Above-ground Biomass of Willow Energy Plantations in Lithuania: Pilot Study

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Abstract

Growing of willow (*Salix* sp.) plantations for energy production is an opportunity to get additional biomass-for-energy without increasing forest felling. This study objective was to create a non-destructive method for the estimation of aboveground yield of willows, which could be suitable for practical use in commercial short rotation willow plantations in Lithuania. Willow plantations of different 1–6-year old were chosen for the study. For the detailed measurements, the model stems and representative plant samples were taken.

A strong dependency between the dry aboveground biomass of willow stems and stem diameter (R^2 = 0.95) was determined and the model M = 0.0003 × $D^{2.4311}$ (where M is the dry biomass; D is the diameter at 55 cm above the ground; *a* and *b* are constants of regression parameters) was worked out for the estimation of dry above-ground biomass of willow plantations. The study results showed that the annual dry aboveground biomass of willows varied in a wide range, from 2 to 10 t ha^{-1} per year. The annual increment higher than 6 t ha^{-1} was found for the older than 4 years plantations grown in more fertile soil (sandy loam), which was additionally fertilized and weeded; also, these plantations had lower initial plant density. The obtained tendencies suggest that it would be reasonable to prolong the rotation period of willow plantations in order to increase annual yield. The study results also supported the idea that more fertile sites should be preferred for cultivation of the commercial willow plantations.

Keywords: *Salix* sp., short rotation, yield, non-destructive method

Introduction

The importance of biomass use for energy has been emphasized for several decades. The European Parliament in the Resolution on climate change noted that energy policy is a crucial element of the European Union (EU) global strategy on climate change, in which renewable energy sources play an important role. The active use of renewable energy sources is one of the key strategic objectives of the National Renewable Energy Development Strategy of Lithuania (2010) and the National Energy Independence Strategy of Lithuania (2012).

Bioenergy crops, as any plant material used to produce bioenergy, are grown specifically for the purpose to produce large volumes of biomass, have high energy potential, and adapt to marginal soils with low productivity (Lemus and Lal 2005). The cultivation of willow (*Salix viminalis* L.) plantations is one of the alternatives for the biomass energy-based forestry and is valued because of their potential for high biomass production in short time periods. Willow short rotation coppice systems are a sustainable method for fulfilling multiple ecological objectives with significant environmental benefits (Schweier and Becker 2013, Amichev et al. 2014), including their efficiency for sequestering carbon (Lemus and Lal 2005). The development of willow biomass enterprises has the potential to play an important role in diversifying and bolstering regional rural economies, increasing energy independence, enhancing environmental protection, and mitigating pollution problems (Snowdon et al. 2013). However, the annual yield of willow plantations should reach the economical break-even level at local scale.

The global area of planted willows comprises over 133,000 ha (Koller et al. 2014), but only 20 percent of these plantations have been used for energy production. In Europe, the total area of short rotation woody crops for energy plantations is relatively small and comprises about 39,200 ha (Don et al. 2014). For comparison, in Sweden, it is more than 16,000 ha of willows (Mola-Yudego 2010), in Germany – about 6,000 ha (Hauk et al. 2014), in Poland – about 8,700 ha (Mosiej et al. 2013), in Latvia – 1,200 ha Lazdina, personal communication), and in Estonia – about 140 ha (Heinsoo and Koppel 2007). Meanwhile, in Lithuania, the short rotation woody crops area is 3,027 ha with a willow plantation area of 2,477 ha (NMA, 2014). Lithuania has a relatively large area of woody energy plantations compared with above-mentioned countries. In order to properly implement the EU directive and the Lithuanian National programmes focused on increasing the use of renewable energy sources, it is relevant to know more exact amounts of biomass that can be obtained from the commercial energy willow plantations. It is rational to clarify the optimal and most effective harvest time of willows. In Lithuania to date, 66 percent of willow plantation owners have not harvested their first rotation crop (Konstantinaviciene and Stakenas 2015). Surveys such as that conducted by Keoleian and Volk (2005) have shown that willows typically reach their best growth 3–4 years after planting, when root systems are well established and more ūxed carbon can be allocated to above-ground biomass. Therefore, the reliable biomass quantities of willows at harvest, the harvesting time to reach the biomass suitability and economic viability, and prediction of yield are much debated questions.

Biomass production depends on climatic and site conditions, additional fertilisation etc. and more ūeld research is required to evaluate the growth potential of *Salix* over a period. For example, Sweden has developed a willow biomass model using non-destructive methods (Nordh and Verwijst 2004). These methods involve direct measurement of shoot heights or diameters of short rotation plants. Several authors indicate established allometric relations between various equation parameters, including height, diameter or shoot dry weight (Hoffman-Schielle et al. 1999, Verwijst and Telenius 1999, Heinsoo et al. 2002). A number of authors have shown willow studies in the Baltic region that were conducted during the recent decade (in Estonia – Heinsoo et al. 2002, in Latvia – Lazdina et al 2007, Āboliņa et al. 2014, in Germany – Schweier and Becker 2013, in Poland – Ericsson et al. 2006); however, far too little attention has been paid to the estimation of commercial willows in Lithuania.

This study aims was to create a non-destructive method for the estimation of aboveground yield of willows, which could be suitable for practical use in commercial short rotation willow plantations and improve the accuracy of estimations in Lithuanian conditions. More specifically, the objectives were to evaluate the optimal growing conditions of willow plantations and specify the most efficient harvest time.

Materials and Methods

Site description

The investigations were carried out in the Kaišiadorys, Švenčionys, Trakai, Kaunas, Alytus and Varėna forest districts, all situated in the central and southern parts of Lithuania during 2013–2015. The mean annual temperature was 6.5 ŗC and the mean annual precipitation was 686 mm.

Totally, thirteen willow (*Salix* sp.) plantations of different age (1–6-year-old) were selected subjectively to represent typical willow plantations within this area (Table 1). The study was performed in two stages: first six plantations were investigated in 2013–2014, the rest of them – in 2014–2015. The initial planting density of willow saplings was 12–18 thousand trees per hectare. The quantity of the stems grown in the study plots ranged from 14 to 88 thousand stems per hectare. The Swedish breed 'Tora' was grown in all studied plantations.

Table 1. The main characteristics of the sampled willow (*Salix* sp.) plantations

Plantation No.	Age, years	Planting density, thou. ha^{-1}	Stem density at sampling, thou. ha^{-1}	Fertilization, weed control	Plot number x plot area (m^2)	Number of model plants	Total stem number
1	5	12	88	+	1 x 20	31	178
2	3	12	66	+	3 x 20	70	400
3	5	12	86	-	2 x 20	63	349
4	4	12	54	+	3 x 22	95	350
5	5	12	48	-	3 x 25	35	360
6	6	12	46	-	3 x 21	31	294
7	4	12	38	+	6 x 22	12	500
8	5	12	36	-	6 x 22	12	475
9	3	18	47	-	3 x 31	12	442
10	4	18	24	-	3 x 31	12	226
11	1	18	14	-	1 x 31	10	45
12	6	14	36	-	3 x 31	12	336
13	2	12	39	-	6 x 22	12	506

The investigations were carried out in the sandy loam and sandy soils. To provide basic information about the soil, soil samples of the upper layers of mineral soil (0–20 cm and 20–40 cm) in 11 plantations (numbers 3–13) were drawn. The sample locations in the test plots were set out systematically by identifying the central point and the corners of the buffer zone of the plot. Five mineral soil samples were taken in each area (a total of 11 plots) from a 0–20 cm soil layer and three soil samples from a 20–40 cm soil layer. The soil samples were pooled to produce one composite sample from each depth and plot. A total of 22 composite samples were formed for the chemical analysis. Soil pH was measured with a glass electrode in the soil: water suspensions (1:2.5 W/W) in 0.01 M $CaCl_2$ for all soil samples collected. The concentration of total N was analysed according to the Kjeldahl method. The mobile potassium (K_2O) and mobile phosphorus (P_2O_5) were determined in soil samples using the Egner-Domingo (A-L) method. Chemical soil analyses were performed by the Agrochemical Research Laboratory of the Lithuanian Agriculture and Forestry Research Centre.

The parameter pH_{CaCl2} varied between 5.2 and 7.2 in a 0–40 cm mineral soil layer (from slightly acid, pH 5.2–6.0 to neutral, pH 6 and higher) and the soils had medium concentrations of nutrients in all studied willow plantations (Table 2).

Table 2. The main chemical parameters of soils in the studied willow (*Salix* sp.) plantations

Plantation No.	Soil texture	pH_{CaCl2}		P_2O_5, mg kg^{-1}		K_2O, mg kg^{-1}		Total N, %	
		Depth of sampling, cm							
		0-20	*20-40*	*0-20*	*20-40*	*0-20*	*20-40*	*0-20*	*20-40*
3	Sand	5.2	5.9	62	76	112	72	0.07	0.05
1,2 and 4*	Sandy loam	6.0	6.1	56	21	163	102	0.12	0.07
5	Sandy loam	5.7	6.2	25	89	130	100	0.21	0.09
6	Sandy loam	5.9	5.9	275	263	118	77	0.13	0.17
7	Sand	5.3	6.2	522	605	158	88	0.13	0.07
8	Sandy loam	6.9	6.8	399	271	338	139	0.16	0.09
9	Sandy loam	6.9	6.9	337	322	306	229	1.78	2.22
10	Sandy loam	6.8	7.1	226	241	220	120	0.20	0.17
11	Sandy loam	6.9	6.8	150	152	236	138	0.16	0.12
12	Sandy loam	6.8	7.2	265	219	224	104	0.17	0.07
13	Sandy loam	7.2	7.2	149	171	205	139	0.13	0.10

* All three plantations were situated next to each other in Kaišiadorys district, and the same soil type was represented.

Three plantations (numbers 1, 2 and 4; see Table 1) were fertilized with utility sludge (about 100 t ha^{-1} of water purification sediment) once during the growing period. They were weeded as necessary. One plantation (number 7) was fertilized with complex mineral fertilizers (100 kg ha^{-1}) twice during the growing period (in the first and second year). It was also weeded in the first and second year. No fertilization or weed control was carried out in other willow plantations.

Field measurements and sampling

The size of individual study plots was slightly different and varied between a range of 20-30 m^2, prioritizing necessary number of stems in individual plot. The total area of all plots amounted to 1,030 m^2. In total, 43 measurement plots were analysed. Within each plot, the stems were calculated and stem diameters were measured at a height of 55 cm above ground of all willow plants. The height of 55 cm for the diameter measurement was taken as a specified parameter for the short rotation plants reasonably used for similar studies (Telenius and Verwijst 1995, Verwijst and Telenius 1999, Heinsoo et al. 2002, Nordh and Verwijst 2004). By the end of the study period, totally 4461 stems were measured in the field.

In the first stage (2013–2014), the higher number of stems was sampled in order to determine the sufficient sample size. When more reasonable sample size was obtained, the stem sampling was limited to 10–12 model stems per plot in the second stage (2014–2015) of the study. Totally, 407 model stems were sampled. Selection of model stems was conducted to encompass the diameter range from each plot, i.e. taking the stems from the lowest to highest diameter groups within each plot. The model stems were sampled in a non-vegetative period. Height (length, cm), diameter (mm) at 55 cm above ground and weight (kg) were measured for each model stem. Stem height was measured with a tape measure with an accuracy of 1 cm.

For determination of moisture contents, the following principle for stem sampling was applied: the total fresh mass of each model stem was determined in the field, and representative fresh stem samples including branches were removed from each stem and weighted in the field. For more accurate sample representation, the stem samples were removed randomly from different parts of stems, i.e. the stem base, middle and stem top. The fresh stem samples were transported to the laboratory in paper bags for the determination of moisture content. In laboratory, all stem samples were dried at 105°C until constant weight and weighed. The constant weight was determined through several control weighings (EN 14774-2:2010). For the whole stem biomass, the sample mass was recalculated from the formula:

$$M_d = M_f \times (m_d/m_f), \quad (1)$$

where M_d is the whole stem dry weight (kg); M_f is the whole stem fresh weight (kg); m_f is the fresh sample weight (g); m_d is the absolute dry sample weight (g).

The willow moisture content was calculated by the following formula:

$$W = (m_f - m_d)/m_f \times 100, \quad (2)$$

where W is the moisture content (%); m_f is the fresh weight (g); m_d – is the dry weight (g).

In order to determine the proportion of stembark and stemwood, the stembark was separated from the randomly selected fresh stems. Totally, 49 stemwood and 49 stembark samples, representing more than 10 percent of all model stems, were taken. All samples were dried at 105°C until constant weight and weighed.

To provide basic information about the calorific value (EN 14918:2009) and ash content (EN 14775:2009) of local willow plants, a combined sample per willow plant was taken and analysed.

Calculations and statistical analyses

Biomass of short rotation willows could be estimated by using a non-destructive method. The estimation of plant dry mass is based on single easily measured variable like stem diameter (Verwijst et al. 1999). Therefore, it allowed applying a regression analysis, as the most suitable method for the assessment of short rotation coppice productivity, in this study. It has well coincided with the experience obtained in earlier studies (Hytönen et al. 1987, Verwijst 1991). As the small values were planned to incorporate into the model, a non-linear regression procedure was chosen for biomass estimation, instead of logarithmic transformation (referring to the study by Verwijst 1991).

A non-destructive method was created using the regression analysis method and the dependences between dry aboveground biomass and stem diameter and height were determined. The general function (Arevalo et al. 2007) was as follows:

$M_d = a \times D^b$, (3)

where M_d is the dry biomass; D is the diameter at 55 cm above the ground; *a* and *b* are constants of regression parameters.

The data were analysed using one-way ANOVA followed by Fisher's LSD test. All statistical analyses were carried out using the SPSS software (PASW Statistics 17.0, SPSS Inc., Chicago, USA).

Results

Aboveground willow biomass

The statistical relationships between the dry aboveground biomass of the model willow trees in the analysed plots and their stem diameter at 55 cm height as well as between biomass and height were evaluated for each studied willow plantation. In a case of aboveground stem biomass and stem diameter at 55 cm height, the coefficients of determination (R^2) ranged from 0.69 to 0.99. The R^2 higher than 0.95 were obtained in the most cases, except for plantation No. 3 ($R^2 = 0.69$) and No. 10 ($R^2 = 0.85$). When stem height was included as a parameter instead of stem diameter, R^2 varied in a range of 0.57–0.96 in different willow plantations with average being $R^2 = 0.85$. The obtained statistical relationship between the stem diameter and aboveground biomass was higher than the one between stem height and aboveground biomass. Therefore, stem diameter, as single easily measured variable, was chosen for the estimation of plant dry mass.

There was no statistically significant difference ($p < 0.05$) between the regression equations obtained for different willow plantations. Therefore, based on the data of all plantations, one equation suitable to estimate total dry willow biomass was worked out (Figure 1):

$M = 0.0003 \times D^{2.4311}$, (4)

where M is the dry biomass; D is the diameter at 55 cm above the ground; *a* and *b* are constants of regression parameters.

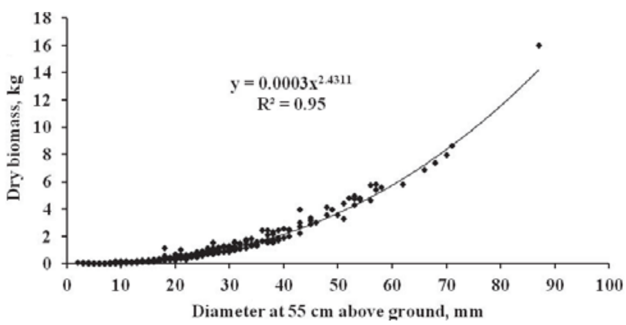

Figure 1. Dependence between aboveground biomass (kg) and stem diameter at 55 cm height above ground (mm) of the model trees of all plantations

This suggests that different willow plantations revealed a general regularity regardless of the internal and environmental factors.

The Equation 4, as a non-destructive method, further was used to calculate dry aboveground willow biomass per hectare for all studied willow plantations. The study results showed that the annual willow biomass yield varied within a wide range from 2 to 10 t ha^{-1} but remained about 5–7 t ha^{-1}, starting from the second-year old willow plants (Table 3). Annual biomass increment of 2–3 t ha^{-1} was obtained in the willow plantations grown on nutrient poor sandy soils. Much higher increment was obtained in the older than 4 years old plantations, which in average was 5–10 t ha^{-1} in the plantations grown in nutrient richer soil-sandy loam. Nevertheless, the annual yield, as well the final biomass, could be caused by synergistic effects of the mentioned factors.

Table 3. Aboveground biomass of the sampled willow (*Salix* sp.) plantations

Plantation No.	Age, years	Biomass, t ha^{-1}	Annual biomass increment, t ha^{-1} yr^{-1}
1	5	52	10
2	3	27	9
3	5	11	2
4	4	27	7
5	5	38	8
6	6	53	9
7	4	10	3
8	5	32	6
9	3	9	3
10	4	12	3
11	1	2	2
12	6	29	5
13	2	15	7

The average relative moisture content of the willows at harvest was 47.5 ± 0.42% (data not shown). 83% of all willow moisture content values varied between 45 and 55%. Data showed a downward trend in the moisture content with the increase of stem diameter and age. Willow plants grown for 5–6 years were slightly dryer than younger plants: the minimum moisture content of 40.0 ± 3.2 % was obtained for 6-years old willows, whereas it varied from 48.0 ± 5.1 to 51.0 ± 0.7 % in 1–2-year old willow plantations.

Biomass of bark and stem without bark

The proportion of bark in the total dry aboveground willow stem biomass varied within the range from 16 to 59 % from the total stem weight. A strong statistical relationship ($R^2 = 0.85$) was obtained between the bark biomass and stem diameter (Figure 2). The increase of stem diameter caused the clear decrease of bark percent in total dry willow biomass.

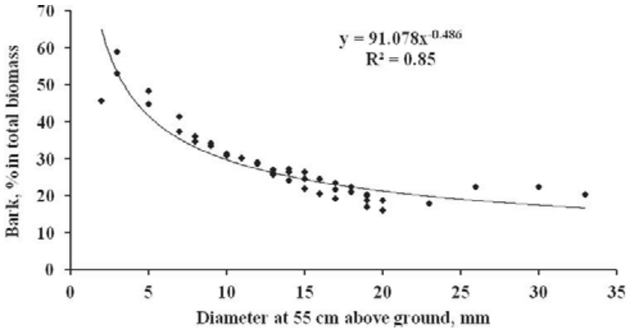

Figure 2. Dependence between bark dry mass (%) in the total biomass of the samples with different diameter and stem diameter at 55 cm above ground (mm)

The bark proportion significantly decreased in the stems with diameter of up to 20 mm but was constant after they had reached the size of 20 mm at stem diameter at 55 cm height (Figure 2). Based on the equation given in Fig. 2, the bark dry mass per 1 hectare of each studied plantation was recalculated and the results have distributed as follows: 0.7; 3.8; 2.4–7.0; 2.7–6.5; 3.4–14.6; 6.7–13.3 t ha^{-1} of dry bark biomass in the 1–6-years old willow plants.

Energy characteristics of willow plants

There was no evident difference between the calorific values of willow bark and stem without bark: only 1.5 percent higher calorific value was obtained for the bark (Table 4).

Table 4. Energy characteristics of model willow (*Salix* sp.) trees

Parameters	Stem with bark	Stem without bark	Bark
Lower calorific value, MJ kg^{-1}	18.32	18.24	18.53
Ash content, %	2.1	0.9	4.9
Amount of energy, toe	0.438	0.436	0.443
Amount of energy, kWh kg^{-1}	5.09	5.07	5.15

However, these energy characteristics could give additional value for practical evidence and the amount of energy that can be obtained from the studied willow energy plantations is given in Table 5.

Table 5. Amount of produced energy from the investigated willow (*Salix* sp.) plantations

Plantation No.	Plantation age, years	Amount of energy, MWh ha^{-1}	Annual amount of energy, MWh ha^{-1} yr^{-1}	Annual amount of energy, toe yr^{-1}
1	5	263	53	4.5
2	3	138	46	4.0
3	5	57	11	1.0
4	4	140	35	3.0
5	5	192	38	3.3
6	6	272	45	3.9
7	4	52	13	1.1
8	5	162	32	2.8
9	3	45	15	1.3
10	4	59	15	1.3
11	1	8	8	0.7
12	6	149	25	2.1
13	2	75	38	3.2

Much higher amount of energy, reaching in average about 200 MWh ha^{-1}, could be produced from the 5–6-years old willow plantations planted on sandy loam comparing to the younger plantations and those plantations grown on sandy soils.

Discussion

Within the willow plantations, a high variation in final biomass production has been recorded. The current study found that the annual increment of aboveground willow biomass grown for 5–6 years period has not exceeded 8–10 t ha^{-1} at harvest in the first rotation. The productivity of willow energy plantations more often depends on the site conditions, climate and other factors. The studied willow plantations were grown under optimal soil pH, which ranged between 5.2 and 7.2 (Table 2). Relatively wide range from pH 5.0 to 8.5 could be recommended for such kind of plantations (Walle et al. 2007, Abrahamson et al. 2010, Snowdon et al. 2013), as well as quite marginal soils in a case of nutrients could be used (Lemus and Lal 2005). The most probable reasons which could explain the lowest annual increment of aboveground willow biomass was infertile sandy soil where the willow plantation was grown for some years. In this plantation, nitrogen concentration was by 2–3 times lower in 0–20 cm depth but no additional fertilization and weed control was applied comparing to other willow plantations. Meanwhile, four times larger willow biomass (see Table 3) was found in the plantation grown on unfertilised and unwedded sandy loam.

This study demonstrated that fertilization gave slightly higher annual increment of willow biomass in the plantations grown on more fertile soil (sandy loam) but no evident increase in the plantations grown on sandy soils. Generally, in Lithuania, the maximum about 2–3 t ha^{-1} of annual increment could be obtained from the willow plantations grown on sandy soils, despite the fact of fertilization. However, the annual biomass increment from 5 to 9 t ha^{-1} could be expected from the unfertilized plantations grown on sandy loam, and up to 10 t ha^{-1} if these plantations were additionally fertilised with utility sludge.

Our results slightly differed from the estimates recorded in earlier studies which showed annual biomass increment up to 10–12 t ha^{-1} for the rotation of 4–5 years (Hoffman-Schielle et al. 1999). Otherwise, the published studies demonstrated a great consistency of the data. The annual biomass production of willow grown commercially in Sweden was about 6 to 12 t ha^{-1} (Dimitriou and Aronsson 2005, Walle et al. 2007), in Italy it comprised about 14–16 t ha^{-1} (Facciotto et al. 2012), in Germany – 7 to 10 t ha^{-1} (Pérez et al. 2011), in Poland – about 12 t ha^{-1} (Buchholz and Volk 2011), in Latvia – about 8 t ha^{-1} (Makovskis et al. 2012), and in Estonia – 5–10 t ha^{-1}

(Heinsoo et al. 2002, Heinsoo and Koppel 2003). Data collected from seven countries (Sweden, Ireland, New Zealand, the USA, the UK, Poland and Estonia) indicated an average yield of 7 t ha^{-1} per year with a range from 2 to 14 t ha^{-1} per year (Snowdon et al. 2013). The differences between the variations occur for a number of reasons, including droughts during the vegetation season, late spring frosts, diseases, soil quality and fertilization (Heinsoo et al. 2002, Makovskis et al. 2012). The biomass production of commercially grown willows strongly depends on site conditions (Dimitriou and Aronsson 2005). Therefore, in order to obtain a higher productivity for energy willow plantations, the soil is a very important factor. Willow growing in Lithuania on infertile sandy soils most often is an unprofitable activity, especially if the owners do not use the additional fertilization (Konstantinavičienė et al. 2014). A complex of factors, describing the site specifics and management, rotation length, planting density should also be taken into account. In the current study, the higher willow planting density (3–4-year old plantations, No. 9 and 10) could be one of the factors which caused lower annual increment and biomass at harvest. This factor must be also foreseen as an obstacle to higher final production. Otherwise, 2.3–3.0 times higher annual yield was produced in the plantations grown in the sandy loam, which was additionally fertilised and the weed control was applied. The willow plantations on the same soil but without any cultivation technique during the rotation period showed lower final productivity.

The optimistic suggestions for the effectiveness of willow plantation growing in Lithuania were concluded by Jakienė et al. in 2013. Authors suggested that willow plantations could produce about 20 t ha^{-1} of dry biomass annually at Lithuanian conditions. Anyway, these data must be interpreted with caution because the willow plantations more often are grown on marginal soils with low productivity.

Summarizing the obtained results, it could be assumed that in order to have higher biomass at harvest and heating value, the rotation period of willow plantations could be prolonged at least up to 5–6 years. Despite slight dieback of willow plants, when they start compete more actively, the biomass of the remnant plants tend to increase considerably. Furthermore, older willow plants seem to have relatively lower moisture content than younger plants.

Harvestable biomass from short rotation willow plantations has relatively high bark proportions, which depends on stem size at harvest (Adler et al. 2005). Our data were consistent with the previously obtained data but we found no evident differences when bark biomass was included for the calculation of energy characteristics of model willow trees.

The analyses of willow fuel calorific value showed that this value is slightly higher for willow plants than for some other forest fuel resources. For example, the calorific value of hazelnuts is 18.6 MJ kg^{-1}, for buckthorn is 17.72 MJ kg^{-1} and for rowan is 17.88 MJ kg^{-1} (Škėma 2011). An average of about 29 MWh ha^{-1} of heat could be obtained from 1 ha of willow energy plantations, thus saving on average about 2.5 tons of the equivalent oil per year. It could be suggested that energy plantations of willows could be used as an additional tool in the context of the EU and Lithuanian policy focused on active renewable energy resources.

Conclusions

A strong dependency between the dry aboveground biomass of willow (*Salix* sp.) stems and stem diameter ($R^2 = 0.95$) was determined and the model $M = 0.0003 \times D^{2.4311}$ (where M is the dry biomass; D is the diameter at 55 cm above the ground; *a* and *b* are constants of regression parameters) was worked out for the estimation of dry above-ground biomass of willow plantations in Lithuania.

The annual dry aboveground biomass of willows varied in a wide range, from 2 to 10 t ha^{-1} per year. The annual increment higher than 6 t ha^{-1} was found for the older than 4 years plantations grown in more fertile soil (sandy loam), which was additionally fertilized and weeded. We assumed that in Lithuania it is be rational to prolong the rotation period of willow plantations at least or more than 5–6 years because of site- and climate-specific reasons as well as to plant the willows on more fertile soils together with fertilisation and weed control, as it gives an additional benefit and higher economic efficiency.

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