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WILLOW PRODUCTIVITY ON A COMMERCIAL PLANTATION IN TRIENNIAL HARVEST CYCLE

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Abstract

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Biomass is a renewable energy source which is easily available around the world. Lignocellulosic biomass is now increasingly often used in developed countries. It is also an important feedstock in the chemical industry. It is used to produce high quality industrial products: polymers, bioethanol from hemicellulose, activated carbon and vanillin etc. Willow (*Salix* spp.) can be successfully used as feedstock in an integrated multi-product biorefinery. The objective of this study was to determine the productivity of new varieties and clones of short rotation willow coppice on a commercial plantation, with its product intended for an integrated multi-product biorefinery. A willow plantation of the area of 10.5 ha was established on April 2010 at the Educational and Research Station in Łężany, belonging to the University of Warmia and Mazury in Olsztyn (north-eastern Poland). Among the studied cultivars, UWM 043 showed the highest survival rate (15 278 plants ha^{-1}). Significantly, the lowest number of plants (7 833 plants ha^{-1}) survived in the case of clone UWM 155. The highest plants were developed by clone UWM 006 and the lowest by Tur variety. The yield of dry matter ranged from 2.79 to 14.23 Mg ha^{-1} yr^{1} d.m. for clones UWM 155 and UWM 006 respectively. The average calorific value of the willow yield was 369.86 GJ ha^{-1}. Considering the highest biomass yield, the highest calorific value was achieved for the UWM 006 clone. It may be concluded that the clones UWM 006 and UWM 043 should be recommended for cultivation with a view to supplying large amounts of lignocellulosic biomass for integrated biorefinery.

Key words: willow, new varieties and clones, yield, biometric features, calorific value of the yield, lignocellulosic biomass

Introduction

Biomass is a renewable energy source which is easily available around the world. For a long time, it was regarded as a fuel for the poor and used in primitive or simple energy installations. Lignocellulosic biomass is now increasingly often used in developed countries. Wide-ranging studies are under way to develop a method of producing bioethanol from lignocellulosic biomass and using agricultural residues as a second generation biofuel, because most biofuels are still produced from sugar cane and maize, using traditional fermentation and biodiesel is produced from traditional annual oil crops (Cheng and Timilsina, 2011; Jefferson et al., 2004; Sanderson et al., 2006). Lignocellulosis is also an important feedstock in the chemical industry. It is used to produce high quality industrial products: polymers, bioethanol from hemicellulose, activated carbon and vanillin (Doherty et al., 2011; González et al., 2009; Hossain and Boyce, 2009; Sagehashi et al., 2006). Willow coppice is one of the sources of lignocellulosic biomass used to produce energy. Being an inedible plant, it can be grown on marginal land or those contaminated or potentially fertilised with sludge (Hangs et al., 2011; Labrecque and Teodorescu, 2001). Biomass obtained from such plantations can be successfully used as feedstock in an integrated multi-product biorefinery (Aresta et al., 2012; Moshkelani et al., 2013) due to its high biomass yield per hectare, usually 10-15 Mg ha^{-1} $year^{1}$, sometimes even more than 20 Mg ha^{-1} $year^{1}$ (Adegbidi, Volk et al., 2001; Stolarski, 2011; Stolarski et

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al., 2008; Wang and MacFarlane, 2012). Many studies are being conducted around the world on integrated multi-product biorefineries. The EuroBioRef project is one of them. This project will develop a new highly-integrated and diversified concept, including multiple feedstocks (non-edible), multiple processes (chemical, biochemical, thermochemical) and multiple products (aviation fuels and chemicals). The EuroBioRef concept achieves integration across the whole system (from feedstock to product diversification) and adapts to regional conditions and integrates with existing infrastructures to minimize the risk to investors. This highly flexible approach allows widening bio-refinery implementation across the full geographical range of Europe and offers opportunities to export bio-refinery technology packages to other local markets and feedstock hotspots (EuroBioRef, 2013).

The aim of this study was to determine the productivity of new varieties and clones of short rotation willow coppice on a commercial plantation, with its product intended for an integrated multi-product biorefinery.

Materials and Methods

A willow plantation of the area of 10.5 ha was established on April 2010 at the Educational and Research Station in Łężany, belonging to the University of Warmia and Mazury in Olsztyn. It is located in north-eastern Poland near Samławki (53°59′N, 21°05′E). The field experiment covered three varieties and four clones of willow (*Salix* spp.), all created by the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn: *Salix viminalis* varieties Start, Tur, Turbo; *Salix viminalis* clones UWM 006, UWM 043; clone UWM 035 *Salix pentandra*; clone UWM 155 *Salix dasyclados*.

The plant density was 18 000 per ha. A strip planting system was applied, in which 2 rows in a strip were arranged at an inter-row distance of 0.75 m, with an inter-row of 1.50 m for separation from the next 2 rows in a strip (with an inter-row distance of 0.75 m, etc.) and the distance between the plants in a row was 0.50 m.

The forecrop for the willow plants was triticale. The following measures were carried out in the preparation of the field for willow plants: spraying with Roundup in order to destroy perennial weeds (4 L ha^{-1}), ploughing, harrowing, soil cultivation with a cultivation unit, sowing of the PRP Sol fertilizer (dose 300 kg ha^{-1}), planting of cuttings, spraying with a soil-applied herbicide (Guardian Complete Mix 664 SE - 3.5 l ha^{-1}), spraying with a herbicide for monocotyledonous weeds (Targa Super 2.5 l ha^{-1}), mechanical and manual weeding in some areas of the plantation (x2). The nitrogen fertilization of the willow was not applied in the first year of vegetation. In the second year of plant growth (2011), nitrogen was sown in the form of ammonium nitrate just before the start of plant vegetation at the dose of 50 kg ha^{-1}. The second part of the nitrogen dose (40 kg ha^{-1}) was applied in the fourth week of May.

The Procedure for Determining Plant Density, Biometric Features and Willow Yield

Four plots were delimited in the area on which each of the cultivars and clones were grown (each with an area of 75 m^2) to determine the plant density and perform the biometric measurements. Before the plants were harvested after the third vegetation period (in 2012), the plant density per 1 ha was determined. The percent of plant loss was determined three years after the plantation was established. Moreover, 20 plants were selected at random at every plot, in which the number of live stems was determined and their height and diameter were measured (the measurement was made 0.5 m above the soil surface).

After the third year of vegetation, in December 2012, willow plants were harvested with a Class Jaguar harvester. The harvester put the chips on a tractor trailer. The trailer with chips from different cultivars was subsequently weighed and the yield of fresh biomass was calculated (Mg ha^{-1}). The yield of dry biomass, (Mg ha^{-1}) was calculated from the moisture content and the fresh biomass yield. The yield calorific value (GJ ha^{-1}) was calculated as the product of the fresh biomass yield and its lower heating value. Furthermore, its coal equivalent was calculated, assuming that the average lower heating value of 1 Mg of hard coal was 25 GJ^{-1}.

Statistical Analysis

The results of the tests were analysed statistically using STATISTICA PL software and the mean arithmetic values of the examined characteristics were calculated. Homogeneous groups for the examined characteristics were determined by means of an SNK (Student-Newman-Keuls) multiple test with the significance level set at $p = 0.05$.

Soil Site

Soil of low quality and usefulness for typical annual crops was selected for the willow plantation. The selected relatively poor soil site allowed the willow yield potential to be evaluated in areas of little use for food or feed crops. The area on which the experimental plantations were located is undulating and very diverse as to heights. Height differences amount, on average, to about 1.5 m, and they reach up to 3.5 m.

The conducted soil analyses showed that the willow plantation was located mainly on soil created from slightly loamy sand and light loamy sand (Table 1). Generally, the land in elevated areas causes the soil to be permanently too dry and the groundwater level is far below 150 cm. On the other hand, short-lived, isolated still water bodies form in troughs in that area during precipitation events. According to the classification of soils in Poland, mainly soils of the 4th, 5th and 6th quality class of arable land occur in that area (the soil classification system in Poland ranges from 1 – the best to 6 – the worst).

The soils were characterized by a slightly acid to base reaction (pH_{KCl} 5.65-7.44) (Table 1). Nutrients for plants were present in the soil in different forms and amounts. From the perspective of plant nutrition, the most important group are the available or assimilable nutrients, which consist of the amounts of the element present in the soil solution, sorption complex and the occurrence in the form of weakly-soluble salts. The macronutrient content in the studied soil varied widely. Generally, slightly loamy sand was the poorest. The P_2O_5 content ranged from 54-182 mg kg^{-1} of soil and the K_2O content ranged from 87-195 mg kg^{-1}. The micronutrient content was also varied (Table 2). Generally, in the evaluation of richness in assimilable nutrients, the studied soils showed from a medium-to-very high content of some elements in the topsoil. The relatively rich soil in its topsoil results mainly from its ploughing and the large amounts of fertilizer applied earlier to cereal crops grown in the area.

Climate Condition

It was found that the years 2010-2012 (in which the experiment was conducted) were close to the multi-year period 1998-2007 (Figure 1) in terms of the air temperatures across the entire plantation. The largest temperature differences between individual years were recorded in the winter. The average air temperatures in individual vegetation periods were similar. The warmest vegetation period was in 2011 (14.4°C) and the coldest was in 2012 (13.5°C). The hottest month of the vegetation period was July, when the average air temperature ranged from 18.5°C in 2011 to 21.4°C in 2010. October was the coldest month of the vegetation period and February was the coldest month of the year.

The rainfall in 2010-2012 varied compared to the same values from the multi-year period. The rainfall in 2011 was lower by 68 mm than the rainfall in the multi-year period, whereas in 2010 and 2012 they were higher by 95 and 138 mm, respectively. The rainfall in each of the vegetation periods 2010-2012 was higher than at the same time in the multi-year period, but its distribution varied significantly. The rainfall in April in 2010 and 2011 was lower than at a similar time during the multi-year period, which undoubtedly may have restricted the initial growth of plants, especially in the year when the plantation was established (2010). The highest rainfalls were recorded in July 2011 and 2012 and were higher by 200% and 184%, respectively, than in 1998-2007.

Results

The number of willow plants at the end of 2012 reached an average of 13 556 per ha and the value of standard devia-

Table 1
Soil formation, its pH and assimilable forms of selected macronutrients in the topsoil (Ap, 0-20 cm)

Profile No.	Soil formation	pH_{KCl}	P_2O_5	K_2O	Mg	B
			mg kg^{-1} of soil			
1	light loamy sand	6.75	182	195	74	11.5
2	slightly loamy sand	7.44	54	87	45	8.8
3	light loamy sand	7.20	128	184	88	108
4	sandy clay	5.65	99	195	84	3.3

Table 2
Assimilable forms of selected micronutrients in the topsoil (Ap, 0-20 cm)

Profile No.	Mn	Cu	Zn	Fe	$N\text{-}NO_3$	$N\text{-}NH_4$	$N\text{-}NO_3$+ $N\text{-}NH_4$	$N\text{-}NO_3$ $N\text{-}NH_4$
	mg·kg^{-1} of soil							
1	186.8	2.5	12.8	1 650	6.87	0.36	7.23	19.08
2	206.8	2.1	8.2	1 100	8.15	1.68	9.83	4.85
3	222.4	3.1	8.2	1 450	7.03	1.30	8.33	5.41
4	116.6	2.6	5.9	1 250	6.46	0.55	7.01	11.75

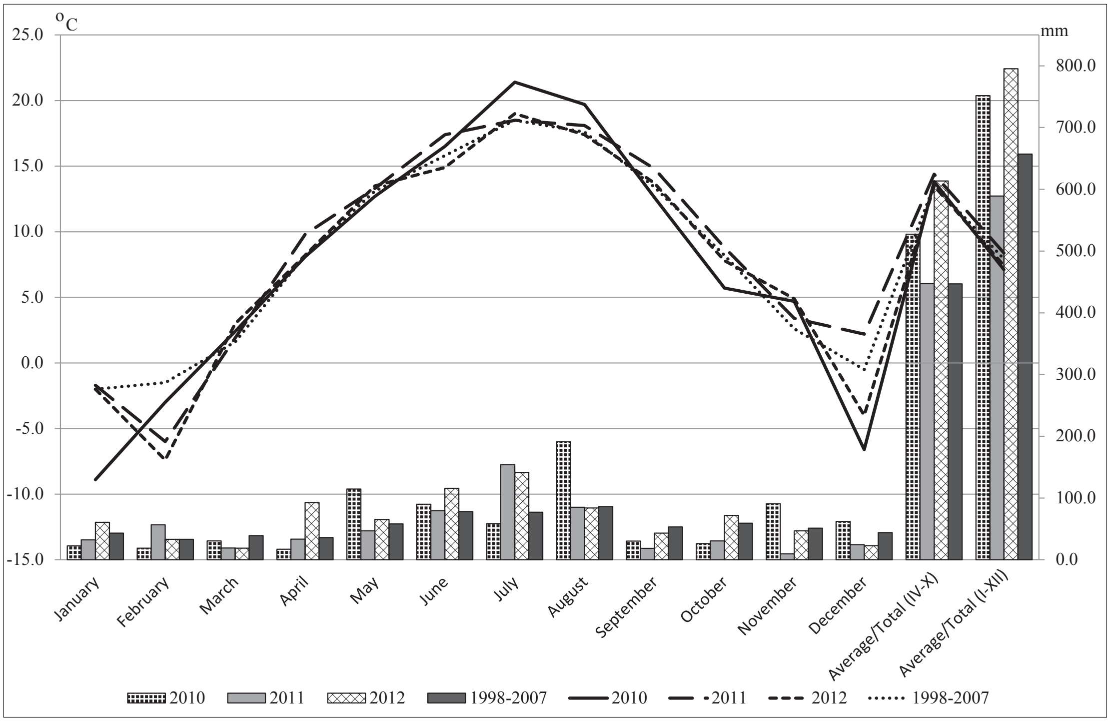

Fig. 1. Climate conditions during the experiment period 2010-2012 and multi-year period 1998-2007; bars represent participation; curves represent air temperatures

tion amounted to over 2 558 plants ha^{-1} (Table 3). Among the studied varieties, UWM 043 showed the highest survival rate – 15 278 plants ha^{-1}. The Start, Turbo and UWM 006 varieties belonged to the same homogeneous group. The Tur and UWM 035 were allocated to the second homogeneous group. Significantly, the lowest number of plants (7 833 plants ha^{-1}) survived in the case of clone UWM 155.

It was also found that willow plants losses after the third year of vegetation were high and amounted on average to 24.7% (Table 3). The value of this feature ranged from 15.12% for UWM 043 to as much as 56.48% for UWM 155. Such high losses resulted due to low precipitation in April 2010, the year of plantation establishment. The very high losses of clone UWM 155 resulted from a drought and damage from a soil-applied herbicide.

The average number of stems in the experiment amounted to 2.68 (Table 4). The (significantly) highest number of stems was found for clone UWM 155 (6.3). Meanwhile, for varieties and clones, the numbers of stems ranged from 1.60-3.15.

The height of the willow plants at the end of the third vegetation season reached an average of 4.99 m in the experiment and the value of standard deviation amounted to 1.35 m (Table 4). The highest plants were developed by clone UWM 006 (7.28 m). The plants of clone UWM 043 were approximately 0.7 m shorter. The lowest plants were produced by Tur variety (3.38 m). The Tur stems were grazed by wild animals in wintertime which resulted in branch propagation, but a low increase in height.

The diameter of the main willow stem averaged 31.86 mm (Table 4). The plants of clone UWM 006 had the thickest stems (48.60 mm on average) and the value of standard deviation amounted to 1.61 mm. The second group in that feature included the clone UWM 043. The Tur variety developed the thinnest stems after the third year of vegetation (18.85 mm).

After the third year of growth, the yield of willow was measured. The average fresh mass of one plant amounted to 3.15 kg (Table 5). The value of this feature varied between 1.56 and 5.84 kg for Tur and UWM 006, respectively. The yield of fresh biomass for these clones was 20.92 Mg ha^{-1} and 86.37 Mg ha^{-1}, respectively. The yield of dry matter amounted on average to 21.76 Mg ha^{-1}. Among all tested varieties, the highest yield was given by the clone UWM 006 (42.68 Mg ha^{-1} d.m.). The yield of dry matter of clone UWM 043 was approximately 8.18 Mg ha^{-1} lower. Start and Turbo varieties were allocated to third homogeneous group. After recalculation of obtained results to one year of plant cultivation, the yield of dry matter ranged from 2.79 to 14.23 Mg ha^{-1} yr^{1} d.m. for clones UWM 155 and UWM 006 respectively.

The average calorific value of the willow yield was 369.86 GJ ha^{-1}, which is equivalent to 4.93 Mg ha^{-1} yr^{1} of medium-

Table 3
Survival of willow plants after the third vegetation period

Variety or clone	Number of plants		Losses	
	plants ha^{-1}	stand. dev. (±)	%	stand. dev. (±)
Start	15 055.6 a	1 000.0	16.36	5.56
Tur	13 388.9 b	111.1	25.62	0.62
Turbo	15 055.6 a	420.7	16.36	2.34
UWM 006	14 777.8 a	462.6	17.90	2.57
UWM 035	13 500.0 b	1 138.6	25.00	6.33
UWM 043	15 277.8 a	584.4	15.12	3.25
UWM 155	7 833.3 c	458.1	56.48	2.55
Mean	13 555.6	2 558.1	24.69	14.21

a, b, c…- homogenous groups

Table 4
Number of stems, height and stem diameter of the willow plants after the third year of vegetation

Variety or clone	Number of stems		Height		Diameter	
	quantity	stand. dev. (±)	m	stand. dev. (±)	mm	stand. dev. (±)
Start	3.15 b	0.25	4.44 d	0.27	24.80 d	1.84
Tur	2.13 c	0.24	3.38 f	0.16	18.85 e	1.99
Turbo	1.75 c	0.34	4.84 c	0.25	33.25 c	4.90
UWM 006	1.60 c	0.28	7.28 a	0.28	48.60 a	1.61
UWM 035	2.15 c	0.50	4.41 d	0.20	32.70 c	1.78
UWM 043	1.70 c	0.26	6.60 b	0.21	40.25 b	1.34
UWM 155	6.30 a	0.12	4.01 e	0.04	24.60 d	0.85
Mean	2.68	1.60	4.99	1.35	31.86	9.85

a, b, c…- homogenous groups

Table 5
Biomass yield of willow after the third year of vegetation

Variety or clone	Fresh biomass one plant		Fresh biomass yield		Dry biomass yield		Dry biomass yield	
	kg	stand. dev. (±)	Mg ha^{-1}	stand. dev. (±)	Mg ha^{-1}	stand. dev. (±)	Mg ha^{-1} yr^{1}	stand. dev. (±)
Start	2.73 c	0.15	41.22 c	4.44	20.30 c	2.53	6.77 c	0.84
Tur	1.56 e	0.13	20.92 e	1.62	11.02 e	0.88	3.67 e	0.29
Turbo	2.83 c	0.32	42.65 c	4.92	20.34 c	2.51	6.78 c	0.84
UWM 006	5.84 a	0.17	86.37 a	4.85	42.68 a	2.45	14.23 a	0.82
UWM 035	2.21 d	0.15	29.96 d	4.23	15.13 d	2.19	5.04 d	0.73
UWM 043	4.59 b	0.46	70.21 b	8.66	34.50 b	4.26	11.50 b	1.42
UWM 155	2.29 d	0.21	17.87 e	0.75	8.37 e	0.39	2.79 e	0.13
Mean	3.15	1.44	44.17	24.43	21.76	12.02	7.25	4.01

a, b, c…- homogenous groups

Table 6
Calorific value of the yield and coal equivalent of willow biomass

Variety or clone	Calorific value of the yield		Calorific value of the yield		Coal equivalent	
	GJ ha^{-1}	stand. dev. (±)	GJ ha^{-1} yr^{1}	stand. dev. (±)	Mg ha^{-1} yr^{1}	stand. dev. (±)
Start	344.59 c	44.59	114.86 c	14.86	4.59 c	0.59
Tur	191.57 e	15.26	63.86 e	5.09	2.55 e	0.20
Turbo	341.54 c	43.55	113.85 c	14.52	4.55 c	0.58
UWM 006	727.40 a	43.35	242.47 a	14.45	9.70 a	0.58
UWM 035	259.66 d	37.45	86.55 d	12.48	3.46 d	0.50
UWM 043	585.39 b	72.09	195.13 b	24.03	7.81 b	0.96
UWM 155	138.83 e	6.96	46.28 e	2.32	1.85 e	0.09
Mean	369.86	204.58	123.29	68.19	4.93	2.73

a, b, c…- homogenous groups.

quality coal (Table 6). Considering the highest biomass yield, the highest calorific value was achieved for the UWM 006 clone (727.40 GJ ha^{-1}; 9.7 Mg ha^{-1} yr^{1} of coal). This was followed by UWM 043, whose calorific value was lower by 19.5%. The lowest calorific value was found for the UWM 155 clone (138.83 GJ ha^{-1}) which is equivalent to 1.85 t of high quality coal.

Discussion

Biomass yield depends on several factors, such as soil quality, species or cultivar, agrotechnology procedures and their quality, planting density and biomass harvest cycle. Apart from the productivity, it is affected by the plant survivability, which affects the total yield per hectare during the period of using the plantation (Tworkowski et al., 2010). This has been confirmed by the author's own research, in which the dry biomass yield ranged from 2.79 to 14.23 Mg ha yr^{1}. The willow was grown on soil with low usability for annual agricultural crops, with variable water availability because of the diverse lie of the land. The rainfall during the first month after the plantation was set up was small, which had a significant effect on the plant growth. According to studies by other authors, the plant yield largely depends on water availability. Willow should be grown on soil with the underground water table not lower than 150 cm. Despite a large demand for water, willow consumes much less of it than traditional field crops (Adegbidi et al., 2001; Borek et al., 2010; Faber, 2008). Stolarski (2009) observed that the yield variability was most affected by the number of plants per hectare, followed by the plant height, stem diameter and the number of stems per plant (in various order). This was confirmed by research results in which the lowest biomass yield of the clone UWM 155 was accompanied by the lowest survival rate of plants compared to other clones. The plant harvest cycle was also very important. The current paper presents the results for a three-year cycle, which is regarded as the optimum option in terms of biomass productivity (converted to a year of plantation use) and a lower consumption of the means of production (Stolarski et al., 2013). The average productivity of the dry biomass of the cultivars under study and willow clones was 7.25 Mg ha^{-1} yr^{1}. Studies by other authors have confirmed the high productivity of dry willow biomass, which may reach from around a dozen to over 20 Mg ha^{-1} year^{1} (Kopp et al., 1997; Kuś and Matyka, 2010; Labrecque and Teodorescu, 2003; Stolarski et al., 2011). However, these results were obtained in strict field experiments, whereas the dry matter yield on commercial plantations is usually smaller by 20-30% and it ranges from a few to 10 Mg ha^{-1} year^{1} (Bullard et al., 2002; Ericsson and Nilsson, 2006; Volk et al., 2006).

On experimental plantations in Sweden, a high yield of willow biomass was achieved – a result which could not be repeated on commercial plantations. The highest average yield (12 Mg ha^{-1} yr^{1} d.m.) was achieved on commercial willow plantations, which were not irrigated, in a three-year harvest cycle (Melin and Larsson, 2005). This relationship was confirmed by the data obtained from 1512 plantations in the years 1986 - 2000, where the average willow biomass yield was only 2.67 Mg ha^{-1} yr^{1} d.m. and the maximum yield reached 20.54 Mg ha^{-1} yr^{1} d.m. (Mola-Yudego, 2011). The typical yield of willow coppice on commercial plantations in the UK usually ranges from 6 to 10 Mg ha^{-1} yr^{1} d.m. (Bullard et al., 2002). The lower yield of commercial plantations is caused by difficulties with the selection and preparation of a field, errors in setting up a plantation, using random clones for planting, ineffective weed control and incorrect fertilisation (Tworkowski et al., 2010). However recent studies of Krzyżaniak, Stolarski et al. (2014) show that short rotation willow coppice could provide reasonable amount of lignocellulosic material. If cultivated varieties, described in this study, on 6810 ha of SRC plantation already functioning in Poland, they would provide over 22 300 tonnes of cellulose and nearly 15 200 tonnes of hemicelluloses a year for integrated biorefineries.

Conclusions

- It was found that willow plants losses after the third year of vegetation were high and amounted on average to 24.7%. The smallest losses were found for clone UWM 043 (15.12%) and the highest for UWM 155 (56.48%).
- The highest yield calorific value was achieved for the UWM 006 clone (727.40 GJ ha^{-1}; 9.7 Mg ha^{-1} yr^{1} of coal). The lowest calorific value was found for the UWM 155 clone (138.83 GJ ha^{-1}) which is equivalent to 1.85 t of high quality coal.
- The high biomass yield achieved in this study for the UWM 006 (14.23 Mg ha^{-1} yr^{1} d.m.) and UWM 043 (11.50 Mg ha^{-1} yr^{1} d.m.) clones indicates both their considerable usability for growing on commercial plantations in a three-year harvest cycle and high usability for growing on low-quality soils.
- It may be concluded that *Salix viminalis* clones UWM 006 and UWM 043 should be recommended for cultivation with a view to supplying large amounts of energy and lignocellulosic biomass for an integrated multi-product biorefinery.

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