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Article

Stem Biomass Production of *Paulownia elongata* × *P. fortunei* under Low Irrigation in a Semi-Arid Environment

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Abstract: In semi-arid regions, afforestation with fast-growing species cultured with low irrigation can be an effective approach for environmental protection. An experiment was conducted to evaluate the stem biomass production of *Paulownia* in a semi-arid climate and clay soils under contrasting low-irrigation and fertilization treatments. The stem biomass at the stand level was estimated by applying allometric equations fitted in sample resprouts and inventory data. The results show that biomass production improved when either irrigation or fertilizer was added, but the combination of a higher dose of irrigation and fertilization did not lead to the highest biomass production; thus water availability was the main factor controlling biomass production. Under the higher dose of irrigation, the absence of a fertilizer effect would be due in part to the fertile soil, which could supply sufficient nutrients for *Paulownia* growth at the higher level of soil moisture. The stem biomass estimated ranged from 2.14 to 4.50 t·ha^{-1} (lower irrigation dose without fertilization, and higher irrigation with fertilization). The greater production was similar to other studies in the Mediterranean area receiving more irrigation. Thus, this study permitted us to understand the potential of *Paulownia* to provide biomass in semi-arid environments with low irrigation due to water use restrictions.

Keywords: fast-growing species; biomass plantations; water-use restrictions; fertilization; Mediterranean climate

1. Introduction

Dry Semi-arid (Bs or steppe) climate covers 14% of the Earth's land surface and is characterized by deficient precipitation during most of the year [1]. Despite the fact that most of the Mediterranean Region is affected by this climate, many crops have been transformed from dry to irrigated agriculture through generalized use of groundwater over the past 30 years. This is the case of Castilla-La Mancha, a Spanish Mediterranean region in which socio-economic development has been linked to agricultural land use. However, groundwater pumping (406 Mm^3 year^{-1}, 98% of which are used in irrigated agriculture) has provoked a steady drop in groundwater levels [2]. The volume of water withdrawal is not compatible with the amount of aquifer recharge, estimated at 320 Mm^3·year^{-1} by the Hydrologic Plan for the Jucar River Basin [2].

To restore aquifer levels, the Regional Water Authority (Hydrographic Confederation of Júcar River) has set a maximum irrigation volume of 3800 m^3 ha^{-1} for timber production. These restrictions together with the low precipitations in the region may result in a reduced economic farmland profitability, and farmland abandonment. The abandonment of agricultural land entails the removal of soil conservation techniques, increasing soil erosion and desertification risk [3].

Another peculiarity of these semi-arid areas is the presence of Vertisols. Vertic character soils occur in flat landscapes with a semi-arid climate and a pronounced dry season [4]. Although some of their physical properties can be considered undesirable, such as high clay content, these soils offer good potential if they are adequately managed [5]. Vertisols contain high levels of organic matter, plant nutrients, and can be very productive when irrigated because of their high moisture-holding capacity [5]. Thus, vertic character soils can offer considerable potential for both crop and biomass production in these semi-arid areas, even with low levels of irrigation due to water use restrictions.

It has been recognized that biomass production can play a key role in maintaining ecological balance and improving the rural livelihood in semi-arid areas [6]. Afforestation with fast-growing species has also been considered as potential fast-response carbon sinks, which can play a role in temporary C storage [7], and can even serve as an effective strategy to mitigate global change [8]. Since the beginning of the CAP (Common Agricultural Policy), rural populations in Mediterranean areas have decreased dramatically and land use has been transformed. Reversing the trend of land abandonment, the promotion of biomass plantations could be now considered part of a global strategy for enhancing rural development and to reduce the net atmospheric accumulation of CO_2 [8].

In general, biomass plantations in semi-arid lands are less attractive due to lower productivity. However some genera, such as *Paulownia,* are gaining ground in these regions given their fast-growing temperament and its adaptability to wide variations in edaphic and climatic factors. The genus *Paulownia* (*Scrophulariaceae*) includes nine species of fast-growing trees that are indigenous to China and East Asia [9]. *Paulownia* wood has been used for the construction, pulp and paper industries. Actually, this genus is suitable to reclaim abandoned farmlands or to restore soils, where special emphasis is focused on biomass production [10]. For this reason, the genus *Paulownia* has been used in several recent studies which have been focused on its potential for timber production [10], its use in agroforestry practices and intercrops [11], biotechnology and *in vitro* cultivation [12], soil activity in *Paulownia* plantations [13], and the chemical composition of its wood [14]. Regarding biomass production, a recent research analyzed the woody biomass yield for clones monitored at different locations in south Spain. In this study, a yield production from 1.4 to 14 t ha^{-1} was obtained [15].

Although *Paulownia* has showed a great adaptation to a wide range of soils (pH range from 5.0 to 8.9) and temperatures [16], this genus is sensitive to soil salinity [16,17] and poor drainage (a clay component greater than 25% and porosity of below 50% are not suitable; [17]). In Mediterranean climate, *Paulownia* production is affected negatively by evapotranspiration, but not by precipitation or temperature [15].

It is well-known that *Paulownia* plantations should be managed with intensive regimes with good water and nutrient supply [17]. Application of water and fertilizer results in considerably enhanced forest plantation growth [7,18], but the influencing effect of water and fertilizer depends primarily on soil fertility and water availability [19]. However, there is considerable uncertainty about the potential of this species to provide biomass in semi-arid environments with low irrigation doses (due to water use restrictions) and calcareous clayey soils. As far as we know, the interaction between low water dose and fertilization has not yet been studied in *Paulownia*.

Hence the principal objective of this study was to evaluate the biomass production of *Paulownia* plantations in semi-arid lands under four contrasting irrigation and fertilization treatments (two levels of "low irrigation dose" and "fertilization"). Assessing the biomass production in *Paulownia* plantations under different water and nutrient treatments will allow us to evaluate the potentiality of these plantations in semi-arid environments.

2. Experimental Section

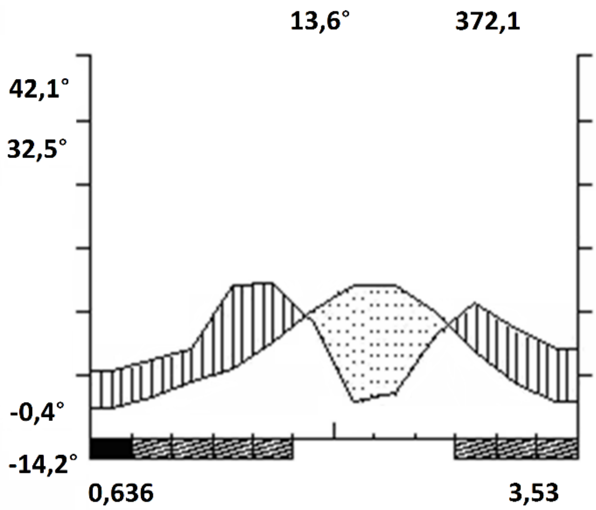
2.1. Study Area

This research was carried out in Albacete (Castilla-La Mancha Region; Figure 1), in abandoned farmlands of Southern Spain (UTM coordinates: 592,203 m, 4,312,644 m; 685 m.a.s.l.). Land use is currently low-volume grazing.

Meteorological information was recorded from "Albacete-Los Llanos" climatic station owned by the State Meteorological Agency of Spain (38°57′6″ N; 1°51′45″ O; 702 m.a.s.l.; data are based on a series of 30 years). This station is located within 2 kilometers of the study area. Climate there is cold semi-arid, type BSk according to the Köppen Classification. Mean annual temperature and precipitation are 13.6 °C and 372.1 mm, respectively. According to the climate diagram by Walter and Lieth the length of dry period is 3.53 months; July, August, and part of June and September (Figure 2). The frost period (months in which the daily average minimum temperatures are below zero) correspond to January. The relationship between the area of the dry and moist seasons is 0.636. Extreme temperatures range from 42.1 (in July) to −14.2 °C (in January). Potential evapotranspiration according to the Thornthwaite method is 743 mm.

Figure 1. Study area: Castilla-La Mancha, a Spanish Mediterranean region with semi-arid climate in Southern Spain.

Figure 2. Climate diagram by Walter and Lieth of the "Albacete-Los Llanos" climatic station. In the diagram, 20 mm of monthly precipitation (right ordinate) is equal to 10 °C average temperature (left ordinate); when the precipitation curve undercuts the temperature curve, the area between them is dotted indicating the dry season (3.53 months); when the precipitation curve supersedes the temperature curve, vertical lines are plotted indicating moist season; the diagram shows in black bars below the horizontal axe the frost period (January); the climate diagram was performed utilizing the software Climoal®.



The study area is located in a doline formed by dissolution of carbonates (limestone and marls) and the background is covered with a silty-clay lithology. The geologic materials correspond to the Pleistocene. Soil sampling in the plantation was carried out by taking random soil samples in two soil horizons (A: 0–10 cm depth, and B: 10–50 cm). To minimize the effects of the inherent soil variability, each sample of soil horizon was composed of a thorough mix of six sub-samples (each of approximately 200 g) randomly collected in the sampling area. Samples were analyzed by taking three replicates in the laboratory, and the mean value of the sample was used.

Based on the physicochemical analysis (Table 1), soil was classified as Calcic Vertisol according to the FAO-Unesco Soil Map [20]. The soil analysis showed a very alkaline soil (pH = 8.5) with clay contents higher than 30% throughout the profile. They were rich in smectitic clay minerals, which is the reason for the 1–2 cm wide cracks on the surface in summer. Given the amounts of clay, this soil had a high cationic exchange capacity (CEC) which ranged between 29.24 and 22.68 meq/100 g (for the upper and the lower horizon, respectively). High organic matter also contributed to increase CEC. Soils were rich in bases: calcium-dominated soils in which calcium and magnesium clear dominated sodium and potassium [4]. Base saturation was 100% throughout all the profiles due to alkaline parent material and climate. The clay mineral type present can immobilize potassium as an exchangeable cation, and K could be limiting according to the K/Mg ratio. Phosphorous availability was medium. However, this soil is characterized by the high amounts of nitrogen (0.26 and 0.24% for the upper and lower horizon, respectively). Additionally, available Soil Mineral Nitrogen (SMN) as nitrate or ammonium was estimated in 15 kg·ha^{-1} (equivalent to a high availability of nitrogen). The vertisols at these semiarid sites in the saline deposition areas were associated with soils with accumulated soluble compounds (Solonchaks) as a result of the high evaporation surplus. However, no salinity problems were found in the studied soils.

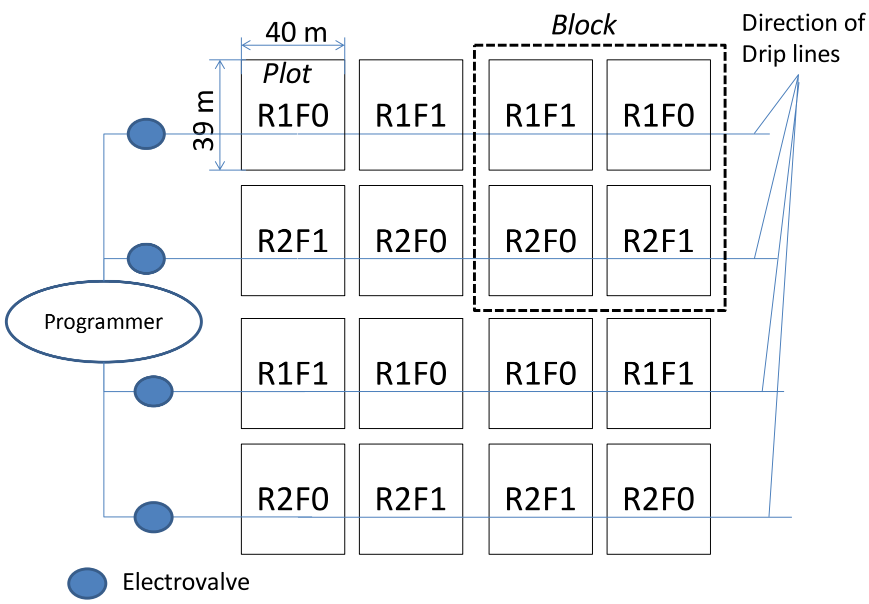
Table 1. Main soil characteristics in the study area (means ± SE).

Soil parameter	Upper horizon (A: 0–10 cm)	Lower horizon (B: 10–50 cm)	Methods
Sand (%)	17 ± 2	19 ± 1	Bouyoucos
Silt (%)	48 ± 2	43 ± 1	Bouyoucos
Clay (%)	36 ± 2	38 ± 2	Bouyoucos
pH (1:2.5)	8.5 ± 0.1	8.5 ± 0.1	1;2.5 water
Electric conductivity (mmhos/cm)	0.37 ± 0.05	0.33 ± 0.04	1:5 saturated paste
Chlorides (ppm)	11 ± 1	8 ± 1	Ion Chromatography
Sulfates (mg/100 g)	39 ± 3	32 ± 2	Ion Chromatography
Organic matter (%)	5.68 ± 0.16	4.28 ± 0.21	Walkley and Black
C/N	13 ± 2	10 ± 3	-
Total carbonates (%)	55.7 ± 7.5	57.4 ± 5.3	Calcimeter Bernard
Active limestone (%)	16.0 ± 2.3	15.1 ± 3.4	Ammonium Oxalate
Total nitrogen (%)	0.26 ± 0.21	0.24 ± 0.18	Kjeldahl
Nitric nitrogen (mg/g)	0.004 ± 0.001	0.004 ± 0.001	Calcium Sulfate extraction
Available phosphorus (mg/g)	0.018 ± 0.0003	0.011 ± 0.0002	Olsen
Available potassium (mg/g)	0.27 ± 0.08	0.02 ± 0.06	Atomic Absorption Spectrometry
Available calcium (mg/g)	3.50 ± 0.45	3.16 ± 0.23	Atomic Absorption Spectrometry
Available magnesium (mg/g)	1.20 ± 0.06	1.22 ± 0.07	Atomic Absorption Spectrometry
Available sodium (mg/g)	0.35 ± 0.03	0.23 ± 0.02	Atomic Absorption Spectrometry
CEC (meq/100 g)	29.24 ± 2.32	22.68 ± 1.98	Sodium Acetate

2.2. Experimental Design

In the study area, a homogeneous experimental area was established on abandoned farmland. In this experimental area, four blocks containing four plots each (39 × 40 m) were set-up representing the combination of the levels of the main factors (treatments of irrigation and fertilization). Separation between blocks was 6 m, and each plot was also separated 6 m from the rest of plots to avoid border effects. In the plots, one *Paulownia* plantation with a plant density of 1666 trees·ha^{-1} (trees separated by 3 × 2 m; 14 × 21 lines) was established, and two crop factors (irrigation and fertilization), with two levels each, were controlled: irrigation with a low dose during the growing season (1000 liters/tree, and 2000 liters/tree; equal to 1666 and 3332 m^3·ha^{-1}·year^{-1} respectively), and fertilization (unfertilized trees; and fertilization with 0.5 kg/tree during the growing season, equal to 833 kg·ha^{-1}). This represents a 2^2 factorial experiment in a complete block design (Figure 3). The clone used in the plantation was *in vitro* 112® (*Paulownia elongata* × *P. fortunei* hybrid) since it has been previously shown to display adaptability to semi-arid climates. The vegetal material was obtained by utilizing *in vitro* techniques in a specialized laboratory. Paulownia seedlings were growing during 4 months at the nursery in flowerpots. After this growing period, the seedlings were planted in the study area. Dendrometric parameters when planting (means ± SE) were: height: 52 cm ± 3 cm, basal diameter: 0.4 cm ± 0.2 cm.

Figure 3. Experimental design to analyze the treatments effects on stem biomass of *Paulownia* trees. Each block represents a replication; R1F0: irrigation with 1000 liters/tree without fertilization; R1F1: irrigation with 1000 liters/tree and fertilization; R2F0: irrigation with 2000 liters/tree without fertilization; R2F1: irrigation with 2000 liters/tree and fertilization.



The experimental plantation was irrigated without exceeding the rules of Land Use Management in the Eastern Mancha Aquifer, with a set annual maximum volume of 3800 m^3·ha^{-1}·year^{-1} for timber plantations. The fertilizer used was granular complex NPK (15-15-15; 15% of nitrogen, 15% of phosphorus pentoxide and 15% of potassium oxide). *Paulownia* trees were planted in spring (April 2008) and were cut in the second spring (March 2009) to encourage coppicing to better form stems and to leave a single resprout per tree [17]. This was done to achieve rapid growth during the following season (summer 2009). Pruning was done (30% live crown ratio, in the second spring) by removing buds and lateral branches to promote upward growth and better quality stems [21]. Water dose was controlled by an automatic drip irrigation system, thus avoiding waterlogging problems. Fertilization was carried out at the start of the growing period (0.25 kg in April 2009) and halfway through the period (0.25 kg in July 2009). Fertilizer granules were placed in a tree basin and were mixed with the ground. To leave the ground in water infiltration conditions, subsoiling with a 40 cm depth was conducted in the firstspring [21].

2.3. Stem Biomass Estimation

A technique based on destructive sampling, allometric models and tree inventory data was applied to accurately measure the stem biomass [22]. For this, allometric relationships between the basal diameter and stem biomass in sample resprouts were fitted. Biomass data from 120 resprouts (30 individuals per treatment randomly selected) were collated at the second summer (October 2009). Sample resprouts were cut and separated into foliage, branch wood and stem biomass. The fresh weight of stems was measured in the field. Biomass was not calculated for the remaining components (branch-wood and foliage biomass) because the amount was negligible and not harvestable. The stem subsample for dry weight consisted of discs, which were 4–5 cm thick in 0.5 m segments. Subsamples were weighed and oven-dried at 70 °C to constant weight. All the fresh weights were converted into biomass values using the moisture content of the subsamples.

The biomass estimation at the stand level was performed using the following allometric nonlinear model with multiplicative error form (Equation (1); [23]):

$$Bt = \alpha \cdot Db^{\beta} \cdot \varepsilon \qquad (1)$$

Where Bt is the stem biomass per resprout (kg dry mass), Db is the basal stem diameter (cm), α and β are the parameters, and ε is the random error. This nonlinear model was transformed into a linear model with additive error taking the naperian logarithm. Indicator or dummy variables (Ij) were added to consider the possible treatments effects in the relationship between Bt and Db:

$$\ln(Bt) = \beta_0 + \beta_1\ln(Db) + \beta_2 I_1 + \beta_3 I_1\ln(Db) + \beta_4 I_2 + \beta_5 I_2\ln(Db) + \beta_6 I_3 + \beta_7 I_3\ln(Db) + \varepsilon' \qquad (2)$$

Where I_1, I_2, I_3 are the indicator variables for the treatments (I_1 = R1F1, I_2 = R2F0, and I_3 = R2F1; Ij = 1 for the considered treatment, and 0 otherwise), and ε' is the random error. This model corresponds to 4 separate lines, one for each value of RxF treatment. Significant parameters ($p < 0.05$) were estimated by comparing the regression lines relating Bt and Db under the four treatments. Parameters were fitted using least-squares regression and the t-statistic tests were used to determine whether there were significant differences between intercepts and slopes at the different levels of the categorical variables ($p < 0.05$; [24]). Observations with /DFFIT/ > $2(p/n)^{0.5}$ were considered influential points (p is the number of coefficients, and n is the number of data [24]) and eliminated.

Finally, the bias introduced in the anti-logarithmic conversions was corrected using the corrector coefficient CF [25]: CF = $\exp(\mathrm{SEE}^2/2)$.

The total stem biomass per plot ($t \cdot ha^{-1}$) was computed by applying the allometric equation to all the resprouts in any given plot, adding the estimated biomass and dividing it by the plot surface in hectares [22]. For this purpose, the basal diameter of all the resprouts in the plots was measured by a digital caliper (precision: 0.001 cm).

2.4. Effects of Irrigation and Fertilization on Stem Biomass Production

To detect the significant effects of the principal factors and their interaction in total biomass production (in $t \cdot ha^{-1}$), a two-way ANOVA ($p < 0.05$) was done. In this statistical analysis, the factor "block" was also included in order to remove the variability accounted by the 4 blocks. However, all block interactions were excluded from the analysis. Fisher's Least Significant Difference (LSD) procedure was used to determine the significant differences between treatment means ($p < 0.05$; [24]). Data analysis was computed using the Statgraphics Centurion XV© statistical package.

3. Results

3.1. Allometric Model for Stem Biomass Estimation

A significant linear model (F-ratio = 1894.51; $p < 0.001$) was fitted for the stem biomass estimation in the sample resprouts (Equation (2)). This model obtained high statistic values for goodness-of-fit (R-Squared adjusted = 92.31%, Standard Error = 0.18 and Mean Absolute Error = 0.139). Table 2 shows the parameters and the significance of the coefficients in the linear regression model, which describe the relationship among *Bt*, *Db* and treatments. According to the p-values obtained, the dummy variables were non-significant. Thus, a strong direct allometric relationship between stem biomass (an accumulative biomass) and diameter was found regardless of treatment, because diameter is the reflection of vigor and productivity of trees.

As a consequence, the final equation for biomass estimation was fitted by removing the dummy variables from model 2 (resulting one model for all the treatments). This corresponds to the simple linear regression between *Bt* and *Db* (equation 1 log-transformed: $\ln(Bt) = \beta_0 + \beta_1 \ln(Db)$; Table 3 and Figure 4). The simplified model resulted highly significant (F-ratio = 1142.58; $p < 0.001$) and reached a high adjusted R^2 (91.14%), and a low SEE (0.19).

Then, the model $\ln(Bt) = -4.462 + 2.784\ln(Db)$ was selected to estimate stem biomass at stand level. This model has the following expression in the allometric form (Equation (1)): $Bt = e^{-4.462} \cdot Db^{2.784} = 0.00115 \cdot Db^{2.784}$. Finally, the bias introduced in the anti-logarithmic conversion was corrected using the factor CF = $\exp(0.1943^2/2) = 1.019$. This factor was applied when the allometric model was used to calculate the biomass of resprouts.

The plot of the studentized residuals against the predicted values of final model suggests that both no-curvature and constant error variance are apparent and they are both normally and randomly distributed (Figure 5). This confirmed the condition of homoscedasticity in residuals and rendered the allometric model valid with the logarithmic transformation done.

Table 2. Parameter estimates for the allometric equation to predict the *Paulownia* resprout biomass (kg of dry mass) according to the basal diameter (*Db*; cm) and treatments (Equation (2)); *P*-values under 0.05 indicate that the model coefficient differed significantly from 0 (at the 5% level of significance); number of cases: 111 (9 observations with /DFFIT/ > 0.52 were considered influential points and they were removed from the model).

Variables	Parameters	Estimate	Standard Error	*T* Statistic	*P*-Value
Intercept	β_0	−4.343	0.237	−18.33	<0.001
ln(*Db*)	β_1	2.694	0.140	19.22	<0.001
I_1	β_2	−0.733	0.383	−1.91	0.059
I_1·ln(*Db*)	β_3	0.396	0.216	1.84	0.069
I_2	β_4	1.125	0.557	0.52	0.600
I_2·ln(*Db*)	β_5	−0.519	0.295	−1.76	0.081
I_3	β_6	0.859	0.657	1.31	0.194
I_3·ln(*Db*)	β_7	−0.402	0.337	−1.19	0.236

The indicator variables representing treatments are: I_1 = R1F1; I_2 = R2F0; I_3 = R2F1; F_0: unfertilized trees; F_1: fertilization with 0.5 kg/tree; R_1: irrigation with 1000 liters/tree; R_2: irrigation with 2000 liters/tree.

Table 3. Parameter estimates for the simplified allometric equation (Equation (1) log-transformed) to predict the *Paulownia* resprout biomass (kg of dry mass) according to the basal diameter (*Db*; cm); *P*-values under 0.05 indicate that the model coefficient differed significantly from 0 (at the 5% level of significance); number of cases: 112 (8 observations with /DFFIT/ > 0.26 were considered influential points and removed).

Variables	Parameters	Estimate	Standard Error	*T* Statistic	*P*-Value
Intercept	β_0	−4.462	0.153	−29.1	<0.001
ln(*Db*)	β_1	2.784	0.0824	33.8	<0.001

Figure 4. Plot of the fitted model for stem biomass estimation in *Paulownia*; the selected allometric model correspond to Equation (1) log-transformed: ln(*Bt*) = −4.462 + 2.784ln(*Db*); *N* = 112.

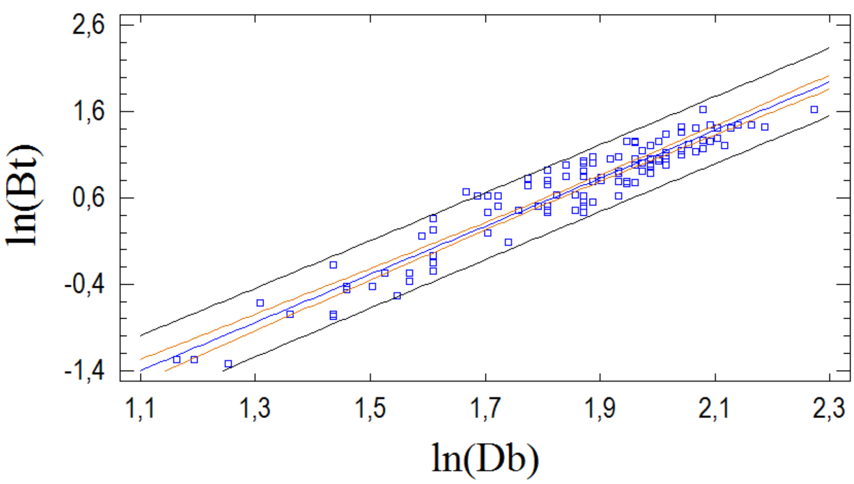
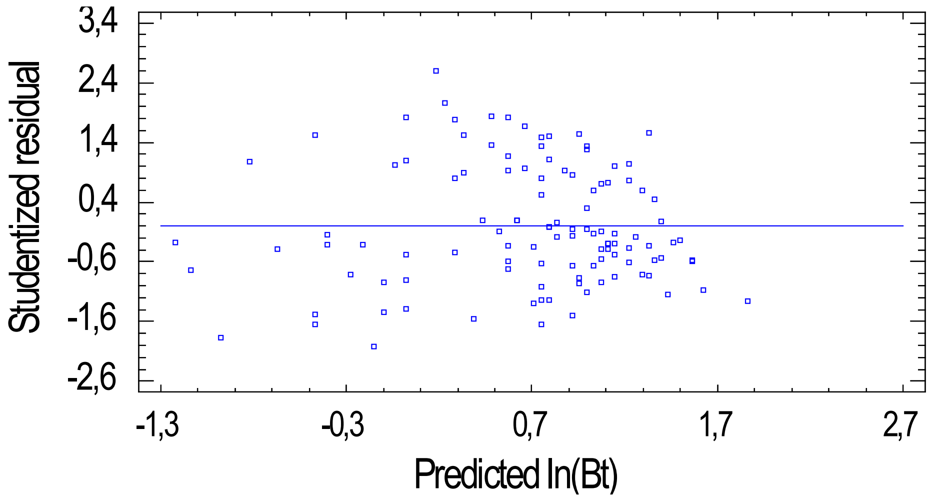


Figure 5. Plot of the studentized residuals against predicted values for the selected model (Equation (1) log-transformed): $\ln(Bt) = -4.462 + 2.784\ln(Db)$; original units are in kilograms of dry mass.



3.2. Effects of Irrigation and Fertilization on Stem Biomass Production

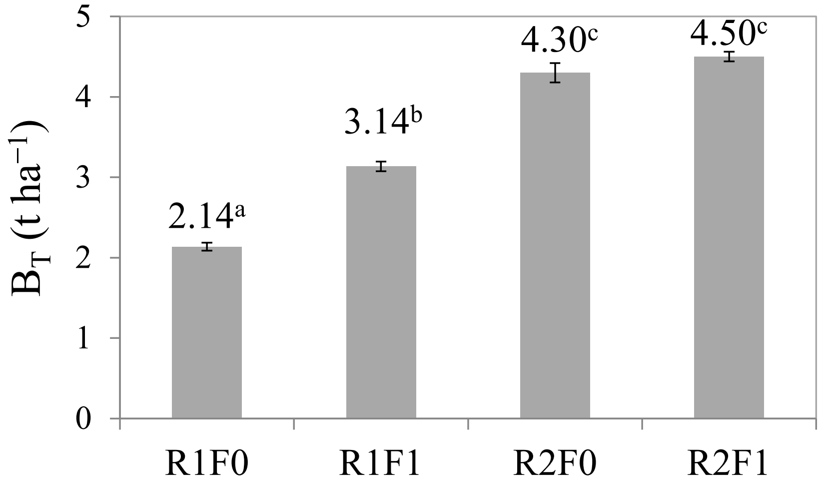
Both irrigation and fertilization significantly affected the average stand biomass value. In addition, the interaction between the two factors was significant (Table 4). The "block" factor was not significant effects; thus differences in biomass production cannot be attributed to soil differences between the 4 blocks.

Table 4. ANOVA to identify the significant effects (p < 0.05) in the stem biomass production ($t \cdot ha^{-1}$) at stand level (n = 16); all the F-ratios are based on the residual mean square error; *D.f.* is the number of degrees of freedom.

Source	Sum of Squares	*D.f.*	Mean Square	*F*-Ratio	*P*-Value
MAIN EFFECTS					
Block	0.093	3	0.031	1.34	0.321
Irrigation	12.43	1	12.43	534.88	<0.001
Fertilization	1.452	1	1.452	62.50	<0.001
INTERACTIONS					
Irrigation x fertilization	0.632	1	0.632	27.21	<0.001
RESIDUAL	0.209	9	0.023		
TOTAL (corrected)	14.81	15			

The results from Figure 6 (LSD post-hoc test; p < 0.05) show that a stronger response in aboveground biomass growth was observed in the resprouts subjected to higher irrigation dose (2000 liters), independently of the fertilization factor. Biomass production was affected only by fertilization treatment with the low irrigation dose (1000 liters).

Figure 6. Mean values (± SE) of the total stem biomass at the stand level for the different treatments (n = 4); values followed by the same letter were not different at the 0.05 level according to the LSD post-hoc test; R1F0: irrigation with 1000 liters/tree without fertilization; R1F1: irrigation with 1000 liters/tree and fertilization; R2F0: irrigation with 2000 liters/tree without fertilization; R2F1: irrigation with 2000 liters/tree and fertilization.



In consequence, although results showed that biomass production improved when either irrigation or fertilizer was added, the combination of a higher dose of irrigation and fertilization did not lead to the highest biomass production. Referring to yield production, and according to the mean values of the stem biomass at stand level (Figure 6), stand biomass accumulation was 2.14 ± 0.05 and 4.50 ± 0.06 t·ha^{-1} (means ± SE) for the treatment with lower and higher biomass production (low irrigation dose without fertilization, and high irrigation dose with fertilization, respectively).

4. Discussion

Based on the results of the statistical analysis, we found that both fertilization and irrigation are significant for the stem biomass production in *Paulownia* trees. These two factors enhanced yield production in forest plantations [8,18,26]. However, our results suggest that irrigation is the more important factor of the two to improve short-term biomass production, which agrees with the results of [7] obtained in *Eucalyptus*. This is because fertilization was a significant factor, but only to enhance biomass production for the lower water dose (1000 liters per tree). This could indicate that complete nutrient absorption may not occur with this lower water dose, in accordance with [27]. Our experimental data partly coincide with the results of previous research, according to which the higher production level was not reached in the most favorable interactions of water, nutrient supply or plant density [19]. Thus, we confirmed no synergistic effects of water and fertilizer application on the growth of *Paulownia* resprouts, at least from a given dose of irrigation.

Several arguments can be used to explain why the growth of fertilized and irrigated *Paulownia* trees with 2000 liters was not significantly higher than that of the trees only irrigated with these 2000 liters. In general, the planting response to several levels of resources depends on soil conditions, which may range from synergistic to antagonistic, or indifferent responses depending on the initial soil conditions [27,28]. Forest management practices, such as site preparation, also influence nutrient and water cycles, buy it is unclear whether these changes significantly affect the productivity of site [29]. According to previous agricultural experiments, the effect of fertilizer is average or good under moderately dry conditions, and this effect becomes stronger when supply leads to optimal and decreases when levels of excess resources (water or nutrients) are reached [19]. In line with this, we consider that with the higher water dose supplied, almost complete absorption of the nutrients in the plant would occur.

Thus, we hypothesize that the high levels of organic matter and nutrients in the soil studied may reduce the fertilizer effect on *Paulownia* growth if there are adequate amounts of water available, and fertilization would not be strictly necessary. Although their physical characteristics may be negative for waterlogging, the fertility of vertic character soils is higher than other soils associated with semi-arid environments. The soils in the study area have a high cationic exchange capacity given the clay contents and high organic matter. Soil organic matter is a vital component of productive soils and is an important source of plant nutrients, especially N and P [8,30]. The most fertile temperate forest soils have high cation-exchange capacity, which allows more nutrients to be held on clay particles and reduces losses by leaching [29]. Additionally, nitrogen is widely recognized as one of the major factors limiting forest productivity, particularly in afforestation and plantations [29]. The N content was also very elevated in the soil studied (0.26% and 0.24%, for the upper and lower horizon, respectively) indicating an adequate substrate for biomass plantations. Under the higher dose of irrigation, an absence of a fertilizer effect on stem biomass production may be due to the fertile soil at the study site, which could supply sufficient nutrients (especially N) for *Paulownia* growth. Similar results were obtained by Hangs *et al.* [31] in *Salix* biomass energy plantations established on a fertile heavy clay soil.

It is certain that fertilizer experiments have shown that it is better to apply a complete fertilizer of nitrogen, phosphate and potassium to enhance *Paulownia* production [16]. However this genus can grow in nutritionally infertile soils if texture and drainage are satisfactory [17]. In comparison with species from high-nutrient environments, typical species from unfertile soils, such as *Paulownia*, absorb considerably fewer nutrients under high-nutrient conditions, but similar quantities and, in some cases, even more quantities, under low availability conditions [30]. In this sense, Hangs *et al.* [31] showed that in clones of *Salix* with greater nitrogen use efficiency fertilization was not significant effect when irrigated. The high stand density of the resprouted plantation of *Paulownia*, together with the effects of root systems, can also reduce the capacity to respond to fertilization.

In the study area, clay content remained uniformly high (>35%) throughout the profile at a depth of at least 50 cm. Thus, infiltration and permeability can be low due to the high clay content. Zhu *et al*. [16] indicated that on excessively clayey soils, growth may be slow down because *Paulownia* root system requires not only suitable water, but also deep, moist and well-aerated soil. However, *Paulownia* plantations can be very productive if soils are properly managed, as suggested [21]. In this sense, preparation of soil by subsoiling could have positive effects by increasing the amount of water and nutrients available to crop trees [26]. The drip irrigation system also helps prevent waterlogging problems. These conservation tillage enhances yield by increasing water infiltration and decreasing evaporation from the soil surface [21]. In consequence, we consider that the high moisture-storage capacity in vertic character soils enhances biomass production, even with a low irrigation dose (2000 liters per tree). This water irrigation regime also ensures plant survival (the lowest values of survival, 95%, were recorded for irrigation with 1000 liters per tree without fertilization). The good soil water storage capacity may be particularly important in these semi-arid regions, as previously indicated [6].

Referring to yield production, the stem biomass obtained in the first resprouts was lower than that offered by other trials in *Paulownia* which applied a higher irrigation dose and in wetter areas (for example [10,16,17], with yields of up to 40 $t \cdot ha^{-1}$). However yield production was relatively high if compared with other experimental *Paulownia* plantings in semi-arid areas. For instance, Durán *et al*. [15] obtained a biomass yield using a short-rotation management system for *Paulownia elongate* × *P. fortunei* clones of between 1.7 and 14 $t \cdot ha^{-1}$, and when employing the same fertilization practices and a water dose of 6000 $m^3 \cdot ha^{-1}$ (in Andalusia, south Spain, with a Mediterranean climate). As *Paulownia* production is affected negatively by evapotranspiration [15], a higher irrigation dose does not necessarily imply better production if higher leaf transpiration and water loss from soil occur. The evapotranspiration at our study site (743 mm, lower than in Andalusia) probably influences higher productivity with minor water consumption.

Finally, the clone *in vitro* 112® planted (a *P. elongate* × *P. fortunei* hybrid) was adapted to the semi-arid climate and to the soil parameters in the study area, thus the genetic conditions to grow in this area were correctly implemented in the clone. Ayan *et al*. [9] also showed that a *P. tomentosa* × *P. fortunei* hybrid achieved the best stem growth of four species. Zhu *et al*. [16] demonstrated that for different *Paulownia* species, *P. fortunei* can suitably grow with clay content at 30%. Barton *et al*. [17] indicated that the most drought-tolerant species were *P. tomentosa and P. elongate*, whereas *P. fortunei and P. tomentosa* were the most tolerant of clay soils. This suggests adequate selection of the planted clone to be utilized in semi-arid climates and in the clay soils of the study area.

5. Conclusions

We conclude that irrigation with 2000 liters per tree can be used in the silvicultural management of *Paulownia* plantations to obtain about 4.3 $t \cdot ha^{-1}$ in the first resprout. Our principal conclusion therefore is that *Paulownia* trees established under low irrigation dose and in clay fertile soils, may not need fertilization at least during the two first years after establishment. With this low irrigation dose, *Paulownia* would be established in these semi-arid regions, thus contributing to aquifer conservation and the use of abandoned farmlands for biomass production. The soil water storage capacity and the good fertility of clay soils might prove particularly important in this semi-arid region.

In the near future, it may be necessary to analyze organic matter and nutrient levels in soil, and to discuss the question if nutrient inputs are higher than harvesting removals, which would better justify fertilization. These issues will be the objective of further studies.

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Author Contributions

All the authors contributed to the planning, research and writing of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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