Survival, early growth and chemical characteristics of *Paulownia* trees for potential biomass production in a cool temperate climate

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Abstract

The results of two experiments to investigate the survival, early growth and chemical characteristics of six Spanish and three Moroccan genotypes of *Paulownia*, grown from container produced and bare root plants, respectively, are described. Both trials were planted in Northern Ireland (NI) and after three growing seasons the overall mean survival and height of the Spanish and Moroccan genotypes were 70.8% and 32.2% and 1.1 m and 2.2 m, respectively. Chemical characteristics, except for nitrogen and ash content, were similar to those reported for other biomass crops such as willow and miscanthus (*Miscanthus × giganteus*). Genotypes that performed well were PWST-33 (*P. fortunei)* from Spain and *P. fortunei* from Morocco. Biomass yields varied significantly (*P* <0.05) and were considerably lower than those reported for other fast growing species grown as energy crops. The results suggest that the potential of *Paulownia* as an energy crop in NI is limited due to its low performance in biomass production. The main constraints to further planting of *Paulownia* in this region are the edaphic and climatic conditions that pertain, which appear not to be conducive to growth of this tree species.

Keywords: *Paulownia, biomass, energy, cool climate*.

Introduction

There is interest in fast growing tree species for cool temperate climates such as in Britain and Ireland (Leslie *et al*. 2012) as the demand for wood as a renewable source of energy increases across these areas. The European Union (EU) member states have been encouraged to instigate a range of actions detailed in a non-binding Forest Action Plan (FAP) that includes expanding new forest plantings including the use of fast growing species for biomass production (Woods 2008). *Paulownia* is a genus that comprises nine species and a few natural hybrids of such fast growing hardwood trees, that is native to China and has been seen in many countries to offer potential for biomass production (Bergmann 2003, Latorre *et al*. 2011, Yadav *et al*. 2013) due to its sprouting ability and reportedly inherently high energy content (Villanueva *et al*. 2011). Varieties of *Paulownia* have been widely cultivated in China, New Zealand, Australia and the United States where its fast growth habit, wood properties and

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agricultural and environmental uses are highly valued (Wang and Shogren 1992). There is considerable literature on the many industrial uses of *Paulownia* in China, Japan and more recently other Asian countries (Woods 2008). Although it has been reported (Woods 2008) that *Paulownia* has a high flame retardancy due to its low lignin content and peculiar vessel structure, suggesting that its combustion properties might be questionable, the species may also be suitable for pulpwood in suitable niche markets (Olson *et al*. 1989). Though widely planted as an ornamental in the western hemisphere (Woods 2008) little has been reported in the literature regarding its suitability in the cool, moist oceanic climate that exists in Britain and Ireland. Further, it has been shown that *Paulownia* species of differing origin show significant differences in growth rate (Ayan *et al*. 2006, Bergmann 2003).

In the UK and Republic of Ireland, Forestry Departments have developed a long-term strategy for forestry which includes a general increase in forest cover of traditional forestry species planting, that also considers the adoption of fast growing, non- and native species in the search for suitable short rotation forestry (SRF) trees for biomass.

The concept of SRF using *Eucalyptus* and other species has also been investigated in the UK and Ireland, but a longer rotation is required compared with short rotation coppice (SRC) willow (*Salix* spp.) and poplar (*Populus* spp.) crops (Kerr 2011, Wickham *et al*. 2010). Both willow and poplar have been grown as SRC for several decades (Tubby and Armstrong 2002). Willow in particular has been widely planted as a biomass fuel crop, but susceptibility to disease, especially rusts caused by varieties of the *Melampsora* genus, greatly curtails growth and productivity, particularly in mono-culture plantations (McCracken and Dawson 1997), though the development of polyclonal planting systems has been shown to greatly reduce the incidence and severity of rust infestations (McCracken *et al*. 2001). Therefore the search for an alternative fast growing tree species to widen the biomass fuel species resource base is desirable to help meet the growing demand for biomass. This may offer an opportunity for genotypes of *Paulownia* derived from advanced breeding programmes that are current in many countries to develop the species (Woods 2008).

These issues do not however, preclude use of *Paulownia* as a possible biomass genus in the UK and specifically within Northern Ireland (NI). This research work describes the results of screening trials to assess survival, early growth as well as chemical and calorific characteristics of a range of *Paulownia* genotypes for use as a biomass crop in NI.

Materials and methods

Site description

The study site was located on a field previously dominated by perennial ryegrass (*Lolium perenne* L.) on a gentle south to southwest facing slope at Hillsborough about

15 km west of the city of Belfast in NI (latitude 54.48° N, longitude 6.08° W) where, in general the climate is dominated by low pressure Atlantic storm systems which cause cool and humid conditions characterised by an annual average summer and winter temperature of 14.5 °C and 4.5 °C, respectively (Smyth *et al*. 2002). The site was chosen as typical of the type of land that was anticipated would become available for an energy crop. A total of 9 genotypes of *Paulownia* trees which were sourced from two tree nurseries that could only supply their standard commercially available plant material were used for the study. Three genotypes (*P. fortunei, P. elongata × fortunei* and *P. elongata*) of two year-old bare rooted plants were shipped from Morocco and held in a cold room for less than two weeks prior to planting. Seedlings of six other genotypes (PWCOT-2: *P. elongata × fortunei*, PW-105: *P. elongata × fortunei × tomentosa,* PWL-1*: P. elongata × fortunei*, PWCOT-1: *P. elongata*, PWST-33: *P. fortunei* and PWST-11: *P. elongata × fortunei*) that had been produced by tissue culture in Spain (COTEVISA) were shipped to the Agri-Food and Biosciences Institute (AFBI) in NI. These were potted in 3 L containers with a peat-based substrate and grown under controlled conditions for 4 months and subsequently acclimatised for two weeks prior to field planting. Before planting, plants from Morocco and Spain were sorted into similar sizes by height (50 cm) and root collar diameter (7-10 mm) and the plants from the two origins established in two separate but adjacent trials less than 20 m apart in May 2009 with the genotypes within each trial planted in 5 and 4 blocks, respectively, in randomised block designs.

The mean annual temperature between 2009 and 2013 at Hillsborough, the nearest recording station (350 m distant) was 8.9 ºC with maximum and minimum temperatures of 24.6 ºC and -8.4 ºC respectively. Mean annual precipitation was 820 mm and the average wind speed was 2.1 ms^{-1} during the same period. The soil in this area is moderately deep, well drained and loamy overlying basalt rock strata. Soil pH where the material was planted was 5.49 and 5.89, respectively. Though the trials were only a few metres apart, their soil mineral concentration in potassium (K), magnesium (Mg) and phosphorus (P) were markedly different (Table 1).

Before planting, existing vegetation on both sites was sprayed with glyphosate, then ploughed and cultivated (power harrowed) 4 weeks later. Each block within the Spanish and Moroccan trial consisted of 6 and 3 plots, respectively; each plot contained 6 plants planted at a spacing of 1.8 m × 1.8 m. Each planting hole was dug

Table 1: *Mineral concentration of potassium (K), magnesium (Mg) and phosphorus (P) from soil of Spanish and Moroccan genotypes experimental trials.*

Experimental site	K (mg litre^{-1})	Mg (mg litre^{-1})	P (mg litre^{-1})
Spanish genotype trial	1287.6	443.4	20.3
Moroccan genotype trial	445.4	109.8	47.4

40 cm wide and 50 cm deep, then backfilled after planting with extracted soil and a jute mat fixed around the base of each tree to suppress weeds. Single guard rows of spare plants were planted around the plots. An electric fence was erected around both trials to prevent damage by farm livestock and/or wildlife. Residual herbicide (Pendimethalin + Isoxaben) was sprayed across the trials after planting. In both sites, fertiliser (Osmocote, Scott plus, 8-9 months longevity at 200g plant^{-1}) was applied to minimise differences due to soil moisture and nutrient deficiencies. Thereafter the inter-row areas were regularly mowed during the growing seasons.

Assessment

Survival, height and number of shoots were evaluated after three growing seasons in the field. Height from ground level was measured to the nearest 0.1 cm for all trees in each plot using an extendable measuring pole (Senshin, 8 metre). Number of shoots with a minimum diameter of 2 cm were counted. Destructive measurements were also made in 2013 at the end of the third growing season. All trees were felled at ground level and above- ground whole tree fresh weight (FWT) was recorded from a suspended balance (Nagata: 600 kg × 0.2. HJS). Harvested samples from each plot were then prepared for laboratory analysis.

Chemical analysis

All fresh fuel samples were weighed then oven dried at 80 °C for 48 hours for dry matter (DM) assessment (%DM = (dry weight/fresh weight) × 100). The dried samples were milled (Fritsch Pulverisette P25) down to 0.8 mm particle size, sealed and labelled in 200 ml jars. Laboratory analysis of Nitrogen (N) content (g kg^{-1} DM) and carbon (C) (g kg^{-1} DM) was by the Dumas method (Elementar VarioMax CN). Gross energy (GE MJ kg^{-1} DM) was measured by bomb calorimetry (Parr 6300 Calorimeter). Phosphorus (P) and potassium (K) content were determined using standard laboratory methods. Flame oxidation at 550 °C in a Vecstar closed combustor furnace was used to determine ash (g kg^{-1} DM) content and the oven dry matter (OVDM g kg^{-1}) assessed at 101 ± 1 °C in a Gallenkamp oven.

Milled fuel samples (5 mg) were analysed in triplicate for volatile (Vc%) and fixed carbon (FC %) content by heating from room temperature to 950 ºC in nitrogen, which was maintained for 30 minutes in a ventilated oven, before returning to room temperature, using a thermogravimetric (TGA) analyser (Mettler Toledo TGA/DSC1, Switzerland).

Combustion characteristics of *Paulownia* genotypes were also analysed using the same instrument, by heating from room temperature to 600 ºC in air at a heating rate of 20 ºC^{-1} min to assess peak primary weight loss (PWl %), char weight loss (CWl %), peak combustion temperature (PTC °C) and char combustion temperature (CTC °C). Gas flow rates were 50 ml min for all thermogravimetric work.

Statistical analysis
Analysis of variance (ANOVA) was performed on the plot means using Genstat (16th Edition) for survival, height, number of shoots, fresh weight, dry matter and data from chemical analyses. Where diagnostic probability plots of the residuals from the analysis of variance indicated that the data were sufficiently normal with homogeneous variance, the untransformed results were presented and the means were compared using a LSD at P <0.05. Variables such as counts or numbers were transformed by taking the square root and percentages by using angular transformations.

Results

Survival
The percentages of *Paulownia* trees surviving after three growing seasons in both trials are shown in Figures 1 and 2. After three growing seasons, considerable mortality was recorded at the Moroccan origin site with overall average survival rates much lower than the Spanish genotypes. Among Spanish genotypes (Figure 1), PW-105 had significantly (P<0.003) lower survival (20.8%) than all other genotypes and PWST-33 had the highest survival rate (95.8%) followed by PWCOT-1 (87.5%). Slightly lower rates were seen in PWCOT-2, PWL-1 and PWST-11 in decreasing order (Figure 1).

Survival of trees of Moroccan origin ranged from 30% to 33.3% (Figure 2) but these differences were not statistically significant.

Growth
The average heights, number of shoots, total fresh weight (TFW) and dry mass (DM%) of Spanish and Moroccan *Paulownia* trees in 2013, after three growing seasons are shown in tables 2 and 3. Among Spanish genotypes, PW-105 was significantly (P <0.007) smaller (0.4 m) than other genotypes and PWST-33 and PWCOT-1 were the

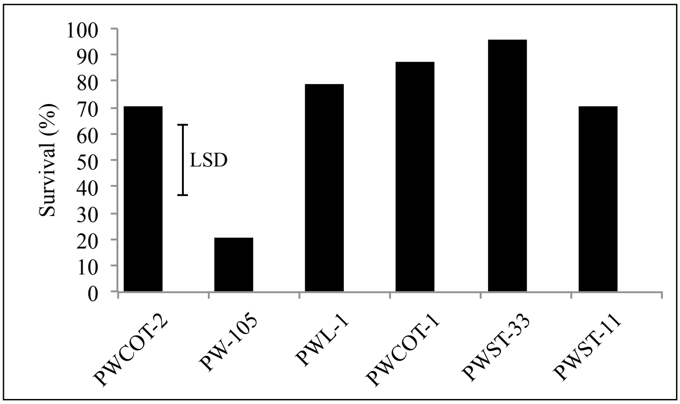

Figure 1: *Percentage survival of Spanish genotypes, three growing seasons after establishment at Hillsborough, Northern Ireland (LSD = least significant difference at the 5% level).*

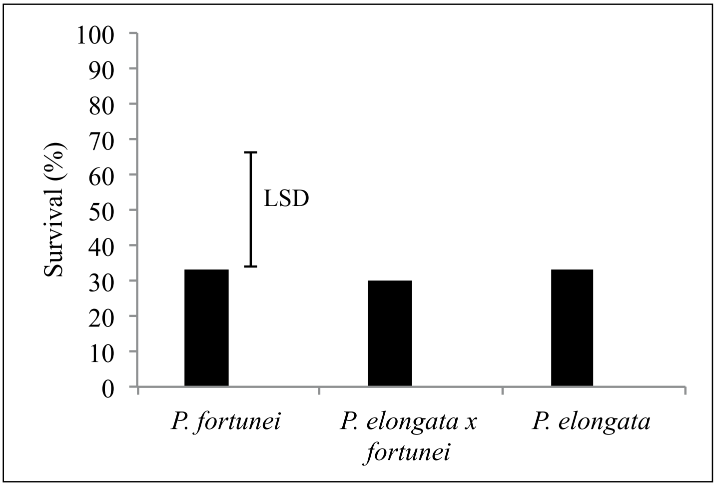

Figure 2: *Percentage survival of Moroccan genotypes, three growing seasons after establishment at Hillsborough, Northern Ireland (LSD = least significant difference at the 5% level).*

tallest (1.5 m). Genotypes PWCOT-2, PWCOT-1 and PWST-33 had significantly more shoots (7.4, 7.5 and 9.0 respectively) than the rest of genotypes and PW-105 had the fewest (2.1). Genotype PW-105, had significantly (*P* <0.001) lower TFW and greater DM than other genotypes whereas PWST-33 yielded the highest amount of fresh biomass.

Growth variables among Moroccan genotypes did not differ significantly (Table 3). However, overall average heights varied by 48% between the tallest and shortest genotypes (*P. fortunei* and *P. elongata,* respectively). All three genotypes had similar number of shoots per plant (4.5) though *P. fortunei* had more TFW and higher DM% than the other two genotypes.

Chemical characteristics

Tables 4 and 5 show chemical characteristics of *Paulownia* from both origins. The concentration of C among Spanish genotypes (Table 4) ranged from 482.9 to 493.2 g kg DM and the genotype PW-105 had significantly (P <0.001) higher C content than other genotypes. Nitrogen also was significantly higher (P <0.001) in PW-105 than all other

Table 2: *Average height, number of shoots, total fresh weight (TFW) and dry mass (DM%) of Spanish* Paulownia *genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	PWCOT-2	PW-105	PWL-1	PWCOT-1	PWST-33	PWST-11	LSD
Height (m)	1.0	0.4	1.1	1.5	1.5	0.9	0.56 **
Shoots (N°)	7.4	2.1	4.6	7.5	9.0	4.8	2.76 ***
TFW (kg)	9.6	0.9	9.3	19.0	23.7	12.6	7.32 ***
DM (%)	37.2	44.1	37.6	34.4	34.7	32.6	5.50 **

Note: ** = p <0.01, *** = p <0.001, LSD least significance at the 5% level.

Table 3: *Mean height, number of shoots, total fresh weight (TFW) and dry mass (DM%) of Moroccan* Paulownia *genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	*P. fortunei*	*P. elongata × fortunei*	*P. elongata*	LSD
Height (m)	3.0	2.1	1.6	2.44 NS
Shoots (N°)	4.5	4.5	4.5	3.59 NS
TFW (kg)	26.4	15.2	2.6	31.66 NS
DM (%)	48.1	42.4	43.4	14.32 NS

Note: NS = not significant, LSD least significance at the 5% level.

genotypes and PWST-33 had significantly lower N concentration than all other genotypes except for PWCOT-1. All Spanish genotypes had similar ash content. There were small differences in P and K among Spanish genotypes with PWST-11 having significantly higher P content than PWST-33 and significantly higher K content than all other genotypes. The PWST-33 contained significantly (p <0.002) less P than the other genotypes. Genotype PW-105 had lower K than other genotypes. The OVDM and GE ranged from 928.7 to 934.9 g kg^{-1} DM and 19.3 to 20.0 MJ kg^{-1} DM, respectively and were statistically similar among these genotypes (Table 4).

For Moroccan genotypes (Table 5) only the OVDM showed significant difference (P <0.002) due to *P. fortunei* having a significantly higher OVDM than the hybrid, though the actual difference was very small (<1.00% of weight) and *P. elongata* had significantly (P <0.05) less OVDM% than the other two genotypes. Overall the averages of C, N and ash were 486.8, 5.3 and 16.1 g kg^{-1} DM, respectively and differences among genotypes were not significant (NS). Content of P and K in the stems did not show statistical differences, but *P. fortunei* had much lower content of these minerals (19.0 and 17.2% respectively). Mean GE between Moroccan genotypes was similar, ranging only from

Table 4: *Average amount of C, N, ash, P, K, oven-dry matter (OVDM), gross energy (GE), volatiles and fixed C in the stems of Spanish genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	PWCOT-2	PW-105	PWL-1	PWCOT-1	PWST-33	PWST-11	LSD	
C (g kg^{-1})	483.6	493.2	486.1	484.7	482.9	486.0	4.07	***
N (g kg^{-1})	6.7	8.0	6.7	6.2	5.7	7.0	0.84	***
Ash (g kg^{-1})	22.6	22.4	21.8	21.0	17.6	24.9	4.32	NS
OVDM (g kg^{-1})	930.7	928.7	933.6	934.9	934.8	932.6	4.80	NS
P (mg kg^{-1})	846.0	791.0	838.0	817.0	673.0	866.0	111.20	*
K (mg kg^{-1})	5921.8	4611.5	5802.1	5990.3	5,318.7	7,366.9	1,268.39	**
GE (MJ kg^{-1})	19.6	20.0	19.6	19.3	19.4	19.3	0.50	NS
Vc %	76.3	75.2	76.9	76.6	77.6	76.3	1.11	**
FC %	14.0	14.6	13.6	13.7	13.0	13.9	0.71	**

Note: * = p <0.05, ** = p <0.01, *** = p <0.001: NS = not significant, LSD least significance at the 5% level.

Table 5: *Mean amount of C, N, ash, P, K, oven-dry matter (OVDM), gross energy (GE), volatiles and fixed C in the stems of Moroccan genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	*P. fortunei*	*P. elongata × fortunei*	*P. elongata*	LSD
C ($g\ kg^{-1}$)	485.9	484.8	489.8	5.02 NS
N ($g\ kg^{-1}$)	4.5	5.2	6.1	1.77 NS
Ash ($g\ kg^{-1}$)	12.6	16.9	19.0	6.86 NS
OVDM ($g\ kg^{-1}$)	939.9	939.4	933.8	4.24 *
P ($mg\ kg^{-1}$)	600.0	782.0	794.0	277.40 NS
K ($mg\ kg^{-1}$)	3,743.5	5,261.8	5,246.8	2,585.38 NS
GE ($MJ\ kg^{-1}$)	19.6	19.6	19.8	0.18 NS
Vc %	78.1	78.1	77.7	2.11 NS
FC %	13.6	14.0	13.5	1.35 NS

Note: * = p <0.05; NS = not significant, LSD least significance at the 5% level.

19.6 to 19.8 MJ kg^{-1} (Table 5). The analysis also revealed (Table 4) that, among Spanish genotypes, there were small (<2.0%) but significant differences (p <0.01) in fixed C (carbon not released with volatiles) while differences were not significant (NS) among Moroccan genotypes (Table 5).

Thermo-gravimetric results

Distinct differences in thermo-gravimetric properties were observed (Table 6 and 7) within genotypes of Spanish origin. Some genotypes, for example PWL-1, PWCOT-1 PWST-33 and PWST-11 (Table 6), had a higher weight loss relative to the phase of combustion, compared to PWCOT-2 and PW-105 which decomposed only when temperatures exceeded 333 °C. However, PW-105 had a significantly higher (467 °C) char combustion temperature than the other genotypes, which appeared to be related to its high DM (Table 2) and fixed C (Table 4) contents.

There were no significant differences (NS) in any of the thermogravimetric variables among the Moroccan genotypes (Table 7).

Table 6: *TGA combustion analyses (peak primary weight loss; PWl %, char weight loss; CWl %, peak combustion temperature; PTC °C and char combustion temperature; CTC °C) results for Spanish* Paulownia *genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	PWCOT-2	PW-105	PWL-1	PWCOT-1	PWST-33	PWST-11	LSD
PWl %	62.4	61.7	64.3	63.2	64.1	63.3	1.69 *
CWl %	28.2	28.5	26.8	27.3	26.7	27.2	1.29 *
PTC °C	333.2	332.6	333.0	333.9	334.2	332.1	1.64 NS
CTC °C	459.4	467.5	458.1	459.7	456.3	453.6	6.18 *

Note: * = p <0.05, ** = p <0.01: NS = not significant, LSD least significance at the 5% level.

Table 7: *TGA combustion analyses results (peak primary weight loss; PWl %, char weight loss; CWl %, peak combustion temperature; PTC °C and char combustion temperature; CTC °C) for Moroccan* Paulownia *genotypes after three growing seasons in the field at Hillsborough, Northern Ireland.*

Variable	*P. fortunei*	*P. elongata × fortunei*	*P. elongata*	LSD
PWl %	65.1	65.7	63.7	2.84 NS
CWl %	27.0	26.3	27.4	2.02 NS
PTC °C	335.1	333.9	333.4	3.69 NS
CTC °C	459.9	457.5	461.2	4.06 NS

Note: NS = not significant, LSD least significance at the 5% level.

Discussion

Survival

Survival among Moroccan genotypes was low. Survival also varied considerably among Spanish genotypes. Survival of Moroccan genotypes was lower than among Spanish genotypes but origin was confounded by differences in type of nursery stock, aspects of climatic and soil conditions. Some of the differences may have been partly due to the Spanish genotypes having been established as containerised plants with well-developed root systems and fertiliser application in the greenhouse which increased nutrient availability in this soil. This observation would support the idea that containerised plants would have an advantage compared to bare rooted plants in harsh environments (Bergmann 1998), although differences in survival are less likely to be associated with ability to form roots than the capacity of plant tissue, especially growing points, to withstand a cool oceanic climate. Although *Paulownia* has been reported to withstand a temperature of -20 °C (Barton *et al*. 2007), a likely reason for the severe reduction in survival of Moroccan plants may have been the exceptionally cold winters during 2010 and 2011 with minimum temperatures of -14 °C and -7.2 °C respectively, registered at Hillsborough. Some genotypes suffered more damage from early or late frost while other varieties survived at temperatures down to -8 °C which suggests that, as for other fast growing such as eucalyptus and poplar species in the UK, freezing conditions present a hazard (Cope *et al*. 2008).

Although *Paulownia* has been reported to grow on a wide range of soils (Wang and Shogren 1992, Barton *et al*. 2007) it has also been reported (Lyons 1993) that sandy, volcanic and deep alluvial soils are more suitable than untreated heavy clay soils as the latter prevent drainage and impede root growth. However soil type, nutrient availability (Table 1) and pH were within the reported range of suitability for *Paulownia* (Woods 2008). Barton *et al*. (2007) suggest that *Paulownia* can grow quite satisfactorily on soils as low as pH 5.0 but for optimum growth it should be between pH 6.5 and 7.0.

Water availability is not a limiting factor in NI, with an average annual rainfall of

820 mm that is generally evenly distributed. Excessive soil moisture may inhibit deep rooting in *Paulownia,* as has been shown for other tree species grown in the UK and Ireland (Paterson and Mason 1999). Barton *et al*. (2007) and Woods (2008) mention that the water table should be at least 1.5 m below the surface. However, soils of both trials in this study were rotovated to improve drainage. Infections by pests and/or pathogens were not observed on any of the trees on the sites and so disease was unlikely to have been a cause of any mortality.

Paulownia does not have a high tolerance to strong winds (Woods 2008) and this might have been another factor affecting survival and growth. Strong winds and exposure have been the most limiting factors to height growth of trees species introduced into Britain and Ireland (Macdonald *et al*. 1957, Savill 1974). Experience in New Zealand (Barton *et al*. 2007) have shown that the breakage of young stems and branches of *Paulownia* trees can occur when wind speed exceeds 40 km hour^{-1}. Similar effects might have occurred in this experiment as the average wind speed was 2.1 m s^{-1} and winds of over 40 km hour^{-1} were recorded at the Hillsborough weather station on several occasions between 2009 and 2013. Other authors (Lyons 1993, Bergmann 2003) have reported survival problems in areas with persistent winds due to the susceptibility of *Paulownia*'s large juvenile leaves to wind damage. Though not directly comparable, it was observed that average survival of Spanish genotypes (with the exception of PW-105) grown from container-grown plants were almost 40 percentage points higher than the mean survival of the Moroccan genotypes in the adjacent trial, but were raised as bare root plants.

Growth

Two of the Moroccan genotypes, *P. fortunei* and *P. elongata x fortunei*, were considerably taller than the Spanish genotypes and *P. fortunei* also had the highest total fresh weight (26.4 kg) and the Spanish PW-105 the lowest (0.9 kg). In general, Moroccan *Paulownia* genotypes were taller than Spanish ones after three growing seasons, but with a much lower survival rate. *Paulownia* growth is generally very dependent on site conditions and tree age (Wang and Shorgen 1992) and growth is most rapid during the year following planting year and subsequent to cutting back (Barton *et al*. 2007). Although the trees were planted at wider spacing (1.8 m × 1.8 m) than SRC willow would be planted (but still narrower compared to other potential SRF tree species), the *Paulownia* trees in this study were generally shorter than those reported for other energy crops in Britain and Ireland (Kerr 2011, Neilan and Thompson 2008). *Salix* spp. in NI, although planted at higher density, can reach over 7 m in 3 years (Dawson 2007). *Populus* spp. when planted at similar spacing can reach 7 m in height and in the south of England plants can reach a height of 2 m in the first season (Jobling 1990).

The results from this study show that *Paulownia* trees grew much more slowly under NI conditions than at Mediterranean and subtropical latitudes (Bergmann 2003, Duran-

Zuazo *et al*. 2013). Wang and Shorgen, (1992) reported that the average height of a 7 year-old *Paulownia* tree is about 8-12 m in China. In the US (Bergmann 2003) with air temperature ranging from 24 ºC to 30 ºC and in more southerly light conditions, two year-old *P. tomentosa,* coppiced in the first year, reached an average height of 4.3 m. These high temperatures and light levels are necessary to achieve potential growth (Lyons 1993, Barton *et al*. 2007), but in NI levels of light are generally lower with relatively few days of clear skies (Smyth *et al*. 2002) which may also have affected tree height growth.

Regarding biomass production, Yadav *et al*. (2013) reported that under favourable conditions the harvestable biomass of *P. elongata* is 92 kg per tree after three growing seasons. Assuming that *Paulownia* trees from both origins were planted at 3,086 trees ha^{-1} in NI, the yield of *P. fortunei*, *P. elongata* × *fortunei* and *P. elongata* would range between the equivalent of 6.6, 3.4 and 1.9 t DM ha^{-1} yr^{-1}, respectively. In the best case scenario, this is ~55% less than the average yield of conventional SRC willow in NI (Dawson 2007) but relatively similar to other potential SRF tree species tested in Britain and Ireland, except for *Eucalyptus* which yields about 10 t DM ha^{-1} yr^{-1} (Kerr 2011, Neilan and Thompson, 2008). On the other hand, despite the high survival of Spanish genotypes (Figure 1), the mean annual yield of just over 4.2 t DM ha^{-1} yr^{-1} for the most successful Spanish genotype (PWST-33) would not be comparable with the poorest willow yield of 7 t DM ha^{-1} yr^{-1} in NI (Dawson 2007). An important factor in these yields was the hollow stems of juvenile growth, observed during harvest, samples of which are illustrated in Figure 3. The void area accounted for at least 1/4 of the total transverse area in the mid and upper sections in two year old stems, though these voids reduce during the third growing season. However, biomass production from these two trials should be treated with some caution given that they are extrapolated from small scale experiments with a small number of trees per plot.

Kerr (2011) reported that species such as alder, ash (*Fraxinus excelsior* L.), birch (*Betula* spp.) and sycamore (*Acer pseudoplatanus* L.) have potential in Britain for SRF

Figure 3: *Transverse sections (left to right) of a 3-year-old harvested stem showing basal (3 years old), mid-section (2 years old) and upper section (1 year old) growth. Note that the stem void area decreases as the tree matures.*

to yield between 5.0 and 7.4 t DM ha^{-1} $year^{-1}$ on a 20-year rotation. Woods (2008) pointed out that *Paulownia* in Georgia in the US can produce 8.4 t DM ha^{-1} in 16 months and Duran-Zuazo *et al*. (2013) reported that *Paulownia* in Spain can provide an average biomass yield of 10.6 t DM ha^{-1} in 24 months. Nevertheless the prediction made by Woods (2008) from a literature review assessment of its potential as a biomass crop, that *Paulownia* trees planted in NI would yield 15 t DM ha^{-1} of biomass yield after three years, is not supported by the results in this study.

Dry matter content of freshly harvested wood varies considerably depending on species, age and time of year and is an essential factor for energy efficiency of potential biomass crops (Forbes *et al*. 2014). Most Spanish genotypes had about 10% lower DM content than those reported for willows and miscanthus cultivated in NI (Dawson 2007, Easson *et al*. 2011), however DM of Moroccan genotypes were more similar. In general *Paulownia* has a DM of 40% when planted in different climatic conditions such as US and Spain (Woods 2008, Latorre *et al*. 2011).

Overall, the genotypes from Spain showed a tendency to produce more shoots than the other genotypes. Although it is strongly recommended (Young pers. comm.[1]) that *Paulownia* trees should be cut back to ground level to promote the formation of new shoots during the second year when trees reach a minimum diameter of 7 cm, this operation was not carried out in this study as trees did not reach that threshold. This practice is also recommended for SRC crops such as willow and poplar in Britain and Ireland to encourage the formation of multi-stemmed stools in the following growing season (Tubby and Armstrong 2002, Wickham *et al*. 2010). It has been reported (Lyons 1993) that *Paulownia* trees can produce 1 to 6 shoots after cutting back following the first year to induce new coppice growth. The early assessment in these trials in NI showed that the numbers of primary shoots is a key component of the growth pattern of *Paulownia* from both origins and its potential use as an energy coppice crop. Willow crops produce on average one to three shoots after the first growing season and poplar 1 or 2 shoots and both species produce multiple stems after being cut back (Tubby and Armstrong 2002, Dawson 2007). Spanish and Moroccan *Paulownia* genotypes produced an average of 6 and 4.5 shoots, respectively, after three growing seasons which would show some potential for coppicing, although it would need to be examined further.

Chemical characteristics

In general there are several factors such as storage and processing that affect the chemical characteristics of biomass crops (Forbes *et al*. 2014). Despite there being large statistical differences in growth characteristics of Spanish varieties, overall the chemical characteristics were similar to those reported for other energy crops including *Paulownia* (Cuiping *et al*. 2004, Latorre *et al*. 2011, Forbes *et al*. 2014) except for N and ash content.

[1] Mr Nigel Young, World Paulownia Europe Ltd, England. 2009.

Forbes *et al*. (2014) reported that within a group of six biomass fuels, willows had the highest content of N (5.7 mg kg^{-1}) which is lower than that found for *Paulownia* in this study (Tables 6 and 7). Ash content of *Paulownia* also appears to be much higher than those reported for *Paulownia* (Cuiping *et al*. 2004) and other fuel crops (Forbes *et al*. 2014). The ash content of *Paulownia* in this study ranged from 17.6 to 22.6 (g kg^{-1}) compared to 5.3 (g kg^{-1}) reported by Cuiping *et al*. (2004) which would suggest that the high N content played a key role in the ash-forming content of these young *Paulownia* trees. Latorre *et al*. (2011) also reported high contents of ash in three *Paulownia* species with high contents of carbonates and chlorates which are undesirable in biomass fuels.

Gross energy from *Paulownia* (Tables 4 and 5) was within the reported range of other biomass material (Forbes *et al*. 2014), particularly willows and miscanthus but was lower than *Pinus*, spruce and forest brash. The fixed carbon which is the residual fraction from pyrolised fuel after deducting ash (Villanueva *et al*. 2011) was also similar to those reported by Forbes *et al*. (2014), suggesting that *Paulownia* might be a suitable fuel. *Paulownia* from both origins (Tables 4 and 5) exhibited higher volatile content than other biomass fuels (Forbes *et al*. 2014), indicating a greater amount of hemicelluloses.

Regarding the thermo-gravimetric behaviour of *Paulownia*, the results showed that the degradation of *Paulownia* follows a closer pattern to willows, wood pellets and conifer material than miscanthus (Forbes *et al*. 2014). However, Villanueva *et al*. (2011), stated that *Paulownia* would exhibit less resistance to the increase in temperature compared to poplar, *Eucalyptus* and *Pinus*. In this study the temperature of degradation was similar to that reported by Villanueva *et al*. (2011) for 5-7 year-old *Paulownia* trees. Further, between the genotypes the percentage weight loss (PWL %) over time displayed similar patterns and the weight loss curves of the mean values for genotypes of both trials were almost identical (Figure 4).

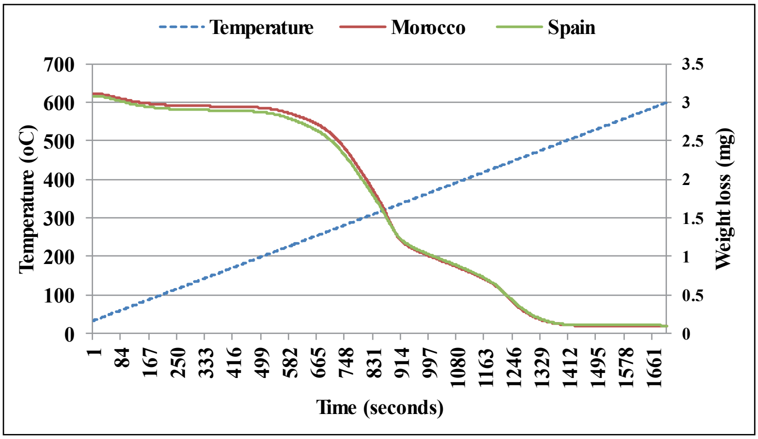

Figure 4: *Thermogram of the mean percentage weight loss (mg) of the Spanish and Moroccan genotypes.*

Conclusions

Survival and growth of *Paulownia* trees in NI could have been restricted by a range of factors including heavy soils and the cool, moist, wet and windy oceanic climate. Survival was satisfactory only for Spanish genotypes suggesting that these were more tolerant of the NI climate than Moroccan genotypes but *Paulownia* is still unlikely to be suited for general planting. The results re-iterate that the introduction and adoption of exotic tree species for either biomass or conventional forestry and their out-planting performance is a complex interaction of many factors, including origin, planting stock and climate.

The chemical characteristics of *Paulownia* trees in this study indicate their suitability for use as a biomass fuel, except for the high contents of N and ash which might have been as a result of a high proportion of juvenile material. Longer growing terms might increase their suitability for operational use.

Paulownia is already grown widely in a range of situations in Mediterranean, tropical and subtropical climates and its wood is a useful raw material for producing biomass fuel; however, the data in this study indicated that growth in NI is far from optimal. There is no clear evidence for their potential use in cool temperate climate and further information is required on performance of these and other genotypes on a wide range of sites. Although the findings cannot be generalised to the whole of Britain and Ireland, where some areas are warmer and sunnier than NI, the use of *Paulownia* as a potential biomass crop in NI appears to be limited and further research is required to provide long-term information on its field performance.

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