forests

Article

Biomass Production and Quality of Twelve Fast-Growing Tree Taxa in Short Rotation under Mediterranean Climate

Joaquín Alaejos [1], Raúl Tapias [1], Francisco López [2], David Romero [1], Federico Ruiz [3] and Manuel Fernández [1,*]

[1] Department of Agroforestry Sciences, School of Engineering, University of Huelva, 21071 Huelva, Spain; jalagut@dcaf.uhu.es (J.A.); rtapias@dcaf.uhu.es (R.T.); dromero.gomez86@gmail.com (D.R.)
[2] Department of Chemical Engineering, School of Engineering, University of Huelva, 21071 Huelva, Spain; baldovin@diq.uhu.es
[3] I + D Forestal, ENCE, Energía y Celulosa S.A., Carretera A-5000, km 7.5, 21007 Huelva, Spain; fruiz@ence.es
* Correspondence: manuel.fernandez@dcaf.uhu.es; Tel.: +34-959-217-712; Fax: +34-959-217-560

Abstract: Sustainable production of lignocellulosic biomass for energy use can contribute to climate change mitigation. This work aims to compare the biomass production of twelve fast-growing woody taxa belonging to the *Eucalyptus*, *Casuarina*, *Populus* and *Paulownia* genera, the quality of their biomass for energy use and its valorizing through transformation into pellets, as well as the effect of the crop on the soil. Over the course of two rotations, plant growth and biomass production were assessed. The yield of aboveground dry biomass ranged from 9 to 61 Mg ha^{-1} year^{-1} (equivalent to 137–867 GJ ha^{-1} year^{-1}). The highest yields were obtained for *Eucalyptus* clones (51–61 Mg ha^{-1} year^{-1}). The N-fixing species *Casuarina equisetifolia* and two *Populus* × *euramericana* clones ('Adige' and 'AF2') also achieved high yields (28–33 Mg ha^{-1} year^{-1}), though significantly smaller than those of the eucalypts. Due to its low wood density, *Paulownia fortunei* was not very productive in terms of biomass (18 Mg ha^{-1} year^{-1}), despite its good growth in diameter and height. However, some management practices, such as not removing nutrient-rich and poor-quality biomass fractions for energy use (leaves and thin branches) from the harvested crop, as well as the use of N-fixing species and by taking into account all nutrient inputs and outputs, can ensure the sustainability of the cultivation systems and improve degraded soils.

Keywords: *Eucalyptus*; *Populus*; *Paulownia*; *Casuarina*; lignocellulosic biomass; renewable energy; wood pellets; degraded soils

Citation: Alaejos, J.; Tapias, R.; López, F.; Romero, D.; Ruiz, F.; Fernández, M. Biomass Production and Quality of Twelve Fast-Growing Tree Taxa in Short Rotation under Mediterranean Climate. *Forests* **2023**, *14*, 1156. https://doi.org/10.3390/f14061156

Academic Editor: Dirk Landgraf

Received: 19 March 2023
Revised: 30 May 2023
Accepted: 31 May 2023
Published: 4 June 2023

1. Introduction

Biomass, as a renewable and clean energy source, has aroused growing interest during the first decades of the 21st century, emphasized by the objectives of reducing CO_2 emissions in the short and medium term set out in international commitments [1–4]. Furthermore, the inevitable depletion of fossil fuels, along with their negative impact on the environment, has seen an increase in all types of renewables to the point that they accounted for 19.3% of the total global energy production in 2015 [5]. In the same year, global energy production from biomass accounted for 68.4% of all renewable sources [6]. While the primary use of biomass, mainly lignocellulosic biomass, in developing countries remains that of cooking, developed countries are significantly increasing its use in the production of thermal and electric energy due to the value-added products derived from it (pellets, chips, biogas, etc.) [7–9], apart from other industrial uses (wood pulp, wood-based panels, etc.) [10].

Ensuring that the growth in demand for lignocellulosic biomass can be met without adversely affecting agroforestry systems requires a regular, manageable and renewable supply of fast-growing tree species [11–13]. This supply is not only compatible with the cultivation of food crops but also contributes to the preservation of the environment and biodiversity [14,15] and rural development [16,17], as well as providing an alternative use for abandoned degraded land. Only in the European Union, 147 million hectares are degraded for one reason or another (soil erosion, low organic matter content, excess inorganic nitrogen fertilization). Many are in danger of abandonment, but many are suitable for establishing short-rotation tree plantations [18,19]. It is worth remembering that one of the first conclusions of the recent study commissioned by the Committee on Agriculture of the European Parliament, entitled “The challenge of land abandonment after 2020 and options for mitigating measures” (https://bit.ly/39ElcFJ, accessed on 20 March 2023), is that about 30% (56 million hectares) of the valuable agricultural area of the European Union run a moderate and high risk of being abandoned (5 million hectares in the short term, before 2030).

Under the Mediterranean climate, woody tree species have been cultivated over the last few decades. Therefore, studies have been carried out on various taxa, such as short rotation forestry crops, mainly belonging to the genera *Populus* and *Eucalyptus* but also *Salix*, *Paulownia*, *Robinia*, *Ulmus*, etc. [16,20–25]. However, most of them consider taxa (provenances/clones) of a single species, and very few compare taxa of different species growing at the same site [17,26,27]. Traditionally, plantations of these fast-growing species have been principally intended for wood production or paper pulp and, under optimal conditions, can produce up to 25 t ha^{-1} $year^{-1}$ dry matter (poplars, willows) and 40 t ha^{-1} $year^{-1}$ (*Eucalyptus* and *Paulownia*) [16,17,21,26,28]. However, under sub-optimal conditions exacerbated by climate change, environmental and cultivation factors (soil fertility, drought, frosts, irrigation, etc.) differentially affect each taxon [17,29]. In this respect, N-fixing species such as *Casuarina* sp. [28] can help to reduce the energy and economic costs of supplying nitrogenous inorganic fertilizers [30]. Thus, it is not clear that currently cultivated taxa are optimal in terms of both their yield and physical–chemical characteristics regarding energy use, and it is worth studying them on degraded soils [9,31,32].

The low energy density of biomass is the main drawback to its efficient energy use caused by the high moisture content, which reduces its heating value, and the low density, which entails handling large volumes, complicating transport and storage [33]. Pelletization presents clear advantages over other biomass fuels that have not been densified since it reduces transportation costs and increases energy conversion efficiency thanks to the low moisture content (less than 10%) [34–36]. Debarked softwood, mainly from pine, is one of the most used for the manufacture of pellets due to its wide worldwide distribution, as well as its low ash content and high heating value, higher than that of hardwood species and of non-woody species. Still, many other species are used with similar or slightly lower values [37].

Hence, this paper presents a study into the suitability of twelve tree taxa for biomass production in southwest Europe under a Mediterranean climate with mild winters. *Eucalyptus*, a genus widely used in forest plantations in the study area, along with other genera, namely *Populus*, *Casuarina* and *Paulownia*, for which fewer data are available in these climatic conditions, were evaluated. The objectives of this study were to assess: (i) plant growth and biomass production of twelve selected taxa belonging to *Eucalyptus*, *Populus*, *Casuarina* and *Paulownia* genera; (ii) the suitability of their biomass for energy use, including its transformation into commercial-quality pellets; and (iii) the changes of the upper soil layer after a cropping period of eight years.

2. Materials and Methods

2.1. Study Area and Experimental Design

The study site was located in the province of Huelva (Spain) UTM, zone 29S, X: 685,016, Y: 4,119,147, 10 m asl., on a permeable alkaline soil (pH = 8.3) with low salinity (EC = 135 μS cm^{-1}), 1.56 kg dm^{-3} bulk density and 18% stoniness. It was a nutrient-poor soil except for Ca and Mg, with low organic matter content and free of active limestone or heavy metal contamination (1st year in Table 1, Tables S1 and S2; the “S” indicates information in the Supplementary Material section). The water table was less than 2 m deep during the wet season but more than 3 m during the summer. The area had been cultivated with woody legumes eight years prior to plantation establishment. The climate is

Mediterranean, marked by mild winters due to oceanic influence and hot and dry summers, with an average annual temperature of 17.4 °C and an average annual precipitation of 558 mm. More details of the climatic variables during the study period are shown in Table S3.

Table 1. Physical–chemical properties of the upper soil layers at the beginning and the end of the study period for all taxa as a whole (mean (SE)). See also Table S1. Asterisks (*) denote significant differences between measurement dates within a soil layer ($p < 0.05$).

Variable	Soil Layer (Depth Range)			
	0–15 cm		15–30 cm	
	1st Year	8th Year	1st Year	8th Year
pH (H_2O, 1:2.5)	8.32 (0.05)	7.98 (0.04) *	8.34 (0.05)	8.05 (0.05) *
Organic Matter (%)	1.22 (0.02)	1.63 (0.06)	0.70 (0.05)	1.17 (0.06)
C/N ratio	4.08 (0.08)	6.81 (0.40)	3.02 (0.04)	6.14 (0.40)
N (%)	0.17 (0.01)	0.15 (0.01) *	0.14 (0.01)	0.11 (0.01) *
Available P (mg kg^{-1}) (1)	8.59 (0.12)	5.40 (0.28) *	7.85 (0.34)	4.50 (0.29) *
Available K (meq/100 g)	0.17 (0.01)	0.16 (0.02)	0.12 (0.01)	0.12 (0.01)
Available Mg (meq/100 g)	1.97 (0.05)	1.51 (0.04) *	1.81 (0.06)	1.54 (0.04) *

Differences between measurement dates for organic matter and C/N ratio were not significant ($p = 0.086$ and 0.059, respectively) but marked an increasing trend. The 4th year has not been shown in the table since it did not differ significantly from the 1st or 8th year and presented intermediate values between both extreme dates. (1) The total P averaged 140.2, 88.3, 132.2 and 72.8 mg kg^{-1}, respectively.

Without going too deeply into details, the main characteristics taken into account for selecting the taxa for this study were rapid growth rate and high biomass yield; adaptability to the edaphoclimatic conditions of the plantation area; regrowth vigor from the stump after tree felling; and tree structure (trunk and branching) suitable for harvest mechanization. After a previous study, 12 taxa were selected (Table 2). Some have already been tested in geographical areas similar to this study. Others have been less frequently used in short rotation crops but, due to their characteristics, were considered likely to be a productive source of biomass in a Mediterranean climate [16,17,21,26,28,38–59]. Because of their evergreen condition, *Eucalyptus* and *Casuarina* can benefit from the mild winter in the area [16,28]. *Eucalyptus globulus* is the most cultivated species in the area, therefore, well adapted. However, *Eucalyptus camaldulensis* and *Eucalyptus trabutii* tolerate drought and clay soils better than the former. *Eucalyptus* × *urograndis* presents very high growth rates but needs high soil moisture content [16]. *Casuarina* sp. are N-fixing species and contribute to soil nitrogen fertilization [60]. Poplar plantations are widespread in the Mediterranean area [27], mainly with I-214, an old-known clone usually used as a reference in many studies [52]. The other selected poplar clones show advantages over I-214 under certain growth conditions [26,53,55].

The experimental unit was composed of three parallel lines of five plants each, with a separation of 2 m between lines and 1 m between plants in the line (5000 plants per hectare) (Figure S1). This high plantation density was selected because some field studies indicated that high planting densities increase the biomass production of the system and shorten the harvest rotation period while decreasing the percentage of bark on the trunks [22,26,27,51–56,61–64]. A randomized complete block design was established, with four blocks (four experimental units per taxon, one experimental unit per block). This field trial configuration was replicated twice (5 plants × 3 lines × 4 experimental units × 2 replicates = 120 plants per taxon). An additional line of plants was planted around each replicate, to avoid the border effect, but not inside or between experimental units (Figure S1). So, each replica occupied an area of approximately 1800 m^2, to which another 800 m^2 were added. These correspond to the plants grown in similar conditions that were used for the allometric equations described below.

Table 2. Woody plant taxa (species/clones) used in the present study and some examples of studies that refer to the plant growth and biomass production of the selected species.

Species	Hybrid	Seedling or 'Clone Name'	Cited
Casuarina cunninghamiana		Seedlings	[38,39]
Casuarina equisetifolia		Seedlings	[28,40]
Eucalyptus camaldulensis		'ENCE'	[41–43]
Eucalyptus × *trabutii*	*E. botryoides* × *E. camaldulensis*	'Biopoplar'	[44–46]
Eucalyptus × *urograndis*	*E. urophylla* × *E. grandis*	'ENCE'	[16,47,48]
Eucalyptus globulus		'ENCE'	[29,44,46,49]
Paulownia fortunei		'UHU'	[17,21,50]
Populus × *euramericana*	*P. deltoides* × *P. nigra*	'Adige'	[17]
Populus × *euramericana*	*P. deltoides* × *P. nigra*	'I-214'	[17,20,26,51–53]
Populus × *euramericana*	*P. deltoides* × *P. nigra*	'AF2'	[17,53–55]
Populus × *euramericana*	*P. deltoides* × *P. nigra*	'Oudenberg'	[26,56]
Populus × *interamericana*	*P. trichocarpa* × *P. deltoides*	'Raspalje'	[17,57–59]

Species: Casuarina cunninghamiana Miq.; Casuarina equisetifolia L.; Eucalyptus camaldulensis Dehnh.; Eucalyptus × trabutii Vilm. ex Trab.; Eucalyptus globulus Labill.; Paulownia fortunei (Seem.) Hemsl.; Populus × euramericana (Dode) Guinier.; Populus × interamericana van Broekhuizen.; Eucalyptus urophylla S.T. Blake; Eucalyptus grandis W. Hill ex Maiden; Eucalyptus botryoides Sm.; Populus nigra L.; Populus deltoides W. Bartram ex Marshall; Populus trichocarpa Torr. and A. Gray ex Hook.

Planting took place in mid-spring 2011, according to the availability of the plants (Figure S2a). Plants of 25 to 40 cm in height coming from rooted shoot cuttings were used in the case of *Eucalyptus*; 15–25 cm tall plants coming from root cuttings in the case of *Paulownia*; hardwood cuttings of 20–25 cm in length for *Populus*; and 20–30 cm tall seedlings for *Casuarina*. Before planting, a deep plowing at 50 cm followed by a shallow tillage (harrowing) and pre-emergent herbicide (Oxifluorfen 24%, 2.5 L ha^{-1}) were applied. Fertilizers were supplied by fertigation: 75, 62.3, 21.8 and 16.0 kg ha^{-1} $year^{-1}$ of N, K, P and S, respectively; 3 kg ha^{-1} $year^{-1}$ of Fe–Zn–Mn (4.5%–1.5%–0.5%) fertilizer chelated by EDDHA; 75 g ha^{-1} $year^{-1}$ of Cu (14%) chelated by EDTA; and 75 and 5 g ha^{-1} $year^{-1}$ of H_3BO_3 and $(NH_4)_2MoO_4$, respectively. Support irrigation was provided every year throughout the summer (from May to September) by means of drippers along the lines, providing between 245 and 550 mm per year, according to the amount of precipitation recorded up to the time of the start, to total 800 to 900 mm annually (rainfall + irrigation). The irrigation water contained 4.6, 0.11 and 0.14 mg L^{-1}, respectively, of N, P and K. Weeding was carried out mechanically three months after planting. Still, it was not necessary to repeat it thereafter due to the high planting density and the rapid growth of the new sprouts after harvesting. It was unnecessary to apply phytosanitary treatments, although some poplar clones ('I-214' and 'Raspalje') suffered slight attacks from *Melampsora* rust and aphids.

2.2. Plant Growth and Biomass Estimation

Throughout the three-year duration of each of the first two rotation periods, measurements of the stem diameter (*D*, at 10 cm above the ground surface to a precision of 0.1 mm in two perpendicular directions), plant height (*H*) and the number of main stems (Nst) were taken, along with mortality rate and phytosanitary status. The plants usually had a single main stem during the first rotation (Figure S2c–e), but several re-sprouted shoots (2 to 5) from the stump after felling (2nd rotation) (Figure S2f–h). These measurements were carried out at the end of each season (4 times per year) on 24 plants per taxon each time (3 plants/taxon × 4 experimental units × 2 replicates = 24 plants/taxon). In order to avoid interference in growth by neighboring taxa, only 3 plants of each experimental unit (2nd, 3rd and 4th plants) were measured, corresponding to the central line and avoiding the two plants at the ends of said line (1st and 5th plants). At the end of each rotation, all the trees were cut down, and all the aboveground biomass (leaves, trunks and branches) was removed from the field trial. Some of these felled trees were used to elaborate the allometric equations described below. A third rotation in 2020 was planned, but it was not measured due to the COVID-19 pandemic, and consequently, the plantation was left unattended. For this reason, only data from two rotations are shown.

The biomass production assessment was carried out every year at the end of winter (February to March), before spring bud break, based on the data of D and H. For this, allometric equations relating D and/or H to shoot dry mass were previously developed [65–67]. Sixteen different equations were tested (including linear, power, exponential, polynomial, logarithmic and quadratic) with combinations of D, H, and D^2 as predictor variables, similar to those performed by other authors [16,17,23,25,40,56,68]. Most of them resulted in a high degree of prediction and fitted well to the measurement data (Tables S4 and S5, [69,70]). However, as the measurement of tree height in high-density stands is less accurate than the diameter of the main stem, for practical simplicity, the potential model was chosen in which only the diameter (D) is used as an independent variable, $Dry\ mass = aD^b$ (Table 3). At least 12 plants per taxon, with a stem diameter (D) ranging from 5 to 160 mm, were cut 10 cm from the ground, oven-dried at 80 °C to constant weight and weighted. They included the full range of sizes obtained in this study. Some plants harvested at the end of the 1st and 2nd rotations were used for this. In addition, other younger plants with a smaller diameter were grown next to the experimental plot under the same growth conditions (Figure S1). Any attempt to apply these models to areas different from the study should first be trialled. Each felled tree was divided into six different fractions: one for leaves and five diameter-based classes for the aboveground woody parts, that is, branches and stems ($d < 25$ mm, 25 mm $< d < 50$ mm, 50 mm $< d < 75$ mm, 75 mm $< d < 100$ mm, $d > 100$ mm; d being the diameter of the branch or stem). Each fraction was separately weighed. Samples of each class were taken and oven-dried at 80 °C to constant weight in order to determine their moisture content and dry weight. Likewise, due to its effect on biomass quality (i.e., on ash and nutrients content, etc.), the proportion of bark and wood for each diameter class was determined on 5 cm thick slices per taxon and diametric class.

Table 3. Relationship between stem diameter at 10 cm above the ground surface (D, cm) and aboveground dry mass (AGDM, kg). AGDM = $a\ D^b$. D ranged from 5 to 160 mm. Significance level, $p < 0.001$ for all cases. n = sample size.

Taxon	a	b	R^2	n
Casuarina cunninghamiana	0.031	2.586	0.985	12
Casuarina equisetifolia	0.026	2.695	0.992	12
Eucalyptus camaldulensis 'ENCE'	0.027	2.670	0.919	12
Eucalyptus × *trabutii* 'Biopoplar'	0.025	2.704	0.981	13
Eucalyptus × *urograndis* 'ENCE'	0.043	2.495	0.969	15
Eucalyptus globulus 'ENCE'	0.031	2.597	0.985	20
Paulownia fortunei 'UHU'	0.006	3.143	0.971	14
Populus × *euramericana* 'Adige'	0.033	2.704	0.979	18
Populus × *euramericana* 'AF2'	0.024	2.721	0.971	22
Populus × *euramericana* 'I-214'	0.044	2.448	0.971	15
Populus × *euramericana* 'Oudenberg'	0.036	2.719	0.986	18
Populus × *interamericana* 'Raspalje'	0.039	2.637	0.980	15

2.3. Physical–Chemical Characterization of Plant and Soil Material

The soil sampling took place in March 2011, 2014, and 2018 (1st, 4th and 8th year, respectively) under each of the taxa, but only for one of the two replicates of the study. Two soil subsamples per experimental unit and soil depth (0–15 and 15–30 cm depth) were taken with a soil core at an equidistant distance (0.5 m) from the planting lines (2 subsamples × 4 experimental units = 8 subsamples per taxon and depth). Previously, at each sampling point, the litterfall (Figure S2b) contained in a soil surface of 0.25 m^2 was sampled and subsequently oven-dried at 80 °C, weighed and stored (15–20 °C) for further analysis. All the subsamples belonging to each taxon and depth were pooled. The soil samples were air-dried at 15–20 °C and sieved (2 mm mesh). Regarding the aboveground plant biomass, eight trees per taxon (one tree per experimental unit, considering the two replicates) were randomly sampled at the end of the 2nd rotation, pooled, oven-dried at 80 °C, ground and stored at 15–20 °C for further physical-chemical characterization. All samples (litterfall, soil, plant biomass) were processed by standardized methods (Table S2). Although the physicochemical properties of biomass allow for evaluating its suitability for energy use, densification into pellets would increase its commercial value. For this reason, pellets were manufactured following the methodology described by Alesso et al. [17]. Briefly, it was ground (Woodstock 3PH, Smartec®, Villar San Costanzo, Italy), sieved to a 0.2–5.0 mm particle size and densified with a pelleting press (PLT-400, Smartec®, Villar San Costanzo, Italy) at 95–105 °C using a raw material with 14% moisture content. The die channels were six millimeters in diameter and 24 mm in length for *Populus* and *Paulownia* but 20 mm for *Eucalyptus* and *Casuarina*. After that, their physical, mechanical and chemical properties were assessed according to the standard ISO 17225-2:2021 [71].

2.4. Data Analysis

All statistical analysis was carried out in the Statistical Package for Social Sciences (SPSS® 20.0, IBM®). The block effect and the replicate were not statistically significant for any parameter, so they were excluded from the models in order to simplify them. The growth (*D*, *H*, Nst) and biomass yield were evaluated in the same plants during the 1st and 2nd rotations, so repeated measures ANOVA was applied [72] by testing the assumptions of normality and sphericity in advance. Hence, the plant (within-Experimental unit, *Eu*) was considered a random effect, and the taxon (*T*) and annual growth (*Year*) as fixed effects. However, each rotation was analyzed separately, as the trees were felled at the end of the first rotation, and new shoots emerged. The full model included the interactions between the main factors:

$$y_{ijkl} = Eu_i + Y_j + T_k + (Eu \times Y)_{ij} + (Eu \times T)_{ik} + (Y \times T)_{jk} + (Eu \times Y \times T)_{ijk} + \varepsilon_{ijkl}$$

Soil characteristics were analyzed by a three-way ANOVA by considering taxon (*T*), soil layer (*Sl*: 0–15 cm and 15–30 cm) and sampling date (*Year*: 2011, 2014 and 2018) as fixed effects. Normality and homoscedasticity were tested in advance. It was not appropriate to apply repeated measures ANOVA because the sampling points were not the same on all three dates.

$$y_{ijkl} = \mu + T_i + Sl_j + Y_k + (T \times Sl)_{ij} + (T \times Y)_{ik} + (Sl \times Y)_{jk} + (T \times Sl \times Y)_{ijk} + \varepsilon_{ijkl}$$

A two-way ANOVA was performed to determine the physical-chemical properties of biomass and litterfall, the taxon (*T*), and the biomass fraction (BF), or the year (Y), being the fixed effects.

$$y_{ijk} = \mu + T_i + Y_j \text{ (or } BF_j) + \varepsilon_{ijk}$$

Data transformation was not necessary. Significant differences were established at $p \leq 0.05$. Tukey's honestly significant difference (HSD) test was used to differentiate within homogeneous groups.

3. Results

3.1. Growth and Biomass Partitioning

Significant differences in height (*H*), stem diameter (*D*) and biomass yield (Figures 1 and 2), both among taxa ($p \leq 0.001$) and years ($p \leq 0.001$), were obtained but not among experimental units or for the main effect interactions ($p \geq 0.075$). The plant height at the end of each rotation cycle averaged 10–12 m for *Eucalyptus* and *Populus*, 9–11 m for *Paulownia* and 8–9 m for *Casuarina*. At the end of the first rotation, the diameter of the single main stem averaged between 6.9 cm for *Populus* × *interamericana* 'Raspalje' and 14.6 cm for *Eucalyptus* × *trabutii* (Figure 2, Table S6), while in the second rotation, the new sprouts grown from the stump gave rise to 2.5–3.3 main stems on average, according to the taxon, whose mean diameters varied from 4.9 to 10.4 cm (Table S6). The largest plants at the end of the rotations exceed 40, 30 and 20 kg of total aboveground dry mass for *Eucalyptus*, *Casuarina* and *Populus*, and *Paulownia*, respectively. For the set of taxa studied, the four eucalyptus taxa stood out for their biomass production. At the same time, among the remainders, *Casuarina equisetifolia* and poplar clones 'Adige' and 'AF2' differed from the least productive (Figure 1). It should be noted that the biomass production during the first year after planting was consistently lower than that of the other years of the first and second rotations.

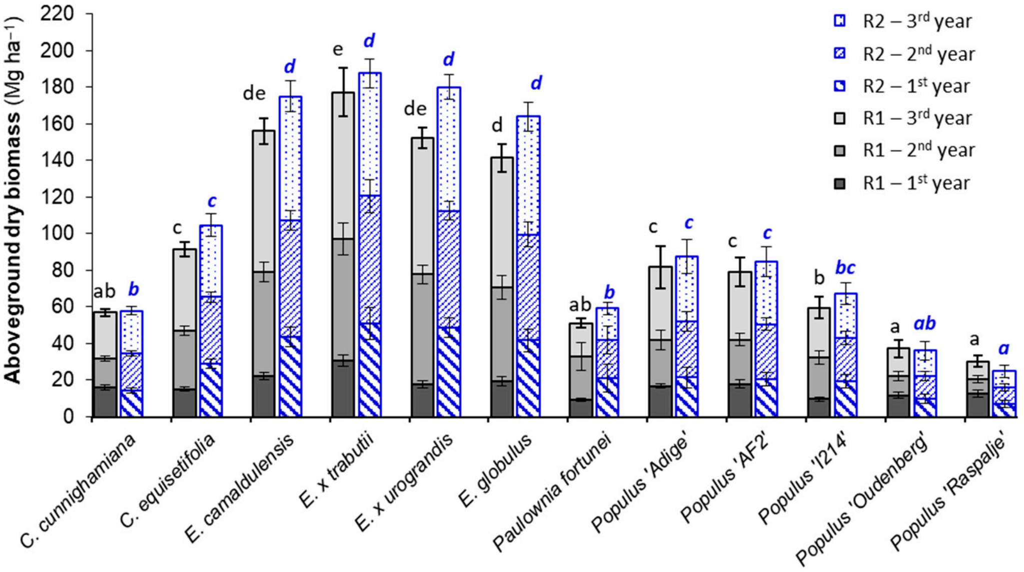

Figure 1. Mean annual yield (±SE) of aboveground dry biomass at the end of each year of the 1st (R1) and 2nd (R2) rotation. Different letters mean significant differences between taxa of accumulated dry biomass at the end of each rotation ($p \leq 0.001$).

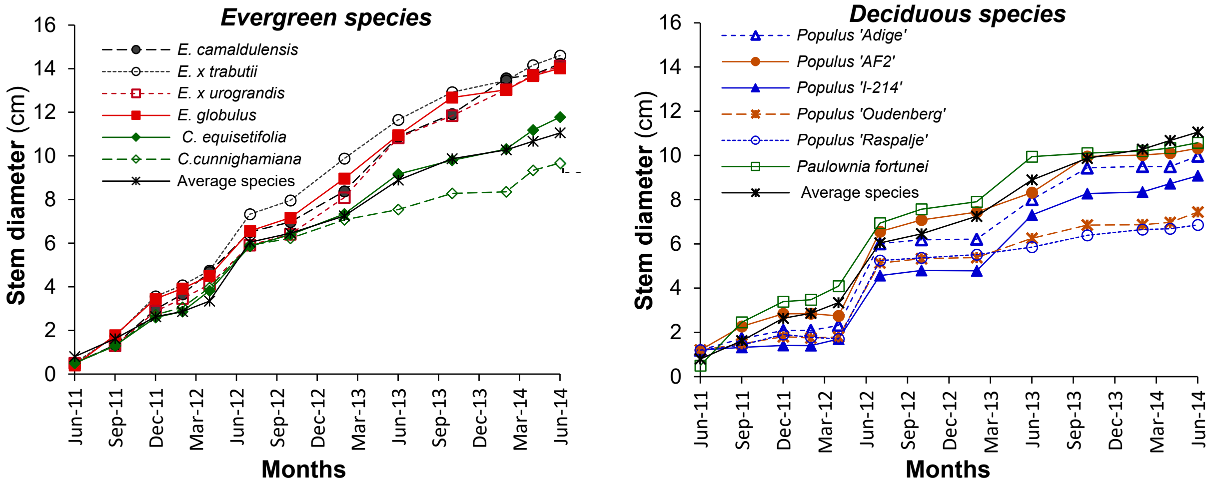

Figure 2. Mean stem basal diameters for all taxa throughout the 1st rotation (2011–2014). They have been plotted in two different graphs to clarify the figure. Different letters at 36 months indicate significant differences between taxa for all 12 taxa of the two graphs as a whole ($p \leq 0.001$). Likewise, the error bars have not been represented to make the graphs clear.

Regarding the distribution of the different fractions of biomass in the plants (Figure 3), we can highlight that overall, the proportion of the largest diameter class ($d > 100$ mm) was lower in the second harvest (end of the second rotation); at the time of the first harvest (1st rotation) the fraction of leaves amounted to 11% for *Paulownia*, 14% for *Populus*, 16% for *Eucalyptus* and 25% for *Casuarina*, while in the second harvest, they were respectively 12%, 15%, 23% and 34%; similarly, the fraction of leaves + thin branches ($d < 50$ mm) in the first rotation amounted to 42, 55, 40 and 55% for *Paulownia*, *Populus*, *Eucalyptus*, and *Casuarina*, respectively, and 41, 62, 57 and 66%, respectively, in the second rotation. The proportion of wood and bark in the stems and branches varied depending on their diameter (Table 4), always resulting in less than 15% when the stems or branches exceeded 75 cm in diameter.

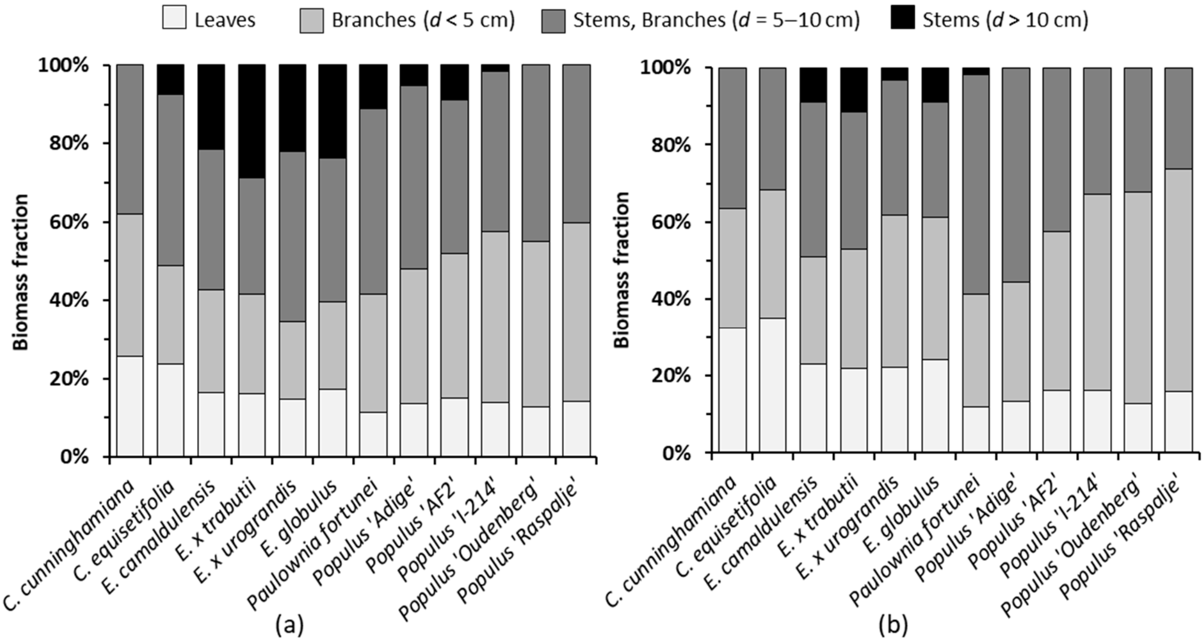

Figure 3. Distribution of the different biomass fractions as a percentage of the total aboveground dry biomass at the end of the 1st (**a**) and the 2nd (**b**) rotation. The stems and branches grouped into three diameter classes are shown to better clarify the graphs.

Table 4. Stems and branches bark proportion (mean (SE)) for each taxon and diametric class on a dry mass basis. Sample size = 3–4 slices per taxon and diametric class. Different letters within a column mean significant differences among taxa ($p \leq 0.05$), but in the last row, differences among diametric classes are shown ($p \leq 0.001$).

Taxon	**Diametric Class (% Bark)**				
	***d* < 25 mm**	***d* = 25–50 mm**	***d* = 50–75 mm**	***d* = 75–100 mm**	***d* > 100 mm**
Casuarina cunninghamiana	30.0 (2.3) bc	21.4 (1.9) b	19.9 (1.6) b	14.3 (1.3) ab	12.5 (1.2) b
Casuarina equisetifolia	32.3 (3.9) bc	19.1 (3.4) ab	17.3 (3.1) b	13.2 (2.6) ab	12.3 (1.7) ab
Eucalyptus camaldulensis	25.5 (2.5) ab	17.3 (1.7) ab	16.2 (1.3) ab	14.3 (1.5) ab	12.1 (1.4) ab
Eucalyptus × *trabutii*	31.3 (3.8) bc	17.2 (1.9) ab	16.9 (1.4) ab	15.2 (1.3) b	12.2 (1.3) ab
Eucalyptus × *urograndis*	24.7 (1.7) a	18.4 (2.0) ab	19.3 (2.3) b	13.8 (1.8) ab	8.6 (1.6) ab
Eucalyptus globulus	24.0 (1.8) a	19.3 (1.9) ab	16.1 (1.2) ab	15.4 (1.3) b	12.7 (1.2) b
Paulownia fortunei	23.1 (2.0) a	16.8 (2.6) ab	13.4 (1.1) ab	10.3 (1.4) a	7.7 (1.5) a
Populus 'Adige'	33.1 (1.5) c	17.4 (1.8) ab	13.6 (1.6) ab	10.9 (1.4) a	10.6 (1.3) ab
Populus 'AF2'	33.4 (2.3) c	18.3 (2.3) ab	15.3 (1.8) ab	10.2 (1.5) a	10.1 (1.5) ab
Populus 'I-214'	26.0 (4.6) ab	19.0 (1.5) ab	13.1 (1.6) ab	12.7 (1.3) ab	10.5 (1.3) ab
Populus 'Oudenberg'	33.9 (3.3) c	16.3 (1.4) a	11.2 (1.5) a	11.5 (1.2) ab	10.6 (1.2) ab
Populus 'Raspalje'	31.4 (2.7) bc	16.6 (1.7) ab	14.6 (2.3) ab	11.5 (1.7) ab	10.5 (1.6) ab
Total	29.2 (1.1) *d*	18.1 (0.9) *c*	15.6 (0.8) *bc*	12.8 (0.8) *ab*	11.0 (0.9) *a*

Except for the three least productive taxa of this trial (*Populus* × *interamericana* 'Raspalje,' *Populus* × *euramericana* 'Oudenberg' and *Casuarina cunninghamiana*), at the end of the second rotation, the biomass yield increased between 5.8% and 18.4% compared to that obtained at the end of the first rotation. Thus, despite the significantly smaller diameter of stems in the second rotation than in the first, the higher number of stems compensated for biomass production. Considering the two harvests (first and second rotations together), the mean annual increment in aboveground dry biomass averaged 19–33 Mg ha^{-1} year^{-1} for *Casuarina* sp., 51–61 Mg ha^{-1} year^{-1} for *Eucalyptus* clones, 18 Mg ha^{-1} year^{-1} for *Paulownia fortunei*, and 9–28 Mg ha^{-1} year^{-1} for hybrid clones of *Populus*.

The litterfall accumulated on the ground surface at harvest time averaged 6.92 (0.36) Mg ha^{-1} of dry matter, without significant differences among taxa (p = 0.333).

3.2. Physical–Chemical Characterization of Plant and Soil Material

Most of the properties of the two uppermost layers of the soil (0–15 and 15–30 cm) did not differ significantly from the beginning (1st year) to the end (8th year) of the trial ($0.051 < p < 0.770$), although the general trend resulted in a decrease in mineral nutrient content and an increase in organic matter and C/N ratio (Table 1 and Tables S1). The only exceptions were the significant decreases in pH (p = 0.001), N (p = 0.014), P ($p < 0.001$) and Mg ($p < 0.001$). In a quick guesstimate for one of the reference nutrients such as N, which initially (1st year) started with an average of 0.17% (0–15 cm) and 0.14% (15–30 cm), and decreased to 0.15% and 0.11%, respectively, seven years later (8th year), we can deduce the following:

- Taking into account the stoniness (18%) and bulk density (1.56 kg dm^{-3}) of the soil, the amount of total N per hectare in the 0–30 cm layer at the beginning of the trial averaged: $(0.0017 + 0.0014\ \mathrm{kg_{of\ N}/kg_{of\ soil}}) \times (0.15\ \mathrm{m} \times 10\,000\ \mathrm{m^2}) \times (1.0 - 0.18) \times 1.56 = 5948$ kg of N;
- The amount of total N per hectare in the 0–30 cm soil layer seven years later (8th year) averaged: $(0.0015 + 0.0011\ \mathrm{kg_{of\ N}/kg_{of\ soil}}) \times (0.15\ \mathrm{m} \times 10\,000\ \mathrm{m^2}) \times (1.0 - 0.18) \times 1.56 = 4989$ kg of N;
- Therefore, after seven years of cultivation, the N content of the soil decreased by an average of $5948 - 4989 = 959$ kg of N. That is, 137 kg ha^{-1} year^{-1} of N, but in a range from 27.4 kg ha^{-1} year^{-1} (*Casuarina equisetifolia*) to 274.1 kg ha^{-1} year^{-1} (*E.* × *trabutii*).

Many of the soil fertility parameters (organic matter and mineral nutrient contents) were higher in the upper layer of the soil (0–15 cm) than in the lower one (15–30 cm). Still, the evolution during the 8 years analyzed did not differ significantly (i.e., the interaction *Year* × *Soil layer* was not significant, $p \geq 0.300$). Likewise, no significant differences were obtained in soil properties due to the cultivation of the different taxa during the first two rotations ($p \geq 0.150$). In this case, only the two taxa that presented the most extreme values of soil N content in the 8th year were differentiated: *Casuarina equisetifolia* (0.15% for the soil layer 0–30 cm altogether) differed from *E.* × *trabutii* (0.11%), p = 0.043.

The mineral composition of the litter sampled at the end of the rotation did not differ among taxa (p = 0.280), the contents being (mean (SE)): 1.15 (0.10), 0.13 (0.02), 0.21 (0.02), 1.41 (0.06), 0.32 (0.02), 0.03 (0.01), 0.14 (0.01), 46.3 (1.1), 5.69 (0.31)% of N, P, K, Ca, Mg, S, Cl, C and H, respectively; and 316.9 (28.6), 63.3 (4.7), 154.3 (14.8) and 5.8 (0.6) mg kg^{-1} of Fe, Mn, Zn and B, respectively.

Regarding the chemical composition of the harvested biomass and the energetic and physical-mechanical properties of the manufactured pellets, the following can be noted:

- No significant differences among experimental units or between the two replicates of the test were found, so global mean values as a whole are shown;
- The mineral composition of the different biomass fractions differed significantly ($0.001 \leq p \leq 0.016$), with the only exception being the H content (p = 0.492). The leaves and bark presented the highest ash and mineral percentages. On the opposite side was the thick wood, with a tendency to higher values if the bark was preserved, but without differing significantly from the debarked one (Table 5), possibly due to the low percentage of bark in this fraction (11.0%–15.6% on average).

Table 5. Mineral composition (mean (SE)) and ash content of each biomass fraction, expressed on a dry mass basis, for all the taxa and trials as a whole. Different letters within a row mean significant differences among biomass fractions ($p \leq 0.016$). Significance level for H: $p = 0.492$.

Variable	**Biomass Fraction**				
	Wood with Bark	**Debarked Wood**	**Bark**	**Thin Branches**	**Leaves**
C (%)	48.1 (0.3) ab	49.9 (0.5) a	48.2 (0.4) ab	47.3 (0.4) b	47.1 (0.4) b
H (%)	6.81 (0.27) a	6.32 (0.39) a	6.02 (0.35) a	7.02 (0.34) a	6.79 (0.34) a
N (%)	0.38 (0.04) a	0.35 (0.06) a	1.48 (0.06) c	0.66 (0.57) b	1.69 (0.05) d
P (%)	0.06 (0.01) a	0.03 (0.01) a	0.11 (0.01) b	0.10 (0.01) b	0.15 (0.01) c
K (%)	0.35 (0.04) a	0.22 (0.03) a	0.51 (0.04) b	0.54 (0.04) b	0.92 (0.05) c
Ca (%)	0.47 (0.07) a	0.35 (0.10) a	1.31 (0.10) b	1.16 (0.09) b	2.34 (0.10) c
Mg (%)	0.14 (0.01) a	0.13 (0.02) a	0.18 (0.02) a	0.14 (0.02) a	0.30 (0.02) b
S (%)	0.03 (0.02) a	0.02 (0.02) a	0.07 (0.03) a	0.06 (0.03) a	0.21 (0.03) b
Cl (%)	0.08 (0.03) a	0.05 (0.04) a	0.26 (0.04) b	0.04 (0.04) a	0.31 (0.04) b
Fe (mg kg^{-1})	50.4 (5.2) a	56.6 (6.8) a	80.2 (6.8) ab	103.9 (6.3) b	531.4 (7.5) c
Mn (mg kg^{-1})	30.9 (3.1) ab	27.6 (4.12) a	75.2 (4.1) c	35.7 (3.8) ab	45.6 (4.5) b
Zn (mg kg^{-1})	33.5 (4.1) ab	23.6 (5.4) a	58.3 (5.4) c	47.9 (4.9) bc	99.6 (5.9) d
B (mg kg^{-1})	8.3 (1.0) a	8.9 (1.3) a	16.6 (1.3) b	13.1 (10.4) ab	49.7 (1.4) c
Ash (%)	1.52 (0.05) b	1.07 (0.06) a	6.59 (0.06) d	2.65 (0.06) c	5.28 (0.08) e

Wood: main stems and thick branches with $d \geq 5$ cm; Thin branches: $d < 5$ cm.

- The differences among taxa were not significant for most of the mineral elements analyzed ($0.058 \leq p \leq 0.921$), except for N ($p < 0.001$), Fe ($p < 0.001$) and C ($p = 0.017$). The *Taxon* × *Biomass fraction* interaction was not significant in any case ($0.130 \leq p \leq 0.996$). Table 6 shows the physical-mechanical and chemical properties of the wood (main stems and thick branches) for the different taxa. *Paulownia fortunei* wood stood out for its low percentage of minerals and ash but had the lowest wood density of all the taxa studied. However, *Casuarina* sp., *Eucalyptus camaldulensis* and *Eucalyptus* × *trabutii*, on the one hand, had the handicap of high mineral concentrations but, on the other hand, they had a high-density wood;
- As a rough estimate, during the studied period, and for all the taxa and the two rotations as a whole, the following can be noted:
  - According to Figure 3, on average, the leaves, thin branches and thick wood represented 16.6, 36.3 and 47.1%, respectively, of the aboveground dry mass, which contained the N concentrations shown in Table 5. So, the average amount of N removed from the field plot with the harvested biomass was 227.6 kg ha^{-1} year^{-1} (from 63.6 kg ha^{-1} year^{-1} for *Populus* 'Raspalje' to 308.9 kg ha^{-1} year^{-1} for *Eucalyptus* × *trabutii*), of which an average of 40.1% (91.3 kg ha^{-1} year^{-1}) corresponded to leaves;
  - The litterfall contained an average of 11.4 kg ha^{-1} year^{-1} of N;
  - The amount of N supplied by the fertilizer was 75 kg ha^{-1} year^{-1}, which must be added to 18.5 kg ha^{-1} year^{-1} supplied by irrigation water (400 mm annually on average);
  - The removed 227.6 kg ha^{-1} year^{-1} of N from the biomass is quite close to the N supplied by fertilization and irrigation water (93.5 kg ha^{-1} year^{-1}); plus, the N removed from the soil litterfall set (137–11.4 = 125.6 kg ha^{-1} year^{-1}); which amounts to 219.1 kg ha^{-1} year^{-1} of N on average;
  - Other inputs and outputs of N have not been considered in this rough approximation (leaching, emission of N oxides, N supplied by rainwater, rock decomposition, other deeper layers of soil, etc.).

Table 6. Physical, mechanical, chemical and energetic properties (mean (SE)) of the studied taxa, expressed on a dry mass basis, for aboveground woody biomass ($d \geq 5$ cm with bark). Those taxa that did not differ for any parameter measured have been grouped in a single column in order to reduce the table size and clarify it. Different letters within a row mean significant differences among taxa ($p \leq 0.017$).

	Populus **'Adige' 'AF2'**	***Populus*** **'I-214', 'Oudenberg' 'Raspalje'**	***Casuarina*** **sp.**	***Paulownia fortunei***	***Eucalyptus globulus***	***Eucalyptus*** **×** ***urograndis***	***Eucalyptus camaldulensis E.*** **×** ***trabutii***
C (%)	48.7 (0.6) ab	49.5 (0.7) b	48.9 (0.5) ab	49.2 (0.5) b	48.0 (0.6) ab	48.4 (0.5) ab	47.7 (0.7) a
N (%)	0.47 (0.05) bc	0.34 (0.06) ab	0.52 (0.05) c	0.30 (0.04) a	0.31 (0.05) a	0.25 (0.05) a	0.27 (0.06) a
S (%)	0.04 (0.01)	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)	0.02 (0.01)	0.03 (0.01)	0.04 (0.01)
Cl (%)	0.04 (0.01)	0.04 (0.01)	0.10 (0.02)	0.03 (0.01)	0.10 (0.02)	0.10 (0.02)	0.10 (0.02)
Fe (mg kg^{-1})	57.0 (8.0) b	44.5 (9.2) ab	61.9 (10.2) ab	23.1 (9.7) a	52.0 (15.1) b	55.7 (14.4) b	64.9 (13.6) b
Ash (%)	1.20 (0.07) b	1.00 (0.07) b	2.15 (0.10) c	0.76 (0.06) a	1.30 (0.12) b	1.17 (0.11) b	2.23 (0.13) c
HHV (MJ kg^{-1})	19.1 (0.3)	19.3 (0.2)	19.2 (0.3)	19.5 (0.3)	19.2 (0.3)	19.5 (0.4)	18.9 (0.3)
LHV (MJ kg^{-1})	17.8 (0.3)	18.0 (0.2)	17.8 (0.3)	18.1 (0.3)	17.7 (0.3)	18.0 (0.3)	17.8 (0.4)
Bd$_p$ (kg m^{-3}) (1)	659 (14)	667 (14)	674 (15)	632 (11)	648 (10)	690 (12)	682 (10)
MD$_p$ (%) (1)	97.6 (1.2)	97.5 (0.9)	96.8 (1.0)	97.7 (0.8)	97.0 (0.8)	96.6 (1.2)	96.5 (1.1)
Moisture$_p$ (%) (1)	6.4 (0.4)	6.7 (0.5)	6.3 (0.6)	6.1 (0.4)	6.8 (0.4)	6.9 (0.5)	6.6 (0.6)
LHV$_p$ (MJ kg^{-1}) (2)	16.5 (0.3)	16.6 (0.3)	16.5 (0.2)	16.9 (0.3)	16.5 (0.3)	16.6 (0.3)	16.5 (0.2)
Wd (kg dm^{-3})	0.42 (0.05) b	0.36 (0.02) b	0.65 (0.03) d	0.27 (0.03) a	0.54 (0.04) c	0.55 (0.03) c	0.61 (0.03) cd
LHV$_v$ (MJ dm^{-3})	7.5 (0.2) b	6.5 (0.1) b	11.6 (0.2) d	4.9 (0.1) a	9.6 (0.2) c	9.9 (0.2) c	10.8 (0.3) cd

Casuarina sp., *C. equisetifolia* and *C. cunninghamiana* are included. HHV (higher heating value) and LHV (lower heating value) on a dry mass basis. Bd$_p$—bulk density of pellets. MD$_p$—mechanical durability of pellets. Moisture$_p$—pellets moisture. Wd—wood density. LHV$_v$—lower heating value of the dry biomass on a volume basis ($p = 0.037$). Significance level (p-values) for thick woody biomass of the taxon effect: C, $p = 0.017$; N, $p < 0.001$; S, $p = 0.921$; Cl, $p = 0.098$; Fe, $p < 0.001$; Ash, $p < 0.001$; Wd, $p < 0.001$. (1) Assessed according to ISO 17225-2:2021. (2) On a wet basis (with the moisture content after manufacturing). Without significant differences among taxa ($p \geq 0.251$), the manufactured pellets had a diameter of 6.01 (0.02) mm, a length of 21.5 (4.6) mm, and an ash melting temperature of ≥ 1230 °C.

4. Discussion

The rate of diameter growth was highest in spring for all taxa due to the coincidence of favorable temperatures with well-water availability [73]. However, autumn and winter growth rates varied according to species, with significant growth recorded for the evergreens (*Eucalyptus* and *Casuarina*) and considerably less or almost zero growth in the case of the deciduous trees such as *Populus* and *Paulownia*. So, as a general rule, the evergreens, *Eucalyptus* and *Casuarina* were observed to increase their diameter throughout the year [16,29]. By contrast, the deciduous trees, *Populus* and *Paulownia*, achieved close to zero growth during the cold season [17,29] as they began to slow down metabolic activity, bud set and leaf fall. This means that, in climate areas with mild winters, evergreen species can take advantage of deciduous ones, taking advantage of sunny days with favorable temperatures for their growth. Similarly, high summer temperatures decreased growth due to their effect on net photosynthesis rates and transpiration [73], which was not as high as in spring, despite having irrigation water.

In terms of genera, the highest diameter growth rates were achieved by *Eucalyptus*, such that the four taxa in this genus exceeded 14 cm in diameter at the end of the first rotation period (3rd year after planting), but with no significant differences among them [74,75]. However, between the two *Casuarina* species, *Casuarina equisetifolia* stood out above *Casuarina cunninghamiana*. These growths were somewhat greater than those obtained by other authors with different *Casuarina* species in other soil and climate conditions than in the present study [28,76]. In the case of *Populus* clones, the good growth response of 'Adige' and 'AF2' over other clones has been shown in other studies [17,26,54,77].

In general, the lowest annual yields in biomass corresponded to the first year after planting. This may be due to the post-transplant effect, whereby plants do not achieve their maximum growth rates until they have reached a certain root system size. For this reason, the first year after the felling, the growth was vigorous since it started from an already installed root system [16,17]. The maximum mean annual biomass at the end of the rotation period was recorded by the *Eucalyptus* genus (51–61 Mg ha^{-1} year^{-1} of aboveground dry biomass). Behind the four *Eucalyptus* taxa, *Casuarina equisetifolia* stood out by producing up to 33 Mg ha^{-1} year^{-1} of dry biomass. These high yields could be due in part to the fact that both genera are evergreen, and thus they can maintain continuous growth throughout practically the whole year, where mild winters allow, as is the case in the study area. In addition, this leads us to conclude that the use of *Casurina equisetifolia* in short-rotation forest plantations for energy production could be appropriate in areas such as that in the current study, especially those with degraded soils. Despite smaller yields than other species (such as *Eucalyptus*), the ability of *Casuarina* sp. to fix atmospheric nitrogen [78,79] makes them highly suitable for cultivation in such kinds of soils without resorting to excessive fertilization and, at the same time, contributing to their restoration [19,28,29,80] and to energy saving [16,17,30]. In this study, it was estimated that up to 173 kg ha^{-1} year^{-1} of N have been fixed by *Casuarina equisetifolia*, taking into account the N contained in its harvested biomass (282.5 kg ha^{-1} year^{-1}), the supplied by fertilization and irrigation (93.5 kg ha^{-1} year^{-1}) and the removal from the whole soil litterfall (16 kg ha^{-1} year^{-1}). In the case of the *Populus* clones, 'Adige' and 'AF2' stood out by giving biomass yields (about 28 Mg ha^{-1} year^{-1}) not dissimilar to *Casuarina equisetifolia*. The biomass yield of *Paulownia fortunei*, such as *Populus*, a deciduous species, was low (18 Mg ha^{-1} year^{-1}), despite having achieved a growth of *D* and *H* similar to the more productive *Populus* clones ('Adige' and 'AF2') and *Casuarina equisetifolia*. This poor performance of *Paulownia fortunei* can be accounted for by the low density of the wood (0.27 kg m^{-3}), which restricts the conversion of volume into dry weight. The low density is a factor that should be taken into account when this species is considered for energy use since it could substantially increase transport and storage costs [80] if it is not densified into pellets. For example, its LHV on a dry mass basis (18.1 MJ kg^{-1}) is in the same range as that of the other taxa studied (17.7–18.0 MJ kg^{-1}), whereas if it is expressed on a volume basis (4.9 MJ dm^{-3}), it differs significantly from all other taxa (6.5–11.6 MJ dm^{-3}). In terms of energy, the LHV of the harvested woody biomass (excluding leaves) was equivalent to 725–867 GJ ha^{-1} year^{-1} (or 201–241 MWh ha^{-1} year^{-1}) for *Eucalyptus*, 238–413 GJ ha^{-1} year^{-1} (or 66–115 MWh ha^{-1} year^{-1}) for *Casuarina*, 288 GJ ha^{-1} year^{-1} (80 MWh ha^{-1} year^{-1}) for *Paulownia* and 137–428 GJ ha^{-1} year^{-1} (38–119 MWh ha^{-1} year^{-1}) for *Populus*.

The obtained biomass yields, surprisingly high for *Eucalyptus*, are in the highest range reported for these plant genera when grown under favorable conditions [16,17,22,24–26,28,52,53,81–84]. This is most likely due to the favorable climatic and edaphic conditions of the field plots, characterized by a Mediterranean climate with mild winters, good availability of nutrients and water, and well-drained fertile soil. It should be noted that in this study, data of the total aboveground dry biomass are mainly shown, which includes leaves, branches and the trunk with bark. In any case, even knowing the production potential of these taxa, caution must be exercised when extrapolating the data to an industrial plantation since the two field plots in this study were very homogeneous, small in area, and have not suffered mortality or damage by biotic or abiotic agents. However, commercial plantations usually extend over larger areas, making them more heterogeneous and more likely to suffer damage from unfavorable agents. There are multiple environmental and plantation management factors that affect growth and biomass production, such as availability of water and mineral nutrients, temperature and precipitation, soil physicochemical properties, plant material (genotype), crop density, etc. [21,26,27,29,52,63,84], making it difficult to compare studies and attribute differences to only one or a few factors. Comparing some results reported for the Iberian Peninsula and other areas under the Mediterranean climate with those of the present study, in plantations supplied with irrigation and fertilization, it can be observed that the annual biomass production is reduced by approximately 10%–55% in areas with lower annual mean temperature (7–14 °C) than that of this study (17 °C) [17,21,26,27,46,49,53,55,64,85]. However, for deciduous species such as those of the genus *Populus*, growth is more related to the maximum temperatures of the warm season than to the mean annual temperature, as well as to the rainfall regime and the dry summer period [52], since during the cold season they are in vegetative rest, without leaves. Suppose deficient management is added to the effect of temperature, which does not provide the plants with all the water (at least >500 mm of annual precipitation or availability of groundwater) or the necessary nutrients to achieve their maximum growth potential. In that case, the latter will be reduced proportionally to such an extent that yields can be below 5 Mg ha^{-1} $year^{-1}$ in some instances [22,24,29,52,54,56–59,84,85].

As a result of global warming caused by climate change, the Mediterranean region's temperature is expected to rise by 0.9–5.6 °C by the end of the 21st century [86]. This seems to favor higher latitudes or altitudes in terms of crop production. Likewise, it could expand the potential area of evergreen species. For example, allowing frost-sensitive species such as eucalyptuses to reach higher altitude sites. However, this increase in temperature is accompanied by a reduction in rainfall of 4%–22%, as well as an increase in extreme weather events, such as heat waves and prolonged droughts, which will negatively affect the plantations and increase dependence on irrigation to achieve high production. It is predicted that many areas from current oceanic or humid subtropical climates might change to a Mediterranean climate in the coming years, and areas from current Mediterranean climates to semi-arid climates [86]. A climate change scenario that implies an increase of 2 °C in temperature and a decrease of 30–40 mm in annual precipitation could mean an 18% reduction in the productivity of these crops [25]. For all these reasons, further research should be carried out on the selection and improvement of cultivated genotypes for their water use efficiency and drought resistance [17,26,52,59,73,87], as well as on improving cultivation techniques to make them more efficient. At the same time, we try to mitigate climate change through the use of renewable energy sources, such as biomass.

The high growth rates of some of the taxa studied gave rise to a trend, although not yet significant, of increasing organic matter and the C/N ratio in the upper layers of the soil, as well as in the litter layer, in increment ranges similar to other studies with fast-growing species [16,17,19,28]. This may be due to a large amount of litterfall every year, mainly leaves, which degrade rapidly in the shady and humid environment of this crop. As the period studied has been short, and the processes of soil evolution are usually slow, it is not surprising that significant differences have not yet been obtained with respect to the original state of the soil that previously supported a fast-growing legume species for 12 years. However, for some of the nutrients analyzed, such as N, P and Mg, significant decreases were detected with respect to the initial contents in the soil. This opposite trend between the increase in organic matter and the decrease in N possibly explains the increase in the C/N ratio. This means that, in this study, the natural loss of nutrients (leaching, denitrification) and the removal of nutrients with the harvested biomass was greater than that supplied by fertilization, and, therefore, the plants took them from the soil according to their growth needs. For example, on average, for all the taxa as a whole, in this study, the decrease in N of the whole soil litterfall was 125.7 kg ha^{-1} $year^{-1}$. Therefore, in order to reduce harvest-related nutrient exports, a more conservative approach involving the removal of only larger diameter stems and branches ($d > 2.5$ cm) might be recommended to retain more of the accumulated nutrient capital on-site [28]. Similarly, on average, if the leaves of the harvested plants had been left on the cultivation soil, this would only imply leaving 16.6% of the harvested dry biomass in the field but 40.1% of the nitrogen (91.3 kg ha^{-1} $year^{-1}$), reducing the fertilization costs and the environmental impact, since only 34.4 kg ha^{-1} $year^{-1}$ of N would have been removed from the soil ($125.7 - 91.3 = 34.4$). This does not apply to deciduous species since they do not have leaves at harvest time. Furthermore, if, in addition to the leaves, the other lower quality biomass fractions for energy use were also left in the cultivation land, that is, the thinnest branches ($d < 2.5$ cm) and the bark of thick branches and stems, the economic and energy impact would be reduced to a greater extent [16]. The high mineral nutrient and ash content of the bark and the high proportion of bark on the thinnest branches (23%–34%) support this recommendation [71,88,89]. Finally, considering the use of N-fixing species, as is the case with the genus *Casuarina* discussed above, alone or mixed with other more productive species would reduce nitrogen fertilization requirements [17,24,28].

Regarding the biomass quality for energy use, on the one hand, and according to the ISO 17225-4 standard [88], wood chips made from thick woody biomass are of good commercial quality, mainly for hybrid poplars, *Paulownia fortunei*, *Eucalyptus globulus* and *Eucalyptus* × *urograndis* (ash content < 1.5%), but also for *Casurina* sp., *Eucalyptus camaldulensis* and *Eucalyptus* × *trabutii* (ash content < 3.0%). On the other hand, adding the thinnest branches and leaves to the wood chips would decrease their commercial quality by increasing the ash content, and for the same reason, the debarking of the thick wood would improve it.

Furthermore, according to standard ISO 17225-2 [71], due to their physical–mechanical, energetic and chemical characteristics (N and S contents, heating values, bulk density, mechanical durability, ash content, moisture, etc.), the manufactured pellets corresponded to commercial quality categories EN*plus*®-A2 (*Paulownia fortunei*, hybrid clones of *Populus*) and EN*plus*®-B (*Eucalyptus globulus*, *Eucalyptus* × *urograndis*), all of them valid for residential use. However, due to the high ash content, *Casurina* sp., *Eucalyptus camaldulensis* and *Eucalyptus* × *trabutii* must be classified as industrial, commercial category I3. None of the manufactured pellets contained heavy metals or halogenated organic compounds, more than typical virgin material values or typical values of the site of origin. Chlorine content was slightly higher than usual for these species [89,90]. Still, it is mainly justified by the proximity to the coast of the field trial, not because it is an intrinsic property of these studied taxa. The resulting pellets possessed the characteristics of hardwood species and were of better quality than herbaceous species pellets. However, they did not reach the maximum standardized quality of pellets derived from conifer debarked wood [16,17,19,79,90–94]. All this is closely related to the chemical composition of the biomass, mainly the lignin and extractive contents. These are two factors that affect the bonding quality of the biomass particles during pelletization [95–98].

Finally, the most immediate use could be in large thermal boilers or cogeneration plants after transformation into chips, especially *Casuarina* sp., *Eucalyptus camaldulensis* and *Eucalyptus* × *trabutii* because they are evergreen species and because of the high density and ash content of the wood. However, to give added value to the biomass, for small or medium-sized thermal boilers, *Eucalyptus globulus*, *Eucalyptus* × *urograndis* and *Populus* wood chips are more recommended. On the other hand, in the case of *Paulownia fortunei*, due to its low density and ash content, its transformation into chips is less recommended, as it can be better valued by transforming it into pellets. In addition, for all the taxa studied, the transformation into pellets of the thick wood of branches and trunks (d > 5 cm) would endow them with added commercial value, thanks to the high biomass production of these species.

Under the Mediterranean climate, woody species have been cultivated for several decades, so agroforestry owners have experience with these crops, mainly in the case of poplars and eucalyptuses [26,27,87]. Traditionally these crops were used to obtain wood and paper pulp, but in the last decade also for biomass for energy use. The commercialization of the product is assured due to the presence of biomass thermoelectric plants. For example, in the region where this study was carried out (Andalusia, Spain), there are 17 power plants with a biomass electricity generation capacity of more than 270 MW, which demand more than 2.5 million tons of agroforestry biomass annually [99], so any place in the region is less than 100 km away from a biomass power plant. In the rest of Spain, another 15 plants with similar characteristics are currently in operation. Moreover, to obtain additional added value through the transformation into pellets, it is worth saying that the pellet market has been expanding in recent years. World pellet production in 2019 was estimated at 40.5 million tons, an increase of 125% compared to seven years ago [100,101]. The consumption of pellets in 2020 in the EU exceeded 19 million tons, an increase of 5% compared to the previous year [102]. Regarding Spain, about 100 pellet production factories, evenly distributed throughout the national territory, produce 1 million tons per year (666% more than 12 years ago), but with a production capacity of up to 2.5 million tons per year.

It would be interesting to analyze in the future if the wood of the studied taxa could be mixed with debarked pine wood to produce commercial pellets of the highest quality for residential use [101], as well as delve into the effect on the soil due to the cultivation process in order not to degrade it and continue advancing in genetic improvement programs that achieve highly productive taxa by increasing their energy properties and nutrients and water use efficiency.

5. Conclusions

- The biomass yield of short-rotation forest tree species (hybrid clones of *Populus* and *Eucalyptus*, monospecific clones of *Eucalyptus* and *Paulownia fortunei*, and *Casuarina* species) averaged 9–61 Mg ha^{-1} year^{-1} under a Mediterranean climate with mild winters, good availability of nutrients and water, and well-drained fertile soil;
- In terms of energy, the LHV of the woody biomass was equivalent to 38–241 MWh ha^{-1} year^{-1} (equivalent to the replacement of about 3400–22 000 L ha^{-1} year^{-1} of diesel);
- Plantation managers must take into account nutrient inputs and outputs in order to ensure the sustainability of the system and to prevent any loss in soil fertility and productivity;
- The biomass quality varied among the taxa studied, but they all have enough commercial quality to add value through their transformation into chips or pellets;
- It is recommended that the lowest quality biomass fractions for energy use (leaves and thinnest branches < 25 mm diameter) should not be removed from the cultivation land due to their contribution to the nutrient cycle;
- The use of N-fixing species, such as *Casuarina* sp., should be considered in future plantations, mainly in degraded soils.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14061156/s1, Figure S1: Experimental design used in the two replicates of the field trial. The two-number code (X.Y) refers to the taxon (X) and each of the experimental units of the taxa (Y). The edge lines are a single line of plants, separated 1 m from each other, using in each section the same taxon as that of the nearest experimental unit; Figure S2: (a) General view of one of the test plots 5 months after planting. (b) Leaf litter between planting lines under *Populus* × *euramericana* 'AF2'. The appearance of *Paulownia* (c), *Populus* × *euramericana* 'Adige' (d) and *Eucalyptus globulus* (e) 18 months after planting. Sprouts from the stump during the second rotation, two years after the felling of *Casuarina* (f), *Eucalyptus* × *urograndis* (g) and *Populus* × *euramericana* 'AF2' (h); Table S1: Physical–chemical properties of the upper soil layers at the beginning and the end of the study period for all taxa as a whole (mean (SE)). Asterisks (*) denote significant differences between the two measurement dates within a soil layer ($p < 0.05$). Analytical methods are shown in Table S2; Table S2: Standard technical methods and instruments used to assess the physical-chemical properties of plant material, soil and litterfall. Taken from [17]; Table S3: Climatic conditions at the field plot during the study period. Modified from [17]; Table S4: Regression models and statistics for the set of species studied; Table S5: Allometric equations $W = aD^bH^c$ and $W = aD^b$ for the different genera under the tested conditions of this study; Table S6: Average (±SE) of the main stems at the end of the first and the second rotation. *D*—stem diameter 10 cm above soil surface; Nst—number of main stems; BA—basal area. The three variables showed significant differences among taxa and between rotations, $p < 0.001$.

Author Contributions: Conceptualization, J.A., M.F., R.T. and F.R.; methodology, J.A., M.F., F.R. and F.L.; software, J.A. and D.R.; validation, J.A. and R.T.; formal analysis, J.A., M.F. and D.R.; investigation, D.R., M.F. and F.L.; resources, J.A., M.F. and F.R.; data curation, J.A. and R.T.; writing—original draft preparation, J.A. and M.F.; writing—review and editing, J.A., M.F. and R.T.; visualization, J.A., M.F. and D.R.; supervision, R.T. and M.F.; project administration, J.A., M.F. and F.L.; funding acquisition, J.A., M.F. and F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Autonomous Community of Andalusia (C01-121 and RNM-6398), and the Economy and Competitiveness Ministry of Spain (ref. CTQ2013-46804-C2-1-R and CTQ2017-85251-C2-2-R), by FEDER funds of the EU, and by the company ENCE, Energía y Celulosa S.A. (8%, 6%, 6%, 70%, 10%, respectively).

Data Availability Statement: Not applicable.

Acknowledgments: The authors want to thank Biopoplar Ibérica S.L. for the provision of some plant taxa.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. United Nations. In Proceedings of the Conference of the Parties on Its Twenty-First Session, Paris, France, 30 November–13 December 2015; Available online: http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf (accessed on 19 February 2023).
2. European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Use of Energy from Renewable Sources. Available online: https://eur-lex.europa.eu/eli/dir/2018/2001/oj (accessed on 15 January 2023).
3. European Commission. Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions Energy Roadmap 2050/* COM/2011/0885 final */. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52011DC0885 (accessed on 15 January 2023).
4. Picchio, R.; Latterini, F.; Venanzi, R.; Stefanoni, W.; Suardi, A.; Tocci, D.; Pari, L. Pellet Production from Woody and Non-Woody Feedstocks: A Review on Biomass Quality Evaluation. *Energies* **2020**, *13*, 2937. [CrossRef]
5. REN21, Renewables. Global Status Report, Renewable Energy Policy Network for the 21st Century, France. Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR2017_Full-Report_English.pdf (accessed on 20 February 2023).
6. Kummamuru, B. WBA Global Bioenergy Statistics. World Bioenergy Association. 2017, p. 80. Available online: http://worldbioenergy.org/uploads/WBA%20GBS%202017_hq.pdf (accessed on 15 January 2023).
7. IEA. World Energy Outlook International Energy Agency. Available online: https://iea.blob.core.windows.net/assets/4a50d774-5e8c-457e-bcc9513357f9b2fb/World_Energy_Outlook_2017.pdf (accessed on 15 January 2023).
8. Antczak, A.; Swierkosz, R.; Szeniawski, M.; Marchwicka, M.; Akus-Szylberg, F.; Przybysz, P.; Zawadzki, J. The comparison of acid and enzymatic hydrolysis of pulp obtained from poplar wood (*Populus* sp.) by the Kraft method. *Drewno* **2019**, *63*, 53–66. [CrossRef]
9. Titus, B.D.; Brown, K.; Helmisaari, H.-S.; Vanguelova, E.; Stupak, I.; Evans, A.; Clarke, N.; Guidi, C.; Bruckman, V.J.; Varnagiryte-Kabasinskiene, I.; et al. Sustainable forest biomass: A review of current residue harvesting guidelines. *Energy Sustain. Soc.* **2021**, *11*, 10. [CrossRef]
10. Małachowska, E.; Lipkiewicz, A.; Niemczyk, M.; Dubowik, M.; Boruszewski, P.; Przybysz, P. Influences of fiber and pulp properties on papermaking ability of cellulosic pulps produced from alternative fibrous raw materials. *J. Nat. Fibers* **2019**, *18*, 1751–1761. [CrossRef]
11. Christersson, L.; Verma, K. Short-rotation forestry—A complement to "conventional" forestry. *Unasylva* **2006**, *57*, 34–39. Available online: https://www.fao.org/3/A0532e/A0532e07.pdf (accessed on 27 January 2023).
12. BIC. Strategic innovation and research agenda (SIRA) Bio-based and renewable industries for development and growth in europe. In *A Public-Private Partnership on Bio-Based Industries*; Biobased Industries Consortium, Ed.; Biobased Industries Consortium: Brussels, Belgium, 2013; Available online: https://ec.europa.eu/research/participants/data/ref/h2020/other/legal_basis/jtis/bbi/bbi-sira_en.pdf (accessed on 20 January 2023).
13. Bogdanski, A.; Dubois, O.; Jamieson, C.; Krell, R. *Making Integrated Food-Energy Systems Work for People and Climate*; FAO: Rome, Italy, 2010; p. 116. Available online: http://www.fao.org/docrep/013/i2044e/i2044e.pdf (accessed on 27 January 2023).
14. Riffell, S.; Verschuyl, J.; Miller, D.; Wigley, T.B. Biofuel harvests, coarse woody debris, and biodiversity—A meta-analysis. *For. Ecol. Manag.* **2011**, *261*, 878–887. [CrossRef]
15. Bessaad, A.; Bilger, I.; Korboulewsky, N. Assessing Biomass Removal and Woody Debris in Whole-Tree Harvesting System: Are the Recommended Levels of Residues Ensured? *Forests* **2021**, *12*, 807. [CrossRef]
16. Fernández, M.; Alaejos, J.; Andivia, E.; Vázquez-Piqué, J.; Ruiz, F.; López, F.; Tapias, R. *Eucalyptus* x *urograndis* biomass production for energy purposes exposed to a Mediterranean climate under different irrigation and fertilisation regimes. *Biomass Bioenergy* **2018**, *111*, 22–30. [CrossRef]
17. Alesso, S.P.; Tapias, R.; Alaejos, J.; Fernández, M. Biomass Yield and Economic, Energy and Carbon Balances of *Ulmus pumila* L., *Robinia pseudoacacia* L. and *Populus* × *euroamericana* (Dode) Guinier Short-Rotation Coppices on Degraded Lands under Mediterranean Climate. *Forests* **2021**, *12*, 1337. [CrossRef]

18. FAO. Combating land degradation for food security and provision of soil ecosystem services in Europe and Central Asia—International year of soil Ed. FAO–Food and agriculture organization of United nations. In Proceedings of the 39th Session of the European Commission on Agriculture, Budapest, Hungary, 22–23 September 2015; Available online: http://www.fao.org/europe/commissions/eca/eca-39/en/ (accessed on 27 January 2023).
19. Fernández, M.; Alaejos, J.; Andivia, E.; Madejón, P.; Díaz, M.; Tapias, R. Short rotation coppice of leguminous tree *Leucaena* spp. improves soil fertility while producing high biomass yields in Mediterranean environment. *Ind. Crop. Prod.* **2020**, *157*, 112911. [CrossRef]
20. Aravanopoulos, F.A. Breeding of fast growing forest tree species for biomass production in Greece. *Biomass Bioenergy* **2010**, *34*, 1531–1537. [CrossRef]
21. Durán Zuazo, V.H.; Jiménez Bocanegra, J.A.; Perea Torres, F.; Rodríguez Pleguezuelo, C.R.; Francia Martínez, J.R. Biomass yield potential of *Paulownia* trees in a semi-arid Mediterranean environment (S Spain). *Int. J. Renew. Energy Res.* **2013**, *3*, 789–793. Available online: https://ijrer.org/ijrer/index.php/ijrer/article/view/844 (accessed on 20 January 2023).
22. Navarro, A.; Stellacci, A.M.; Campi, P.; Vitti, C.; Modugno, F.; Mastrorilli, M. Feasibility of SRC species for growing in mediterranean conditions. *Bioenerg. Res.* **2016**, *9*, 208–223. [CrossRef]
23. Bouvet, A.; Nguyen-The, N.; Melun, F. Nutrient concentration and allometric models for hybrid eucalyptus planted in France. *Ann. For. Sci.* **2013**, *70*, 251–260. [CrossRef]
24. Oliveira, N.; del Rio, M.; Forrester, D.; Rodríguez-Soalleiro, R.; Pérez-Cruzado, C.; Canellas, I.; Sixto, H. Mixed short rotation plantations of *Populus alba* and *Robinia pseudoacacia* for biomass yield. *For. Ecol. Manag.* **2018**, *410*, 48–55. [CrossRef]
25. Seserman, D.-M.; Pohle, I.; Veste, M.; Freese, D. Simulating Climate Change Impacts on Hybrid-Poplar and Black Locust Short Rotation Coppices. *Forests* **2018**, *9*, 419. [CrossRef]
26. Sixto, H.; Cañellas, I.; van Arendonk, J.; Ciria, P.; Camps, F.; Sánchez, M.; Sánchez-González, M. Growth potential of different species and genotypes for biomass production in short rotation in Mediterranean environments. *For. Ecol. Manag.* **2015**, *354*, 291–299. [CrossRef]
27. Oliveira, N.; Sixto, H.; Cañellas, I.; Rodríguez-Soalleiro, R.; Pérez-Cruzado, C. Productivity model and reference diagram for short rotation biomass crops of poplar grown in Mediterranean environments. *Biomass Bioenergy* **2015**, *72*, 309–320. [CrossRef]
28. Parrotta, J. Productivity, nutrient cycling, and succession in single-and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta*, and *Leucaena leucocephala* in Puerto Rico. *For. Ecol. Manag.* **1999**, *124*, 45–77. [CrossRef]
29. Madejón, P.; Alaejos, J.; García-Álbala, J.; Fernández, M.; Madejón, E. Three-year study of fast-growing trees in degraded soils amended with composts: Effects on soil fertility and productivity. *J. Environ. Manag.* **2016**, *169*, 18–26. [CrossRef]
30. Giuntoli, J.; Agostini, A.; Edwards, R.; Marelli, L. Solid and gaseous bioenergy pathways: Input values and GHG emissions. In *Calculated According to the Methodology Set in COM (2016) Version 2, EUR 27215 EN*; Publications Office of the European Union: Luxembourg, 2017. [CrossRef]
31. Vanguelova, E.; Pitman, R. Impacts of short rotation forestry on soil sustainability. In *Short Rotation Forestry: Review of Growth and Environmental Impacts, Forest Research Monograph, Forest Research*; McKay, H., Ed.; Forest Research Alice Holt Lodge: Farnham, Surrey, UK, 2011; p. 37. ISBN 978-0-85538-827-0.
32. Augusto, L.; Achat, D.L.; Bakker, M.R.; Bernier, F.; Bert, D.; Danjon, F.; Khlifa, R.; Meredieu, C.; Trichet, P. Biomass and nutrients in tree root systems-sustainable harvesting of an intensively managed *Pinus pinaster* (Ait.) planted forest. *GCB Bioenergy* **2014**, *7*, 231–243. [CrossRef]
33. Nunes, L.J.R.; Matias, J.C.O.; Catalão, J.P.S. Mixed biomass pellets for thermal energy production: A review of combustion models. *Appl. Energy* **2014**, *127*, 135–140. [CrossRef]
34. Carone, M.T.; Pantaleo, A.; Pellerano, A. Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of *Olea europaea* L. *Biomass and Bioenergy* **2011**, *35*, 402–410. [CrossRef]
35. Stelte, W.; Sanadi, A.R.; Shang, L.; Holm, J.K.; Ahrenfeldt, J.; Henriksen, U.B. Recent developments in biomass palletization—A review. *BioRes.* **2012**, *7*, 4451–4490. [CrossRef]
36. Nielsen, N.P.K.; Gardner, D.J.; Poulsen, T.; Felby, C. Importance of Temperature, Moisture Content, and Species for the Conversion Process of Wood Residues Into Fuel Pellets. *Wood Fiber Sci.* **2009**, *41*, 414–425. Available online: https://forestbioproducts.umaine.edu/wp-content/uploads/sites/202/2010/10/George-Marra-Award-Articlepdf_1273348264.pdf (accessed on 19 February 2023).
37. Bajwa, D.S.; Peterson, T.; Sharma, N.; Shojaeiarani, J.; Bajwa, S.G. A review of densified solid biomass for energy production. *Renew. Sustain. Energy Rev.* **2018**, *96*, 296–305. [CrossRef]
38. El-Juhany, L.I.; Aref, M.; El-Wakeel, A.O. Evaluation of above-ground biomass and stem volume of three *Casuarina* species grown in the central region of Saudi Arabia, Emir. *J. Food Agric.* **2002**, *14*, 8–13. [CrossRef]
39. Mason, P.; George, D. Biomass potential of tree species for biofuel production in Southeast Queensland. In Proceedings of the International Proceedings of Chemical, Biological and Environmental Engineering (IPCBEE) 2nd International Conference on Geological and Civil Engineering, Dubai, United Arab Emirates, 10–11 January 2015. [CrossRef]
40. Tumwebaze, S.B.; Bevilacqua, E.; Briggs, R.; Volk, T. Allometric biomass equations for tree species used in agroforestry systems in Uganda. *Agrofor. Syst.* **2013**, *87*, 781–795. [CrossRef]
41. Kuyah, S.; Dietz, J.; Muthuri, C.; van Noordwijk, M.; Neufeldt, H. Allometry and partitioning of above- and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes. *Biomass Bioenergy* **2013**, *55*, 276–284. [CrossRef]

42. Hunter, I. Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertiliser, at 3 years of age, in southern India. *For. Ecol. Manag.* **2001**, *144*, 189–199. [CrossRef]
43. Ounban, W.; Puangchit, L.; Diloksumpun, S. Development of general biomass allometric equations for *Tectona grandis* Linn.f. and *Eucalyptus camaldulensis* Dehnh. plantations in Thailand. *Agric. Nat. Resour.* **2016**, *50*, 48–53. [CrossRef]
44. Ferrari, G.; Scaramuzzi, G. Influenza della distanza d'impianto sulla densiti del legno in *Eucalyptus globulus* ed *E.* x *trabutti*. *Cellul. E Carta* **1982**, *33*, 44–52.
45. Palanti, S.; Susco, D.; Feci, E. Natural durability of eucalypt from Italian plantations against fungi and cerambicid *Trichoferus holosericeus* Rossi. *Eur. J. Wood Prod.* **2010**, *68*, 59–62. [CrossRef]
46. Giulietti, V.; Roncucci, N.; Nassi o Di Nasso, N.; Tozzini, C.; Ragaglini, C.; Guidi, W.; Taccini, F.; Bonari, E. Suitability of Eucalyptus short rotation coppice in the Mediterranean environment: Preliminary results. *Asp. Appl. Biol.* **2011**, *111*, 279–283.
47. Viera, M.; Bonacina, D.M.; Schumacher, M.V.; Calil, F.N.; Caldeira, M.V.W.; Watzlawick, L.F. Biomass and nutrients in *Eucalyptus urograndis* stands in southeastern Mountain Range-RS. *Ciências Agrárias* **2012**, *33*, 2481–2490. [CrossRef]
48. Santos, F.M.; Balieiro, F.C.; Ataide, D.H.; Diniz, A.R.; Chaer, G.M. Dynamics of aboveground biomass accumulation in monospecific and mixed-species plantations of *Eucalyptus* and *Acacia* on a Brazilian sandy soil. *For. Ecol. Manag.* **2013**, *363*, 86–97. [CrossRef]
49. Pérez-Cruzado, C.; Merino, A.; Rodríguez-Soalleiro, R. A management tool for estimating bioenergy production and carbon sequestration *in Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. *Biomass Bioenergy* **2011**, *35*, 2839–2851. [CrossRef]
50. Muthuri, C.W.; Ong, C.K.; Black, C.R.; Ngumi, V.W.; Mati, B.M. Tree and crop productivity in *Grevillea*, *Alnus* and *Paulownia*-based agroforestry systems in semi-arid Kenya. *For. Ecol. Manag.* **2005**, *212*, 23–39. [CrossRef]
51. Cañellas, I.; Huelin, P.; Hernández, M.J.; Ciria, P.; Calvo, R.; Gea-Izquierdo, G.; Sixto, H. The effect of density on short rotation *Populus* sp. plantations in the Mediterranean area. *Biomass Bioenergy* **2012**, *46*, 645–652. [CrossRef]
52. Pérez-Cruzado, C.; Sanchez-Ron, D.; Rodríguez-Soalleiro, R.; Hernández, M.J.; Sánchez-Martín, M.; Cañellas, I.; Sixto, H. Biomass production assessment from *Populus* spp. short-rotation irrigated crops in Spain. *GCB Bioenergy* **2014**, *6*, 312–326. [CrossRef]
53. Paris, P.; Mareschi, L.; Sabatti, M.; Pisanelli, A.; Ecosse, A.; Nardin, F.; Scarascia-Mugnozza, G. Comparing hybrid *Populus* clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. *Biomass Bioenergy* **2011**, *35*, 1524–1532. [CrossRef]
54. Pannacci, E.; Bartolini, S.; Covarelli, G. Evaluation of four poplar clones in a short rotation forestry in central Italy. *Ital. J. Agron.* **2009**, *4*, 191–198. [CrossRef]
55. Sabatti, M.; Fabbrini, F.; Harfouche, A.; Beritognolo, I.; Mareschi, L.; Carlini, M.; Paris, P.; Scarascia-Mugnozza, G. Evaluation of biomass production potential and heating value of hybrid poplar genotypes in a short-rotation culture in Italy. *Ind. Crops Prod.* **2014**, *61*, 62–73. [CrossRef]
56. Verlinden, M.; Broeckx, L.; Bulcke, J.V.D.; Van Acker, J.; Ceulemans, R. Comparative study of biomass determinants of 12 poplar (*Populus*) genotypes in a high-density short-rotation culture. *For. Ecol. Manag.* **2013**, *307*, 101–111. [CrossRef]
57. Dillen, S.; Djomo, S.; Al Afas, N.; Vanbeveren, S.; Ceulemans, R.J. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. *Biomass Bioenergy* **2013**, *56*, 157–165. [CrossRef]
58. Laureysens, I.; Bogaert, J.; Blust, R.; Ceulemans, R. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. *For. Ecol. Manag.* **2004**, *187*, 295–309. [CrossRef]
59. Kauter, D.; Lewandowski, I.; Claupein, W. Quantity and quality of harvestable biomass from *Populus* short rotation coppice for solid fuel use—A review of the physiological basis and management influences. *Biomass Bioenergy* **2003**, *24*, 411–427. [CrossRef]
60. He, X.H.; Critchley, C. Frankia Nodulation, Mycorrhization and Interactions Between *Frankia* and Mycorrhizal Fungi in *Casuarina* Plants. In *Mycorrhiza*; Varma, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 767–781. [CrossRef]
61. Resquin, F.; Navarro-Cerrillo, R.M.; Carrasco-Letelier, L.; Rachid Casnati, C. Influence of contrasting stocking densities on the dynamics of above-ground biomass and wood density of *Eucalyptus benthamii*, *Eucalyptus dunnii*, and *Eucalyptus grandis* for bioenergy in Uruguay. *For. Ecol. Manag.* **2019**, *438*, 63–74. [CrossRef]
62. Eufrade-Junior, H.J.; Rebessi de Sousa, J.M.; Guerra, S.P.S. Efeito da adubação mineral e densidade de plantio nas características dendrométricas de plantações de eucalipto de rápido crescimento. *Ci. Fl. Santa Maria* **2021**, *31*, 350–366. [CrossRef]
63. Nardini, C.; Schwerz, F.; Dourado Neto, D.; Eloy, E.; Elli, E.F.; Sgarbossa, J.; Tibolla, L.B.; Schmidt, D.; Caron, B.O. Biomass and radiation use efficiency in *Eucalyptus* plantations as affected by spacing of planting. *Sci. For.* **2020**, *48*, e3413. [CrossRef]
64. Ramalho, F.M.G.; Pimenta, E.M.; Goulart, C.P.; De Almeida, M.N.F.; Vidaurre, G.B.; Hein, P.R.G. Effect of stand density on longitudinal variation of wood and bark growth in fast-growing *Eucalyptus* plantations. *iForest* **2019**, *12*, 527–532. [CrossRef]
65. Chan, N.; Takeda, S.; Suzuki, R.; Yamamoto, S. Establishment of allometric models and estimation of biomass recovery of swidden cultivation fallows in mixed deciduous forests of the Bago Mountains, Myanmar. *For. Ecol. Manage.* **2013**, *304*, 427–436. [CrossRef]
66. Fehrmann, L.; Kleinn, C. General considerations about the use of allometric equations for biomass estimation on the example of *Norway spruce* in central Europe. *For. Ecol. Manag.* **2006**, *236*, 412–421. [CrossRef]
67. Henry, M.; Picard, N.; Trotta, C.; Manlay, R.J.; Valentini, R.; Bernoux, M.; Saint-André, L. Estimating tree biomass of sub-Saharan African forests: A review of available allometric equations. *Silva Fenn.* **2011**, *45*, 477–569. [CrossRef]

68. Magar, L.B.; Khadka, S.; Joshi, J.R.R.; Pokharel, U.; Rana, N.; Thapa, P.; Sharma, K.R.S.R.; Khadka, U.; Marasini, B.P.; Parajuli, N. Total Biomass Carbon Sequestration Ability Under the Changing Climatic Condition by *Paulownia tomentosa*. Steud. *Int. J. Appl. Sci. Biotechnol.* **2018**, *6*, 220–226. [CrossRef]
69. Fatemi, F.R.; Yanai, R.D.; Hamburg, S.P.; Vadeboncoeur, M.A.; Arthur, M.A.; Briggs, R.D.; Levine, C.R. Allometric equations for young northern hardwoods: The importance of age-specific equations for estimating aboveground biomass. *Can. J. For. Res.* **2011**, *41*, 881–891. [CrossRef]
70. Senelwa, K.; Sims, R.E.H. Tree biomass equations for short rotation eucalypts grown in New Zealand. *Biomass Bioenergy* **1997**, *13*, 133–140. [CrossRef]
71. UNE-EN ISO 17225-2. Solid biofuels-Fuel Specifications and Classes-Part 2: Graded Wood Pellets (ISO 17225-2:2021). ISO: Geneva, Switzerland, 2021. Available online: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma/?c=N0067970 (accessed on 15 January 2023).
72. McFarquhar, M. Modeling Group-level repeated measurements of neuroimaging data using the univariate general linear model. *Front. Neurosci.* **2019**, *13*, 352. [CrossRef]
73. Whitehead, D.; Beadle, C.L. Physiological regulation of productivity and water use in *Eucalyptus*: A review. *For. Ecol. Manag.* **2004**, *193*, 113–140. [CrossRef]
74. Guo, L.B.; Sims, R.E.H.; Horne, D.J. Biomass production and nutrient cycling in *Eucalyptus* short rotation energy forests in New Zealand. I: Biomass and nutrient accumulation. *Bioresour. Technol.* **2002**, *85*, 273–283. [CrossRef]
75. Sims, R.E.H.; Senelwa, K.; Maiava, T.; Bullock, B.T. *Eucalyptus* species for biomass energy in New Zealand. Part II: Coppice performance. *Biomass Bioenergy* **1999**, *17*, 333–343. [CrossRef]
76. Goel, V.L.; Behl, H.M. Growth and productivity assessment of *Casuarina glauca* Sieb. ex. Spreng on sodic soil sites. *Bioresour. Technol.* **2005**, *96*, 1399–1404. [CrossRef] [PubMed]
77. Benetka, V.; Bartakova, I.; Mottl, J. Productivity of *Populus nigra* L. ssp. *nigra* under short-rotation culture in marginal areas. *Biomass Bioenergy* **2002**, *23*, 327–336. [CrossRef]
78. Karthikeyan, A.; Chandrasekaran, K.; Geetha, M.; Kalaiselvi, R. Growth response of *Casuarina equisetifolia* Forst. rooted stem cuttings to *Frankia* in nursery and field conditions. *J. Biosci.* **2013**, *38*, 741–747. [CrossRef] [PubMed]
79. Gauthier, D.; Diem, H.G.; Dommerges, Y.R.; Ganry, F. Assessment of N fixation by *Casuarina equisetifolia* inoculated with *Frankia* ORS021001 using ^{15}N methods. *Soil Bid. Biochem.* **1985**, *17*, 375–379. [CrossRef]
80. Fernández, M.; García-Albalá, J.; Andivia, E.; Alaejos, J.; Tapias, R.; Menéndez, J.; Martín, R.T. Sickle bush (*Dichrostachys cinerea* L.) field performance and physical–chemical property assessment for energy purposes. *Biomass Bioenergy* **2015**, *81*, 483–489. [CrossRef]
81. Coble, A.P.; Autio, A.; Cavaleri, M.A.; Binkley, D.; Ryan, M.G. Converging patterns of vertical variability in leaf morphology and nitrogen across seven *Eucalyptus plantations* in Brazil and Hawaii, USA. *Trees* **2014**, *28*, 1–15. [CrossRef]
82. Pérez, C.; Frangi, J.; Goya, J.; Luy, A.; Arturi, M. Contenido de nutrientes en las raíces finas y el mantillo de rodales de *Eucalyptus grandis* de diferente edad en la Mesopotamia Argentina. *Bosque* **2013**, *34*, 303–310. [CrossRef]
83. Stolarski, M.J.; Krzyżaniak, M.; Szczukowski, S.; Tworkowski, J.; Bieniek, A. Dendromass derived from agricultural land as energy feedstock. *Pol. J. Environ. Stud.* **2013**, *22*, 511–520.
84. Berdón, J.B.; Calvo, A.J.M.; Barroso, L.R.; Alcobendas, A.I.P.; Cortés, J.G. Study of *Paulownia*'s Biomass Production in Mérida (Badajoz), Southwestern Spain. *Environ. Ecol. Res.* **2017**, *5*, 521–527. [CrossRef]
85. Carmona, R.; Nuñez, T.; Alonso, M.F. Biomass yield and quality of an energy dedicated crop of poplar (*Populus* spp.) clones in the Mediterranean zone of Chile. *Biomass Bioenergy* **2015**, *74*, 96–102. [CrossRef]
86. Ali, E.; Cramer, W.; Carnicer, J.; Georgopoulou, E.; Hilmi, N.J.M.; Le Cozannet, G.; Lionello, P. Cross-Chapter Paper 4: Mediterranean Region. In *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 2233–2272. [CrossRef]
87. Carignato, A.; Vázuez-Piqué, J.; Tapias, R.; Ruiz, F.; Fernández, M. Variability and Plasticity in Cuticular Transpiration and Leaf Permeability Allow Differentiation of *Eucalyptus* Clones at an Early Age. *Forests* **2020**, *11*, 9. [CrossRef]
88. UNE-EN ISO 17225-4:2021. Solid biofuels—Fuel specifications and classes—Part 4: Graded wood chips (ISO 17225-4:2021). ISO: Geneva, Switzerland, 2021. Available online: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0067999 (accessed on 10 March 2023).
89. Morhart, C.; Sheppard, J.; Spiecker, H. Above Ground Leafless Woody Biomass and Nutrient Content within Different Compartments of a *P. maximowicii* × *P. trichocarpa* Poplar Clone. *Forests* **2013**, *4*, 471–487. [CrossRef]
90. Stolarski, M.J.; Stachowicz, P.; Dudziec, P. Wood pellet quality depending on dendromass species. *Renew. Energy* **2022**, *199*, 498–508. [CrossRef]
91. Nunes, L.; Rodrigues, A.; Loureiro, L.; Sá, L.; Matias, J. Energy Recovery from Invasive Species: Creation of Value Chains to Promote Control and Eradication. *Recycling* **2021**, *6*, 21. [CrossRef]
92. Vasiliki, K.; Ioannis, B. Utilization perspectives of wood and bark of the invasive species of *Ailanthus* and *Acacia* in the production of pellets. In Proceedings of the International Forestry and Environment Symposium, Trabzon, Turkey, 7–10 November 2017; Available online: http://users.auth.gr/jbarb/Publications/IFES2017-209_Utilization.pdf (accessed on 10 March 2023).

93. Kumar, R.; Pandey, K.K.; Chandrashekar, N.; Mohan, S. Study of age and height wise variability on calorific value and other fuel properties of *Eucalyptus* hybrid, *Acacia auriculaeformis* and *Casuarina equisetifolia*. *Biomass Bioenergy* **2011**, *35*, 1339–1344. [CrossRef]
94. Telmo, C.; Lousada, J. Heating values of wood pellets from different species. *Biomass Bioenergy* **2011**, *35*, 2634–2639. [CrossRef]
95. Telmo, C.; Lousada, J. The explained variation by lignin and extractive contents on higher heating value of wood. *Biomass Bioenergy* **2011**, *35*, 1663–1667. [CrossRef]
96. Holm, J.K.; Henriksen, U.B.; Hustad, J.E.; Sørensen, L.H. Toward an Understanding of Controlling Parameters in Softwood and Hardwood Pellets Production. *Energy Fuels* **2006**, *20*, 2686–2694. [CrossRef]
97. Stelte, W.; Holm, J.K.; Sanadi, A.R.; Barsberg, S.; Ahrenfeldt, J.; Henriksen, U.B. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. *Biomass Bioenergy* **2011**, *35*, 910–918. [CrossRef]
98. Jenkins, B.M.; Baxter, L.L.; Miles, T.R., Jr.; Miles, T.R. Combustion properties of biomass. *Fuel Process. Technol.* **1998**, *54*, 17–46. [CrossRef]
99. Agencia Andaluza de la energía. La bioenergía en Andalucía. 2020. Available online: https://www.agenciaandaluzadelaenergia.es/sites/default/files/Documentos/3_2_0068_20_LA_BIOENERGIA_EN_ANDALUCIA.PDF (accessed on 2 May 2023).
100. World Bioenergy Association. Global Bioenergy Statistics 2021. Available online: https://www.worldbioenergy.org/uploads/211214%20WBA%20GBS%202021.pdf (accessed on 2 May 2023).
101. Fernández, M.; Tapias, R.; Camacho, V.; Alaejos, J. Quality of the Pellets Obtained with Wood and Cutting Residues of Stone Pine (*Pinus pinea* L.). *Forests* **2023**, *14*, 1011. [CrossRef]
102. Bioenergy Europe. Policy Brief: Pellets. Bioenergy Europe Statistical Report 2021. Available online: https://bioenergyeurope.org/article/328-pellets.html (accessed on 2 May 2023).