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Siberian elm responses to different culture conditions under short rotation forestry in Mediterranean areas

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Abstract: This work explores the possibilities of biomass production, for energy purposes, of Siberian elm in Mediterranean areas, including marginal lands with poor soil and low water availability. To achieve this, the influence of soil type, planting density, and water availability on biomass production were analyzed after the first 3 years of the growing cycle in 2 different locations. Moreover, a method to estimate biomass production as a function of some morphological parameters of the trees, as well as the use of leaf water potential as a good indicator of trees' water status, are discussed. The analysis of parameters having an influence on elm growth showed that soil type is the most important factor to obtain a good yield. In soils with enough nutrients and higher water-holding capacity, biomass productions in the range 13–14 Mg DM ha^{-1} were achieved even under rainfed conditions. In irrigated plots, Siberian elm production was more than double the production of biomass under rainfed conditions; however, significant differences were not found between the 2 different irrigation doses under study. Biomass yield was greater for the highest planting density (6666 plants ha^{-1}). Leaf water potential has been shown to be a useful tool for finding out plant water status. Tree growth showed a direct relationship to midmorning leaf water potential, and it was equal to 0 for leaf water potentials lower than –1.83 MPa; this value indicates a great resistance to drought by the species.

Key words: Biomass, planting density, irrigation, short rotation forestry, Siberian elm, soil type

1. Introduction

Currently, the most studied and utilized species in short rotation forestry (SRF) plantations for energy purposes are mainly willow and poplar, which have elevated water consumption levels. In countries with scarce water resources, such as Spain and southern EU Mediterranean countries, promoting energy crops with high water requirements could further deplete the already scarce water resources and damage the local economy (Galan del Castillo and Velazquez, 2001), so these species should only be grown in areas where water is abundantly available (Sevine et al., 2011). Moreover, most of the abandoned lands in the cited countries are marginal lands, with poor soil and low water availability. In this context, the use of other SRF species like Siberian elm can be a more realistic alternative energy crop for those areas.

Siberian elm (*Ulmus pumila*) has a fast growth rate and, moreover, it is able to grow on poor soil, is very resistant to drought and severe cold (Moore, 2003), and, unlike other elms, is resistant to Dutch elm disease. Some studies carried out in the United States have revealed that elm has much potential as an energy crop (Geyer and Mechilar, 1986; Geyer et al., 1987; Geyer, 1989), and the work of Iriarte and Fernández (2006) revealed promising possibilities for elm to be used as an energy crop under a Mediterranean climate.

Drought resistance is one of the most relevant characteristics of the Siberian elm, which is a very important feature for adaptation to the studied areas. Accordingly, this aspect has been studied in this work. Leaf water potential is a physiological trait that is closely associated with drought resistance; this can be used as a selection criterion for species adapted to water scarcity (Van Heerden and Krüger, 2002). With the same water availability, if a higher leaf water potential is observed, this plant will have more drought tolerance. Moreover, leaf water potential can be used to ascertain the plant water status (Girona et al., 2006; Qu et al., 2008), which helps to schedule irrigations.

In order to optimize the biomass production, planting density was revealed as another key parameter in SRF plantations (Armstrong et al., 1999; Cañellas et al., 2012). Different studies carried out with poplars show that optimal density is diverse and depends on climatology and soil type (Sixto et al., 2007).

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In the described context, the aim of this work is to study the performance of the Siberian elm under different culture conditions in 2 localities in the center of Spain, which have Mediterranean climates, with the purpose of determining its potential and possibilities to be used as an energy crop in those areas. The influence of soil type, planting density, and water availability on yield after 3 vegetative periods is assessed. Moreover, and given the small amount of information available, models to predict the biomass production on the plantations, as well as the suitability of the use of the leaf area potential to assess the water stress situations, have also been investigated.

2. Materials and methods

2.1. Sites description

The research was carried out in 2 different parcels located in the province of Soria, in the center of Spain. The first plot was situated in the municipality of Cubo de la Solana (CS), and the second plot was in the municipality of Almazán (ALM). Both locations have a continental Mediterranean climate with low precipitation levels, cold winters, and short summers. Meteorological data was recorded from weather stations located at the planting site during the 3 years of experimentation (2010, 2011, and 2012). The most important meteorological parameters obtained were mean air temperature and precipitation. The mean temperatures in CS and ALM were very similar (Figure 1); ALM was a bit hotter than CS during the vegetative periods, but the mean temperature difference was always less than 1 °C. The monthly values of precipitation show that CS was slightly rainier; in this place, 422 mm per year was recorded, while 316 mm per year was registered in ALM.

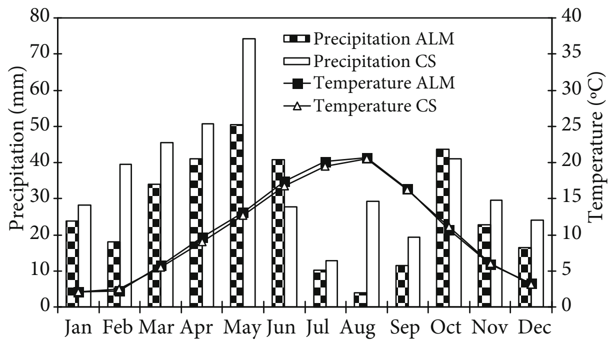

Figure 1. Monthly values of mean temperature (°C) and precipitation (mm) recorded in CS and ALM during 2010, 2011, and 2012.

The soil analysis performed on samples collected at depths of 0–30 cm showed very poor soil in CS, with very low content in organic matter and nitrogen; moreover, it has a fairly low pH and is an extremely sandy soil with a lot of gravel, which provides low water-retention capacity. Although ALM is very close to CS (15 km to the south), the physical and chemical characteristics of the soil are very different; ALM has a more clayey soil and, with the absence of gravel, it has higher carbon and nitrogen content and a basic pH value. Table 1 details the location coordinates and the soil characteristics of the experimental parcels.

2.2. Experimental design

In this project, the first cutting cycle was studied; all elms were cut down 3 years after plantation. In CS, the experiment was conducted in 2 plots (Table 2); elms under rainfed conditions were planted in the first plot and elms

Table 1. Location and soil characteristics.

		Cubo de la Solana	Almazán
Location	Latitude	41°36′N	41°29′N
	Longitude	2°30′W	2°31′W
	Altitude (m a.s.l.)	1100	960
Soil	Gravel (%)	39.9	3.1
	Sand (%)	88.9	40.4
	Silt (%)	7.6	15.0
	Clay (%)	3.5	44.6
	Texture	Sand	Clay
	pH (H_2O)	5.90	8.00
	Organic matter (%)	0.92	6.50
	Organic carbon (%)	0.53	3.78
	N (%)	0.03	0.23

Table 2. Different growing conditions under study in the 2 considered locations.

Locality	Water availabilities	Density (plants ha^{-1})	No. of repetitions	Area of each repetition (m^2)
Cubo de la Solana (CS)	Rainfed	3333	3	60
		6666	3	60
	Low dose (I1)	6666	3	60
	High dose (I2)	3333	3	60
		6666	3	60
Almazán (ALM)	Rainfed	3333	3	60

under 2 different irrigation conditions were studied in the second plot. Irrigation was applied with a drip irrigation system during the 3 trial years. During the first year, the water supplied in all irrigated plots of CS was the same for all relevant plots (about 3000 m^3 ha^{-1}); the second year, the water used for irrigation was 1800 m^3 ha^{-1} in the plots irrigated with a lower dose (I1) and 4300 m^3 ha^{-1} in those with the higher dose (I2); and in the third year, I1 plots received 1950 m^3 ha^{-1} and I2 plots received 5200 m^3 ha^{-1}. Until now, few research projects have been carried out with Siberian elm and its water requirements are not well known. For this reason, the water supply needed during the summer was determined, taking into account the evapotranspiration estimated for other woody energy crops that were grown under similar conditions (Guidi et al., 2008) and the meteorological data recorded. The rainfed plots and the I2 plots were divided into subplots, some of which were planted at a density of 3333 plants ha^{-1} (spacing 3 × 1 m) and others at a density of 6666 plants ha^{-1} (spacing 3 × 0.5 m). On the other hand, all elms grew at a density of 6666 plants ha^{-1} in the I1 plots. There was 1 additional border row to avoid adjacent plot affects, and 3 replications were carried out for each of the growing conditions. Each replication was 60 m^2 in size; 4 rows of 10 trees each were planted in the highest density subplots, while 4 rows of 5 trees each were established in the lowest density subplots.

In ALM there were also 3 replications of only 1 treatment. Plant spacing was 3 × 1 m and each repetition had an area of 60 m^2 (4 rows of 5 plants). All the elms were planted under rainfed conditions, although irrigation was applied during the first month after planting in order facilitate the establishment of the crop.

2.3. Plant material and crop management

Tree planting was done manually in November 2009 in the CS trial. In ALM, the elms were also planted manually, but the planting was done in the spring of 2010 (the last fortnight of April). Rooted elm plants, which had been sown at a nursery the previous spring (2009), were utilized in both plots. All the samaras were collected from Siberian elm trees growing in the central part of Spain.

Due to the poor quality of the soil, the total surface in CS was fertilized in April 2010 using a dose of 400 kg ha^{-1} of a fertilizer mixture ($N:P_2O_5:K_2O$, 8:15:15). The plots were not fertilized in ALM.

Regarding plagues and illnesses, no control was necessary in any plot during the 3 study years. Only agricultural operations were carried out to remove weeds. Each year, 2 or 3 mechanical weed controls were done between the rows during the vegetative period.

2.4. Aboveground biomass

According to several studies carried out with other woody energy crops, standing aboveground biomass can be estimated considering the relationships between basal diameter or basal area, height, and dry biomass (Laureysens et al., 2005; Ciria et al., 2007). To investigate this, at the end of the first, second, and third vegetative periods, 90 trees were cut down. The same number of trees from each of the different growing conditions was randomly collected every year.

The dry weight per plant, the basal diameter at 10 cm height of the living shoots, and the total height of the selected trees were measured for each tree; moreover, diameters and heights of all elms in each plot were also measured every year.

Total basal area (mm^2) and total height (cm) were the variables used and, as a dependent variable, the dry biomass production per plant (g $plant^{-1}$) was considered. A regression model was obtained at the end of each vegetative period. The final regression model was validated using real production values, since all the subplots were cut and weighed at the end of the third vegetative period.

2.5. Growth dynamics and water stress control

Leaf water potential determinations were carried out in the highest density plots of CS to determine and control water stress. Three samples were collected in each experimental unit (rainfed, I1, and I2 plots). These leaf water potential measurements were taken every 2 weeks during the third vegetative period.

The selected leaves were well exposed to sunlight; they were always collected at the same tree height (between 1 and 2 m), and all measurement was done in less than 1 h by the pressure chamber technique (Scholander et al., 1965). Leaf water potential was consistently measured at midmorning (between 1000 and 1100 hours), considering the fact that some recent studies showed that leaf water potentials at predawn, midmorning, noon, and evening are correlated (Yuanwen and Mingxian, 1991; Xu et al., 2010). Water potential is greater in the morning and evening, and lower at midday (more negative).

At the same time, 15 elms from each of the different growing conditions were randomly selected to study their growth throughout the third vegetative period. Measuring started in mid-June and was performed monthly. The basal diameter at 10 cm aboveground of every stem was obtained from the sample trees. The monthly values of total basal area growth in the highest density plots of CS were then related to the mean values of the 2 monthly water stress measurements.

2.6. Statistical analysis

Using the software StatGraphics, analysis of variance (ANOVA) was performed to detect significant differences in growth variables and yields. Homogeneity of variance and normality were tested before analyzing the data with ANOVA. Duncan's test was used to separate means. The regression models were also calculated using the same software.

3. Results

3.1. Survival

The percentage of plant mortality after planting was slightly higher in CS; a survival rate of approximately 90% was obtained in CS and 98% in ALM. All the trees that died were replaced during the spring of 2010. In CS, the replacement was carried out in mid-April, while the dead elms were replaced in mid-May in ALM. There were no new deaths during the following 3 years.

3.2. Vegetative period and water supplied

Sprouting was very early in spring, during the first days of April, and growth continued until the beginning of autumn in late September. The start of the vegetative period in ALM was later the first year because the planting date was in late April.

During the 3 vegetative periods under study, the mean precipitation was 145 mm and 199 mm per year in ALM and CS, respectively. The period of water supply varied depending on the weather conditions, but irrigation was generally necessary between mid-June and mid-September. Water requirements were greater during the second fortnight of July and the first fortnight of August, while irrigation was hardly necessary in early June and in late September.

3.3. Elm growth and water stress during the third vegetative period

From 1 April to 13 June, the basal area increase was considerably higher in ALM than in CS, where similar basal area increases were obtained in all plots (Figure 2). It should be taken into account that, before the first sampling date (in mid-June), all plants grew without irrigation. Between 14 June and 16 July, in CS, the elms irrigated with a higher dose showed faster growth rates than in the previous months during spring time; the plots irrigated with a lower dose maintained the same growth rate, while rainfed plots grew slightly more slowly. On the other hand, in spite of having no irrigation, the elms planted in ALM increased their basal area faster than in the first period. Between the second and the third measurements (July and August 2012), the basal area increase was still higher in ALM and in the I2 plots of CS. In contrast, the growth rate continued to decrease in the rainfed plots of CS. During this third period, I1 plots were especially sensitive to drought and they showed a very low growth rate, even lower than in rainfed plots. At the end of the growing season, the basal area increments tended to be more similar; there were decreases in ALM and in the I2 plots of CS, while there were increases in the rest of the plots.

Regarding water stress measured in the highest density plots of CS, midmorning leaf water potential was very similar for the 3 different water availabilities at the beginning of summer (Figure 3), since the water supply had started only a few days earlier. Later, leaf water potential

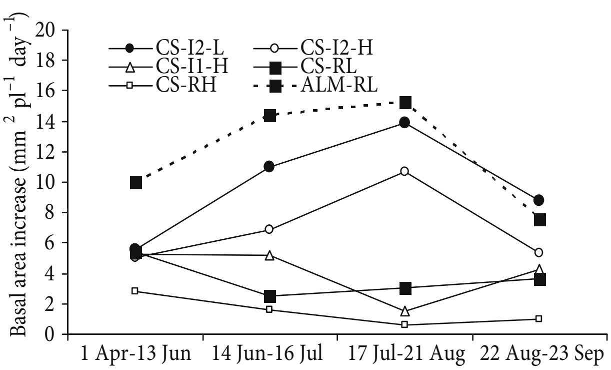

Figure 2. Basal area increase (mm^2 $plant^{-1}$ day^{-1}) during the third vegetative period. CS: Cubo de la Solana, ALM: Almazán, R: rainfed, I1: irrigated 1, I2: irrigated 2; L: low density; H: high density.

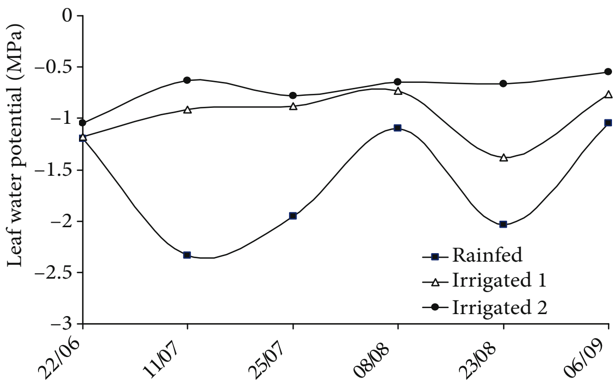

Figure 3. Midmorning leaf water potential in the highest density plots of CS during the third vegetative period.

increased slightly in irrigation plots and decreased sharply in rainfed plots. On 8 August, particularly high values were observed in rainfed plots, probably due to the rainfall recorded 2 days earlier. On 23 August, a technical problem with the irrigation system could explain the lower leaf water potential obtained in the I1 plots; however, I2 plots did not seem to notice this water reduction. In early September, the temperature began to go down and leaf water potential increased in the 3 different irrigation conditions.

A significant relationship was found between midmorning leaf water potential and daily basal area increment per plant (P = 0.0364). Growth increased linearly with leaf water potential and an R^2 value of 49% was obtained (Figure 4). According to this model, the basal area increase would be equal to 0 for midmorning leaf water potential equal to −1.83 MPa or less.

3.4. Growth of Siberian elm at the end of the third vegetative period

On average, Siberian elms grown under rainfed conditions in CS only developed 1.08 stems on the trunk (Table 3). Elms irrigated with a lower dose showed a similar mean,

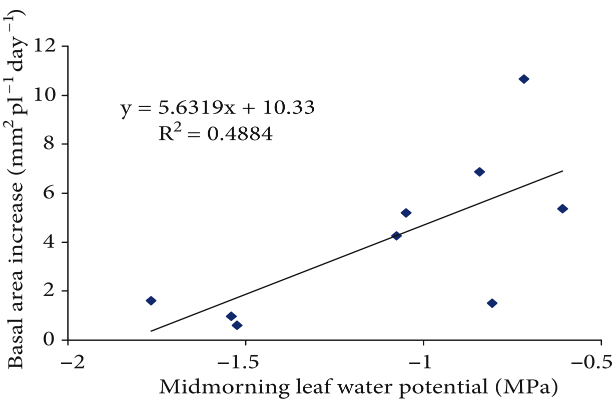

Figure 4. Relationship between midmorning leaf water potential (MPa) and basal area increase (mm^2 plant^{-1} day^{-1}) in the subplots established at a density of 6666 plants ha^{-1} in CS.

while elms irrigated with a higher dose, and also the elms planted in ALM, had a greater number of stems (between 1.35 and 1.73 stems on average). The plots established at a density of 3333 plants ha^{-1} showed the highest averages.

Mean diameter of stems ranged from 3.5 to 5.5 cm. The greatest diameter observed was 7.95 cm in CS and 10.24 cm in ALM. Multistem trees often showed smaller diameters than single-stem trees. For this reason, to determine the plant growth, it seemed more adequate to estimate an increase in thickness by total basal area than by mean diameter of stems.

There were significant differences in basal area per tree among treatments (Table 4). Duncan's multiple range test revealed significant differences among irrigated and rainfed elms in CS but not between the 2 different irrigation conditions. The total basal area per plant showed significantly larger values in the lowest density plots, but, as can be deduced by the data of Table 3, the ratio of the average total basal area of the lowest to highest planting density was smaller than the similar ratio referring to the corresponding planting densities. The greatest total basal area was displayed by the elms grown in ALM, where the soil quality was better.

There were also significant differences in height among treatments (Table 4). In CS, lower heights were observed for rainfed elms, with mean values of little more than 2 m. In irrigated plots, the mean height was approximately 1 m greater than in rainfed plots, while the trees had a mean height of nearly 4 m in ALM, where the tallest elm was observed (5.24 m height). Statistical analysis did not show significant differences between the 2 irrigation doses. The growth, in terms of tree height, was significantly influenced by density, but the effect was not consistent between different levels of water availability.

3.5. Biomass production

Once the total basal areas and heights were known, dry biomass production per plant could be estimated using a nondestructive method, as already described. The linear regression model for estimating overground biomass at the end of the first vegetative period used total basal area and tree height data (Table 5). The rest of the equations used only total basal area due to de fact that the R^2 value obtained is fairly high and because using other variables produced only a very slight increase in values of this coefficient. In spite of using tree heights, the equation showed lower R^2 values for the first year (63.04%), while weights were better estimated at the end of the second and third vegetative periods (86.61% and 88.70%, respectively). The equations resulting at the end of each vegetative period can only be used to estimate tree weights within a specific range of basal areas. Therefore, another model was obtained using data from the 3 years. The new equation showed a good R^2 value (91.59%).

Table 3. Growth parameters of 3-year-old Siberian elms. CS: Cubo de la Solana, ALM: Almazán, R: rainfed, I1: irrigated 1, I2: irrigated 2; L: low density; H: high density; Cv: coefficient of variation; Max: maximum value; Min: minimum value. *: Different letters indicate statistically different means according to the Duncan test (P ≤ 0.05).

		Number of stems*	Total height* (m)	Stem diameters* (cm)	Total basal area* (cm^2)
CS-RL	Mean	1.08	2.27 (b)	4.42	17.98 (b)
	Cv	40.73	20.90	28.55	44.61
	Max	4	3.11	6.62	34.42
	Min	1	0.76	1.00	0.78
CS-RH	Mean	1.08	2.01 (a)	3.46	11.14 (a)
	Cv	28.28	24.41	30.80	55.20
	Max	3	3.00	5.61	24.74
	Min	1	0.74	0.80	0.88
CS-I1-H	Mean	1.02	3.12 (d)	5.48	25.35 (c)
	Cv	14.74	16.84	23.19	32.28
	Max	2	3.75	7.35	42.39
	Min	1	1.84	1.18	1.09
CS-I2-L	Mean	1.71	2.87 (c)	4.26	30.66 (d)
	Cv	80.00	21.04	54.66	24.27
	Max	5	3.69	7.95	49.61
	Min	1	1.50	0.61	5.44
CS-I2-H	Mean	1.35	3.17 (d)	4.52	25.27 (c)
	Cv	65.50	17.03	40.81	33.99
	Max	5	4.02	7.81	47.85
	Min	1	1.00	0.84	1.68
ALM-RL	Mean	1.73	3.72 (e)	4.78	38.10 (e)
	Cv	75.76	16.05	47.83	21.50
	Max	6	5.24	10.24	82.39
	Min	1	1.85	1.16	8.22

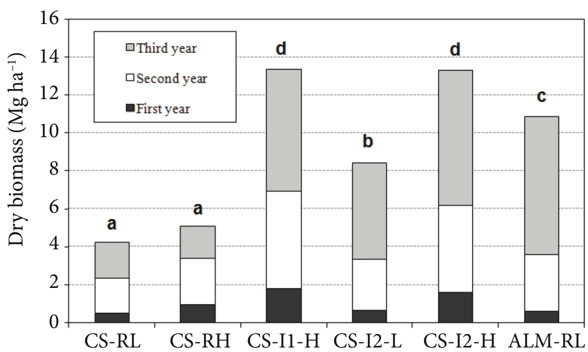

Figure 5. Estimated dry biomass production at the end of each vegetative period. Different letters indicate statistically different means according to the Duncan test (P ≤ 0.05). CS: Cubo de la Solana, ALM: Almazán, R: rainfed, I1: irrigated 1, I2: irrigated 2; L: low density; H: high density.

At the end of the third growing season, the elms were cut down and the regression models could be validated with the actual data (Table 6). In most cases, the difference between the estimated mean production and the actual mean production was between 10% and 20%. The annual model for the third vegetative period and the model for the entire cycle showed similar values.

Both models underestimated the yield in ALM, where the actual production was about 13.74 Mg DM ha^{-1}. In CS, the production was overestimated in the plots planted at a density of 3333 plants ha^{-1}, and it was underestimated in the rest.

The previous models were used to estimate yield throughout the cycle. Annual models were used to predict annual dry biomass production in each plot, except for the production in the rainfed plots planted with the highest

Table 4. Analysis of variance (ANOVA) for basal area and total height. DF: Degrees of freedom. *: Significant differences ($P \leq 0.05$).

		Sum of squares	df	Mean square	F	Sig
Total basal area (mm^2)	Between groups	26,677.9	5	5335.6	87.6	0.0 *
	Within groups	21,557.9	354	60.9		
	Total	48,235.8	359			
Total height (m)	Between groups	117.9	5	23.6	80.5	0.0 *
	Within groups	103.7	354	0.3		
	Total	221.6	359			

Table 5. Regression model to estimate dry biomass weight per tree in grams (DB). AB: Total basal area (mm^2); h: total height (cm); R^2: R-squared adjusted for DF; MAE: mean absolute error.

	Regression model
First year	DB = −43.5554 + 0.318699AB + 0.626922h
	R^2 = 0.630 MAE= 30.97
Second year	DB = 53.9707 + 0.573709AB
	R^2 = 0.866 MAE = 134.28
Third year	DB = −504.438 + 0.990885AB
	R^2 = 0.887 MAE = 356.05
All years	DB = −229.927 + 0.89778AB
	R^2 = 0.916 MAE= 215.18

Table 6. Estimated mean production and actual mean production at the end of the third vegetative period. Dry biomass in Mg ha^{-1}. R: Rainfed, I1: irrigated 1, I2: irrigated 2; L: low density; H: high density.

Treatment	Actual production (Mg ha^{-1})	Estimated production (Mg ha^{-1})		Difference (%)	
		Equation 3rd year	Equation all years	Equation 3rd year	Equation all years
CS-RL	3.55	4.26	4.61	19.9	30
CS-RH	4.89	4.00	5.08	−18.3	3.8
CS-I1-H	15.57	13.38	13.64	−14.1	−12.4
CS-I2-L	7.30	8.44	8.41	15.7	15.2
CS-I2-H	14.79	13.33	13.59	−9.9	−8.1
ALM-RL	13.74	10.90	10.63	−20.7	−22.6

density; these were better estimated by the model that used data from all 3 years. The results showed that *Ulmus pumila* had a low growth rate during the first vegetative period, which was higher during the second year (Figure 5). During the third vegetative period, the biomass increase was similar to the second year in the rainfed plots in CS; however, it was much greater in the I2 plots and in ALM.

According to the values obtained using the regression models, taking into account the 3-year cycle, the biomass production in I2 plots planted at a density of 6666 trees

ha^{-1} was significantly greater than in the I2 plots planted with the lowest density. Although no significant differences were found, average biomass production was also higher at the density of 6666 trees ha^{-1} in the rainfed plots. The irrigated plots were twice as productive as the rainfed plots at a density of 3333 plants ha^{-1}, while the production was 3 times greater in irrigated plots than in rainfed plots at a density of 6666 plants ha^{-1}. In both densities there were significant differences between rainfed and irrigated plots; however the analysis did not reveal significant differences between the 2 irrigation conditions. Siberian elm production was almost triple in ALM compared to CS under the same growing conditions, reflecting that soil type is the more influencing parameter on biomass productivity under the conditions studied.

4. Discussion

The survival rate after planting was higher in ALM than in CS; this difference could be attributed mostly to soil conditions during winter time after planting in CS. The elms planted in autumn in CS were flooded for a long period during that winter because of the abundant rainfall. It should be taken into account that Siberian elm is fairly intolerant to wet ground conditions (Loucks and Keen, 1973). In Spain, similar mortality rates to those observed in ALM (2%) have been reported in other studies (Fernández et al., 2009; Sanz et al., 2011), while mortality was about 10% in CS.

Other authors indicated that Siberian elm has a very long vegetative period (Argent et al., 1985); this was confirmed in the present study where the elms sprouted between 2 and 3 weeks earlier than other woody energy crops (poplar, black locust), which were also studied by this research group in the same location. The growth of the elms also finalized 1 or 2 weeks later every year. This longer vegetative period will have a positive effect on yield.

The Siberian elm had less active growth in the first months after sprouting, in contrast to other species such as poplar or willow, which presented the quickest growth rate at the beginning of the vegetative period. (Labrecque, 1993; Karačić and Weih, 2006). The elms under study sprouted very early but barely grew at all during approximately 1 month because of low temperatures. In other plots in the same location, different types of poplar clones studied by this research group sprouted 3 weeks later, but their growth rates were higher than elm growth rates during the first weeks after sprouting. The elms planted in ALM and the well-watered elms in CS, after reaching their maximum growth during July and August, showed a slower growth rate towards the end of the growing season. This could be due to the lower temperatures recorded, which, on the other hand, allowed the rainfed elms to grow slightly faster during the last weeks in CS (Figure 2).

In rainfed plots of CS plantation, leaf water potential fluctuated between –1.2 and –2.33 MPa. Similar values, below –2 MPa in summertime (Kitsaki and Drossopoulos, 2005), have been reported for olive trees grown under rainfed conditions in the Mediterranean area. Considering the conclusions of other research projects carried out with vines where the shoot growth was equal to 0 for leaf water potentials at midmorning of less than –1.18 MPa (Baeza et al., 2007), the rainfed elms under study here were able to grow with major water stress, and leaf water potential demonstrated that *Ulmus pumila* was highly resistant to drought. A direct relationship between growth and midmorning leaf water potential was obtained in the previously mentioned study about vines (R^2 = 59%). As shown in Figure 4, this relationship was also found for elms although with a lower R^2 value, which, nevertheless, was significant at the 95% confidence level, and the model explained 49% of the variability.

The mean number of stems per tree observed in this study (Table 3) was less than that mentioned by other authors (Geyer and Iriarte, 2007; Fernández et al., 2009; Sanz et al., 2011), who reported 1.6 to 3.2 stems per tree on average at the end of the first vegetative cycle. The greatest diameter of a stem was only slightly over 10 cm; it was obtained in the rich soil of ALM plots. Taking into account this diameter, the low number of stems, and the maximum total height, which was a little more than 5 m, it can be concluded that the sizes obtained could be suitable for harvesting with the machinery used in SRF.

The results did not show a clear effect of density on the total height of trees, and studying the growth of Siberian elm at higher planting densities would be very interesting. Although the highest density plots showed higher height-to-basal area ratios, there was no important competition for light in rainfed plots of CS because of their smaller size; water was the most relevant limiting factor in these plots, especially in the highest density plots where lower heights were observed. Conversely, light was an important limiting resource in the irrigated plots, where the elms that were grown at a higher density were significantly taller than the elms planted with lower density

The high coefficient of variation observed in the values of the characteristics of the individual trees seems to indicate a large genetic variability which, in turn, reveals the still scarce level of selection of the species and the necessity to perform genetic selection work in order to obtain improved and more productive elms.

Choosing a suitable soil was more important than irrigation and planting density to obtain a good yield. Biomass production of Siberian elm was more than 3 times greater in soils with enough nutrients and higher water-holding capacity than in sandy soils, achieving a yield of about 14 Mg DM ha^{-1} after the first 3-year rotation cycle under rainfed continental Mediterranean conditions. Other studies indicated that Siberian elms, as well as other energy crops such as poplar or willow, prefer well-aerated soils (Loucks and Keen, 1973; Tüfekçioğlu et al., 2005); however, in this study, elms grew best in less sandy soils.

In spite of showing an acceptable yield under rainfed conditions, Siberian elm production in irrigated plots was more than double the production of biomass without irrigation. Therefore, *Ulmus pumila* could easily achieve production of more than 10 Mg DM ha^{-1} per year in well-watered rich soils: that is to say, yields similar to other woody energy crops, such as poplar or willow. The analysis of planting density revealed that yield was greater in the highest density plots under study, although it must be taken into account that other lower spacings should be studied in future research projects. In the present study, biomass production at a density of 6666 plants ha^{-1} was between 20% and 60% greater than at a density of 3333 plants ha^{-1}; therefore, basal area was not double, although the density was.

During the first vegetative period, the production growth rate values were low, but this parameter increased exponentially in the following years. In some cases, especially in irrigated plots and in ALM, the production the third year was much greater than the total production in the 2 previous seasons (Figure 5). The same conclusion was obtained from a study carried out in Madrid (Spain) where rainfed elms plantations with a density of 6666 plants ha^{-1} produced 10.3 Mg DM ha^{-1} after 2 years, while production was almost 4 times as great (39.5 Mg DM ha^{-1}) after the third vegetative period (Sanz et al., 2011). Once the growth dynamic during this first cycle is known, studying the yield after regrowth will be necessary in order to determine the real potential of Siberian elm as an energy crop.

The present study showed significantly lower yields than in the aforementioned trial carried out in Madrid; these higher yields could be attributed to the fairly higher mean temperature recorded in the capital of Spain. In a study carried out under similar climate conditions in Teruel, Spain, the mean yield was 15.3 Mg DM ha^{-1} in rainfed plots planted at a density of 3333 plants ha^{-1} when the elms finished the third vegetative period (Fernández et al., 2009); that is similar to the production obtained in some plots in this study. *Ulmus pumila* has also been studied in other Mediterranean countries such as Italy, where more than 20 Mg DM ha^{-1} were obtained in most of the plots after 2 growing seasons (Pérez et al., 2012). These results were achieved with a density of 8333 plants ha^{-1} in fertile soil in the Po Valley, where the mean annual temperature is about 2 °C higher than in Soria and the annual rainfall is 750 mm. The first studies carried out with Siberian elm as an energy crop were done in the United States, where diverse results were obtained. In eastern Kansas, Siberian elm yield harvested 7 years after planting was 9.8 Mg DM ha^{-1} year^{-1} at a density of 7000 plants ha^{-1} and 6.6 Mg DM ha^{-1} year^{-1} at a density of 3200 plants ha^{-1} (Geyer et al., 1987). However, the yields after 3 years ranged from 0.7 Mg DM ha^{-1} year^{-1} to 5.2 Mg DM ha^{-1} year^{-1} in different plots distributed throughout the state of Kansas (Geyer, 1993). Production also varied between 4.5 Mg DM ha^{-1} year^{-1} and 16.9 Mg DM ha^{-1} year^{-1} when Siberian elms were cut annually for 6 years using a spacing of 0.3 × 0.3 m in this same North American state (Geyer, 2006). This last study, as well as others carried out in Spain (Iriarte, 2008; Fernandez et al., 2009; Sanz et al., 2011), revealed that elm growth increases after some cuttings; therefore, yield should be greater in the following cycles.

Siberian elm is not considered an invasive plant in Spain (BOE, 2011) and other Mediterranean countries; however, due to its adaptability, high rate of germination, and fast growth, Siberian elm is listed as a noxious tree in New Mexico (Moore, 2003) and is considered invasive in other US states. It competes with native plants, especially in sparsely vegetated or disturbed areas. The US Department of Agriculture recommends controlling the population of Siberian elm using chemical or mechanical methods and bans its cultivation in different southwestern states (USDA, 2012). In these areas, the existing mass of elms could be extracted to obtain an important amount of biomass and, moreover, to control its spread. Other invasive species, such as kudzu (*Pueraria montana* var. *lobata*), have recently been proposed to produce bioenergy while also attempting to control their populations (Sage et al., 2009)

Finally, the overall conclusion from this work is that the Siberian elm features good characteristics to be proposed as a woody energy crop in Mediterranean areas. Biomass production was greater in soils with lower sand content. The yield at a density of 6666 plants ha^{-1} was greater than at a density of 3333 plants ha^{-1}. Siberian elm production in irrigated plots was more than double the production without irrigation, but, after a certain amount of water, the growth was limited by other factors (soil characteristics) and the analysis did not reveal significant differences between the 2 irrigation doses.

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