone (Chiarabaglio & Coaloa, 2004).

On 60 trees per biomass species (20 trees per replication), DBH, H and crown lateral size were measured to evaluate the average tree size (for common hazel was measured the main sprout); the biomass yield of species in SRC was estimated at the end of 2010 before harvest, with the "model tree method" (Truax *et al.*, 2014; Proietti *et al.*, 2016). As regards to data concerning growth (DBH) and yields of species in the SRC model, the normality of distribution was evaluated by Kolmogorov-Smirnov and Lilliefors tests, and the data were processed with analysis of variance (ANOVA). The average values were compared by Tukey's test (HSD) with a significance of $p<0.05$ (using 'Statistica 7.1' Statsoft software, 2018). Both for poplar 'I-214' and common walnut, growth data were also included in a linear mixed model analysis (LMM) to evaluate the influence of age, spacing and their interaction, and the influence of SRC rows on growth and yield of common walnut. For this analysis we used the software R 3.4.2 version (R Core Team, 2017).

Results and discussion

SRC aboveground biomass production

Five years after planting, the measurable parameters showed strong differences of growth among the biomass species (Table 1). Regarding the survival values, most of the species maintained a survival rate higher than 90%. The poplar reached higher values compared with other species both in diameter (18.7 ±3.9 cm) and height (14.8 ±2.1 m); field elm and hybrid plane showed interesting results, with diameters of 11.2±2.7 cm and 9.0 ±1.8 cm, and heights of 9.4 ±1.4 m and 9.7 ±1.5 m, respectively. The other species showed lower growth performances. The lateral size of crown of biomass species varied from 1.72 m (for hop hornbeam) to 3.36 m (for field elm) 5 years after planting (in Table 1, the values 'CD', related to crowns' diameters of all biomass species). The fast-growing species, namely field elm and poplar (biomass production), began to be competitive with common walnut (timber production); thus, their harvest should not be postponed for more than 5 years, while other less productive biomass species may be more suitable for longer rotation periods. Due to high growth performances, and despite the high mortality, the highest dry biomass productivity was shown by the 'AF2' poplar clone (39.9 Mg ha^{-1}), followed by field elm, hybrid plane and common hazel (31.9, 14.8 and 12.6 Mg ha^{-1}, respectively).

Table 1. ANOVA and Tukey's test of mean dendrometric parameters (DBH, H), survival (S), crown diameter (CD) and dry biomass (Odb) yield of species grown for biomass in SRC (short rotation coppice) model measure at the end of five years of growth.

Biomass species	S (%)		DBH (cm)		H (m)		CD (m)		Odb (Mg ha^{-1})	
Hornbeam (Cb)	98	A	4.4	E	4.5	C	1.89	BCD	5.7	B
Common hazel (Ca)	97	A	3.3	F	4.7	C	1.88	CD	12.6	B
Hop hornbeam (Oc)	92	A	4.0	EF	5.1	C	1.72	D	8.8	B
Narrow-leaf ash (Fr)	98	A	6.0	D	5.5	B	1.96	BCD	10.9	B
Field elm (U)	93	A	11.2	B	9.4	B	3.36	A	31.9	A
Hybrid plane (Pl)	88	A	9.0	C	9.7	B	2.59	BC	14.8	B
Poplar 'AF2' (P)	63	B	18.7	A	14.8	A	2.62	B	39.9	A
Average	90		8.07		7.77		2.29		17.80	
F values	9.8		340.9	***	84.5	***	15.3		27.10	***

Different letters in each column represent significantly different groups.

Effect on growth and wood quality of intra-row spacing

In Table 2 we compare the values of DBH and volume ha^{-1} of poplars grown with different distances. Before poplar harvesting (at 10 years), the average tree volume reached a value of approximately 1 m^3. The volume of poplar 'I-214' trees grown at a 5 or 6 m distance in the line was higher than that of the trees grown at a 4 m of distance, but if we consider the total volume per hectare, the effect of wider spacing can contrast the effect of higher growth of diameters in terms of production. Considering the results of LMM analysis (Table S1 [suppl]) the effect on DBH growth of the interaction 'Age × Distance' is positive and significant ($p \leq 0.05$); during the years of growth a wider distance allowed a greater diameter. The LMM model emphasizes a strong negative effect (coefficient: -7.976) of planting distance on the final yield (volume ha^{-1}), not adequately counterbalanced by higher growth of diameters. Finally, the LMM results showed a positive effect of age on the final yield and significant differences at $p \leq 0.001$ level (Table S2 [suppl]).

Considering the common walnuts, all trees planted with different spacing reached in 2017 similar values of DBH (mean 18.5 ±0.2 cm) and H (mean 12.1 ±0.3 m). The best walnut height performances (12.6 ±0.3 m) were measured at the widest spacing (8 m), compared to the 11.6 ±0.3 m and 12.2 ±0.3 m, respectively obtained for the 7 m and 6 m spacing (Table 2).

Table 2. Average and standard error (SE) of parameters of growth production and quality of poplar 'I-214' (a), at the harvest time (10 years) and growth of common walnuts (b) (after 12 years of growth) based on different plantation distances. DBH: diameter at breast height. VOL: aboveground volume per hectare. H: total height.

Distance (m)	DBH (cm)	SE (cm)	H (cm)	SE (cm)	VOL (m^3/ha)	SE %
Poplar I-214 (a)						
4	33.6	±0.3	23.2	±0.2	109.3	±0.3
5	34.2	±0.3	22.8	±0.2	98.3	±0.3
6	36.3	±0.4	22.5	±0.2	86.9	±0.3
Average	34.70		22.82		98.16	
F value	n.s.		n.s.		n.s.	
Common walnut (b)						
6	17.8	±0.2	12.2	±0.3		
7	18.9	±0.3	11.6	±0.2		
8	18.7	±0.2	12.6	±0.3		
Average	18.48		12.13			
F value	n.s.		n.s.			

The LMM analysis (Tables S3 and S4 [suppl]), pointed out the effect of different SRC on walnut growth. The different SRC species influenced both the DBH and the H development of common walnut, with statistical significance for age and distance between trees factors. The LMM applied both to DBH and H underlines a significant and negative influence of some species, such as field elm that also showed a wider crown increasing with age, and a positive growing influence of other species, such as common hazel and hornbeam (Tables S3 and S4 [suppl]).

Interesting results for biomass production were obtained with species grown in SRC: poplar clone 'AF2', field elm, hybrid plane and common hazel produced 8, 6.4, and 2.5 Mg ha^{-1} yr^{-1} of dry matter respectively, with a 5-year rotation period covering only 64% of the total surface. In the Po Valley, the literature indicates productions of about 10-15 Mg ha^{-1} yr^{-1} of dry matter for intensive SRC (Bergante & Facciotto, 2015).

The clone 'I-214' grew faster under a density of 80-150 trees ha^{-1}. After 10 years, poplar trees reached a commercial size for industrial transformation with a DBH similar to that in the best poplar monoculture managed with an intensive system. Wider spacing led to a density of 83 or 91 trees ha^{-1}, respectively, in comparison to 114 trees ha^{-1} under the narrower spacing. A lower tree density allowed to obtain trees with larger diameters with a consequent larger percentage of a valuable assortment (plywood) but smaller production in terms of total volume (-20%). In more fertile soil and using a more productive clone, a DBH of approximately 40-45 cm was obtained, with 91 poplar trees ha^{-1} under a 9-year rotation period (Pelleri *et al.*, 2013). Poplar diameters of approximately 40-50 cm instead of 30-35 cm can be obtained in 10-12 years, as in the case of traditional monoculture (Vietto *et al.*, 2012; Buresti & Mori, 2016). These larger logs produce higher yields in terms of peeling and a reduction in production costs (Castro *et al.*, 2013).

In this plantation, common walnut trees grow quite well: after 12 years, the growth and stem shape of these trees were good, with a DBH of about 18-19 cm, a 12-13 m height and 2.5-3.0 m first portion of stems without branches. Similar results were obtained in other Northern Italian plantations, where common and hybrid walnut, planted at a 7.4 m distance from different poplar clones, showed a similar growth pattern (Pelleri *et al.*, 2013). In the plantations examined in the present study, the wider intra-row spacing of 7 and 8 m (corresponding to 65 and 57 trees ha^{-1}) seemed to be more appropriate and will probably allow all trees to reach the required veneer industry diameter (40 cm) in 25-30 years.

Mixed plantations have showed interesting results, often better than those of walnut monoculture from the productive, economic-financial (Pra *et al.*, 2019; Coaloa *et al.*, 2020) and environmental point of view (Pelleri *et al.*, 2020).

Currently, few results regarding the end of walnut rotation period are available, but walnut grown in a polycyclic plantation showed similar DBH growth and better stem quality than the best walnut monoculture (Fernández-Moya *et al.*, 2019). The use of nurse trees can often quantitatively and qualitatively improve the development of walnut, enhancing the environmental micro-site conditions, and provides fundamental support for management (Pelleri *et al.*, 2020). Intercropping with suitable N-fixing trees may be useful to ensure high levels of crop tree timber production in case of low soil fertility (Marron & Epron, 2019).

Conclusion

Polycyclic plantations are a recent model able to produce, in the same land surface, different assortments (veneer, plywood, packaging and biomass for energy) using various crop trees characterized by different growth rates and rotation periods. This new type of mixed plantation is more environmentally sustainable compared to monoculture. In fact, the use of mixtures of different crop trees with nurse trees and shrubs (including N-fixing trees) reduces the cultivation workload and external input of fertilizers, pesticides, weed control and irrigation. On the other hand, this type of plantation allows diversification of wood production and spreads it over time: biomass every 5 years, poplar for plywood every 10 years and valuable broadleaved timber every 25-30 years. In the work presented, the association did not cause growth problems neither for the SRC species, nor for the poplar, and currently not even for the walnut. However, after an observation period of twelve years some practical indication can be given. In SRC mode, the poplar gave the best results and similar production has been obtained by field elm. The hybrid plane is another interesting species, but a longer rotation (7 years) is more suitable. The best intra-row spacing to maximize growth, production and timber quality of poplar for industry purposes is 5 or 6 meters; narrowed spacing (4 m) seems to be unsuitable to obtain sufficient percentage of logs suitable for peeling. As for the walnut, the observation period is currently too short to have a final indication but considering the needs of the species and other experiences an intra-row spacing of 8 m for walnut could be more appropriate to obtain, in 25 years, trees with a DBH 40 cm suitable for veneer.

In summary, polycyclic plantations are an interesting alternative to pure poplar or walnut plantations able to provide interesting result under the economic point of view and significant benefits to the environment, landscape and society in suitable areas if properly planned and managed.

Acknowledgements

The authors wish to thank the farming plantation owners at 'Cascina Cascinazza', Mr. Piero and Carlo Gattoni for their collaboration on the survey in each phase. Special thanks go to Dr. Enrico Buresti Lattes, creator, and main passionate promoter of this new type of plantation design. The authors thank Dr. Massimo Gennaro, for his valuable contribution in the revision of the language.

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