creaJournals

Annals of Silvicultural Research
45(1), 2020: 12-20
https://journals-crea.4science.it/index.php/asr

Research paper

Collection: "4th Italian National Congress of Silviculture"
Torino, 5-9 November 2018

Comparison between two and five years rotation models in poplar, willow and black locust Short Rotation Coppices (SRC) in North West Italy

Gianni Facciotto [1*], Sara Bergante [1], Laura Rosso [1], Gianfranco Minotta [2]

Received: 9/01/2019 *Accepted: 27/11/2019* *Published: 21/07/2020*

ABSTRACT Currently, SRC plantations should produce multiple assortments, both for industrial and energetic uses, for being economically profitable. SRC trials comparing two different cultivation models (very high density model -- vHDM, 8,333 trees ha^{-1} with 2 years rotation; high density model -- HDM, 1,667 trees ha^{-1} with 5 years rotation) were established in 2005 in two sites (Casale Monferrato and Cavallermaggiore), on agricultural land with alluvial soils in the Western Po Valley (Italy). Both models were applied to poplar (clone 83.141.020), willow (clone S76-008) and black locust (provenance Energy). After 6 years from planting, the two treatments did not show significant differences in terms of cumulative biomass yield, with poplar being the most productive species at Casale Monferrato (64.65 and 63.76 Mg ha-$^{-1}$ with HDM and vHDM, respectively). Poplar production potential was confirmed at Cavallermaggiore (105.83 and 57.22 Mg ha^{-1}, respectively). Black locust showed the lower yield at both sites. In HDM poplar exhibited the highest stem DBH, at both sites, reaching mean values of 15.0 and 17.8 cm at Casale Monferrato and Cavallermaggiore, respectively. In HDM, poplar was the only species capable to reach stem dimensions compatible with industrial destinations at the end of the first 5- years rotation.

KEYWORDS: biomass yield, planting density, cultivation model.

Introduction

On a global scale, increasing energy demand and the need to mitigate climate change emphasize the importance of renewable energy sources. Bio-energy from tree plantations is thus expected to become one of the alternative solutions for energy supply in many countries (Mizey and Racz 2010). A lot of research projects on biomass production from fast growing woody species such as poplar (*Populus* spp.), willow (*Salix* spp.), black locust (*Robinia pseudoacacia* L.) and others, have been conducted throughout the world in order to detect the more suitable planting material and cultural practices to provide high yields and favourable economic results (Manzone et al. 2017, Posza and Borbely 2017, Bender et al. 2016, Bergante and Facciotto 2015, Pleguezuelo et al. 2015, Benetka et al. 2014, Mughini et al. 2014, Redèi et al. 2008, Busti et al. 2007, Facciotto et al. 2007, Bonari et al. 2004). Given the low market price of woody biomass and consequent low returns, there is still a need for research about many aspects of short rotation woody crops, such as plantation design, rotation length and farm organization (Canellas et al. 2012). Indeed, the choice of planting density influences tree growth, timing of cultural inputs, rotation length, wood quality and, finally, yields and income.

In Italy, typical Short Rotation Coppice (SRC) crops are established with densities of 5,500-8,500 trees ha^{-1} with 2 or 3-year rotation lengths using mainly poplar clones (Facciotto et al. 2014, Sabatti et al. 2014, Di Matteo et al. 2012). In other countries, under suitable environmental conditions, it is possible to reach densities of about 40,000 trees ha^{-1} and more with willow clones (Danfors et al. 1998, Kopp et al. 1997). Generally in sites with available water (rain or soil) and cool-temperate climate, very high density are more productive than low density SRC plantations (Armstrong et al. 1999); however, yield is not always linearly correlated with planting density (Kopp et al. 2001, Danfors et al. 1998, Kopp et al. 1997), due to the high competition effects and difficult weed and pest control (Mitchell 1995). With these SRC models each tree produces many stems of small diameter, so wood quality is low and the harvested biomass is suitable only for combustion or particle boards.

SRC plantations established with densities of 1,100-1,670 trees ha^{-1} and grown with a 5-year rotation cycle have the potential to produce larger assortments suitable not only for energy but also for other more profitable uses (i.e. packaging, oriented strand board - OSB and pulp industries), so widening the market for the woody material produced by the crop. At present, experimental data on yield performances of these 5-year rotation crops are still scarce in Italy, although they could be an alternative to the typical energy woody crops for many farms located in the Po Valley (Manzone et al. 2014, Gonzales-Garcia 2012) due to the better quality of the harvested wood and greater similarity to the traditional ten-year rotation poplar stands widely distributed in the Po Valley and destined for the plywood industry. Indeed, lengthening of the harvest interval may increase the net energy yield of SRC plantations (Nassi et al. 2010, Paris et al. 2015) as well as stand

1 CREA – Forestry and Wood Centre
2 Università degli Studi di Torino, Department of Agricultural, Forest and Food Sciences (DISAFA) -Italy
*Corresponding author: gianni.facciotto@crea.gov.it

http://dx.doi.org/10.12899/asr-1962

biodiversity (Weger et al. 2013), thus improving the environmental sustainability of these systems.

SRC trials comparing two different cultivation models: very high density model - vHDM (8,333 trees ha^{-1} with 2-year rotation), and high density model – HDM (1,667 trees ha^{-1} with 5-year rotation) both applied to poplar (clone *Populus* × *canadensis* Mönch 83.141.020, breeder: CREA Forestry and Wood, Italy), willow (hybrid of *Salix babilonica* L. ex *Salix matsudana* Koidz. S76-008 breeder: CREA Forestry and Wood, Italy) and black locust (provenance of *Robinia pseudoacacia* L. Energy from Hungary) were therefore conducted at two sites in the Western Po Valley, Piedmont Region (North-West Italy).

Material and methods

Site description

Two experimental plantations were established in the spring of 2005 at two sites in the Western Po Valley (Tab. 1): at the "Mezzi" farm near Casale Monferrato (Site 1) and belonging to the CREA Forestry and Wood,, the Research Agency of the Italian Ministry of Agricultural, Food and Forestry Policies; at the "Allasia Plant" farm close to Cavallermaggiore (Site 2). The climate is transitional between the Continental and Mediterranean type, with hot dry summers, rainy autumns and springs and cool winters; the growing season is from April to October (Tab. 1). The sites have deep and sandy or sandy-loam soils with neutral or moderately alkaline pH, low salinity and active limestone (Tab.1). The water table is below 4 m in both sites.

Table 1 - Climate (mean of 30 years) and soil (top 30 cm) properties at the two sites. Mean annual precipitation (R). Mean precipitation from April to October (vR). Mean annual temperature (T). Average maximum monthly temperatures (Tmax).Average minimum monthly temperatures (Tmin).

	Site1	Site 2
Latitude	45°08' N	44° 43' N
Longitude	08° 27' E	07° 41' E
Altitude m asl	116	285
R mm	746.0	626.5
vR mm	402.0	503.5
T °C	12.9	11.5
Tmax °C	24.1	25.2
Tmin °C	0.2	0.5
Sand %	87.0	85.7
Silt %	9.7	11.0
Clay %	3.3	3.3
pH	8.0	7.2
P2O5 tot %	1.6	1.5
K2O ass. mg/100g	2.4	0.2
N2 Kjeldahl g/kg	0.50	0.13
C org. %	4.64	1.71

Experimental plots

Experimental plots were established with 8,333 trees ha^{-1} in vHDM and 1,667 trees ha^{-1} in HDM spaced 3 m between rows × 0.40 m along the row and 3 × 2 m, respectively. Rotation length was two and five years for vHDM and HDM, respectively. Each model was established with poplar, willow and black locust using clones/provenances recently selected for biomass by CREA Forestry and Wood, under the Po Valley environments. Each plantation covered an area of 0.30 ha. Poplar and willow vHDM plots were established with stem cuttings 20 cm in length prepared in late winter - early spring and hydrated for a few days before planting. One-year-old seedlings were planted in vHDM black locust plots; at the time of planting these seedlings were subjected to stem pruning to stimulate shoot emission.

HDM plots were created using poplar and willow one- year-old stems deprived of roots and branches; these stems were hydrated for ten days and then planted (vertically) in holes 80 cm deep. Black locust HDM plots were established with one-year-old seedlings left unpruned to favour the development of single-stem individuals.

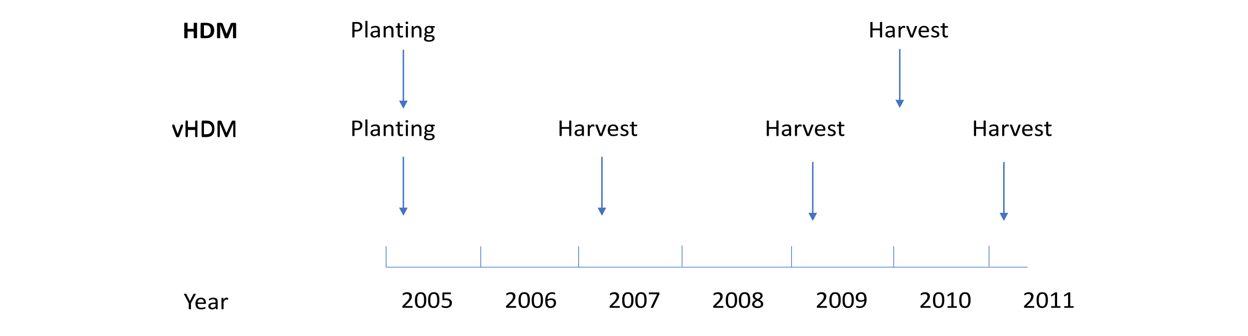
Before planting the soil was ploughed 40 cm deep, harrowed and treated with NPK (15:15:15) fertilizer, at a dose of 600 kg ha^{-1}. A mixture of herbicides (Metholachlor 2.5 l ha^{-1} + Pendimetalin 2.5 l ha^{-1}) was applied immediately after planting; subsequently, weed control was performed with mechanical interventions (harrowing) during the first year from planting and after each harvesting in vHDM and during the first two years after planting in HDM. Two insecticide treatments with Chlorpyrifos-methil + Deltamethrin 2 kg ha^{-1} were applied against the leaf beetle (*Chrysomela populi* L.) in poplar plots.

The experimental plantations were irrigated three times during the first, second and third growing season. Watering was suspended starting from the 4th year. Sprinkler (30 mm for each event) and flooding irrigation were applied at Site 1 and Site 2, respectively.

After each harvest, vHDM plots were treated with slow-release N fertilizer (70 kg ha^{-1}) and with Glufosinate ammonium (8 kg ha^{-1}) for weed control.

The harvesting was performed every two years in vHDM with different strategies. First and second harvest in combined activity with a circular saw, collectioning with a telescopic handler and separated chipping machine. Third harvest in one operation with a Class harvester and chipping machine. In HDM model an operator felled the trees with a chainsaw, which were then collected with a telescopic handler; chipping was done separately three months later (Spinelli et al. 2012). Fig. 1 shows the timing of the harvest operations in vHDM and HDM plots.

Figure 1 - Time of planting and frequency of harvesting operation in HDM (very high density model 1,667 trees ha^{-1}, 5 years rotation) and vHDM (high density model 8,333 trees ha^{-1}, 2 years rotation) plots.



Data collection

The following parameters were recorded at the end of each growing season on the studied trials:

1. Plant rooting (%) at the end of the first growing season;
2. Plant survival (%) from the second to sixth year after planting;
3. Stem diameter at breast height (DBH) (mm) of all living shoots over 150 cm in height;
4. Number of living sprouts per tree/stump.

Stem DBH was measured on all the tree/stump samples collected in the middle part of the plots (9 trees/stumps per plot in HDM and 69 trees/stumps in vHDM)

Cumulative biomass yield was expressed in dry matter per hectare (Mg dm ha^{-1}) and was estimated using the following power equations applied to all measured shoots (dominant and dominated). The power equations were derived from the literature for vHDM (poplar: Facciotto et al. 2005; black locust: Facciotto and Bergante 2005; willow: Cerrillo et al. 2008) or specially improved for HDM model measuring single trees during the harvest (DBH, total length and fresh weight; on a subsample dry weight also).

1.	Poplar vHDM	$dw = 0.5560 * D_{130}^{2.1952}$	n=1900	R^2=0.93
2.	Willow vHDM:	$dw = 1 * D_{130}^{2.107687}$	n=300	R^2=0.99
3.	Black locust vHDM:	$dw = 1 * D_{130}^{2.128}$	n=210	R^2=0.99
4.	Poplar HDM:	$dw = 0.1019 * D_{130}^{2.3448}$	n=81	R^2=0.92
5.	Willow HDM:	$dw = 0.0821 * D_{130}\ 2.^{4528}$	n=47	R^2=0.92
6.	Black locust HDM:	$dw = 0.0991 * D_{130}^{2.5366}$	n=39	R^2=0.94

where 'n' is number of sampled trees, 'dw' is dry weight in g for vHDM or kg for HDM, and 'D_{130}' is stem DBH in mm for vHDM or cm for HDM. To assess the differences between the actual weight of shoot samples collected during harvest and the predicted values of power equations derived from the literature, the root mean square error (RMSE) was calculated. It resulted as 77 g, 147 g and 212 g for poplar, willow and black locust, respectively.

Statistical design and analysis

Experimental plots were arranged in a split-plot design with three replications. Density treatment was allocated in the whole plot and species in the sub plot.

A multifactor ANOVA was conducted separately for each site considering density (1,660 *vs* 8,333 trees ha^{-1}) and species (poplar *vs* willow *vs* black locust) factors. The analyses were done using the SPSS statistical package. Figure 2 was performed using R software (ver. 3.5.1, 2018) and package 'ggplot2' (Wickham 2016).

Results and Discussion

Site 1 - Casale Monferrato

At the end of the first year, HDM and willow exhibited the highest rooting percentage between models and among species, respectively (Tab. 2), with mean values varying from 77% (HDM) to 90% (willow). These percentages were similar to those observed in other SRC trials conducted in the Po Valley (Bergante et al. 2010). The differences decreased over time and after six years from planting survival percentage was statistically similar between models and among species. At the end of the trials the mean survival rate was 77 and 56% for HDM and vHDM, respectively. The slight increase in survival percentage observed in black locust plots over the years was due to new stumps originating from the root suckers after the harvesting operations. The high mortality observed in vHDM willow plots was due to the action of rodents which prefer young willow shoots (Danell et al. 1991, Gill 1992). Biomass yield did not show any statistical difference between models, while poplar exhibited a higher production than willow and black locust at the 5th and 6th year after planting (Tab. 3) and this difference was statistically significant.

At the end of the trials mean biomass values varied from 51.63 (HDM) to 55.58 Mg ha^{-1} (vHDM), being 64.21, 51.60 and 45.01 Mg ha^{-1} for poplar, willow and black locust, respectively. Black locust vHDM plots showed a constant increase in biomass yield throughout the three harvesting cycles, while poplar and

Table 2 - Site 1: Rooting (1st year) and survival (from 2nd to 6th year) values (%) and ANOVA results (F values).

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
HDM	Poplar	93	93	89	89	75	65
	Willow	99	96	96	94	92	84
	Black Locust	79	76	72	72	71	83
vHDM	Poplar	76	75	74	74	67	66
	Willow	82	73	53	45	37	37
	Black Locust	73	70	64	58	59	66
Average:							
HDM		90	88	86	85	79	77
vHDM		77	73	64	59	54	56
	Poplar	84	84	81	81	71	65
	Willow	90	84	75	69	65	60
	Black Locust	76	73	68	65	65	75
F values:							
Model (M)		19.97**	16.11	13.56	18.01	14.9	4.21
Specie (S)		4.66**	3.1	2.78	3.75	0.76	4.22
M × S		0.95	1.59	5.99*	5.56*	10.82**	10.79**

** significant p≤0.05; ** highly significant p≤0.01*

Table 3 - Site 1: cumulative dry matter biomass yield (Mg ha^{-1}) at the 2nd, 4th, 5th and 6th year after planting (HDM was harvested at the 5th year, vHDM at the 2nd, 4th and 6th year) and ANOVA results (F values).

Model	Species	2nd y	4th y	5th y	6th y
HDM	Poplar	8.15	48.10	64.25	64.65
	Willow	13.40	44.58	53.55	54.92
	Black Locust	4.05	27.08	33.42	35.32
vHDM	Poplar	14.19	39.05	45.64	63.76
	Willow	12.55	29.69	34.41	48.27
	Black Locust	12.37	28.41	36.26	54.71
Average:					
HDM		8.54	39.92	50.40	51.63
vHDM		13.04	32.39	38.77	55.58
	Poplar	11.17	43.58	54.95	64.21
	Willow	12.98	37.13	43.98	51.60
	Black Locust	8.21	27.75	34.84	45.01
F values:					
Model (M)		4.96	1.57	1.63	0.08
Specie (S)		3.69	4.33	6.82**	7.08**
M × S		3.64	1.15	2.65	2.78

*** highly significant p≤0.01*

willow exhibited an increase in biomass yield from the first to the second cycle and a decrease from the second to the third. Black locust reached the lowest productivity among HDM plots; this was probably due to the use of unpruned seedlings as planting material and therefore to a slow plant recovery after transplanting, as suggested by the relatively low biomass yield in the second year (Tab. 3). On the whole, the yield trends observed in these trials at Site 1 are consistent with data reported by other authors working with the same species (Verlinden et al. 2015, Paris et al. 2011, Facciotto and Bergante 2005). Geyer et al. (2006) reported no differences in biomass yield for black locust SRC plantations established on the central plains of the USA and submitted to cutting cycles of one, two or five years. Lamerre et al. (2015) observed similar yields in poplar SRC established in an alley-cropping agroforestry system and harvested with 3 and 6-year rotation cycles in Germany. In SRC plantations established in Scotland with poplar, alder and willow, the harvest of biomass reduced yield by 26% with respect to the non-coppiced, single stem trees (Proe et al. 2002), while Weger et al. (2013) reported an increase in biomass yield along with the length of the rotation in poplar SRC established in the Czech Republic, but these effects were not so evident in the present trials.

The resprouting capacity after cutting is an important physiological trait influencing biomass yield in SRC crops (Ceulemans and Deraedt 1999); it is a genetic property that varies according to species and genotype, and frequently considered in the selection phase because it affects production, wood quality and ease of harvesting (Dillen et al. 2013). Tables 4 and 5 report the mean sprout number observed on each stump in HDM and vHDM, respectively. In HDM differences among species started to become significant during the 4th year, with black locust showing the highest value for this factor (1.7 sprouts per stump) followed by willow (1.5), while no sprouts were detected on poplar plants during the first 5-year rotation. After the first harvesting all three species exhibited a good sprouting ability with a number of sprouts per stump equal to 9.4, 4.6 and 4.0 for willow, black locust and poplar, respectively. In vHDM the differences between species were already significant at the end of the first 2-year cycle, with the highest value evidenced by willow (1.5 sprouts per stump) followed by black locust (1.1). In these plots the number of sprouts increased considerably after the second cutting and remained almost stable during the other years. At the end of the trials the number of sprouts per stump was 6.1, 4.2 and 2.8 for willow, poplar and black locust, respectively. Therefore, willow exhibited the highest sprouting ability regardless of the model, as already observed in other SRC trials (Cerrillo et al. 2008, Facciotto et al. 2008, Weih 2004).

Table 4 - Site 1: number of sprouts per stump and ANOVA results (F values) in HDM plots.

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
HDM	Poplar	1.0	1.0	1.0	1.0	1.0	4.0
	Willow	1.0	1.6	1.5	1.5	1.5	9.4
	Black Locust	1.0	1.6	2.1	1.7	1.6	4.6
Average:		1.0	1.4	1.5	1.4	1.4	6.0
F values:		-	0.99	4.91	9.80*	20.17**	10.80**

* *significant p≤0.05; ** highly significant p≤0.01*

Table 5 - Site 1: Site 1: number of sprouts per stump and ANOVA results (F values) in vHDM plots.

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
vHDM	Poplar	1.1	1.2	4.9	3.8	5.0	4.2
	Willow	1.5	2.5	6.4	4.4	7.4	6.1
	Black Locust	1.1	1.3	2.6	2.0	3.7	2.7
Average:		1.2	1.6	4.7	3.4	5.4	4.4
F values:		30.04**	64.74**	14.94**	17.75**	30.27**	23.60**

*** highly significant p≤0.01*

Table 6 - Site 2: rooting (1st year) and survival (from 2nd to 6th year) values (%) and ANOVA results (F values).

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
HDM	Poplar	77	80	80	80	80	77
	Willow	99	99	99	97	97	84
	Black Locust	99	100	99	92	99	95
vHDM	Poplar	84	84	85	85	83	81
	Willow	94	94	92	92	87	83
	Black Locust	75	67	69	66	64	65
Average:							
HDM		92	93	92	90	92	85
vHDM		84	82	82	81	78	76
	Poplar	81	82	82	82	81	79
	Willow	96	96	96	95	92	84
	Black Locust	87	84	84	79	82	80
F values:							
Model (M)		2.95	28.69*	27.63*	20.95*	13.58	6.93
Specie (S)		32.13**	6.63*	8.06*	4.31	3.97	0.4
M × S		31.46**	10.61**	10.63**	3.95	8.37*	5.75*

* *significants p≤0.05; ** highly significant p≤0.01*

Site 2 - Cavallermaggiore

At Site 2 most of the rooting and survival values (Tab. 6) were higher than those observed at Site 1. During the first 3-4 years of the trials survival rate was higher in HDM than in vHDM, and for willow than for poplar and black locust plants. In the subsequent years the statistical differences disappeared, even if HDM maintained higher absolute survival rates than vHDM. Only the interaction model x species remained significant till the end of the trials. Six years after planting survival rates were 77, 84 and 95% for poplar, willow and black locust, respectively in HDM plots and to 81, 83 and 65% for the same species in vHDM plots.

Biomass yield also reached higher values at Site 2 (Tab. 7), but the differences between models and among species were not significant, probably because of the high variability of the observed data (Fig. 2). At the end of the trials mean cumulative biomass values were equal to 83.93 and 62.75 Mg ha^{-1} for HDM and vHDM, respectively and to 81.53, 70.37 and 68.12 Mg ha^{-1} for poplar, willow and black locust, respectively. Therefore even at this site poplar confirmed its high production potential, particularly in HDM plots. On the whole, the trends of biomass accumulation observed here were similar to those detected at Site 1.

Table 7 - Site 2: cumulative dry matter biomass yield (Mg ha^{-1}) in the 2nd, 4th, 5th and 6th year from planting (HDM was harvested at the 5th year, vHDM at the 2nd, 4th and 6th year) and ANOVA results (F values).

Model	Species	2nd y	4th y	5th y	6th y
HDM	Poplar	7.46	57.74	102.88	105.83
	Willow	12.32	49.35	66.66	73.46
	Black Locust	7.60	45.62	66.88	72.50
vHDM	Poplar	5.38	28.30	41.86	57.22
	Willow	10.80	35.73	51.91	67.29
	Black Locust	11.04	34.85	48.86	63.74
Average:					
HDM		9.12	50.90	78.81	83.93
vHDM		9.08	32.96	47.54	62.75
	Poplar	6.42	43.02	72.37	81.53
	Willow	11.56	42.54	59.28	70.37
	Black Locust	9.32	40.23	57.87	68.12
F values:					
Model (M)		0.00	7.91	13.89	6.93
Specie (S)		7.26*	0.18	2.19	1.36
M × S		2.52	2.06	5.72*	3.74

** significants p≤0.05*

Table 8 - Site 2: number of sprouts per stump and ANOVA results (F values) in HDM plots.

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
HDM	Poplar	1.0	1.3	1.1	1.1	1.0	9.0
	Willow	1.0	1.1	1.0	1.0	1.0	8.0
	Black Locust	1.0	1.1	1.5	1.5	1.4	4.3
Average:		1.0	1.13	1.20	1.22	1.17	7.08
F values:		-	1.2	19.9	26,0	14.8	27.5

*** highly significant p≤0.01*

Table 9 - Site 2: number of sprouts per stump and ANOVA results (F values) in vHDM plots.

Model	Species	1st y	2nd y	3rd y	4th y	5th y	6th y
vHDM	Poplar	1.1	1.2	3.9	2.8	6.3	5.1
	Willow	1.6	1.6	7.4	5.1	10.3	8.3
	Black Locust	1.3	1.5	2.0	1.7	3.0	2.0
Average:		1.36	1.44	4.43	3.20	6.54	5.13
F values:		19.6**	-	66.8**	21.4**	22.4**	56.9**

*** highly significant p≤0.01*

Figure 2 - Cumulative dry matter yield (Mg d.m. ha^{-1}) ± SE at 6th year after planting.

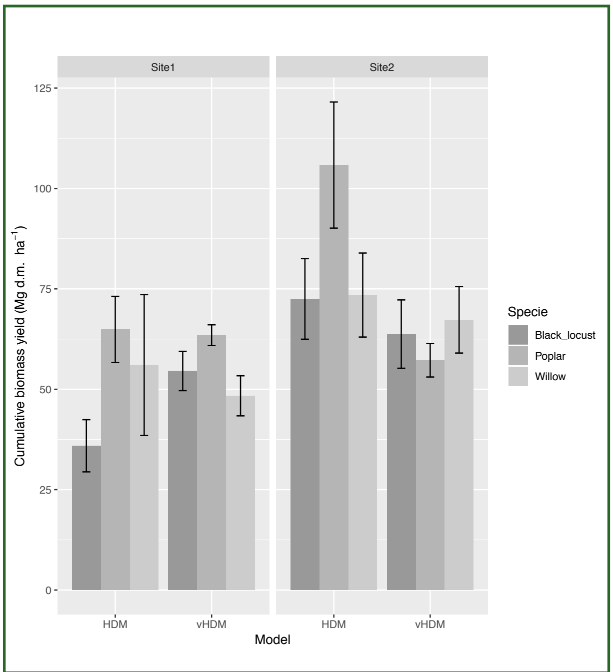


Table 10 - Stem DBH (cm) at the end of the first 5 year rotation and ANOVA results (F values) in HDM plots.

	Site1	Site 2
Poplar	15.0	17.8
Willow	10.2	10.0
Black Locust	7.3	12.4
F values:	45.98**	31.44**

*** highly significant p≤0.01*

The differences in number of sprouts became significant among species starting from the third year of the trials in HDM (Tab. 8), with black locust showing the highest value till the end of the first 5-year cycle (1.4 sprouts per stump). Poplar instead showed the highest resprouting ability after the first harvesting (9.0 sprouts per stump), followed by willow (8.0). In vHDM, significant differences among species were already appreciable after the first year from planting (Tab. 9), with willow showing the highest value (1.6 sprouts per stump), followed by black locust (1.3). Willow maintained the highest values till the end of the trials, with 8.3 sprouts, followed by poplar (5.1).

Stem diameter in HDM plots

Stem DBH measured in HDM plots at the end of the 5th growing season is reported in Tab. 10 for both sites. Poplar exhibited the highest stem DBH regardless of site, reaching mean values of 15.0 and 17.8 cm at Site 1 and Site 2, respectively. Willow and black locust had DBH values much lower than 15 cm, which can be considered as the minimum compatible with the industrial uses of the harvested biomass such as packaging, OSB and pulp industries. The slight diameter growth observed with black locust particularly at Site 1 might be due to the root sprouts emitted by many single-stem individuals during the first rotation. These sprouts could have affected negatively the growth of the main stem when the vigour of young seedlings was still relatively low.

Conclusions

In these trials HDM and vHDM did not show significant differences in terms of biomass yield six years after planting; both models can allow a fast accumulation of biomass as required in SRC crops.

Among the tested planting materials, poplar clone 83.141.020 exhibited the highest yield and, in HDM plots, it was the only one to reach a mean DBH compatible with industrial uses. Thus, this clone/species appears to be the most capable of achieving the objectives of this crop and, at least at the moment, it should be preferred for the establishment of HDM plantations in the Western Po Valley. However, HDM plants revealed a good resprouting ability when cut at the end of the first 5-year rotation cycle regardless of the tested species. Therefore, from the second rotation onwards, HDM will probably produce only wood for energy or particle boards unless sprouts are properly thinned to recover a single-stem structure. However, to achieve more robust results, trials should be extended to other clones/species and to several HDM rotations in order to evaluate the trend of biomass yield throughout subsequent cycles.

References

Armstrong A., John C., Tubby I. 1999 - *Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop*. Biomass and Bioenergy 17: 305-314. Doi:10.1016/S0961-9534(99)00054-9

Bender M., Tiedemann M., Teuber L., Geldermann J. 2016 - *Online and stochastic optimization for the harvesting of short rotation coppice*. Journal of Cleaner Production 110: 78-84. Doi: 10.1016/j.jclepro.2015.08.120

Benetka V., Novotna K., Stochlova P. 2014 - *Biomass production of* Populus nigra *clones grown in short rotation coppice systems in three different environments over four rotations.* iForest - Biogeosciences and Forestry 7: 233-239. Doi: /10.3832/ifor1162-007

Bergante S., Facciotto G., Minotta G. 2010 - *Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis.* Central European Journal of Biology 5 (4): 522–530. Doi: 10.2478/s11535-010-0028-y

Bergante S., Facciotto G. 2015 -*Yields of poplar SRC and vSRC grown with different fertilization and irrigation management.* In : Proceedings of 23rd European Conference & Exhibition, Setting the course for a biobased economy. Vienna, Austria, June 1-4: 65-67.

Bonari E., Picchi G., Fraga A., Ginanni M., Guidi W., Piccioni E. 2004 - *Comparison of three coppice intervals on a nine years old poplar biomass production.* In: Proceeding of 22a Sesion Internacional del Alamo. Chile-Argentina, 28 noviembre-9 diciembre: 80-81.

Busti M., Facciotto G., Coaloa D., Balsari P., Airoldi G., Manzone M., Mosso A., Brun F., Tarasco G., Barra S., Filipponi E., Dezzutto S., Allasia E., Regione Piemonte 2007 - *Study, experimentation and* *feasibility analysis for biomass energy production from short rotation tree crops in Piemonte's farmlands: the Biofil project*. In: Proceedings 15th European Conference & Exhibition, From Research to Industry and Markets. Berlin, Germany, May 5-8: 1230-1232.

Canellas I., Huelin P., Hernandez M.J., Ciria P., Calco R., Gea-Izquierdo G. 2012 - *The effect of density on short rotation* Populus *sp. plantations in the Mediterranean area.* Biomass and Bioenergy 46: 645-652. Doi: 10.1016/j.biombioe.2012.06.032

Cerrillo T., Facciotto G., Bergante S. 2008 - *Biomass production of different willow's combinations: preliminary results*. In: Proceedings of 16th European Conference & Exhibition, From Research to Industry and Markets. Valencia, Spain, June 2-6: 567-569.

Ceulemans R., Deraedt W. 1999 - *Production physiology and growth potential of poplars under short-rotation forestry culture.* Forest Ecology and Management 121 (1-2): 9-23. Doi: 10.1016/S0378-1127(98)00564-7

Danell K., Hjältén J., Ericson L., Elmqvist T. 1991 - *Vole Feeding on Male and Female Willow Shoots along a Gradient of Plant Productivity.* Oikos 62 (2): 145-152. Doi:10.2307/3545259

Danfors B., Ledin S., Rosenqvist H. 1998 - *Short-Rotation Willow Coppice Growers' Manual*. Upsala, Sweden. Swedish Institute of Agricultural Engineering. 40 p.

Dillen S.Y., Djomo S.N., Al Afas N., Vanbeveren S., Ceulemans R. 2013 - *Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years.* Biomass and Bioenergy 56: 157-165. Doi: 10.1016/j.biombioe.2013.04.019

Di Matteo G., Sperandio G., Verani S. 2012 - *Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density.* iForest - Biogeosciences and Forestry 5: 224-229. Doi: 10.3832/ifor0628-005

Facciotto G., Zenone T., Failla O. 2005 - *Aboveground biomass estimation for Italian poplar SRF.* In: Proceedings of 14th European Conference & Exhibition, Biomass for Energy, Industry and Climate protection. Paris, France, October 17- 21: 299-299.

Facciotto G., Bergante S. 2005 - *Black Locust for SRF: economic and production evaluation*. In: Proceedings of 14th European Conference & Exhibition, Biomass for Energy, Industry and Climate protection. Paris, France, October 17- 21: 383-385.

Facciotto G., Bergante S., Mughini G., Gras M., Nervo G. 2007 - *Tecnica e modelli colturali per cedui a breve rotazione.* L'Informatore Agrario 63 (40): 38-42.

Facciotto G., Di Candilo M., Bergante S., Baratto G., Diozzi M. 2008 - *Willow clones for biomass production in SRC plantations.* In: Proceedings of 16th European Conference & Exhibition, From Research to Industry and Markets. Valencia, Spain, June 2-6 June: 611-613.

Facciotto G., Navarro A., Mastrorilli M., Bergante S., Nervo G. 2014 - *Biomass production of poplar SRC in Southern Italy*. In: proceedings of VI IUFRO International Poplar Symposium, Vancouver, July 20-23: 170.

Geyer W.A., Coleman M.D., Stanturf J.A. 2006 - *Biomass production in the Central Great Plains USA under various coppice regimes*. Biomass and Bioenergy 30 (8/9): 778-783. Doi: 10.1016/j.biombioe.2005.08.002

Gill R.M.A. 1992 - *A Review of Damage by Mammals in North Temperate Forests. 2. Small Mammals*. Forestry: An International Journal of Forest Research 65 (3): 281–308. Doi: /10.1093/forestry/65.3.281

Gonzales-Garcia S., Bacenetti J., Murphy R.J., Fiala M. 2012 - *Present and future impact of poplar cultivation in the Po Valley (Italy) under different crop management systems*. Journal of Cleaner Production 26: 56-66. Doi: /10.1016/j.jclepro.2011.12.020

Kopp R.F., Abrahamson L.P., White E.H., Burns K.F., Nowak C.A. 1997 - *Cutting Cycle and spacing effects on biomass production by a willow clone in Ney York*. Biomass and Bioenergy 12 (5): 313-319. Doi: 10.1016/S0961-9534(96)00077-3

Kopp R.F., Abrahamson L.P., White E.H., Volk T.A., Nowak C.A., Fillhart R.C. 2001 - *Willow biomass production during ten successive annual harvests*. Biomass and Bioenergy 20: 1-7. Doi: 10.1016/S0961-9534(00)00063-5

Lamerre J., Schwarz K.U., Langhof M., Wuhlisch G., Greef J.M. 2015 - *Productivity of poplar short rotation coppice in an alley-cropping agroforestry system*. Agroforestry Systems 89 (5): 933-942. Doi: 10.1007/s10457-015-9825-7

Manzone M., Bergante S., Facciotto G. 2014 - *Energy and economic evaluation of a poplar plantation for woodchips production in Italy.* Biomass and Bioenergy 60: 164–170. Doi:10.1016/j.biombioe.2013.11.012

Manzone M., Bergante S., Facciotto G., Balsari P. 2017 - *A prototype for horizontal long cuttings planting in Short Rotation Coppice.* Biomass and Bioenergy 107: 214–218. Doi:10.1016/j.biombioe.2017.10.013

Mitchell C.P. 1995 - *New cultural treatments and yield optimization*. Biomass and Bioenergy 9: 11-34

Mizey P., Racz L. 2010 - *Cleaner production alternatives: biomass utilization options.* Journal of Cleaner Production 18: 767-770. Doi: 10.1016/j.jclepro.2010.01.007

Mughini G., Gras M., Salvati L. 2014 - *Growth performance of selected eucalypt hybrid clones for SRWC in central and southern Italy*. Annals of Silvicultural Research 38 (1): 7-12. Doi:10.12899/ASR-847.

Nassi O Di Nasso N., Guidi W., Ragaglini G., Tozzini C., Bonari E. 2010 - *Biomass production and energy balance of a 12-year-old short-rotation coppice poplar stand under different cutting cycles.* GBC Bioenergy 2 (2): 89-97. Doi/10.1111/j.1757-1707.2010.01043.x

Paris P., Mareschi L., Sabatti M., Pisanelli A., Ecosse A., Nardin F., Scarascia-Mugnozza G. 2011 - *Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield.* Biomass and Bioenergy 34 (4): 1524–1532. Doi:10.1016/j.biombioe.2010.12.050

Paris, P., Mareschi, L., Sabatti, M., Tosi, L., Scarascia-Mugnozza, G. 2015 - *Nitrogen removal and its determinants in hybrid* Populus *clones for bioenergy plantations after two biennial rotations in two temperate sites in northern Italy*. iForest, Biogeosci. Forestry 8: 668–676. Doi:10.3832/ifor1254-007.

Pleguezuelo C.R.R., Zuazo V.H.D., Bielders C., Bocanegra J.A.J., Pereatorres F., Martínez J.R.F. 2015 - *Bioenergy farming using woody crops. A review*. Agronomy for Sustainable Development 35 (1): 95-119. Doi: 10.1007/s13593-014-0262-1

Posza B., Borbely C. 2017 - *Economic and environmental model of short rotation coppice (SRC)*. Gazdalkodas 61 (4): 310-321.

Proe M.F., Griffiths J.H., Craig J. 2002 - *Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry*. Biomass and Bioenergy 23: 315-326.

R Core Team 2018 - *R: a language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Redèi K., Osvath-Bujtas Z., Veperdi I. 2008 - *Black Locust (*Robinia pseudoacacia *L.). Improvement in Hungary: a review*. Acta Silvatica et Lignaria Hungarica 4: 127-132.

Sabatti M., Fabbrini F., Harfouche A., Beritognolo I., Mareschi L., Carlini M., Paris P., Scarascia-Mugnozza G. 2014 - *Evaluation of biomass production potential and heating value of hybrid poplar genotypes in a short-rotation culture in Italy.* Industrial Crops and Products 61: 62-73. Doi: 10.1016/j.indcrop.2014.06.043

Spinelli R., Scweier J., De Francesco F. 2012 - *Harvesting techniques for non-industrial biomass plantations.* Biosystems engineering 113 (4): 319-324. Doi:10.1016/j.biosystemseng.2012.09.008

Verlinden M.S., Broeckx L.S., Ceulemans R. 2015 - *First vs. second rotation of a poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics*. Biomass and Bioenergy 73: 174-185. Doi:10.1016/j.biombioe.2014.12.012

Weger J., Vavrova K., Kasparova L., Bubenik J., Komarek A. 2013 - *The influence of rotation lenght on the biomass production and diversity of ground beetles* (Carabidae) *in poplar short rotation coppice.* Biomass and Bioenergy 54: 284-292. Doi: 10.1016/j.biombioe.2013.02.012.

Weih M. 2004 - *Intensive short rotation forestry in boreal climates: present and future perspectives.* Canadian Journal of Forest Research 34 (7): 1369-1378.

Wickham H. 2016 - *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. 360 p.