# Production and composition of biomass from short rotation coppice in marginal land: a 9-year study

M. J. Fernández*, R. Barro, J. Pérez, P. Ciria

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT)

CEDER-CIEMAT (Energy Department, Biomass Unit), Autovía A-15, sal. 56 - 42290 Lubia, SORIA (Spain)

*Corresponding author, Tel: +34 975 281013, Fax: +34 975 281056, E-mail: miguel.fernandez@ciemat.es

## ABSTRACT:

The production and chemical composition of the biomass of four fast growing woody crops are studied across species and rotation cycles. High-density plantations of poplar, willow, black locust and sycamore were monitored for 9 years over 3-year rotation cycles in marginal land in the Mediterranean area. The fuel quality properties of the produced biomass was assessed using proximate and ultimate analysis, biomass and ash chemical composition (23 elements), and ash melting behaviour.

Willow, poplar and black locust energy crops produced 12, 9 and 7 dry Mg $ha^{-1}$ $yr^{-1}$ on average, indicating that these species can be well adapted to the unfavourable conditions of poor soils in low productivity areas in the Mediterranean region. In contrast, sycamore was not well adapted to the particular climate and soil conditions and provided very poor yields. The chemical composition of the biomass varied across species and rotation cycles. The results obtained from the chemical analysis of these woody species showed that they provided good quality for use in combustion processes, with low amounts of trace elements and chlorine (≈ 0.01 wt%), sulphur (≈ 0.04 wt%) and nitrogen (≈ 0.5 wt%), with the exception of black locust (N= 0.86 wt%). No sintering problems are expected during the combustion of the studied biomass. This study provides valuable information for the large-scale implementation of fast growing woody species dedicated to energy crops in low productivity areas of the Mediterranean region.

Keywords: biomass, yield, woody species, quality, chemical analysis, combustion.

# 1 INTRODUCTION

The new EU Renewable Energy Directive (RED II) 2018/2001/EC [1] stipulates that 32% of member states´ total energy consumption should come from renewable sources by 2030, increasing by 12% the target previously set in RED I (2009/28/EC) for 2020 [2]. In that global scenario, where a balance between food provision, energy production and environmental sustainability is needed, the use of marginal lands to grow energy crops has very recently become a topic of interest for research [3]. Even though the concept of "marginal land" can vary depending on the context [4], this term can be used to refer to low quality agricultural areas that are unsuitable for producing food due to low productivity caused by poor soils and/or unfavourable climates [5-6]. A previous study estimated that a total area of 63.7 Mha in Europe is marginal land suitable for the production of bioenergy resources, which represents less than 30% of overall marginal land in Europe [7]. In Spain, a previous study identified about 2 Mha of arable marginal lands where traditional food crops are not economically sustainable and could have bioenergy potential [8]. Most of them are low productivity areas whose winter cereal grain production is below 1.5 Mg ha$^{-1}$ due to poor soils with an organic matter content below 2%.

Poplar and willow, among others, have been previously identified as potential energy crops for cultivation on marginal lands, as they are fast-growing species that can be adapted to the most unfavourable site conditions [3,9]. Poplar trees are quite abundant in the Iberian Peninsula, particularly in riverside plantations in temperate-cold or temperate climates from sea level up to 1500 m. Poplar is probably one of the most well-known and extensively used fast growing forest trees in short rotation intensive culture plantations dedicated to biomass production on an international basis. Species, clones and interspecific hybrids have been tested in multisite experiments all over the world [9]. Willows have a high potential for biomass production all over Europe. The willow is known to present favourable biological attributes in addition to having a higher tolerance than the poplar to a wide variety of climate and soil conditions, which is particularly important under the ensuing climatic change [10-11].

In contrast to poplar and willow, the experience in Europe with sycamore and black locust for dedicated energy crops is very limited. Their great adaptability to water limitations make them highly attractive options for biomass production under Mediterranean conditions, particularly considering the predicted rise in summer temperatures over the 21st century, as foreseen by the Intergovernmental Panel on Climate Change (IPCC) in all of the assessed emission scenarios [12]. Plane trees are being extensively used in the Mediterranean region for ornamental purposes in urban areas and are characterised by their high growth rate and high sprouting capacity [13]. Consequently, the potential of sycamore as a bioenergy feedstock has attracted interest in Spain and a prediction model has even been developed to estimate pruned biomass obtained from sycamore in urban parks and green areas [14]. However, using plane trees as a dedicated energy crop might have limited possibilities in the Mediterranean region, as preliminary studies suggest that sycamore in short rotation coppice (SRC) provide lower yields than other fast-growing forest trees under the same conditions [10,15]. On the other hand, black locust is another species that could also potentially be highly productive under Mediterranean climate conditions [16-18]. It is a nitrogen-fixing species that belongs to the Leguminosae family with a considerable resprouting capacity after cutting [19].

Biomass production aside, literature regarding the composition and quality of the produced biomass is scarce, particularly in the case of emergent energy crops such as sycamore and black locust. In this scenario, there was an urgent need to further investigate the potential of these crops by taking into consideration not only their potential yields in the long term but also their properties. Even though woody biomass exhibits lower amounts of ash, N, Cl and other troublesome elements than herbaceous biomass, it might not be exempted from causing corrosion and sintering problems in combustion processes or negative environmental impacts [20-21]. Lately, the quality requirements of woody biofuels regarding ash, N, Cl, S, trace elements and other properties have been established in the international standard ISO 17225 “Fuel Specifications and classes” for specific trade forms of solid biofuels such as pellets [22], briquettes [23], and wood chips [24]. Biomass from short rotation coppice, fast growing species characterised by high bark-to-wood ratios, could exceed the maximum values allowed in these quality requirements and that could limit their use in the residential sector and small-scale applications.

The objective of this work is to evaluate biomass production and the combustion properties of the biomass of four fast growing woody species (poplar, willow, black locust and sycamore) produced under short rotation conditions across three 3-year rotation cycles in marginal land under Mediterranean conditions. The results obtained can be of great interest for the commercial implementation of dedicated energy crops in the Mediterranean region, particularly for low productivity agricultural areas.

# 2 MATERIALS AND METHODS

## 2.1 Biomass

The following species and clones were used in this study: *Populus x euramericana* (`I-214´), *Salix matsudana x Salix* spp. (`Levante´), *Platanus hybrida* (`Girona´), and *Robinia pseudoacacia* (`Nyirsegi´). The poplar and willow clones studied have previously shown high adaptability to Mediterranean climates [25-27], even in low productivity semi-arid areas in the case of the I-214 poplar clone [28].

## 2.2 Climate

The plantation site was located at the Centre for the Development of Renewable Energy Sources (CEDER-CIEMAT) with coordinates 41° 36´ North, 2° 30´ West (Figure 1). This research centre is located in the province of Soria at an altitude of 1,099 m above sea level. According to the Köppen-Geiger classification, the climate in Soria is considered temperate with a dry season and temperate summer [29]. The climatic conditions are Mediterranean continental, with frost only between October and April and occasional snow (25 snow days per year). Summers have mean temperatures around 18 ºC and maximum temperatures well above 30 ºC (see Table 1). Even though historical annual rainfall averages are about 500 mm [30], it is important to note that rainfall in this region can vary largely from year to year. As can be seen in Table 1, rainfall was below 400 mm in 2009, which is a value more typical of arid regions, whereas 600 mm of rainfall was recorded in 2010, 2013 and 2014. It is important to note that irrigation was applied based on crop requirements and weather conditions, using studies of potential evaporation, water use efficiency and water stress. The procedures used were established in other research projects [31]. Plots were drip irrigated during the dry months (from May to September), i.e. poplar and willow with 395.0 mm and black locust and sycamore with 193.5 mm on average.

**Table 1**: Weather conditions measured (annual and global mean values) and at the experimental site.

### 2.4 Soil

Table 2 shows the soil characteristics at the experimental site before planting. The soil has a sandy texture with more than 80% as sand, 35% of gravels, low organic matter (≤0.6%), and also low contents of available P and K. It is a light and well-drained soil, with a very low retention capacity for water and nutrients, which could result in losses by leaching. For all these reasons, it can be considered a marginal, poor, low productive soil, which demands a fractionation of fertiliser applications to give time to the plant to absorb those nutrients and avoid losses by leaching.

**Table 2**: Soil characteristics at the experimental site.

## 2.5 Experimental design and agronomical practices

High-density plantations (10,000 trees per hectare, spaced 2.5 m × 0.4 m apart) of poplar, willow, black locust and sycamore were established with three replications in April 2009 (Figure 1).

**Figure 1**: Location and distribution of species and trees at the experimental plantation. Each black dot represents an individual tree.

Figure 1 also shows the distribution of species at the experimental location (left) and the distribution of trees per replicate subplot (right). Each replicate subplot consisted of 49 trees (black dots), resulting in square experimental units in which only the 9 central trees were monitored to avoid the border effect (Figure 1). Blank blocks in Figure 1 indicate plots belonging to other experimental trials. Manual planting was performed in all species. Cuttings were used for poplar and willow, and seedlings for black locust and sycamore.

Before planting, NPK fertilisation (8-15-15) was applied in April at 600 kg/ha at the experimental site. All plots, except for black locust, received additional fertilisation two months later with NPK (12-12-17) and microelements (0.1 wt% Fe; 0.02 wt% B and 0.01 wt% Zn) at 125 kg/ha, and with NPK (22-8-10) at 250 kg/ha in April 2011, 2013, and 2015. Deltamethryn 2.5 w/v-% was applied at the beginning of each vegetative period for beetle (*Melasoma populi*) control in poplar and willow plots.

## 2.6 Harvesting, sampling and analysis

To estimate biomass yields, 27 trees per species (9 trees per replication) were cut at the end of 2011, 2014 and 2017 (three different 3-year rotation cycles). The nine central trees of each replicate subplot were severed 10 cm above the ground at the end of each growth period (between December and January) and all of the aboveground biomass was used to determine biomass production. This biomass was also later used for analysis after sample preparation according to ISO 14780.

Once biomass weight was determined, the collected biomass (9 trees per replicate subplot) was completely chipped and milled, and representative samples were obtained after homogenisation, dividing, drying, and grinding, as indicated in the ISO 14780 standard. Physical and chemical tests were performed in the CEDER-CIEMAT Laboratory of Biomass Characterisation according to the international standards for solid biofuels, which are listed in Table 3. Dry matter yields were determined by taking into account the weight of all the aboveground biomass before and after being oven-dried at 105 ºC until constant weight.

**Table 3:** Standards and analytical methods of the properties measured in the woody SRC.

## 2.7 Ash melting behaviour

Ash fusibility was based on the changes in shape detected during the heating of a cylindrical ash pellet (ash produced at 550 ºC) from room temperature to 1450 ºC in an air atmosphere. An optical heating microscope measured the initial deformation, hemisphere and fluid temperatures, following CEN/TS 15370-1 [32].

The earth-alkaline to alkaline oxides ratio was used to predict the sintering behaviour of the studied fuels [33]. The performance of this index was evaluated elsewhere for different fuels, and it is calculated by using the following equation:

$\text{Rake/ak} = (\text{CaO} + \text{MgO}) / (\text{K}_2\text{O} + \text{Na}_2\text{O})$

In general, biomass with Rake/ak indices higher than 2 should not present any risk of sintering at combustion temperatures of about 800 ºC [33-34]. Below this value, the risk of sintering increases.

### 2.8 Statistical analysis

The statistical differences across species and rotation cycles on the production and the quality parameters of the produced biomass were evaluated by analyses of variance (ANOVA) using the Statgraphics Plus 5.0 software. Significant effects were revealed at $\alpha = 0.05$. Fisher´s least significant difference (LSD) at the 95.0% confidence level was used to evaluate the differences among mean results.

## 3 RESULTS AND DISCUSSION

### 3.1 Biomass yields

Biomass production is studied across species and rotation cycles (Figures 2). Willow provided the best yields (12 dry Mg $ha^{-1}$ $yr^{-1}$ as average), followed by poplar and black locust (8.9 and 6.8 dry Mg $ha^{-1}$ $yr^{-1}$, respectively). Therefore, it seems that these woody species can be adapted relatively well to the harsh and unfavourable edaphoclimatic characteristics of marginal lands in the Mediterranean area.

In contrast and even though the mortality of sycamore plants was zero, the biomass production of this species was extremely low, not even reaching 3 dry Mg $ha^{-1}$ $yr^{-1}$. Sycamore was not well adapted to the particular climate and soil conditions of the study site, and exhibited vegetative growing problems, probably in connection with the high altitude of the location (1099 m above sea level) and the significant temperature differences between day and night that characterised that area.

Biomass production decreased significantly in the third rotation cycle for all species (Figure 3), from 8-9 dry Mg $ha^{-1}$ $yr^{-1}$ on average during the first and second rotation cycles to 5 dry Mg $ha^{-1}$ $yr^{-1}$ in the third rotation cycle (Figure 2, right). The drop in biomass production in the third rotation cycle could be an indication of the end of the productive cycle of these species in arable marginal land, with willow production dropping over 50% between the first and the third rotations. By considering only the first and second rotation cycles, yields averaged 15.0, 10.1, and 7.7 dry Mg $ha^{-1}$ $yr^{-1}$ for willow, poplar and black locust, respectively [9].

**Figure 2:** Dried biomass yield (mean and LSD intervals) across species (left) and rotation cycles (right).

**Figure 3:** Dried biomass yield (Mg $ha^{-1}$ $yr^{-1}$) across species and rotation cycles.

Other studies under marginal conditions reported similar biomass yields for black locust in Germany (5.8 Mg $ha^{-1}$ $yr^{-1}$) [35], willow in North America, Northern Europe and Australia (5-11 Mg $ha^{-1}$ $yr^{-1}$) [3], and poplar in Germany (7.6 Mg $ha^{-1}$ $yr^{-1}$) [36] and USA (6-15.8 Mg $ha^{-1}$ $yr^{-1}$) [3]. Stolarski et al. [37] obtained lower yields for black locust (1.6-2.0 Mg $ha^{-1}$ $yr^{-1}$) and willow (5.1-9.1 Mg $ha^{-1}$ $yr^{-1}$) on poor soil in Poland after a 4-year rotation when no mineral fertilisers were applied, and similar yields were obtained for poplar (5.5-9.2 Mg $ha^{-1}$ $yr^{-1}$). Moreover, it is worth mentioning that productivity improved significantly when using soil amendments [16,35,37], which could be a viable option to increase the energy and economic value of short-rotation woody crops in low productive areas.

Aravanopoulos reviewed the existing literature regarding the breeding of fast-growing forest tree species dedicated to biomass production in Greece under a diverse range of local climate and soil conditions [10], finding higher production rates in poplar and willow than in sycamore. This indicates that sycamore might not perform as well as other fast-growing species in some Mediterranean areas, particularly on marginal land with a continental influence, such as the area tested in this study.

### 3.2 Biomass characteristics and quality

In this section, the physical and chemical characteristics of the biomass obtained from the different fast-growing tree species across 3 rotation cycles are presented, and their fuel characteristics are evaluated. In addition, the combustion quality of the pellets and wood chips that could be produced from this biomass are discussed and compared to the requirements of ISO 17225-2 [22] and ISO 17225-4 [24] that grade wood pellets and chips, respectively.

#### 3.2.1 Physical and chemical characteristics

Table 4 shows the results of the physical and chemical characterisation of poplar, black locust, willow and sycamore across rotation cycles. Moisture is generally high in SRC at harvest time. Mean moisture content for the trees studied in this work was around 40%, which indicates the need to introduce a drying step during the storage of the biomass, prior to its combustion or other thermochemical use.

Ash content is an important property from a quality perspective, as it causes emissions in the effluents of the thermal processes, as well as a reduction of the heat exchanged in a boiler due to the ash layer that adheres to the tubes of the heat exchangers. Regardless of the species considered, the produced biomass exhibited 2-3 % ash. According to ISO 17225-2 [22], if this biomass was used to produce wood pellets, they would be classified as class I3 (≤ 3% ash) for industrial use. The wood chips produced from this raw material could be classified as class B1 for commercial and residential applications (ISO 17225-4 [24]). The ash content of poplar, willow, black locust and sycamore is three to four times higher than pine sawdust, which is usually considered a high quality biofuel for the domestic sector.

Corrosion in heat-exchanger tubes is not expected to be an issue, as all the species considered showed a low chlorine content (<0.01-0.02 %) and fulfilled all the requirements found in the applicable quality standards.

S and N content in the fuel has been previously correlated with the formation of $SO_2$ and NOx emissions during combustion [39]. As the emission of $SO_2$ and NOx are the biggest cause of acid rain today, lower S and N contents in the fuel are desirable. Samples averaged 0.6 % N, within the range typically found for SRC biofuels [38]. The average S content in the produced biomass was relatively low (≤0.05 wt%), and much lower than that the sulphur present in fossil fuels such as gas-oil. Directive 1999/32/EC establishes a S limitation of 0.1 % for gas-oil for domestic applications.

**Table 4**: Proximate and ultimate analysis of the biomass across species and rotation cycles, and significance levels from ANOVA.

The significance levels for the two factors considered are also shown in Table 4. The chemical composition of the biomass varied significantly across species and rotation cycles

(Table 4, Figure 4). Black locust and poplar exhibited significantly higher calorific values (18.3-18.4 MJ/kg) than sycamore and willow (18.1-18.2 MJ/kg). Ash content also varied significantly across species, but mean values were maintained between 2.1% (black locust) and 2.6% (poplar).

Although significant from a statistical point of view, the differences detected among species and rotations for GCV, NCV, C, and H are very small and with no practical relevance (Table 4). As expected, GCV and C (figures not shown) followed the same trend as NCV. Net caloric values increased slightly from 18.2 MJ/kg in the first rotation cycles to 18.3 MJ/kg in the third rotation cycle. At the same time, ash also increased in the third rotation cycle (from 2.3 % up to 2.6%). Bark to wood ratio is expected to increase in SRC as crops age due to the proliferation of small branches and twigs. Bark typically has higher ash content than wood, and it is also known to possess energy-rich compounds such as lignin, resins, and oils, which cause calorific value to increase [28].

**Figure 4:** Net calorific value and ash content (mean and LSD intervals) across species (left) and rotation cycles (right).

It is important to highlight the elevated N content of black locust (Figure 5) in comparison with the other species considered, as black locust is a legume that fixes N from the atmosphere through its root nodules. Black locust averaged 0.86% N while mean contents for poplar, sycamore and willow were between 0.43-0.53% N. The N content of the biomass was not dependent on the rotation cycle. S content was low, and it varied between 0.03 and 0.05%. In general, it seems that poplar and willow presented lower S content (0.03%) than black locust and sycamore (0.05%). No clear trend was observed for this element with the rotation cycle.

**Figure 5:** Nitrogen and sulphur contents (mean and LSD intervals) depending on species (left) and rotation cycle (right).

Taking into account the normative parameters and chemical composition of the biomass of the studied energy crops and by comparison with the current limits set in ISO 17225-2 [22] and -4 [24] that grade wood pellets and chips, respectively, it could be said that the biomass from poplar, willow and sycamore plantations could be used as raw material to produce class B1 wood chips for domestic and residential applications or class I3 wood pellets for industrial applications (ash content ≤ 3.0%). However, the biomass from black locust energy crops is not within the specifications of the international standard that grades wood pellets for industrial applications, since it exceeds the N requirements (≤0.6%). This biomass could be used, in principle, to produce class B1 wood chips (ash content ≤ 3%).

The interactions between species and rotations were not significant in the following parameters: GCV, NCV, H, N and S (see Table 4). In contrast, ash did present interaction because the ash content in all species was equal for the first and second rotation cycles. The ash content was different among species in the third rotation cycle. It should be noted that ash content as well as carbon did generate interaction at the 95% confidence level but not at 99%.

### 3.2.2 Ash analysis, ash recycling and ash melting behaviour

The biomass ash of the species considered showed a similar chemical composition (Table 5), where calcium and potassium are the major ash-forming elements, with global averages of 0.66 wt% and 0.28 wt%, respectively, followed by phosphorous (0.072 wt%), magnesium

(0.064 wt%) and silicon (0.025 wt%). The rest of the elements were found at trace levels (<0.01 wt%).

**Table 5:** Chemical composition of the biomass across species and rotation cycles, and significance levels from ANOVA.

Similar to Table 4, the significance levels for the two factors considered are shown in Table 5. Ash chemical composition depended on the rotation cycle, although no clear pattern could be derived. However, and similar to what was observed in the case of the ash content, Ca (Figure 6), the main ash-forming element, was higher in the biomass coming from the third rotation cycle in comparison with the previous ones. As mentioned above, the elevated ash content levels detected in the biomass from the third rotation cycle were related to a higher bark to wood ratios. Calcium tends to be accumulated in the bark tissues in the form of oxalates and carbonates. K, Mg, and Si, which are also relevant elements from a quality perspective, did not vary with the rotation cycle (Table 5).

Regarding the ash chemical composition across species (Figure 6-left and 7), it could be said that mean levels of ash, Ca, K, Si, and Mg tend to be generally higher for poplar and lower for black locust, although not always attaining significance. Other authors also found significant differences between the chemical composition of poplar and willow groups [40-41].

**Figure 6:** Calcium content (mean and LSD intervals) depending on species (left) and rotation cycle (right).

**Figure 7:** K, Mg, Si, Mn, P, and Zn content (mean and LSD intervals) depending on species.

In contrast to the proximate and ultimate analyses, interactions in chemical composition between species and rotations were significant in most of the parameters: Ca, K, Si, Mg, P, Al, Mn, Ti and Zn (see Table 4). In general, and similarly to ash content, calcium, the main inorganic element in ash, generated interactions because its content was equal for the first and second rotation cycles in all species, but different among species in the third rotation cycle. Nevertheless, calcium did generate interaction at the 95% confidence level but not at 99%.

Trace elements were very low (Table 6) and always within the limits established for wood pellets and wood chips, in ISO 17225-2 [22] and ISO 17225-4 [24] standards, respectively. Biomass grown in uncontaminated soils is not expected to surpass the above-mentioned requirements. The experimental area is located in the province of Soria, a region characterised by a very low population density (<9 inhabitants per km2) due to the rural exodus in favour of the cities and industrialised areas. Therefore, this rural, unpopulated, and under-industrialised region, is not expected to be polluted with heavy metals as the ones that are being tested in this section.

**Table 6:** Trace elements of the biomass obtained from the short rotation woody crops during the third rotation cycle, and ISO 17225 requirements, parts 2 (woody pellets) and 4 (woody chips).

In order to study the possibility of recycling the ashes generated in the combustion of the studied SRC and reusing them as crop fertilisers, the maximum content of trace elements that could be present in the ashes collected in a combustion power plant was estimated by recalculating the content of trace elements from biomass to ash by means of the following equation: %ELEMENT ash = %ELEMENT biofuel / ASH CONTENT * 100

It is important to note that when using this method, the levels are over-estimated because it does not take into account the losses derived from the volatilisation of these elements that would occur during combustion, particularly for elements with a very high volatilisation potential such as Hg and Cd. The levels obtained (Table 7) are well below the limits established in the European Directive 86/278/EEC that regulates the heavy metals of sewage sludge intended for soil application on agricultural land within the European Union, and thus the ashes generated from the combustion of these short rotation crops could in principle be used as crop fertilisers in agriculture.

However, several European countries have introduced requirements that are more stringent than this directive. For example, the levels of some elements in the ashes obtained from the studied biomass could exceed the limits established in Dutch regulations [42], the most restrictive national legislation in Europe. Further research is needed regarding the agricultural use of the different fractions of biomass ashes, as they are known to greatly differ in their particle size and chemical composition. In this sense, there is also a need to adapt regulations to the specific soil and climate conditions of the different regions.

**Table 7:** Maximum levels of trace elements expected in the ash obtained after the combustion of the studied woody crops, and permissible limits of toxic elements for land application of sewage sludge. Units in mg/kg, dry basis

The ash fusibility test indicated (results not shown) that all the species considered presented a good ash melting behaviour, with deformation temperatures higher than 1450 ºC for most samples.

It is not possible to compare the deformation temperatures since they are greater than the maximum values the available instruments can measure (1450 ºC). To overcome this limitation, the relation between alkaline earth oxides and alkaline oxides (R) was used to predict the ash melting behaviour [33]. The alkaline-earth to alkali oxide ratio also suggested that all the studied species showed a similar ash sintering behaviour (Figure 8). This index improved during the third rotation cycle, in connection with the increase in Ca that was also noticed in the biomass produced during this cycle. In any case, this index was always maintained at levels higher than 2, and therefore the produced biomass is not expected to present any risk of sintering at normal boiler operating temperatures [33].

**Figure 8:** Alkaline-earth to alkali oxide ratio (mean and LSD intervals) across species (left) and rotation cycles (right).

## 4 CONCLUSIONS

The studied short rotation woody crops presented notably diverse results across species with regard to their biomass production and chemical composition, which could affect the combustion behaviour of the fuels produced from this biomass and their dedicated use.

Willow, poplar and black locust produced 12, 9 and 7 dry Mg ha$^{-1}$ yr$^{-1}$ on average over the three rotation cycles established over 9 years, indicating that these species can be well-adapted to the unfavourable conditions of poor soils in low productivity areas in the Mediterranean region. In contrast, sycamore trees was not well adapted to the particular climate and soil conditions and provided extremely low yields, not even reaching 3 dry t ha$^{-1}$ yr$^{-1}$ (9-year average), which suggests that the production of this biomass for dedicated energy crops might not be adequate for some Mediterranean areas, in particular marginal land with a continental influence.

Biomass production sharply decreased during the third rotation cycle, suggesting the end of its productive cycle. Biomass produced in the third rotation cycle showed higher ash, Ca and calorific values than those observed during the previous rotation cycles, which was connected to higher bark-to-wood ratios as a consequence of the proliferation of small branches and twigs. Although significant, these increases were not found to affect the combustion properties of this biomass to any remarkable extent.

Based on the ash chemical composition, the predictions of the alkaline earth to alkaline oxide ratio and the results obtained in the ash fusibility test, the biomass produced in the short rotation woody crops studied is not expected to pose sintering problems at normal combustion temperatures. Moreover, the low levels of heavy metals and other trace elements measured in the biomass produced suggest that, in principle, the ashes generated in the combustion of these woody short rotation crops could be applied to agricultural soils as crop fertilisers.

Results suggest that poplar and willow biomass from dedicated energy crops in marginal land in the Mediterranean region could be used to produce wood chips, class B1, for domestic and residential applications or wood pellets, class I3, for industrial applications. However, black locust biomass, a leguminous species with a high N-fixation capacity, would not be an appropriate raw material to produce industrial pellets because its N content could exceed the limits established in standard ISO 17225-2. However, the biomass produced from black locust energy crops could be used to produce wood chips, class B1.

This study highlights the importance of taking into account not only biomass production but also the chemical composition of the biomass produced from dedicated energy crops, as it can highly affect the combustion properties of the fuel and its future use. It provides long-term information about biomass production and the combustion properties of the biomass produced in marginal land, which could be highly valuable when choosing woody species to produce biomass from energy crops for combustion purposes in the low productivity areas of the Mediterranean region. A future study of how the application of different soil enrichment techniques affects long-term biomass production and combustion properties of biomass produced on poor soil could also be very useful to increase the energy and economic value of short rotation woody crops.

# 4 REFERENCES

[1] Directive 2018/2001/EC of 11 December 2018 on the promotion of the use of energy from renewable sources.

[2] Directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources.

[3] M.A. Mehmood, M. Ibrahim, U. Rashid, M. Nawaz, S. Ali, A. Hussain, M. Gull, Biomass production for bioenergy using marginal lands, Sustain Prod Consum 9 (2017) 3-21.

[4] G. Pulighe, G. Bonati, M. Colangeli, M.M. Morese, L. Traverso, F. Lupia, C. Khawaja, R. Janssen, F. Fava, Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean region, Renew Sust Energ Rev 103 (2019) 58-70.

[5] C.S. Ciria, M. Sanz, J. Carrasco, P. Ciria, Identification of arable marginal lands under rainfed conditions for bioenergy purposes in Spain. Sustainability 11 (2019) 1833-1849.

[6] R. Confalonieri, B. Jones, K. Van Diepen, J. Van Orshoven, Scientific contribution on combining biophysical criteria underpinning the delineation of agricultural areas affected by specific constraints, JRC Science and Policity Report, European Commission, 2014.

[7] S. Galatsidas, N. Gounaris, D. Vlachaki, E. Dimitriadis, F. Kiourtosis, D. Keramitzis, et al., Revealing bioenergy potentials: mapping marginal lands in Europe—The Seemla approach, in: Proceedings of the 26th European Biomass Conference and Exhibition, Copenhagen, 2018, pp. 31-37.

[8] C.S. Ciria, M. Sanz, J. Carrasco, P. Ciria, Identification of arable marginal lands under rainfed conditions for bioenergy purposes in Spain, Sustainability 11 (2019) 1833-1849.

[9] S. Njakou, A.A. Zenone, T. De Groote, S. Bergante, G. Facciotto, H. Sixto, P. Ciria, J. Weger, R. Ceulemans, Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU, Renew Sust Energ Rev 41 (2015) 845-854.

[10] F.A. Aravanopoulos, Breeding of fast growing forest tree species for biomass production in Greece, Biomass Bioenerg 34 (2010) 1531-1537.

[11] M. Castaño-Díaz, M. Barrio-Anta, E. Afif-Khouri, A. Cámara-Obregón, Willow short rotation coppice trial in a former mining area in northern Spain: effects of clone, fertilization and planting density on yield after five years, Forests 9 (2018) 154-171.

[12] IPCC Fifth Assessment Report (AR5), Climate Change 2014: Synthesis Report, Intergovernmental Panel on Climate Change (IPCC), United Nations, Available from, https://archive.ipcc.ch/ (last accessed: 06/06/2019).

[13] J.C. Domec, J. Boone, E. Ashley, M. Fischer, A. Noormets, J.C. Williamson, J. Boone, J.S. King, Productivity, biomass partitioning, and energy yield of low-input short-rotation American sycamore (*Platanus occidentalis* l.) grown on marginal land: effects of planting density and simulated drought, Bioenerg. Res. 10 (2017) 903–914.

[14] M. Sajdak, B. Velázquez-Martí, I. López-Cortés, A. Fernández-Sarría, J. Estornell, Prediction models for estimating pruned biomass obtained from Platanus hispanica Münchh. used for material surveys in urban forests, Renew Energ 66 (2014) 178-184.

[15] H. Sixto, I. Cañellas, J. van Arendonk, P. Ciria, F. Camps, M. Sánchez, M. Sánchez-González, Growth potential of different species and genotypes for biomass production in short rotation in Mediterranean environments, Forest Ecol Manag 354 (2015) 291-299.

[16] M. Manzone, S. Bergante, G. Facciotto, Energy and economic sustainability of woodchip production by black Locust (*Robinia pseudoacacia* L.) plantations in Italy, Fuel 140 (2015) 555-560.

[17] C. Carl, J.R.K. Lehmann, D.Landgraf, H. Pretzsch, *Robinia pseudoacacia* L. in short rotation coppice: seed and stump shoot reproduction as well as UAS-based spreading analysis. Forests 10 (2019) 235-257.

[18] K. Rédei, I. Csiha, Z. Keserü, Black locust (*Robinia pseudoacacia* L.) short-rotation crops under marginal site conditions, Acta Silv. Lign. Hung. 7 (2011) 125-132.

[19] J. Luken, A. Hinton, D. Baker, Assessment of frequent cutting as a plant-community management technique in power-line corridors, Environ Manage 15 (1991) 381-388.

[20] C. Yin, L.A. Rosendahl, S.K. Kær. Grate-firing of biomass for heat and power production, Prog Energ Combust 34 (2008) 725– 754.

[21] Y. Niu, H. Tan, S. Hui. Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures, Prog Energ Combust 52 (2016) 1–61.

[22] ISO 17225-2, Solid biofuels—Fuel Specification and Classes- Part 2: Graded wood pellets. International Organization for Standardization, 2014.

[23] ISO 17225-3, Solid biofuels—Fuel Specification and Classes- Part 3: Graded wood briquettes. International Organization for Standardization, 2014.

[24] ISO 17225-4, Solid biofuels—Fuel Specification and Classes- Part 4: Graded wood chips. International Organization for Standardization, 2014.

[25] D. Kauter, I. Lewandowski, W. Claupein, 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 Bioenerg 24 (2003) 411-427.

[26] P. Paris, L. Mareschi, M. Sabatti, A. Pisanelli, A. Ecosse, F. Nardin, G. Scarascia-Mugnozza, Comparing hybrid *Populus* clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield, Biomass Bioenerg 35 (2011) 1524-1532.

[27] L. Rosso, G. Facciotto, S. Bergante, L. Vietoo, G. Nervo, Selection and testing of Populus alba and Salix spp. as bioenergy feedstock: Preliminary results, Appl Energ 102 (2013) 87-92.

[28] M.J. Fernández, R. Barro, J. Pérez, J. Losada, P. Ciria, Influence of the agricultural management practices on the yield and quality of poplar biomass (a 9-year study), Biomass Bioenerg 93 (2016) 87-96.

[29] Iberian Climate Atlas. Air temperature and Precipitation (1971-2000), Agencia Estatal de Meteorología de España e Instituto de Meteorología de Portugal (Eds.), 2011.

[30] AEMET, State Meteorological Agency, Ministry for Ecological Transition, Spanish government. http://www.aemet.es/en/portada (last accessed: 05/06/2019).

[31] I. Pérez, Evaluation of *Ulmus pumila* L. and *Populus spp*. as energy crops in short rotation. Universidad Politécnica de Madrid (2016), PhD thesis [In Spanish].

[32] CEN/TS 15370-1, Solid Biofuels — Determination of ash melting behaviour – Part 1: Characteristic temperatures method. European Committee for Standarization, 2006.

[33] M.J. Fernández, J.E. Carrasco, Comparing methods for predicting the sintering of biomass ash in combustion, Fuel 84 (2005) 1893-900.

[34] M. Fernández, J. Carrasco, I. Mediavilla, R. Barro, T. Brunner, I. Obernberger, Holistic approach to predict the ash melting behaviour of European solid biofuels, in: Proceedings of the 27th European Biomass Conference and Exhibition, Lisbon, 2019, pp. 608-616.

[35] H. Gruenewald, B.K.V. Brandt, B.U. Schneider, O. Bens, G. Kendzia, R.F. Hüttl, Agroforesty systems for the production of woody biomass for energy transformation purposes, Ecol Eng 29 (2007) 319-328.

[36] J. Scheweier, G. Becker, Economics of poplar short rotation coppice plantations on marginal land in Germany, Biomass Bioenerg 59 (2013) 494-502.

[37] M.J. Stolarski, M. Krzyzaniak, S. Szczukowski, J. Tworkowski, D. Zaluski, A. Bieniek, J. Golaszewski, Effect of Increased Soil Fertility on the Yield and Energy Value of Short-Rotation Woody Crops, Bioenerg Res 8 (2015) 1136–1147.

[38] ISO 17225-1, Solid biofuels—Fuel Specification and Classes- Part 1: General requirements. International Organization for Standardization, 2014.

[39] I. Obernberger, T. Brunner, G. Bärnthaler, Chemical properties of solid biofuels—significance and impact, Biomass Bioenerg 30 (2006) 973-982.

[40] P.J. Tharakan, T.A. Volk, L.P. Abrahamson, E.H. White, Energy feedstock characteristics of willow and hybrid poplar clones at harvest age, Biomass Bioenerg 25 (2003) 571-580.

[41] N. Liu, S.U. Larsen, U. Jørgensen, D. Murach, C. Pflugmacher, H. Hartmann, P.E. Lærke, Combustion quality of poplar and willow clones grown as SRC at four sites in Brandenburg, Germany, Biomass Bioenerg 106 (2017) 51-62.

[42] H. Hudcová, J. Vymazal, M. Rozkošný, Present restrictions of sewage sludge application in agriculture within the European Union, Soil Water Res 14 (2019) 104–120.

## 5 ACKNOWLEDGEMENTS

This research is the result of projects RTA2008-00025-C02-01 and RTA2011-00006-00-00, which were funded by the Ministry of Economy and Competitiveness (Spain).

**Table 1**: Weather conditions measured (annual and global mean values) and at the experimental site.

| Year | AMT (ºC) | AmT (ºC) | MMT (ºC) | MmT (ºC) | MT (ºC) | P (mm) | Solar radiation (Wh m$^{-2}$) | Relative humidity (%) |
|---|---|---|---|---|---|---|---|---|
| 2009 | 34.7 | -14.0 | 17.7 | 4.4 | 10.8 | 389.8 | 1.6 | 64.8 |
| 2010 | 33.4 | -11.0 | 15.6 | 4.2 | 9.6 | 598.5 | 1.5 | 68.0 |
| 2011 | 35.7 | -11.9 | 17.9 | 4.9 | 11.1 | 379.6 | 1.6 | 66.5 |
| 2012 | 37.0 | -10.3 | 17.7 | 4.5 | 10.6 | 344.4 | 1.7 | 62.9 |
| 2013 | 33.8 | -8.8 | 16.5 | 3.2 | 9.5 | 595.0 | 1.6 | 70.4 |
| 2014 | 33.3 | -6.7 | 18.0 | 3.6 | 10.7 | 596.0 | 1.6 | 68.7 |
| 2015 | 36.0 | -9.5 | 18.1 | 4.6 | 11.0 | 488.1 | 1.6 | 67.1 |
| 2016 | 34.7 | -7.5 | 17.3 | 4.8 | 10.7 | 540.2 | 1.4 | 69.5 |
| 2017 | 35.3 | -11.7 | 18.5 | 4.8 | 11.9 | 314.8 | 1.7 | 63.0 |
| Mean | 34.9 | -10.2 | 17.5 | 4.3 | 10.7 | 471.8 | 1.6 | 66.8 |
| C.V. | 3.6 | 23 | 5.1 | 13 | 7.0 | 25 | 5.1 | 4.1 |

AMT: Absolute maximum temperature, AmT: Absolute minimum temperature, MMT: Mean maximum temperature, MmT: Mean minimum temperature, MT: Mean temperature, P: Precipitation. , C.V.: Coefficient of variation.

**Table 2**: Soil characteristics at the experimental site.

| | Horizon | |
|---|---|---|
| Parameter | 0-30 cm | 30-60 cm |
| Clay (%) | 8.1 | 8.4 |
| Silt (%) | 5.9 | 6.6 |
| Sand (%) | 86 | 85 |
| Soil texture | sandy | sandy |
| Gravels (%) | 35 | 39 |
| Density (Mg m$^{-3}$) | 1.4 | 1.4 |
| pH | 6.8 | 6.5 |
| Organic matter (%) | 0.6 | 0.4 |
| Carbonates (%) | 1.9 | < 0.1 |
| $N_{Olsen}$ (%) | 0.03 | 0.03 |
| $P_{av}$ (mg kg$^{-1}$) | 6.7 | 7.4 |
| $K_{av}$ (mg kg$^{-1}$) | 61 | 66 |

av: available

**Table 3**: Standards and analytical methods of the properties measured in the woody SRC.

| Property | Analytical technique | Standard |
|---|---|---|
| Sample preparation | Homogenisation, subsampling, milling | ISO 14780:2017 |
| Moisture | Drying at 105 ºC | ISO 18134-2:2015 |
| Ash | Calcination at 550 °C | ISO 18122:2015 |
| Volatile matter | Heating at 900 °C | ISO 18123:2015 |
| C, H, N | Elemental analysis: IR and TCD (Leco) | ISO 16948:2015 |
| S and Cl | Combustion bomb (Ika) + IC (Methrom) | ISO 16994:2016 |
| Calorific value | Calorimetry (Ika) | ISO 18125:2017 |
| Major elements | MW digestion (Milestone) + ICP-OES (Thermo Fisher) | ISO 16967:2015 |
| Minor elements | MW digestion (Milestone) + ICP-MS (Thermo Fisher)<br>For Hg: Gold amalgamation + AAS (Milestone) | ISO 16968:2015 |
| Ash fusibility | Optical heating microscopy (Hesse) | CEN/TS 15370-1 |

**Table 4**: Proximate and ultimate analysis of the biomass across species and rotation cycles, and significance levels from ANOVA.

| Species | Rotation cycle | Moisture (% wb) | Ash (% db) | Carbon (% db) | Hydrogen (% db) | Nitrogen (% db) | Sulphur (% db) | Chlorine (% db) | GCV (MJ/kg db) | NCV (MJ/kg db) |
|---|---|---|---|---|---|---|---|---|---|---|
| Black locust | 1st | 29.4 | 2.1 | 48.6 | 6.2 | 0.84 | 0.05 | 0.02 | 19.55 | 18.21 |
| Black locust | 2nd | 37.2 | 2.2 | 48.8 | 6.1 | 1.00 | 0.05 | 0.01 | 19.64 | 18.31 |
| Black locust | 3rd | 30.5 | 2.1 | 49.3 | 6.2 | 0.76 | 0.04 | 0.02 | 19.77 | 18.42 |
|  | Average | 32.4 | 2.2 | 48.9 | 6.2 | 0.86 | 0.05 | 0.02 | 19.65 | 18.31 |
|  | rsd (%) | 13 | 3.2 | 0.74 | 0.83 | 14 | 18 | 33 | 0.55 | 0.56 |
| Poplar | 1st | 45.8 | 2.4 | 49.3 | 6.1 | 0.44 | 0.03 | 0.01 | 19.71 | 18.39 |
| Poplar | 2nd | 53.0 | 2.2 | 49.1 | 6.0 | 0.48 | 0.04 | 0.01 | 19.64 | 18.34 |
| Poplar | 3rd | 43.6 | 3.1 | 49.6 | 6.0 | 0.44 | 0.03 | < 0.01 | 19.69 | 18.38 |
|  | Average | 47.5 | 2.6 | 49.3 | 6.0 | 0.45 | 0.03 | nd | 19.68 | 18.37 |
|  | rsd (%) | 10 | 18 | 0.51 | 0.85 | 5.7 | 10 | nd | 0.20 | 0.16 |
| Sycamore | 1st | 43.9 | 2.3 | 48.8 | 6.0 | 0.54 | 0.05 | 0.01 | 19.48 | 18.17 |
| Sycamore | 2nd | 45.8 | 2.2 | 48.6 | 6.0 | 0.54 | 0.06 | 0.01 | 19.45 | 18.15 |
| Sycamore | 3rd | 40.6 | 2.4 | 49.2 | 6.0 | 0.51 | 0.04 | 0.02 | 19.47 | 18.17 |
|  | Average | 43.4 | 2.3 | 48.9 | 6.0 | 0.53 | 0.05 | 0.01 | 19.47 | 18.16 |
|  | rsd (%) | 6.1 | 3.6 | 0.69 | 0.32 | 3.1 | 18 | 50 | 0.06 | 0.06 |
| Willow | 1st | 52.2 | 2.1 | 48.8 | 6.1 | 0.36 | 0.03 | 0.01 | 19.44 | 18.11 |
| Willow | 2nd | 53.9 | 2.3 | 48.6 | 6.0 | 0.47 | 0.04 | 0.01 | 19.48 | 18.17 |
| Willow | 3rd | 45.3 | 2.7 | 49.8 | 6.0 | 0.46 | 0.03 | 0.01 | 19.68 | 18.37 |
|  | Average | 50.5 | 2.4 | 49.1 | 6.0 | 0.43 | 0.04 | 0.01 | 19.53 | 18.22 |
|  | rsd (%) | 9.0 | 12 | 1.3 | 0.64 | 13 | 11 | 22 | 0.65 | 0.74 |
|  | Global average | 43.4 | 2.4 | 49.1 | 6.0 | 0.57 | 0.04 | nd | 19.58 | 18.27 |
|  | Min. | 29.4 | 2.1 | 48.6 | 6.0 | 0.36 | 0.03 | < 0.01 | 19.44 | 18.11 |
|  | Max. | 54 | 3.1 | 49.8 | 6.2 | 1.00 | 0.06 | 0.02 | 19.77 | 18.42 |
| **Significance levels from ANOVA** |  |  |  |  |  |  |  |  |  |  |
| **Species** |  | nd | 0.013 | 0.001 | < 0.001 | < 0.001 | < 0.001 | nd | < 0.001 | 0.001 |
| **Rotation cycle** |  | nd | 0.010 | < 0.001 | 0.001 | 0.075 | 0.002 | nd | 0.015 | 0.014 |
| **Species-Rotation** |  | nd | 0.013 | 0.009 | 0.001 | 0.114 | 0.316 | nd | 0.150 | 0.143 |

wb: wet basis; db: dry basis; GCV: gross calorific value at constant volume; NCV: net calorific value at constant pressure; nd: not determined.

**Table 5:** Chemical composition of the biomass across species and rotation cycles, and significance levels from ANOVA.

| Species | Rotation cycle | Al (% db) | Ca (% db) | Fe (% db) | K (% db) | Mg (% db) | Mn (% db) | Na (% db) | P (% db) | Si (% db) | Ti (% db) | Zn (% db) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Black locust | 1st | 0.0022 | 0.59 | 0.0045 | 0.24 | 0.037 | 0.0018 | 0.0056 | 0.064 | 0.023 | < 0.0002 | 0.0013 |
| Black locust | 2nd | 0.0012 | 0.60 | 0.0065 | 0.29 | 0.063 | 0.0025 | 0.0051 | 0.065 | 0.027 | < 0.0002 | 0.0034 |
| Black locust | 3rd | 0.0029 | 0.59 | 0.0025 | 0.23 | 0.053 | 0.0017 | 0.0020 | 0.059 | 0.020 | 0.0003 | 0.0023 |
|  | Average | 0.0021 | 0.59 | 0.0045 | 0.25 | 0.051 | 0.0020 | 0.0042 | 0.062 | 0.023 | nd | 0.0023 |
|  | rsd (%) | 41 | 1.3 | 44 | 13 | 25 | 21 | 46 | 5.0 | 15 | nd | 43 |
| Poplar | 1st | 0.0020 | 0.72 | 0.0038 | 0.31 | 0.076 | 0.0065 | 0.0044 | 0.079 | 0.027 | < 0.0002 | 0.0042 |
| Poplar | 2nd | 0.0012 | 0.60 | 0.0065 | 0.29 | 0.063 | 0.0025 | 0.0051 | 0.065 | 0.027 | < 0.0002 | 0.0034 |
| Poplar | 3rd | 0.0044 | 0.88 | 0.0038 | 0.34 | 0.078 | 0.0025 | 0.0030 | 0.088 | 0.029 | 0.0004 | 0.0034 |
|  | Average | 0.0025 | 0.73 | 0.0047 | 0.31 | 0.072 | 0.0038 | 0.0042 | 0.077 | 0.028 | nd | 0.0037 |
|  | rsd (%) | 65 | 19 | 33 | 8.8 | 12 | 61 | 26 | 15 | 5.3 | nd | 12 |
| Sycamore | 1st | 0.0025 | 0.66 | 0.0045 | 0.29 | 0.090 | 0.0125 | 0.0036 | 0.102 | 0.030 | < 0.0002 | 0.0014 |
| Sycamore | 2nd | 0.0012 | 0.60 | 0.0065 | 0.29 | 0.063 | 0.0025 | 0.0051 | 0.065 | 0.027 | < 0.0002 | 0.0034 |
| Sycamore | 3rd | 0.0034 | 0.67 | 0.0029 | 0.26 | 0.060 | 0.0019 | 0.0023 | 0.067 | 0.023 | 0.0003 | 0.0026 |
|  | Average | 0.0023 | 0.64 | 0.0046 | 0.28 | 0.071 | 0.0056 | 0.0037 | 0.078 | 0.026 | nd | 0.0025 |
|  | rsd (%) | 46 | 5.6 | 39 | 5.8 | 24 | 106 | 39 | 27 | 13 | nd | 40 |
| Willow | 1st | 0.0009 | 0.62 | 0.0034 | 0.23 | 0.056 | 0.0043 | 0.0039 | 0.066 | 0.015 | < 0.0002 | 0.0027 |
| Willow | 2nd | 0.0012 | 0.62 | 0.0067 | 0.30 | 0.064 | 0.0025 | 0.0053 | 0.067 | 0.028 | < 0.0002 | 0.0035 |
| Willow | 3rd | 0.0038 | 0.76 | 0.0032 | 0.30 | 0.068 | 0.0022 | 0.0026 | 0.076 | 0.025 | 0.0004 | 0.0030 |
|  | Average | 0.0020 | 0.67 | 0.0044 | 0.28 | 0.063 | 0.0030 | 0.0039 | 0.069 | 0.023 | nd | 0.0030 |
|  | rsd (%) | 79 | 12 | 44 | 14 | 9.1 | 39 | 34 | 7.7 | 28 | nd | 13 |
|  | Global average | 0.0022 | 0.66 | 0.0046 | 0.28 | 0.064 | 0.0036 | 0.0040 | 0.072 | 0.025 | nd | 0.0029 |
|  | Min. | 0.0009 | 0.59 | 0.0025 | 0.23 | 0.037 | 0.0017 | 0.0020 | 0.059 | 0.015 | < 0.0002 | 0.0013 |
|  | Max. | 0.0044 | 0.88 | 0.0067 | 0.34 | 0.090 | 0.0125 | 0.0056 | 0.102 | 0.030 | 0.0004 | 0.0042 |
| **Significance levels from ANOVA** |  |  |  |  |  |  |  |  |  |  |  |  |
| **Species** |  | 0.126 | 0.004 | 0.761 | 0.009 | 0.003 | 0.013 | 0.565 | 0.024 | 0.031 | nd | 0.001 |
| **Rotation cycle** |  | < 0.001 | 0.006 | < 0.001 | 0.255 | 0.903 | < 0.001 | < 0.001 | 0.040 | 0.224 | nd | 0.001 |
| **Species-Rotation** |  | < 0.001 | 0.031 | 0.135 | 0.005 | < 0.001 | < 0.001 | 0.118 | < 0.001 | < 0.001 | nd | < 0.001 |

db: dry basis; nd: not determined.

**Table 6:** Trace elements of the biomass obtained from the short rotation woody crops during the third rotation cycle, and ISO 17225 requirements, parts 2 (woody pellets) and 4 (woody chips).

| Especies | As (µg/g db) | Cd (µg/g db) | Cr (µg/g db) | Cu (µg/g db) | Hg (µg/g db) | Ni (µg/g db) | Pb (µg/g db) |
|---|---|---|---|---|---|---|---|
| **Black locust** | < 0.2 | < 0.1 | < 1.0 | 2.9 | 0.002 | 3.6 | < 1.0 |
| **Poplar** | < 0.2 | 0.2 | < 1.0 | 2.4 | 0.002 | < 1.0 | < 1.0 |
| **Sycamore** | < 0.2 | 0.1 | < 1.0 | 4.3 | 0.001 | 3.5 | < 1.0 |
| **Willow** | < 0.2 | 0.2 | < 1.0 | 2.5 | 0.002 | < 1.0 | < 1.0 |
| **ISO 17225-2** | ≤ 1 | ≤ 0.5 | ≤ 10 | ≤ 10 | ≤ 0.1 | ≤ 10 | ≤ 10 |
| **ISO 17225-4** | ≤ 1 | ≤ 2 | ≤ 10 | ≤ 10 | ≤ 0.1 | ≤ 10 | ≤ 10 |

**Table 7:** Maximum levels of trace elements expected in the ash obtained after the combustion of the studied woody crops, and permissible limits of toxic elements for land application of sewage sludge. Units in mg/kg, dry basis.

| Especies | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | Mn |
|---|---|---|---|---|---|---|---|---|---|
| **Black locust** | < 9 | < 5 | < 46 | 135 | 0.09 | 167 | < 46 | 1081 | 918 |
| **Poplar** | < 8 | 8 | < 38 | 92 | 0.08 | < 38 | < 38 | 1406 | 1474 |
| **Sycamore** | < 9 | 4 | < 43 | 185 | 0.04 | 151 | < 43 | 1061 | 2422 |
| **Willow** | < 8 | 8 | < 42 | 105 | 0.08 | < 42 | < 42 | 1274 | 1265 |
| **86/278/EEC limits** | nl | 20-40 | 100-150 | 1000-1750 | 16-25 | 300-400 | 750-1200 | 2500-4000 | nl |
| **Dutch limits** | 15 | 1.25 | 75 | 75 | 0.75 | 30 | 100 | 300 | nl |

nl: not limited

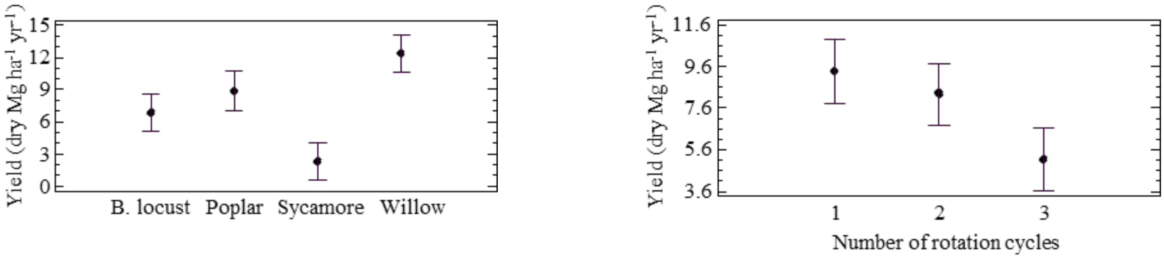

**Figure 2:** Dried biomass yield (means and LSD intervals) across species (left) and rotation cycles (right).

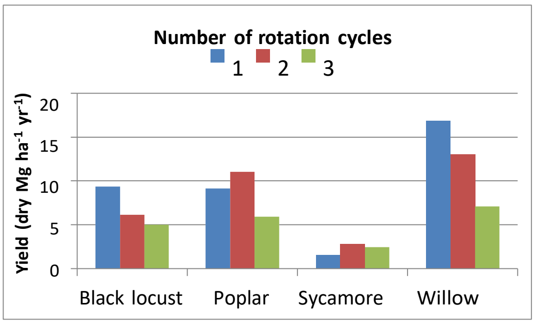

**Figure 3:** Dried biomass yield (Mg ha$^{-1}$ yr$^{-1}$) across species and rotation cycles.

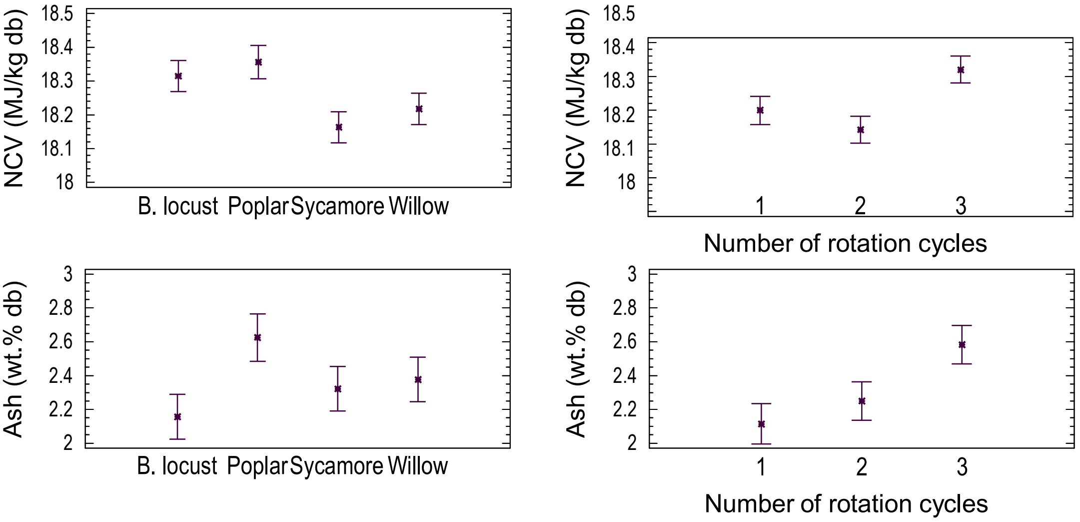

**Figure 4:** Net calorific value and ash content (means and LSD intervals) across species (left) and rotation cycles (right).

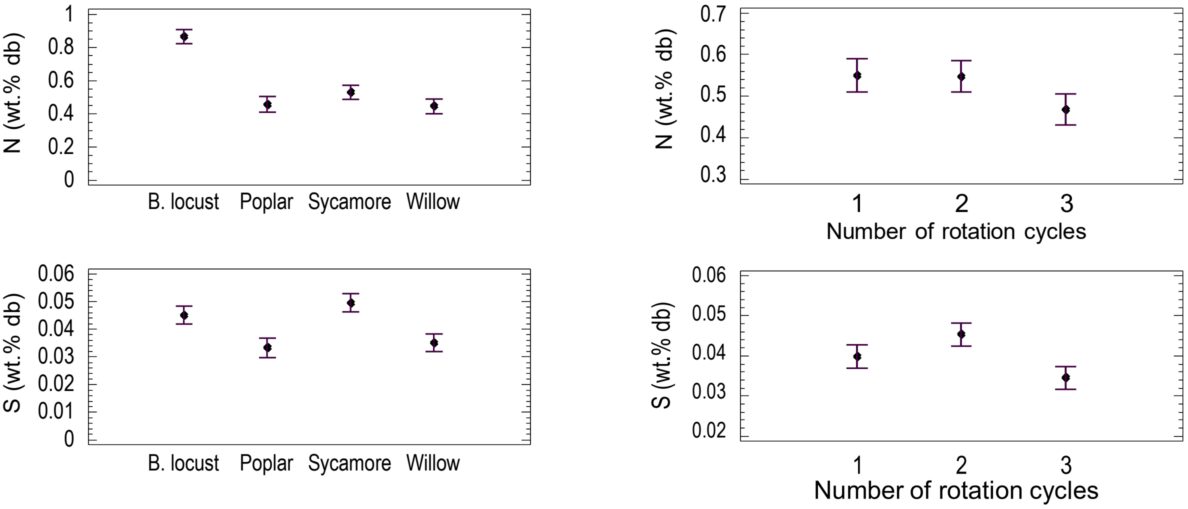

**Figure 5:** Nitrogen and sulphur contents (means and LSD intervals) depending on species (left) and rotation cycle (right).

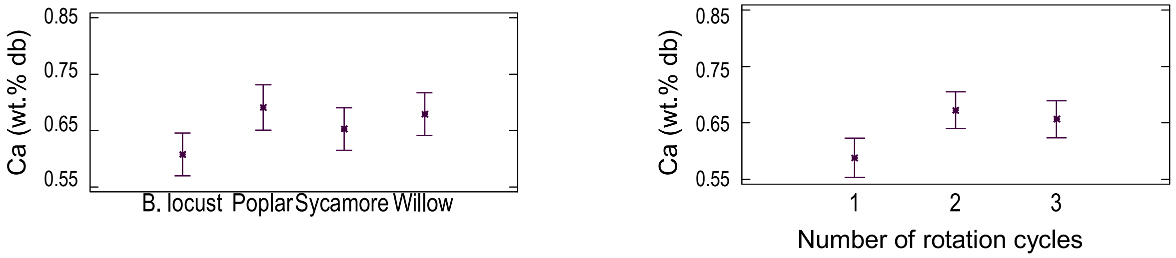

**Figure 6:** Calcium content (means and LSD intervals) depending on species (left) and rotation cycle (right).

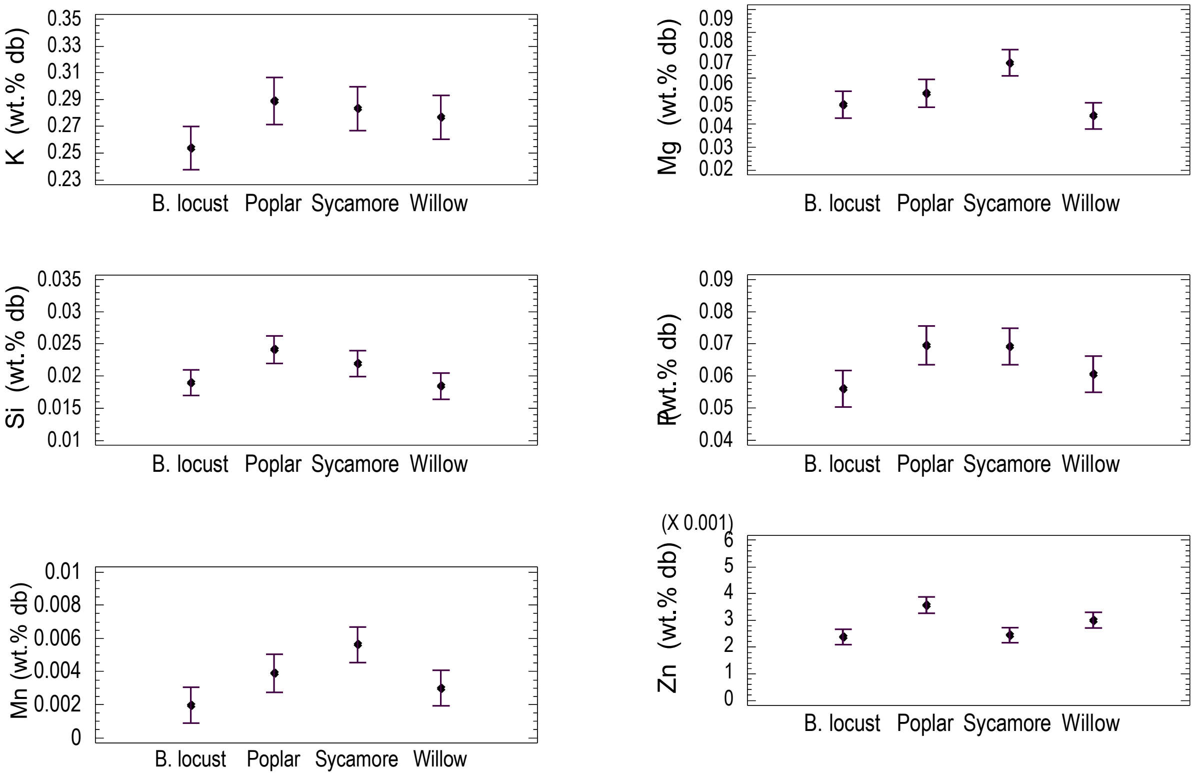

**Figure 7:** K, Mg, Si, Mn, P, and Zn contents (means and LSD intervals) depending on species.

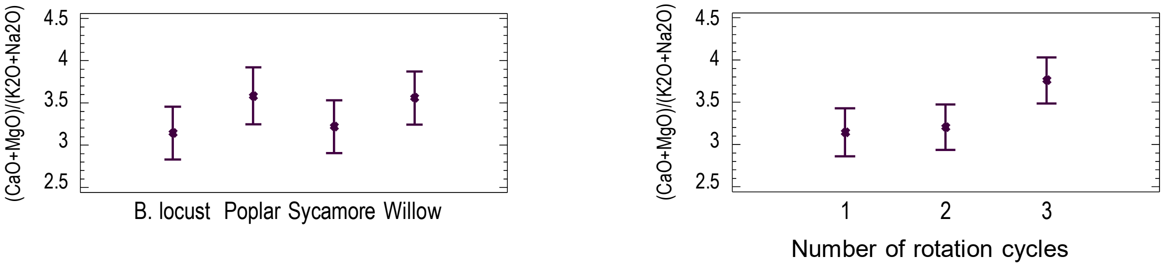

**Figure 8:** Alkaline-earth to alkali oxides ratio (means and LSD intervals) across species (left) and rotation cycles (right).

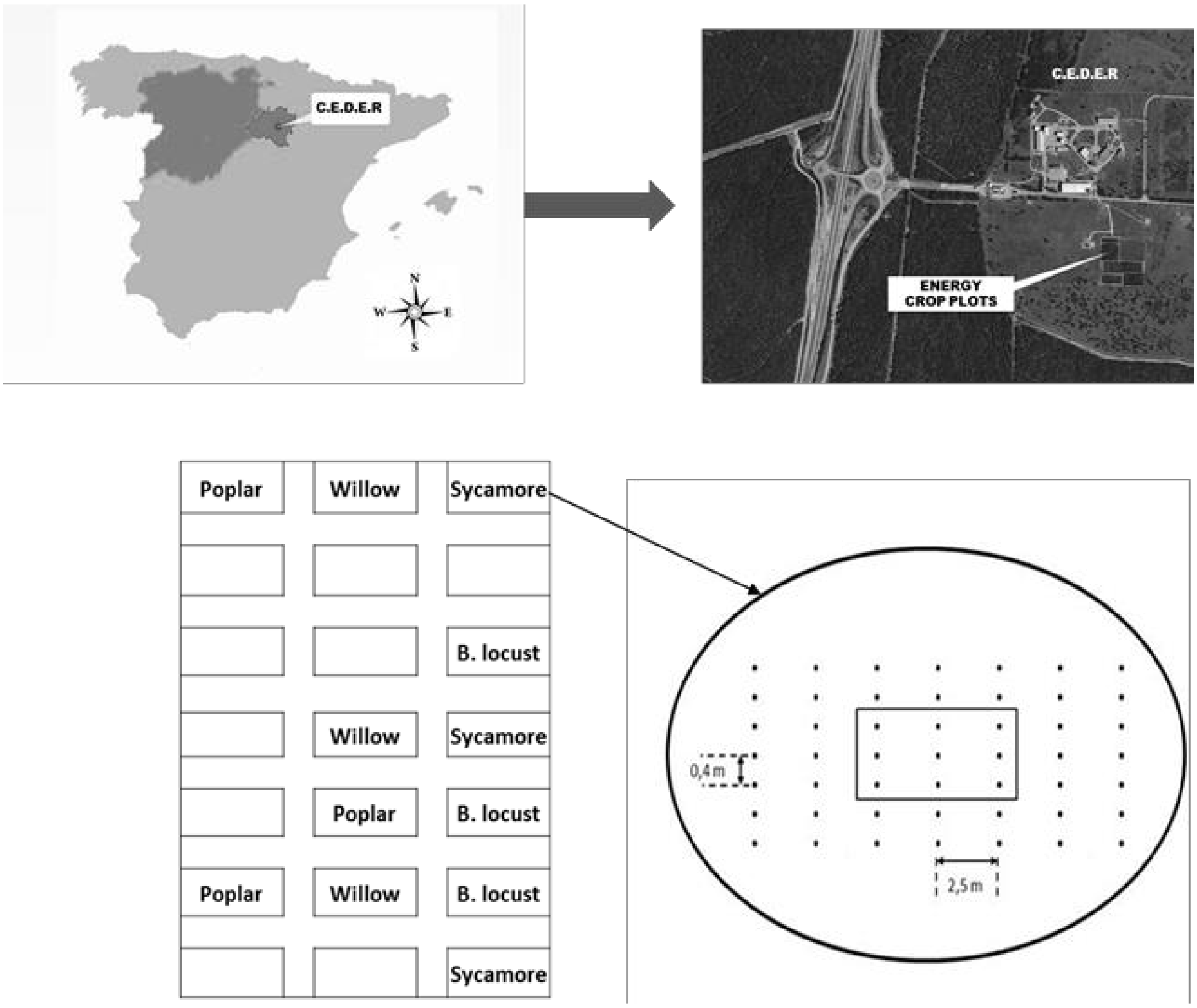

**Figure 1**: Location and distribution of species and trees at the experimental plantation. Each black dot represents an individual tree.

Interactive Map file (.kml or .kmz)

Click here to access/download

Interactive Map file (.kml or .kmz)

CEDER-CIEMAT woody short rotation crops.kml