Biomass Yield Potential of Paulownia Trees in a Semi-Arid Mediterranean Environment (S Spain)

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Received: 03.09.2013 Accepted: 04.10.2013

Abstract- Short-rotation woody crops (SRWC) are key for woody-biomass production and management systems because they constitute renewable energy feedstocks for biofuels, bioenergy, and bioproducts that can be strategically located in the landscape. This study evaluates the potential biomass production of *Paulownia elongate x fortunei* and two of their clones (Cotevisa 2 and Suntzu 11) under short-rotation management in six different locations in Andalusia (S Spain). According the findings, Cotevisa 2 appeared to be most productive (1.8 fold higher) in terms of biomass than Suntzu 11. Also, significantly higher woody-biomass yield was registered for both clones ranging between 7.2 and 14.0 t ha^{-1} d.m. in Villanueva del Río y Minas (Sevilla province). By contrast, significantly lower paulownia biomass production was found at Palma del Río (Córdoba province) between 1.7 and 2.3 t ha^{-1} d.m.. As with biomass yield, both Cotevisa 2 and Suntzu 11 paulownia clones at Villanueva del Río y Minas (Sevilla) registered significantly higher carbon amounts (7.4 and 3.2 t C ha^{-1} d.m., respectively). These findings highlight that these renewable-energy sources offer important advantage in terms of greenhouse-gas emissions, and thus attention has been drawn to other environmental benefits and impacts associated with these systems that may offer other potential public benefits.

Keywords Woody biomass, Carbon biomass, Short-rotation plantation, Andalusia.

1. Introduction

According to the literature, in the future, plantations will become the leading source of bio-energy on a global scale. In particular, European farmers are progressively expanding the cultivation of energy crops, following the shifts in the Common Agricultural Policy as well as the expansion of energy sector [1,2]. The European biomass demand is predicted to grow almost 50% by 2020, and consequently the development of the biomass sector is crucial. Moreover, the European directive (2009/28/EC) has established that by 2020 at least 20% of primary energy consumption should come from renewable sources.

In this context, García et al. [3] analysed the situation of biomass energy resources in Andalusia (S Spain), particularly the residual biomass produced in the olive sector, most of which contributes to regional energy [4]. Andalusia is rich in renewable resources, especially in biomass, which in this region provides 6.3% of the total primary energy consumption and 78.7% of the renewable energy consumption. In addition, Rosúa and Pasadas [5], reporting the situation of biomass energy resources in Andalusia, quantified the pruning debris from different crops (grapevines, olive trees, fruit trees, and poplar trees) for domestic heating. However, woody energy crops, including short-rotation coppice, appear to reflect the expectations of farmers.

In European countries with a long tradition of woody crops are usually established on fertile sites, using rotation periods of 10-15 years in southern Europe, and 25-40 years in Belgium, Germany, and the Netherlands, with variations depending on the final product and local climatic conditions. Woody biomass is a renewable resource that provides feedstock for pulp and paper industry as well as for the energy and the biofuel industry [6,7].

The short-rotation woody crops (SRWCs) with fast growing species (*Populus, Salix, Eucalyptus, Platanus, Pinus*, *Paulownia,* etc.) and their respective hybrids with coppicing abilities that could be cultivated as purpose-grown wood on sites that enable high productivity. SRWCs have a variety of inherent logistical benefits and economic advantages in comparison to other lignocellulosic energy crops. That is, trees could be harvested year-round while continuing to grow year after year, providing biomass and reducing storage and inventory-holding costs as well as degradation losses typifying the storage of annually harvested biomass.

Concretely, the Dragon Tree *Paulownia fortunei*, indigenous to China, is commonly regarded as an exceptionally fast-growing drought-tolerant tree of universal adaptability, with various uses, particularly timber production [8,9]. This species has been introduced into other countries, such as Japan, USA, and Australia, as well as other regions such as Europe [10]. In this sense, the genus *Paulownia* has attracted growing attention as a SRWC with considerable interest as an industrial raw material despite that its growth in marginal areas remains to be studied. According to Kalaycioglu et al. [11], this tree can be harvested only 15 years after planting to achieve high added-value products with high biomass production and resprouting potential: up to 50 t ha^{-1} yr^{-1}, which is among the highest reported (especially compared with annual crops). Specifically, in Spain this species (*Paulownia elongata* × *fortunei*) has been introduced for biomass production, although research on its adaptability to the Mediterranean climate is limited and scant data is currently available. This tree can produce as much biomass in one year as other species in several, and suggested uses are related to generating energy from wood chips [11,12].

On the other hand, the estimation of carbon (C) stocks in vegetation is crucial for determining the significance of biomass and C allocation in agricultural landscapes as well as for improving our understanding of its potential contribution to global C stocks [13,14]. According to Calfapietra et al. [15], the short rotation of forestry plantations offers a promising approach for reducing atmospheric CO_2 through fossil-fuel substitution, this being critical in order to foster new opportunities to finance farming energy, agroforestry projects, and plantations for woody-biomass production [16]. Concretely, due to the high cellulose content of this tree, cellulosic ethanol could be produced as a renewable energy fuel; moreover, this ethanol can reportedly reduce greenhouse-gas emissions sharply in comparison to ethanol produced via a sugar/starch-based fermentation.

In the present study, we seek to determine the potential production as well as to estimate the biomass carbon stocks of *Paulownia elongate x fortunei* (hereafter paulownia) by monitoring two of their fast-growing clones (Cotevisa 2 and Suntzu 11) under short-rotation management system in six different locations of Andalusia (S Spain).

2. Material and Methods

2.1. Site Description, Experimental Set-Up, And Plant Material

The study was conducted with *Paulownia elongate x fortunei* trees (hereafter paulownia) at six different experimental sites in Andalusia, southern Spain (Figure 1). The climate in the area is typically Mediterranean semiarid with irregular rainfall concentrated in autumn and winter, the average rainfall and temperature ranging from 383.9 to 617.7 mm and from 14.4 to 17.5 °C, respectively (Table 1). In general, most of soils used were well-drained with a sandy loam texture and reasonable soil organic carbon (> 26 g kg^{-1}).

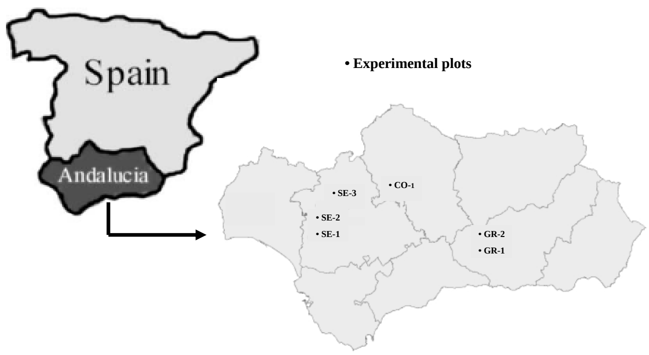

Fig. 1. Location of experimental plots with paulownia clones in Andalusia (S, Spain). GR-1, Purchil (Granada province); GR-2, Moclin (Granada province); CO-1, Palma del Río (Córdoba province); SE-1, Montequinto (Sevilla); SE-2, La Rinconada (Sevilla); SE-3, Villanueva del Río y Minas (Sevilla province)

Table 1. General site characteristics for six different locations

Location	Province	Mean annual		Geographic coordinates
		T (ºC)	R (mm)	
Purchil	Granada (GR-1)	15.1	383.9	37º 10' N 3º 38' W
Moclin	Granada (GR-2)	14.4	617.7	37º 18' N 3º 45' W
Palma del Río	Córdoba (CO-1)	17.6	592.1	37º 37' N 5º 20' W
Montequinto	Sevilla (SE-1)	17.3	522.9	37º 21' N 5º 56' W
La Rinconada	Sevilla (SE-2)	17.5	532.7	37º 29' N 5º 53' W
Villanueva del Río y Minas	Sevilla (SE-3)	17.4	576.3	37º 34' N 5º 46' W

T, temperature; R, rainfall

The potential biomass production of paulownia was monitored under a randomized complete block with three replicates and with a rotation every 2-year coppicing cycle over 10-12 years. Two paulownia clones, i.e. Cotevisa 2 and Suntzu 11, with a planting density of 3 x 2 m were tested under the monitoring scheme R_2P_1 (Table 2).

The experimental orchards were irrigated and managed according to conventional practices in the area (6,000 m^3 ha^{-1} yr^{-1}), using the same fertilization (50 kg N, 50 kg P_2O_5, and 50 kg K_2O per hectare) practices.

Table 2. Biomass yield trials under short-rotation management system for fast-growing paulownia (*Paulownia elongate x fortunei*) clones at six different locations

Clone	S (m)	PD (stands ha^{-1})	Year			R / P
			Pla	Cop	Har	
Cotevisa 2	3 x 2	1,650	2009	2010	2011	R_2P_1
Suntzu 11	3 x 2	1,650	2009	2010	2011	R_2P_1

S, Spacing; PD, Planting density; Pla, planting; Cop, Coppiced, Har, harvested; R, year rotation; P, year production

2.2. Measurements and Statistical Analysis

At the end of the 2011 season the fresh biomass was recorded in the field 24 months after planting. From the biomass weighed, representative samples were selected to determine the oven-dried biomass ratios. In the laboratory, the fresh biomass samples were oven dried at 70ºC to constant weight (usually within 24-48 h). The ratios of average fresh to oven-dried biomass were applied to convert fresh biomass into dry biomass.

For the determination of the C content, biomass samples from different plots and clones were taken to the laboratory. All were powdered and analysed for C determination by an elemental analyser (FISONS EA 1108 CHNSO, Carlo Erba®). The C stock was determined in the different experimental plots by multiplying the biomass yield by the C content. In addition, samples were collected to determine the low-heating value (LHV) and high-heating value (HHV) of paulownia biomass.

Analysis of variance was performed to ascertain whether the biomass yield of the different paulownia clones and site cultivation varied. Differences between individual means were tested using the least significant difference test (LSD) at $p < 0.05$ using Statgraphics v. 5.1 package program. Finally, the data were treated by correlation analysis to evaluate the relationships ($p < 0.01$) among paulownia woody biomass and environmental factors.

3. Results and Discussion

3.1. Paulownia Biomass Production

Figure 2 shows the total dry matter from aboveground biomass for each paulownia clone at different locations, being 1.8-fold higher for clone Cotevisa 2 in relation to Suntzu 11, especially for locations SE-3, GR-1, and SE-1. Also, significantly higher woody-biomass yield was registered for both Cotevisa 2 and Suntzu 11 with 14.0 and 7.2 t ha^{-1} d.m., respectively, in SE-3 (Villanueva del Río y Minas, Sevilla province) ($p < 0.05$). By contrast, significantly lower paulownia biomass production was found at CO-1 (Palma del Río, Córdoba province) for Cotevisa 2 and Suntzu 11, with about 1.7 and 2.3 t ha^{-1}, respectively. Martínez et al. [17], studying *Paulownia elongate x fortunei* CV stands 17 months old under a Mediterranean climate and similar experimental conditions, reported lower values than those found in our study for biomass yield, ranging from 2.6 to 6.1 t ha^{-1} d.m.. The same authors registered much lower biomass amounts for paulownia trees harvested after 5 and 13 months old with about 0.60 and 0.90 t ha^{-1} d.m., respectively. This suggests that, for better results, a two-year coppicing cycle is recommended, a procedure that has been widely extended in other woody crops such as poplar [18,19].

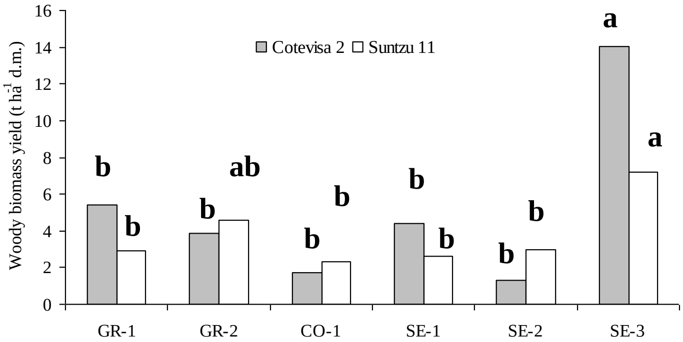

Fig. 2. Paulownia biomass yield for clones monitored at different locations in Andalusia (S Spain). Different lower-case letters between columns statistically differ at 0.05 (LSD test). GR-1, Purchil (Granada province); GR-2, Moclin (Granada province); CO-1, Palma del Río (Córdoba province); SE-1, Montequinto (Sevilla province); SE-2, La Rinconada (Sevilla province); SE-3, Villanueva del Río y Minas (Sevilla province)

On the other hand, the average HHV on a dry basis for paulownia clones Cotevisa 2 and Suntzu 11 was of 19.07 and 18.96, and for LHV of 13.83 and 13.72 MJ kg^{-1}, respectively. These values are in line with those reported by López et al. [20] for paulownia, making it unique as an energy crop due to its heating properties (i.e. ash content, sulphur, nitrogen chloride, etc.) in comparison to other solid biofuels such as poplar, locust, or willow. As the heating value depends on the quantitative conversion of the fuel C and hydrogen to water and carbon dioxide and is a function of fuel chemical composition [21], any notable variations could indicate differences in the chemical composition of the biomass fuel. Therefore, the low variability in heating values of wood between the clones tested reinforces the assumption of elemental similarity in the wood of the paulownia clones studied. On the other hand, according to Kiaei [22], in terms of physical and mechanical properties, paulownia is unsuitable for structural applications due to low wood density and poor mechanical properties.

Table 3 shows general paulownia woody-biomass yield for both clones as a function of environmental factors at the locations monitored. The woody-biomass production was negatively affected only by the ET_O ($p < 0.01$), while this latter parameter was positively associated with temperature and precipitation, similarly between relative humidity vs. temperature, and precipitation vs. temperature. Contrarily, an inverse relationship was found between relative humidity and precipitation as well.

Table 3. Correlation coefficients (Pearson) among paulownia woody biomass with environmental parameters

	P	T	RH	ET_O	WB
WB	0.119*	ns	ns	-0.423**	1
ET_O	0.779**	0.494**	ns	1	
RH	-0.308**	0.687**	1		
T	ns	1			
P	1				

WB, woody biomass; P, precipitation; T, temperature; RH, relative humidity; ET_O, potential evapotranspiration. ns, not significant; *, significant at $p < 0.05$; **, significant at $p < 0.01$

In general, greater precipitation did not guarantee a boost in biomass yield for both clones, this being the case for locations GR-1 (~ 4.2 t ha^{-1} d.m.) and GR-2 (~ 4.3 t ha^{-1} d.m.) with 383.9 and 617.7 mm yr^{-1}, respectively. Similar results were found for the mean annual temperature of 14.4 and 17.6 ºC for GR-2 (~ 4.3 t ha^{-1} d.m.) and CO-1 (~ 2.0 t ha^{-1} d.m.), respectively. In this sense, according to Lyons [23], paulownia trees thrive best in high-rainfall areas with more than 800 mm if there is good soil drainage, with temperatures ranging from 24 to 30ºC.

3.2. Paulownia Biomass C Stocks: Environmental Benefits

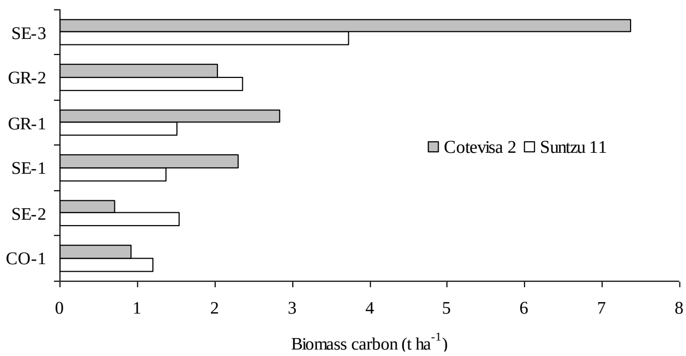

Fig. 3. Biomass carbon stock in relation to the clones monitored at different locations in Andalusia (S Spain): GR-1, Purchil (Granada province); GR-2, Moclin (Granada province); CO-1, Palma del Río (Córdoba province); SE-1, Montequinto (Sevilla province); SE-2, La Rinconada (Sevilla province); SE-3, Villanueva del Río y Minas (Sevilla province)

Figure 3 presents the potential biomass C fixation per area for each paulownia clone studied at different locations. As in the case of the biomass yield, both Cotevisa 2 and Suntzu 11 paulownia clones at SE-3 registered significantly higher C amounts (7.4 and 3.2 t C ha^{-1} in contrast to CO-1 location of 0.9 and 1.2 t C ha^{-1}, respectively). In average terms for the descending tendency in CO_2 fixed by biomass was: SE-3 > GR-2 > GR-1 > SE-1 > SE-2 > CO-1. In this context, Martínez et al. [17] reported lower values of CO_2 fixed by paulownia biomass, i.e. between 2.9 and 7.4 t ha^{-1} in Castilla La Mancha (central Spain), which is lower than those found in our experiment, in which values ranged from 20.3 (SE-3) to 3.9 (CO-1) t CO_2 ha^{-1} in Andalusia (S Spain).

Due to its highly efficient photosynthesis activity, paulownia offers C-fixation, particularly under high light and temperature, even if harvested soil organic C increases within the plantation from accumulation of organic matter such as leaf drop, and the extensive root systems capable of C sequestration. Therefore, paulownia cultivation may help reduce greenhouse-gas emissions: 1) by generating large amounts of C-rich biomass that can be used as an alternative fuel, with considerable potential for reducing greenhouse-gas emissions; and 2) by transferring the C-rich biomass to the soil through the deposition of litter, roots, and root exudates, thereby alleviating perturbation that encourages organic-matter decomposition and CO_2 release [24,25].

Therefore, this demonstrated that trees are efficient converters of solar energy into biomass, and paulownia appeared to be one of the most, if not the most, efficient in terms of growth and the production of usable biomass. Also, paulownia could significantly shorten the time necessary to gain long-term profits from energy farming in Mediterranean environments.

4. Conclusion

Interest in short-rotation bioenergy crops focuses mainly on their faculty to produce large amounts of lignocellulosic biomass that can be used as fuel for heat or electricity generation. The present study, seeking to determine the rates of biomass production possible from 2-year-old paulownia trees in short-rotation management, demonstrates that high planting densities can provide maximum biomass yields of 7.2-14.0 t ha^{-1} d.m. at Villanueva del Río y Minas, Sevilla province, depending on clones.

These yields were achieved under suboptimal environmental conditions for paulownia and with a return to optimal conditions and higher planting densities it may be feasible to achieve greater yields. The CO_2 yields by paulownia woody biomass were in the same line and ranged from 20.3 for Villanueva del Río y Minas, Sevilla province to 3.9 t ha-1 for Palma del Río, Córdoba province.

In addition, the high heating values for paulownia support the contention that this species is the most suitable feedstock for use as a solid biofuel, being higher than those found for other woody crops used for energy. In general, our findings demonstrate that biomass productivity was greater for the paulownia clone Cotevisa 2, offering promising possibilities for energy farming in a Mediterranean environments.

Acknowledgements

This publication was sponsored by the Technical Assistance contract "Agronomic and economic assessment of energy crops in Andalusia" (CAICEM-11-89).

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