A characterisation of eucalyptus short rotation forestry plantations in Ireland

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Abstract
This paper details the characterisation of the biomass for use as a wood fuel of fifteen eucalyptus plantations (including twelve *Eucalyptus nitens* stands, two with *E. gunnii* and one with *E. delegatensis*) being grown on a short rotation in Ireland. Two of the plantations were mature (22 and 23 years old), while 13 of the plantations were more recently established (5 to 7 years old). Mortality rates were high, ranging from 11% to 62%. Trees were sampled and analysed for moisture content, ash content, calorific value, chemical composition (C, H, N, Cl, S) and ash melting behaviour. A biomass expansion factor was developed from the sample tree data to estimate total aboveground biomass from merchantable biomass and total height. Productivity on the measured sites ranged between 0.4 – 12.6 odt (oven dry tonnes) ha^{-1} yr^{-1} of aboveground biomass. The chemical composition analysis indicated that the eucalyptus trees tested had higher than typical values for chlorine content for bark, branch, tops, and foliage partitions, as quoted in EN14961-1, which may be problematic for some biomass boilers. Tests carried out on ash melting behaviour indicated that the wood and branch partitions have a low ash melting point. The results are somewhat limited, as the eucalyptus plantations in Ireland currently are either less than 10 years of age, or over 20.

Keywords: *Renewable energy, wood fuel characteristics, biomass partitions, biomass expansion factor.*

Introduction
The Department of Agriculture, Food, and the Marine (DAFM) recently implemented a new Forestry for Fibre scheme which aims to promote the planting of forests which can provide a clearfell crop within 10 – 15 years (DAFM 2015). The management objectives of such forests are to produce fibre material for use primarily in the panel board and wood energy markets rather than for sawn timber. This scheme, in combination with the Agro-forestry scheme, has a target of planting 3,300 ha by 2020. A clear distinction is made by this grant scheme not to include short rotation coppice or fast-growing trees that have a rotation of less than 10 years between harvests. The scheme is therefore supporting single-stem forests that will have stem dimensions larger than woody multi-stemmed energy crops such as willow coppice.

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This type of forest silvicultural system is referred to as Short Rotation Forestry (SRF) (Christersson and Verma 2006). The DAFM scheme supports a number of species including eucalyptus.

Legal obligations specified in the European Renewable Energy Directive (European Directive 2009/28/EC) set goals for Ireland to produce at least to 16% of all energy consumption from renewable sources by 2020. SRF could potentially help Ireland achieve this target, which will contribute to achieving energy security as well as protection of the environment through a reduction of greenhouse gas emissions.

In Europe, SRF has become increasingly attractive due to the increased demand for biomass (Johansson and Karačić 2011). Over 10 million m^3 of eucalyptus wood is consumed in southern European countries each year (DIEF 2000). Interest in the genus is also increasing in more northern countries. A recent study by Leslie et al. (2012) on the potential for eucalyptus as a wood fuel in the UK concluded that "the interest in using biomass as a source of energy has provided a catalyst for the re-examination of the potential role of eucalyptus in short rotation forestry in Britain". The British Forestry Commission have identified that eucalyptus in particular can produce biomass at a faster rate than many other species. Kerr (2011) reported that *Eucalyptus glaucescens* (Maid. and Blakeley) can produce 2.5 – 7.6 odt ha^{-1} yr^{-1}, and *E. gunnii* (Hook. f.) can produce 1.5 – 8.2 odt ha^{-1} yr^{-1} in the UK. This has been echoed in Ireland by Thompson et al. (2012), who concluded that "eucalyptus can play a role in providing a source of fibre or fuel to help meet the current demands for this material in Ireland". Thompson et al. found that three 17-year-old *E. nitens* ((Dean and Main.) Maid.) plantations produced mean annual increments (MAIs) ranging from 26.2 – 32.0 m^3 ha^{-1} yr^{-1}, equating to 11.4 –13.9 odt ha^{-1} yr^{-1}, based on their reported basic wood density of 435 kg m^{-3}.

In order to describe the qualities of a species for use as a wood fuel, a number of further parameters are required. Basic density Basic density, the dry wood mass per unit volume, expressed in kg m^{-3} (Thygesen 1994) is an important wood fuel characteristic, as it describes the amount of wood present per unit volume. The calorific value describes the energy content of the biomass per unit mass. The gross calorific value assumes that all water created in the combustion process is condensed and the heat of enthalpy is recovered (Serup and Kofman 2005). The net calorific value accounts for the loss of energy from the enthalpy of the water produced in the combustion. It is calculated using the hydrogen, nitrogen, and oxygen contents of the fuel (EN 14918: 2009). When the net calorific value and basic density are known, the energy content of any quantity of fuel at any moisture content can be calculated. The ash content of biomass is the inorganic, incombustible component. It is expressed as a percentage of the dry matter weight, % ash content on a dry basis (EN 14775: 2009). A high ash content means that less of the biomass is combustible as a fuel, and that there is more ash to be disposed of at the end of the combustion process. It is also important to characterise the ash melting behaviour as ash deposition may cause slagging and fouling of a boiler system (Coates et al. 2014). Slagging is the deposition of sticky, molten ash on the furnace walls and hottest parts of the boiler system which experience radiant heat transfer directly from combustion flames; fouling takes place in the relatively cooler parts of the system where flue gas and fly ash cool and form deposits, often on heat exchanger tubes. The chemical composition is important in the calculation of net calorific value, as described above. The chemical composition can also influence the usability of biomass as a fuel because of potential emissions and suitability for combustion under certain boiler configurations (Stam et al. 2009). Chlorine content is a concern for boiler operators, as high concentrations can cause corrosion of the boiler (SEAI 2004). Carbon, hydrogen and nitrogen are also important elements to quantify for carbon accounting purposes, as well as for life cycle analysis of biomass supply chains.

The objective of this paper is to characterise short rotation eucalyptus plantations in Ireland in terms of their survival, volume production and biomass dry matter production. In addition, the paper also describes estimates of wood fuel parameters such as calorific value, ash content, and ash melting behaviour – specific to various tree partitions. The concentrations of carbon, hydrogen, nitrogen, chlorine and sulphur are also reported. These parameters are known to be important characteristics of wood fuel allowing useful energy content to be described, and are also the characteristics which may limit their use under certain conditions.

Materials and methods

Spatial data were received from the Forest Service and Coillte GIS division to locate every eucalyptus plantation on record in Ireland. Information from previous publications was also used to identify older plantations. The data were filtered to identify sites five years and older. This was to ensure that the plantations visited were fully established. Within sites, areas were further stratified if considerable differences in height were apparent between stand areas. Each stratum was considered a separate site, and a full set of measurements were taken on each. Figure 1 displays the study site locations. Using British Forestry Commission inventory prescriptions (Matthews and Mackie 2006), between six and twelve plots were located in each study site depending on the area: 6 plots for sites of 0.5 – 2.0 ha, 8 plots for sites of 2 – 10 ha, and 10 plots or more for sites over 10 ha. The plots were located across the longest possible transect through each site. In each plot, the DBH of every tree was recorded, the total height of three trees were estimated using a digital hypsometer (Haglof Vertex IV Digital Hypsometer): the tree with largest DBH (for use in estimating top height), the tree whose DBH was closest to average, and the tree with smallest DBH[1]. In three plots per site, additional measurements were collected: for each of the three height trees, the base diameter, diameter at one third of total height and the height at 7 cm diameter were recorded with a Criterion (Lasertech Criterion RD1000), and the crown projection was measured using a densitometer (GRS Densitometer). In these plots, an ecological site classification of the sampling plots was carried out according to Ray et al. (2009). This involved the assessment of such parameters as soil type, soil water regime, and soil nutrient regime using a soil pit in each plot, and the identification of key indicator plants. The canopy cover at each site was estimated as a percentage of the ground area using a densitometer along three transects through the stand, as described by Geographic Resource Solutions (2016). The base diameter, DBH, upper stem diameter at one third total height, and height at 7 cm diameter were used with Smalian's formula to calculate timber volume. These data were used to develop a local basal area to merchantable volume equation (using a linear model) for each site. The equations were used with plot data to calculate merchantable volume per DBH measurement. The merchantable biomass for each DBH measurement was calculated by multiplying the merchantable stem volume by a basic density value obtained from felled sample trees (detailed below). The volume and biomass were summed in each plot to estimate the site totals.

On three sites, (one *E. delegatensis* (T.T. Bak.) site, and two *E. nitens* sites),

Figure 1: *Site numbers and locations of sampling sites. Asterisks mark sites where destructive sampling was carried out.*

[1] Inherent in this was the assumption that the tree had to have reached a minimum height of 1.3 m to have a DBH.

sample trees (n = 10 per site) were sampled to develop a biomass expansion equation which was applied to the other sites. Samples were also taken of tree partitions to characterise wood fuel parameters such as basic density, ash content, calorific value, chemical analysis and ash melting behaviour. The trees were felled by chainsaw. The total height, and the stem diameter at 1 m intervals up to merchantable height (7 cm diameter) were measured.

Sample trees were then partitioned into the following:

- stem: the wood and bark of the merchantable stem (≥7 cm diameter). This did not include branches.
- top: the wood and bark obtained from the un-merchantable stem section of the tree. This did not include branches.
- wood: the wood, free from bark of the merchantable stem.
- bark: bark only from the merchantable stem.
- live branches: wood and bark from live branches of the tree.
- dead branches: wood and bark from dead branches of the tree.
- foliage: leaves from live branches.

Disks were cut every three metres along the stem (Figure 2) and analysed for moisture content and basic density to estimate the biomass in the stem. The volume of the disks was determined by submersion in a water bath, and density was calculated as dry mass divided by green volume. The branches and tops were weighed, chipped on site with a Linddana TP200 chipper, and sampled for moisture content. For all partitions, the moisture content was determined by oven drying at 105 °C for 48 hours. The sample material from each partition from all trees was then mixed, divided and prepared to a particle size of less than 1 mm as set out in ISO 14778: 2011. For each of these mixed samples, ash content, expressed as percentage dry weight, was determined using a Carbolite muffle furnace at 550 °C, according to EN 14775: 2009. Gross calorific value was determined using a Parr 5500 oxygen bomb calorimeter, according to EN 14918: 2009. Carbon, hydrogen, nitrogen and sulphur content were measured using an Exeter Analytical CE 440 elemental analyser. Chlorine content was determined through a titrimetric method. Net calorific value was calculated from the equation in EN 14918: 2009:

$$NCV_{db} = GCV_{db} - 212.2 \times H - 0.8 \times (O + N) \qquad [1]$$

where:

H = the hydrogen content, in percentage mass, of the moisture-free (dry) biomass (including the hydrogen from the water of hydration of the mineral matter as well as the hydrogen in the biofuel substance);

O = the oxygen content in percentage by mass, of the moisture-free biomass;

N = the nitrogen content, in percentage by mass, of the moisture-free biomass.

The wood fuel parameter data is presented in tables for each partition along with the values quoted as typical in the EN Solid Biofuel Standards. The sample tree data has been used with non-linear regression to parameterise a single tree merchantable biomass to aboveground biomass model.

Figure 2: *Sampling* Eucalyptus delegatensis*. This involved sectioning stems and cutting disks for analysis.*

Results

Local merchantable volume and merchantable biomass equations

Figure 3 illustrates the local single tree basal area (m^2) to single tree merchantable volume (m^3) function for each site. These relationships were used to calculate the merchantable volume for each tree where only a DBH measurement was taken.

DBH to total height equation

A DBH to total height equation was developed from measurements taken from a total of 305 trees. A Chapman-Richards model form was used, as per Coates et al. (2012). The model form is as follows:

$$Total\ height = 1.3 + \beta_1 \times \left[1 - \exp\left(-\beta_2 \times DBH\right)^{\frac{1}{\beta_3}}\right] \quad [2]$$

where total height was estimated in metres and DBH in centimetres.

β_3 was set to 0.7, as per Coates (2012), as this gave a better fit when tested. The rest of the model was parameterised as follows: β_1 = 16.7116 (SEE 0.849), β_2 = 0.0478 (SEE 0.004). The function was also adjusted to localise to each sample plot by using the height and DBH of a tree per plot as inputs, as per Coates et al. (2012) as this allows the model to better predict for the other trees in the plot. Figure 4 illustrates the data and the fitted model. Using this equation, an associated height was estimated for every DBH measurement.

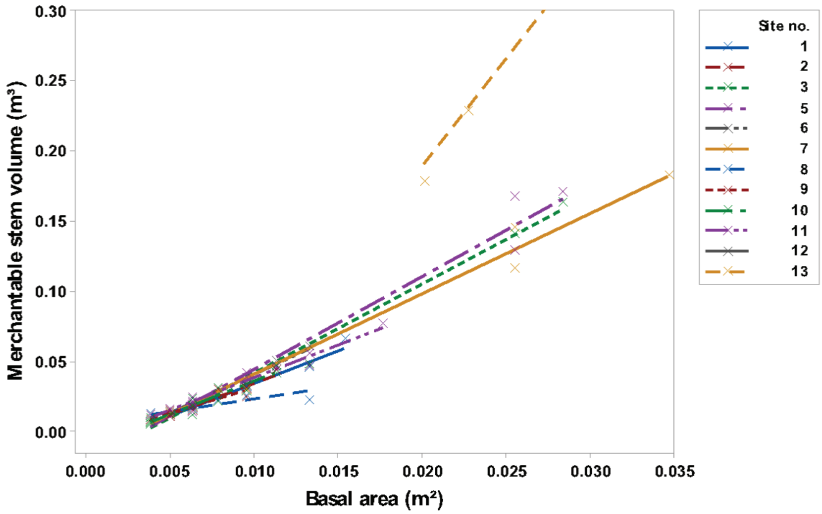

Figure 3: *Site-level single-tree relationships between basal area (m^2) and merchantable stem volume (m^3).*

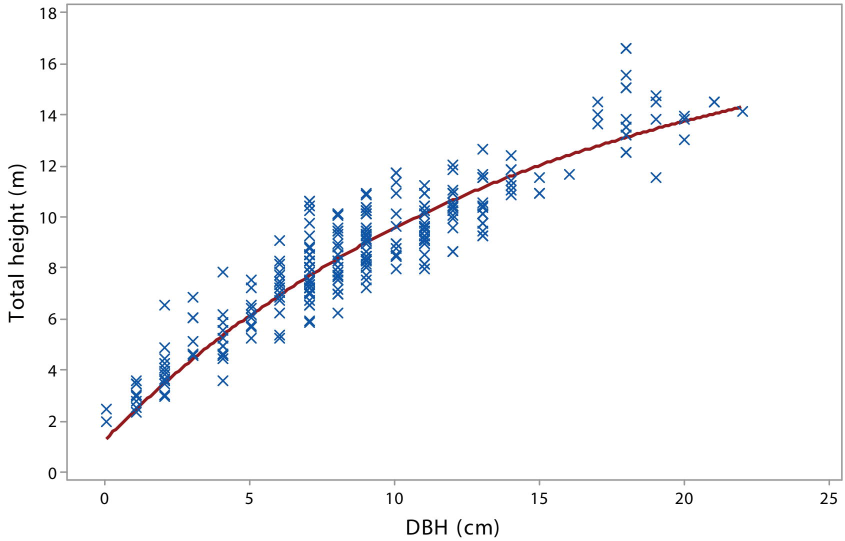

Figure 4: *Scatterplot of DBH (cm) and total height (m) fitted with a Chapman-Richards model.*

Single tree biomass expansion factor equation

A biomass expansion factor (BEF) is the ratio between merchantable stem biomass and total aboveground biomass. An equation to estimate single tree BEFs from total height was developed using regression analysis. A model form using the natural logarithm of tree height, as described by Levy (2004) for BEF modelling, was first fitted to the data. However, this model form was found to be unsuitable due to the limited range of the available data. Instead, an asymptotic convex model was fitted to the data using nonlinear regression. An asymptotic model form was chosen as the BEF cannot be less than 1, but should approach 1 as height increases and the stem forms an ever-larger proportion of aboveground biomass. The model form is as follows:

$$BEF = \beta_1 - \beta_2 \times \exp\left(-\beta_3 \times Total\ height\right) \qquad [3]$$

The asymptote (β_1) was estimated at a starting value of 1. The parameterisation of the model resulted in the following coefficients: β_1 = 1.07625 (SEE 0.027), β_2 = -12.6343 (SEE 3.603), β_3 = 0.2630 (SEE 0.0298). Figure 5 displays the data and fitted model. On each site, a BEF was calculated for every DBH measurement using the associated height estimate. This was then used to expand merchantable biomass estimates per tree to total aboveground biomass.

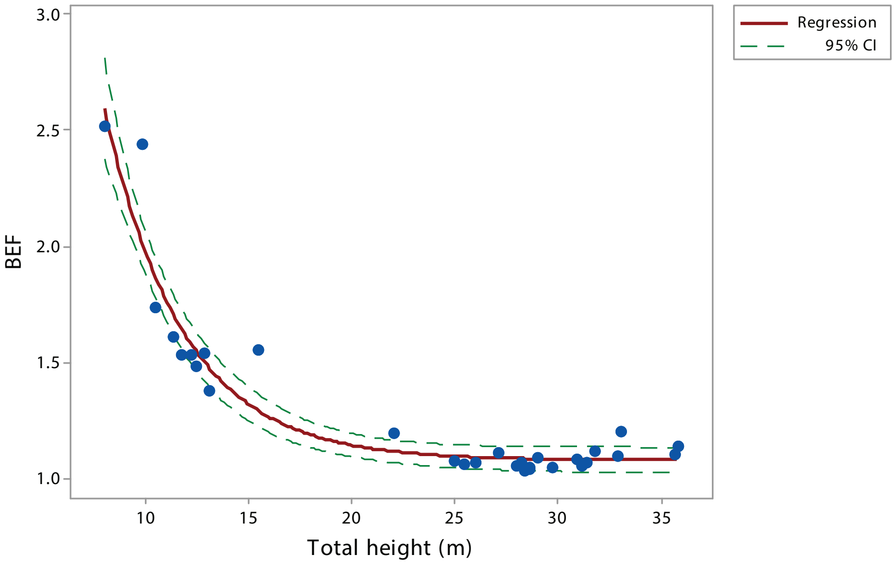

Figure 5: *Scatterplot of tree total height versus biomass expansion factor. The model fitted to the data was: BEF = 1.07625 + 12.6343 × e* $^{(-0.262992 \times \text{Total height (m)})}$.

Basal area to biomass equation

For trees which were less than 7 cm DBH, a separate formula was used to estimate their biomass. As these trees have no merchantable volume, a BEF cannot be used, so a direct relationship between basal area and aboveground biomass was formed from a small number of trees (n = 5). A simple straight-line equation explained the relationship with an R^2 of 98.1%. The equation of the model for estimating single tree aboveground biomass was as follows:

$$Aboveground\ biomass\ (dry\ kg) = 0.0305 + 2271 \times Basal\ area\ (m^2) \qquad [4]$$

Productivity Results

The sampling sites are described in Table 1 (including their ecological site classification), survival, top height and basal area. Fifteen sites were measured: twelve *E. nitens* sites, two *E. gunnii* sites, and one *E. delegatensis* site. It was found that the soil nutrient regime was poor to medium on all sites, and the soil moisture regime was dry to moist. The majority of the sites were five to seven years old, with two of the sites being more mature (22 and 23 years of age). All the stands visited had been established on reforestation sites. Tree mortality was relatively high, up to 62% mortality in the case of site number 4. The average mortality over all the sites was 28%. Even though the mortality was high for all younger plantations (5 – 7 years), only one standing dead tree was observed, indicating that mortality occurred early in the rotation. In the older plantations, 400 standing dead trees ha^{-1} were observed on site 13, while no data were recorded for site 12 due to windblow. Top height for the 7-year-old plantations ranged from 7 m to 13 m. The 22 and 23-year-old plantations had top heights of 28 m and 33 m, respectively.

Table 2 details the merchantable volume and biomass, residue biomass, and aboveground biomass estimates for all sites. Overall, the aboveground biomass productivity at the younger sites ranged from 0.4 odt ha^{-1} yr^{-1} to 6.4 odt ha^{-1} yr^{-1}. The most productive of these was site 5, which had 65 m^3 of merchantable standing volume after seven growing seasons. This equated to 27 odt ha^{-1} merchantable stem biomass. The quantity of (harvest) residues on this site were estimated as being 18 odt ha^{-1}. Therefore, the total aboveground biomass on the site was 45 odt ha^{-1}, indicating a productivity of 6 odt ha^{-1} yr^{-1}. The older sites had a productivity of 8.2 odt ha^{-1} yr^{-1} for site 12, and 12.6 odt ha^{-1} yr^{-1} for site 13.

The wood fuel parameters of the analysed partitions are detailed in Tables 3 and 4. Ash contents were higher than typically quoted wood biomass values for both stem and bark partitions. The ash content of the stem was 1.2%, slightly higher than the EN value range of 0.2% to 1.0%. The ash content of the bark was nearly twice the upper range of typical values quoted in EN literature at 5.7%. However, there was large variability in the samples, as reflected in the standard deviation. Gross and net calorific values for bark were lower than typical EN values, as would be expected from material with higher ash content. Contents of C, H, N, and O were as expected, with some small variability from typical values. Sulphur was also within the expected range for all partitions. Chlorine, however, was observed as being higher than the typical values for all partitions. The stem and wood partitions were both on average over twice the higher value of the typical range. The bark partition was observed as having a chlorine content of 0.34%, which is approximately seven times the typical EN value. The tops and live branches partitions were also approximately 6 – 7 times the typical EN value for residues. The foliage and bark were the two partitions with the highest concentrations of chlorine. The ash melting behaviour of the partitions, expressed as the mode of results, were all above 1,500 ^{o}C, except for the wood and the live branches partitions, which were both below 850 ^{o}C.

Discussion

Mortality was observed in all the study sites. On the 5- to 7-year-old sites, the percentage mortality ranged from 11 to 62%, with the average being 28%. There was no correlation between the canopy cover and the mortality, which was tested statistically

Table 1: *Soil, site and stand characteristics of the study sites. The tree species at sites 1 – 11 and 13 was E. nitens; site 12 was E. delegatensis and E. gunnii was growing at sites 14 and 15.*

Site (GS)[a]	Soil type[b]	Soil nutrient regime[c]	Soil moisture regime[d]	Elevation (m)	Surviving trees ha^{-1} (incl. <7 cm DBH)	Mortality (%)	Canopy cover (%)	Standing dead trees (n ha^{-1})	Stocking (trees >7 cm DBH)	Trees <7 cm DBH (n ha^{-1})	Top height (m)	Basal area (m^{2}ha^{-1})
1 (6)	BG/PG	P - M	F - M	189	1,600	36	43	0	1,330	270	10	9.9
2 (7)	LBE	M	M	168	1,414	43	44	0	771	643	9	5.3
3 (7)	LBE	M	M	173	1,863	25	66	0	1,250	613	13	11.3
4 (7)	BG	P - M	VM	168	950	62	22	0	210	740	7	1.1
5 (7)	LBE	M	M	169	1,400	44	48	0	1,213	187	13	14
6 (7)	LBE/BG	M	M	172	1,467	41	42	0	417	1,050	12	4.3
7 (7)	LBE	M	M	174	1,917	23	61	0	1,150	767	13	12.2
8 (7)	GI	P	SD	184	1,967	21	40	1	833	1,134	9	4.9
9 (7)	GBE/P	P	SD	151	2,217	11	53	0	1,100	1,117	9	6.1
10 (7)	GS	P - M	SD	171	2,100	16	52	0	1,138	962	10	7.7
11 (6)	PG	P	M	153	2,200	12	55	0	1,300	900	11	8.8
12 (22)	LBE	VP	MD	92	436	-	-	-	436	0	28	34.8
13 (23)	PG/SW	M	VM	180	842	-	-	400	842	0	33	49.8
14 (5)	PG	VP	M	223	2,200	12	25	0	0	2,200	5	NA
15 (5)	PG/SW	P - M	VM	243	1,783	29	36	0	67	1,716	6	0.28

[a] Growing seasons in brackets.
[b] Where BG is brown gley, PG is podzolic gley, LBE is loamy brown earth, GI is gravelly iron pan soils, GBE is gravelly brown earth, P is podzol, GS is gravelly, sandy brown earth and SW is surface water gley.
[c] Where VP is very poor, P is poor, VP is very poor.
[d] Where VM is very moist, M is moist, F is fresh, SD is slightly dry and MD is moderately dry.

Table 2: *Productivity estimates of the study sites.*

Site[a]	Age[b]	QMDBH (cm)	Average merchantable roundwood (m^3 per tree)	Merchantable roundwood (m^3 ha^{-1})	Stem basic density (kg m^{-3})	Merchantable stem biomass (odt ha^{-1})[c]	Residue biomass (odt ha^{-1})	Aboveground biomass (odt ha^{-1})	Productivity (aboveground biomass) (odt ha^{-1} yr^{-1})
1	6	11	0.02	31		13	15	28	4.7
2	7	10	0.02	15		6	12	18	2.6
3	7	11	0.04	44	412	18	16	34	4.9
4	7	8	0.01	2		1	4	5	0.7
5	7	13	0.05	65		27	18	45	6.4
6	7	12	0.04	18		7	9	16	2.3
7	7	12	0.04	50		21	17	38	5.4
8	7	9	0.02	13		5	13	18	2.6
9	7	9	0.01	16		7	15	21	3.0
10	7	10	0.02	23		9	15	25	3.6
11	6	10	0.02	30		12	17	30	5.0
12	22	32	0.88	385	435	167	13	180	8.2
13	23	27	00.8	666	394	262	27	289	12.6
14	5	0	0	0		0	0	2	0.4
15	5	8	0	1		0	0	5	1.0

[a] Species at sites: 1 – 11, 13: *E. nitens*; 12: *E. delegatensis*; 14, 15: *E. gunnii*.
[b] Growing seasons.
[c] Estimated using a basic density of 412 kg m^{-3} for site no.s 1-11, 14 and 15, 435 kg m^{-3} for site no. 12, and 394 kg m^{-3} for site no. 13.

Table 3: *Wood fuel parameters per tested partitions (standard deviations in parenthesis).*

Partition	Gross calorific value (GJ t^{-1})	Carbon content (%)	Hydrogen content (%)	Nitrogen content (%)	Chlorine content (%)	Sulphur content (%)	Oxygen content (%)	NCV (GJ t^{-1})
Stem	**19.2**	**46.40**	**5.70**	**0.18**	**0.08**	**0.010**	**46.41**	**17.96**
	(0.1)	(2.77)	(0.16)	(0.10)	(0.03)	(0.017)	(2.89)	
Bark	**17.7**	**46.09**	**5.38**	**0.40**	**0.34**	**0.017**	**42.04**	**16.56**
	(1.4)	(5.92)	(0.46)	(0.13)	(0.05)	(0.015)	(2.03)	
Wood	**19.4**	**48.64**	**6.12**	**0.19**	**0.07**	**<0.01**	**44.48**	**18.05**
	(0.3)	(2.54)	(0.23)	(0.04)	(0.03)		(2.23)	
Live branches	**19.9**	**49.92**	**5.85**	**0.51**	**0.14**	**0.013**	**41.39**	**18.61**
	(0.3)	(2.11)	(0.19)	(0.09)	(0.03)	(0.015)	(1.85)	
Dead branches	**19.5**	**48.51**	**5.92**	**0.32**	**0.10**	**0.007**	**43.87**	**18.21**
	(0.1)	(2.77)	(0.31)	(0.07)	(0.10)	(0.006)	(3.18)	
Tops	**20.1**	**48.68**	**5.97**	**0.55**	**0.13**	**0.017**	**42.25**	**18.81**
	(0.2)	(3.66)	(0.06)	(0.40)	(0.05)	(0.029)	(4.65)	
Foliage	**22.4**	**54.12**	**5.92**	**1.49**	**0.22**	**0.113**	**34.54**	**21.15**
	(0.5)	(3.42)	(0.15)	(0.14)	(0.04)	(0.042)	(3.71)	

Where Stem and Wood partitions refer to virgin materials with or without insignificant amounts of bark. Bark refers to virgin bark materials, and residues refers to virgin harvesting residues.
For reference, typical values are quoted from **EN14961-1** (including Gross Calorific Value (GCV) and Net Calorific Value (NCV) in MJ kg^{-1}, all other parameters on a percentage dry basis (db)): ***Stem/Wood****;* Ash: 0.2 to 1.0, GCV: 19.4 to 20.4, NCV: 18.4 to 19.2, Carbon: 48 to 52, Hydrogen: 5.9 to 6.5, Oxygen: 41 to 45, Nitrogen: <0.1 to 0.5, Sulphur: <0.01 to 0.05, Chlorine: < 0.01 to 0.03. ***Bark***; Ash: 0.8 to 3.0, GCV: 18.0 to 22.7, NCV: 17.1 to 21.3, Carbon: 47 to 55, Hydrogen: 5.3 to 6.4, Oxygen: 32 to 42, Nitrogen: 0.1 to 0.8, Sulphur: <0.02 to 0.20, Chlorine: <0.01 to 0.05. ***Residues*****:** Ash: 2 to 10, GCV: 19.5 to 20.0, NCV: 18.3 to 18.5, Carbon: 50 to 51, Hydrogen: 5.8 to 6.1, Oxygen: 40 to 43, Nitrogen: 0.3 to 0.8, Sulphur: 0.01 to 0.08, Chlorine: <0.01 to 0.02.

Table 4: *Wood fuel parameters per biomass partition relating to ash content (standard deviation in parenthesis) and deformation.*

Partition	Ash content (% db)	Ash deformation					
		Init. deform. (°C)	Soften. (°C)	Hemisph. (°C)	Flow (°C)	Rs (°C)	Slagging potential
Stem	1.2 (0.1)	>1,500	>1,500	>1,500	>1,500	>1,500	Weak
Bark	5.7 (4.7)	>1,500	>1,500	>1,500	>1,500	-	Weak
Wood	0.5 (0.3)	<850	<850	<850	<850	-	Severe
Live branches	2.2 (0.4)	<850	<850	<850	<850	-	Severe
Dead branches	1.3 (0.5)	>1,500	>1,500	>1,500	>1,500	-	Weak
Tops	2.4 (0.6)	>1,500	>1,500	>1,500	>1,500	>1,500	Weak
Foliage	3.6 (0.6)	>1,500	>1,500	>1,500	>1,500	-	Weak

Init. deformation refers to initial deformation temperature, where the test piece shows the first signs of rounding due to melting. Soften. is the the softening temperature, where the height of the test piece is equal to its width. Hemisph. is the hemisphere temperature, where the test piece has melted sufficiently to form a hemisphere. Flow refers to the temperature where the test piece has effectively melted. Rs refers to the slagging index.

with regression analysis, which suggests that the mortality was not a response to light competition. There was also only one dead tree observed on any of these sites, indicating that the mortality had occurred either during or shortly after planting. The exceptional weather events of 2010, where temperatures fell below -12 ^{o}C in counties Waterford and Cork, could have contributed to the mortality. Another source of mortality may have been poor plant handling during establishment. According to the Forestry Programme 2014 – 2020, for grant aid purposes, the stocking of eucalyptus plantations must be maintained at a minimum of 80% over the ten years of premium payment. This was not achieved by nine out of the thirteen plantations, so they would not be eligible to receive premium payments due to mortality if they were planted as part of the Forestry for Fibre afforestation scheme. These mortality rates are likely to be affecting the productivity on the sites in some cases. However, as discussed by Thompson et al. (2012), the optimal stocking for volume production for eucalyptus in Ireland may lie somewhere between 1,800 and 2,000 plants ha^{-1}. Considering Thompson's recommendations, it may be the case that even with high mortality rates, the appropriate stocking level is being achieved on eight out of thirteen of the newly planted sites.

Two more observations were also made which may be relevant to the plot growth recorded. On each site the trees planted directly adjacent to windrows were distinctly larger and had suffered lower mortality. It appeared possible that the release of nutrients, or shelter effect, from the windrows had greatly increased the diameter and height of these trees as can be seen in Figure 6 (left). This was a feature seen on all of the young plantations (windrows were not observed on the older plantations). Insect damage was also observed, caused by the beetle *Paropsisterna selmani* (see Figure 6, right). This damage was widespread and was evident on all the young *E. nitens* plantations, but was not observed on the older plantations. Only a visual record of presence was made, but the damage appeared to affect all the trees inspected on the sites. According to Bars (2013), such damage could cause up to a 50% reduction in volume production.

The productivity on the sites ranged from 0.4 – 12.6 odt ha^{-1} yr^{-1}, depending on stand development. Unfortunately, there are no plantations in Ireland between 8 and 21 years old, and so an understanding of the productivities for the recommended rotation length of 10 – 15 years has not been estimated. Thompson et. al. (2012) observed productivities of 11 – 14 odt ha^{-1} yr^{-1} in Irish plantations of 16 to 28 years of age, which are similar to the older plantations observed here. Kerr (2011), reported that, on a short rotation in the UK, *E. glaucescens* can produce 2.5 – 7.6 odt ha^{-1} yr^{-1}, and *E. gunnii* can produce 1.5 – 8.2 odt ha^{-1} yr^{-1} for rotations of less than 10 years. The majority of the younger plantations here in this study were achieving within this range, with the exception of site 4, which has suffered high mortality, and 14 and

Figure 6: *Left: A seven-year-old* Eucalyptus nitens *plantation in Kilmacthomas, Co. Waterford (sample site no. 6). Note the change in size of trees with proximity to the windrow. Right: Leaf damage caused by* Paropsisterna selmani *in Kilworth, Co. Cork (sample site no. 1).*

15 which had only 5 growing seasons. This indicates that the eucalyptus resource in Ireland is performing similarly to the UK, where it has been evaluated by Kerr (2011) that eucalypts have (along with Rauli) the highest potential productivity of any SRF species they reviewed, including Italian alder, red alder, hybrid aspen, sycamore, silver birch, ash, and sweet chestnut. This suggests that the plantations in Ireland are performing well, and may when harvested, be a valuable resource in terms of biomass, but also for the quantification of SRF potential in Ireland.

There may be concerns with how fit for use as a feedstock into biomass boilers some of the eucalyptus partitions are, due to the chemical makeup of the wood and residues. The high chlorine levels of all partitions compared to the EN typical values suggests that there may be issues for some boilers in burning eucalyptus because of the corrosive potential of chlorine. For example, Bord na Móna Edenderry co-fires biomass with peat and has a fuel specification limiting maximum chlorine content to less than 0.1%, expressed on a dry matter basis (O'Halloran 2013). This would mean that eucalyptus residues would not be suitable for co-firing in such a power plant

A further aspect of note, with regard to the fuel specification, was the ash melting behaviour. Ash deformation point was observed as being above 1,500 °C for all partitions except for the wood and the live branches partitions. Interestingly, the results show that the wood partition material has potential to produce severe slagging with a deformation temperature of below 850 °C, whereas the stem partition, which is wood *and* bark, had a much higher deformation point, above 1,500 °C, and a weak potential for slagging. Bord na Móna Edenderry specifies fuel intakes with a minimum ash melting point of greater than 1,000 °C. Therefore, due to the chlorine content and ash melting behaviour of the samples tested, the only partition suitable for co-firing in the Edenderry power plant would be the stem partition. However, this would not be the case for all boilers, and some are chlorine resistant or operate at lower temperatures which allow for higher chlorine levels. Also, as can be seen from Figure 6, as the stands increase in height, the proportion of the residue to total biomass reduces. In the older plantations, this has been estimated as being 7 – 9%, whereas, as expected, in the 7-year-old plantations, it is estimated as being in the region of 40 – 80%. Therefore, the implication of the chlorine content of the genus will be less as the stands age.

Conclusions

It was observed that the potential for biomass yields in Ireland will be in the region of 6.4 odt ha^{-1} yr^{-1} at age 7, rising to 12.6 odt ha^{-1} yr^{-1} at age 23. Comparing this to literature from the UK, it can be stated that the plantations in Ireland are performing well.

The mortality rates were high. The average mortality rate was 28%, and ranged from 11% to 62%. There was only one standing dead tree identified in the 5- to 7-year-old plantations, indicating that mortality had occurred very early in the rotation, possibly due to the exceptionally low temperature events of 2010.

The analysis of sample tree partitions identified that the bark, branches, tops, and foliage may be unsuitable for combustion in certain boilers due to the high levels of chlorine and potential for slagging. This has implications for markets for eucalyptus biomass, particularly as the branches, tops, and foliage are the partitions which make up logging residues, a commonly used wood fuel product. If there is a significant amount of this material being mobilised in the future, then boilers should be configured appropriately to accept it.

A biomass expansion factor equation was developed for the analysis within this paper. This model should be transferable for other stakeholders who wish to make biomass estimates of eucalyptus plantations in the future.

The lack of data from plantations aged 8 – 21 years has restricted the development of productivity estimates for the likely range of harvest years. The biomass expansion factor has been formulated to give first estimates of biomass for eucalyptus in Ireland, but more data should be added as it becomes available.

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