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INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2014, 28, 201-211
doi: 10.2478/intag-2014-0009

Thermophysical and chemical properties of perennial energy crops depending on harvest period

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Received August 31, 2012; accepted May 14, 2013

A b s t r a c t. This paper presents analyses of the thermophysical and chemical properties of eleven perennial crop species harvested in one-year rotation cycles. The crops included four species grown for biomass in the form of straw, five species producing semi-wood biomass, and two species yielding wood biomass. The research comprised three consecutive crop harvests. In each harvesting season, biomass samples for analyses were taken on six dates at one-month intervals. Thermophysical and chemical properties of the biomass were significantly differentiated within the main experimental factors and their interactions. The biomass produced by Virginia mallow had the best quality parameters as solid fuel. In fact, it achieved the lowest water content and the highest lower heating value during all of the analyzed seasons and harvest dates. The biomass of the species yielding straw or semi-wood products attained better quality as solid fuel on later harvest dates. In turn, the quality of willow biomass remained practically unchanged between the harvest dates.

K e y w o r d s: biomass, perennial crops, lower heating value, ash content, chemical composition

INTRODUCTION

Energy security, next to food or ecological security, is one of the key factors ensuring the existence and development of our civilization. At present, energy is mostly obtained from fossil fuels. But as more fossil fuels are recovered, their supplies are being depleted. Although new resources are discovered, their recovery is usually more difficult, expensive and dangerous to the environment. It should also be emphasized that the EU countries, including Poland, are increasingly more dependent on energy supplies from other, non-EU states. In 2005-2008, the EU dependence on foreign energy resources rose from 52.5 to 53.9%. For Poland, the respective values were 17.6 and 31.7% (Eurostat, 2011). For this reason alone, it is essential to become at least partly independent of external suppliers of energy resources. This explains the growing interest in renewable energy sources (RES) which can reduce our reliance on imported fossil fuels and improve the diversification of energy supplies.

Energy generation from renewable supplies is also important from the social and economic standpoint. The RES can considerably stimulate employment and economic development. In 2009, the renewable energy sector in 27 EU states gave direct or indirect employment to over 912 thousand people, including 283.7 thousand people engaged in the production of energy from solid biomass (Eur Observ'ER, 2010). In Poland, the respective figures were 19.1 thousand and 7.0 thousand people. Moreover, the economic activity associated with the renewable energy sector in the EU countries was assessed at the value of 120 185 mln EUR in 2009. Among the EU states, the biggest turnover in this sector was in Germany (36 650 mln EUR); in Poland, it equalled 1 410 mln EUR. These data prove that RES are profitable for both social and economic reasons. Finally, energy generation from renewable resources, unlike energy obtained from fossil fuels, has measurable environmental benefits.

These are the reasons why the role of RES in primary energy generation in Poland and other EU countries has been gaining in importance over the past years. Since 2001, an increase has been observed in the generation of primary

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energy from RES (GUS, 2011). From 2001 to 2009, the generation of primary energy from renewable sources in Poland rose from 5.1 to 9.0%. In the same time period, the share of RES in the EU countries increased from 10.6% to 18.3%. The dynamic growth in RES has also been witnessed globally (Eurostat, 2011; Renewables, 2011).

Biomass is the main source of energy generated from renewable sources in the world, the EU and in Poland, with the respective shares of 62.5%, 46.0% and 86.1% (Eurostat, 2011; GUS, 2011; Renewables, 2011). Biomass is mainly obtained from waste generated by agriculture, forestry, timber industry, urban green and municipal organic waste management. But one of the main target sources of biomass will consist of field plantations of perennial energy crops. It is expected that perennial energy crops should be highly productive and their biomass should be characterized by a high lower heating value and a low content of ash. Perennial crop species are divided into the ones yielding wood, semi-wood and straw biomass which differs in its quality parameters as solid fuel (Redei *et al*., 2008; Stolarski *et al*., 2008; Kollas *et al*., 2009; Fortier *et al*., 2010; Przyborowski *et al*., 2012). The thermophysical and chemical characteristics of biomass from different crop species are also affected by the harvest time and the course of weather during that period (Stolarski *et al*., 2010).

The objective of this study was to determine the effect of the water content, ash content, on the higher heating value, lower heating value and composition of elements in biomass of eleven perennial crops depending on the harvest time in three consecutive harvest seasons.

MATERIAL AND METHODS

The biomass for analyses was obtained from a field collection of perennial plants maintained by the Department of Plant Breeding and Seed Production at the University of Warmia and Mazury in Olsztyn (N 53°45' E 20°27'). The first factor of the experiment consisted of eleven perennial crop species which can yield straw, semi-wood or wood biomass. The four species which produce biomass as straw are *Miscanthus x giganteus* (J.M.Greef & M.Deuter), Amur silvergrass (*Miscanthus sacchariflorus* Maxim. Hack.), *Chinese silvergrass (Miscanthus sinensis* Andersson) and prairie cordgrass (*Spartina pectinata* Bosc ex Link). Among the species yielding semi-wood biomass, the following were tested: Virginia mallow (*Sida hermaphrodita* Rusby L.), Jerusalem artichoke (*Helianthus tuberosus* L.), cup plant (*Silphium perfoliatum* L.), Japanese knotweed (*Reynoutria japonica* Houtt.) and giant knotweed (*Reynoutria sachalinensis* Nakai). Finally, the crops producing biomass in the form of wood were represented by two species of willow: *Salix viminalis* L. and *Salix dasyclados* Willd.

The second factor was the date of harvesting the biomass after the growing season. Biomass samples were taken on six dates in one-month intervals: 4th week of November, 4th week of December, 4th week of January, 4th week of February, 4th week of March and 4th week of April. Finally, the third factor comprised three successive seasons of harvest at the turn of the years: 2008/2009, 2009/2010 and 2010/2011. For brevity, the mean values from the three subsequent biomass harvest seasons in particular months are presented in a Table 1. Differences in the results from the three harvest seasons, in turn, are described and presented in the form of standard deviation for each property in each month.

On each of the above dates and in each year, a few whole shoots from five randomly chosen plants of each species were cut manually so as to achieve a sample of the fresh weight of about 0.4 kg. Shoots were cut down at 5-10 cm above the ground. Afterwards, shoots of a given species were fragmented in the field with hand pruning scissors, packed in plastic bags and transported to a laboratory.

Analyses of the thermophysial (higher and lower heating value, moisture and ash content) and chemical (carbon, hydrogen and sulphur) properties of the biomass were performed in the laboratory. All the analyses were made in three replicates. First, the water content was determined with the oven-dry method. For this purpose, the biomass was dried at 105±2°C in a Premed KBC G-65/250 dryer until solid mass was obtained (PN 80/G-04511). Afterwards, the dry biomass was ground in an analytical mill, IKA KMF 10 basic (IKA Werke Gmbh CO.KG, Germany), using a 1 mm mesh sieve. Next, the higher heating value (HHV) of dry biomass was determined with the dynamic method using an IKA C 2000 calorimeter (IKA Werke Gmbh CO.KG, Germany) according to standard PN-81/G-04513. Samples weighing 0.5 g each were pelleted in an IKA WERKE C-21 press and left until dry. Biomass tablets were dried in a laboratory oven at 105±2°C, weighed up to 0.1 mg, placed in a quartz crucible and inserted into a bomb calorimeter for analysis in a pure oxygen environment at 30 atm pressure. Based on the water content and higher heating value, the lower heating value (LHV) of biomass was determined according to Kopetz *et al.* (2007). The total ash content was determined in an ELTRA TGA-Thermostep (ELTRA Gmbh, Germany) thermogravimetric analyzer in accordance with the following standard methods: ASTM D-5142, D-3173, D-3174, D-3175, PN-G-04560:1998 and PN-ISO 562. The weight of a sample for determination of ash was about 1.5 g. The content of carbon, hydrogen and sulphur in dry biomass was determined in an ELTRA CHS 500 (ELTRA Gmbh, Germany) automatic analyzer according to standards PN/G-04521 and PN/G-ISO 35. The weighed amount for analyses was about 0.15 g.

The results were processed statistically with a three-factor analysis of variance ANOVA. Using the multiple SNK (Student Newman-Keuls) test which groups means of similar values, homogenous groups were distinguished at the level of significance α = 0.01. Arithmetic means and standard deviation for the analyzed characteristics were also computed. All the statistical analyses were completed with the software programme STATISTICA 9.0 (StatSoft, Inc.).

RESULTS

The water content in the biomass from the tested species on particular harvest dates was differentiated by the atmospheric conditions in the time period preceding the harvest and on the day of biomass collection (Table 1). The main factors were the air temperature and atmospheric precipitation. In the periods with atmospheric precipitation, the water content of the straw and semi-wood biomass species increased. Under sunny weather and higher air temperatures above zero centigrade, the biomass of these species was exposed to the natural drying process. In contrast, the willow species yielding wood biomass responded only slightly to changes in the weather conditions.

The thermophysical and chemical properties of the biomass were significantly differentiated within the main experimental factors and their interactions (Table 2). The water content of the biomass produced by the tested crop species was significantly varied (Table 3). The highest water content was determined in the biomass of willow *Salix dasyclados* (55.54%), while the other willow species, *Salix viminalis*, was in the second homogenous group (53.92%).

T a b l e 1. Weather conditions one day prior to and on the day of biomass sample collection

Harvest dates		One day prior biomass sample collection		Day of biomass sample collection	
Months	Season of harvest	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)
November	2008/2009	-1.7	0.0	-1.5	0.0
	2009/2010	8.0	1.6	7.1	0.0
	2010/2011	2.8	0.2	3.5	1.4
December	2008/2009	-2.5	0.0	-2.5	0.0
	2009/2010	-15.1	0.0	-14.8	0.0
	2010/2011	-9.1	0.0	-10.2	0.0
January	2008/2009	-1.4	0.0	-0.3	0.0
	2009/2010	-8.5	0.0	-9.8	0.0
	2010/2011	2.4	0.4	0.9	0.0
February	2008/2009	0.4	2.0	0.3	0.0
	2009/2010	-0.9	0.0	2.0	0.0
	2010/2011	-12.9	0.0	-11.2	0.0
March	2008/2009	-0.9	0.2	-0.4	0.0
	2009/2010	7.3	5.2	7.4	0.0
	2010/2011	8.7	0.0	6.4	0.0
April	2008/2009	10.0	0.0	10.4	0.0
	2009/2010	3.5	0.0	5.9	0.0
	2010/2011	16.1	0.0	16.5	0.0

T a b l e 2. Significance of main effects and first order interactions for the analyzed characteristics

Characteristics	Species	Month	Year	Species x month	Species x year	Month x year	Species x month x year
Water content	*	*	*	*	*	*	*
Ash content	*	*	*	*	*	*	*
Higher heating value	*	*	*	*	*	*	*
Lower heating value	*	*	*	*	*	*	*
Carbon (C)	*	*	*	*	*	*	*
Hydrogen (H)	*	*	*	*	*	*	*
Sulphur (S)	*	*	*	*	*	*	*

*p<0.01.

The average water content of the other species was significantly lower, for example it ranged from 34.4 (*Miscanthus sacchariflorus*) up to 44.37% (*Miscanthus x giganteus*) in the biomass from three species of the genus *Miscanthus*. Significantly the lowest water content was determined in the biomass of *Sida hermaphrodita* (25.71% on average). This species was also characterized by the lowest water content on practically all harvest dates and seasons. A significant decrease in the water content of biomass was achieved by delaying the harvest (Table 3). The highest moisture was determined in November (56.11% on average). In December and January, it was on a lower and comparable level, but began to decrease significantly in the later months. The lowest results were obtained in April, 26.23% on average for all the species. The decrease in the biomass water content on later harvest dates was particularly distinct in the species yielding semi-wood or straw biomass (Fig. 1). In respect of woody crops, changes in the biomass water content were very small.

The average content of ash after combustion of the biomass produced by the analyzed perennial crop species was 2.74% d.m. at standard deviation of 0.92 (Table 3). It was highly variable between the semi-wood species, ranging from 2.69% d.m. for *Sida hemaphrodita* to 3.87% d.m. for *Helianthus tuberosus*. With respect to the grassy species, the ash content oscillated within 2.56 and 3.29% d.m. Significantly the lowest ash content was determined in the biomass of *Salix viminalis* (on average 1.53% d.m.). The highest ash content among the analyzed crops was determined in November (3.31% on average), but in April it was nearly 1% lower. A particularly big decrease in the ash content was observed in the biomass of semi-wood and straw crop species (Fig. 1). In the biomass of woody species, the value of this property was generally much lower and changed only slightly with time.

The HHV of the biomass produced by the tested crops was on average 19.06 MJ kg^{-1} d.m. (Table 4). Significantly the highest HHV was determined for the biomass of both willow species. The HHV achieved for the other species ranged from 18.52 to 19.41 MJ kg^{-1} d.m. (*Helianthus tuberosus* and *Reynoutria japonica*). The biomass harvested in particular months was characterized by significantly different HHV, although it oscillated within a relatively narrow range of 19.01-19.12 MJ kg^{-1} d.m. The LHV of the tested biomass was on average 10.27 MJ kg^{-1} with a standard deviation of 3.29 (Table 4). Among the analyzed species, *Sida hermaphrodita* was characterized by significantly the highest LHV throughout the whole experiment, as it was 13.34 MJ kg^{-1} on average. LHV of the remaining semi-wood species was on an average level of 10.5 MJ kg^{-1}. For the grassy species, the LHV oscillated within the average of 9.54 MJ kg^{-1} (*Miscanthus x giganteus*) to 11.57 MJ kg^{-1} (*Miscanthus sacchariflorus*). Significantly the lowest LHV was found for the willow species producing woody biomass (almost 7.5 MJ kg^{-1} on average). Postponing the harvest caused a significant increase in LHV. In November, for example, the average LHV was 6.99 MJ kg^{-1}, but in April it rose to an average of 13.42 MJ kg^{-1}. Distinctly significant and especially beneficial modifications in the three-year average LHV induced by delayed harvest were observed in semi-wood and straw biomass crops (Fig. 2).

The average content of carbon determined in the biomass of the analyzed perennial crop species was 48.58% d.m. (Table 5). The highest carbon content was found in the biomass of *Salix viminalis* and *Reynoutria japonica* and significantly the lowest value of this trait was determined in the biomass of *Helianthus tuberosus* (46.60% on average). On the first three dates of harvest, the biomass had a lower carbon content compared to the subsequent dates (Table 5, Fig. 3).

The content of hydrogen in the biomass of the tested species was on average 5.69% (Table 5). Significantly the highest hydrogen content was determined in the biomass of *Salix viminalis* (5.81% d.m. on average). The second homogenous group comprised *Salix dasyclados* and *Spartina pectinata*. The third homogenous group consisted of all the remaining grass species and *Sida hermaphrodita*. The lowest content of hydrogen during the whole experiment was found in *Helianthus tuberosus*. The content of hydrogen from November to January was within 5.43 to 5.66% d.m., being significantly higher from February to April. An increase in the content of this element was demonstrated for all the groups of analyzed species as the harvest was delayed (Fig. 3).

The biomass of the tested perennial crops contained small amounts of sulphur *ie* 0.039% d.m. on average (Table 5). Significantly the highest content of this element was demonstrated in *Spartina pectinata* (0.060% d.m. on average). In the other grass species, the content of sulphur ranged on average from 0.030% d.m. (*Miscanthus x giganteus*) to 0.050% d.m. (*Miscanthus sacchariflorus*). In the semi-wood plants, the content of sulphur varied from an average of 0.029% d.m. in *Reynoutria sachalinensis* to 0.039% d.m. in *Helianthus tuberosus*. Postponing the harvest date caused a decrease in the content of sulphur in all the types of biomass (Fig. 3).

DISCUSSION

At present, both in Poland and in other European countries, many perennial crop species are tested towards their potential use in different branches of economy (Angelini *et al*., 2009; Heneman and Červinka, 2007; Stolarski *et al*., 2011; Strašil and Kára, 2010; Szyszlak-Bargłowicz *et al*., 2012). In the future, lignin and cellulose biomass from dedicated plantations of perennial crops set up on farmland can turn into one of the primary resources for energy generation and other industrial applications. The possible reasons are lower outlays such as on fertilisers, plant protection chemicals or fuels needed to produce this type of biomass as compared to cultivation of annual crops. Moreover, the perennial character of such plantations means that their negative impact on

T a b l e 3. Water content (%, w/w) and ash content (% d.m.) in the biomass of the tested species in different months, means for three harvest seasons

Species	Month						Mean
	XI	XII	I	II	III	IV	
			Water content				
Miscanthus x giganteus	58.36±3.52 b	52.69±1.86 e	52.18±2.29 e	42.68 4.76 k	37.11 4.61 n	23.23 9.51 t	44.37 12.83 d
Miscanthus sacchariflorus	53.19±4.71 d	44.79±11.91 j	39.88±17.97 lm	24.47±5.58 st	25.49±17.47 s	18.77±8.80 w	34.43±16.34 g
Miscanthus sinensis	53.55±6.42 d	45.04±3.19 j	42.69±4.29 k	32.12±3.86 p	25.38±13.45 s	18.97±1.012 w	36.29±13.92 f
Spartina pectinata	54.01±1.24 d	45.66±4.66 i	46.69±10.76 i	41.46±8.03 kl	36.95±5.73 n	21.43±7.84 tu	41.03±12.04 e
Sida hermaphrodita	42.76±3.55 k	24.47±1.98 st	25.62±1.87 s	22.17±3.96 tu	21.24±6.05 tu	17.99±7.16 w	25.71±9.08 i
Helianthus tuberosus	63.49±4.54 a	39.24±5.90 m	37.07±19.00 n	25.57±2.56 s	21.78±4.69 tu	17.93±5.70 w	34.18±17.34 h
Silphium perfoliatum	57.39±6.15 c	35.97±13.67 no	40.35±13.09 l	39.33±7.46 m	25.22±9.14 s	18.50±6.80 w	36.13±15.13 f
Reynoutria japonica	63.00±10.33 a	53.92±13.37 d	58.41±1.79 b	49.65±5.81 g	29.64±12.54 r	20.83±10.23 u	45.91±17.87 c
Reynoutria sachalinensis	62.55±7.79 a	50.80±15.90 f	48.01±13.35 h	34.73±3.06 o	28.72±16.23 r	21.55±10.92 tu	41.06±17.66 e
Salix viminalis	53.28±2.43 d	54.10±0.40 d	54.60±0.45 cd	53.72±1.34 d	53.65±1.49 d	54.14±2.03 d	53.92±1.41 b
Salix dasyclados	55.63±0.72 c	56.04±0.71 c	56.38±1.93 c	55.20±1.60 cd	54.86±1.42 cd	55.15±2.04 cd	55.54±1.37 a
Mean	56.11±7.31 a	45.70±11.72 b	45.62±12.78 b	38.28±11.93 c	32.73±14.18 d	26.23±15.20 e	40.78±15.67
			Ash content				
Miscanthus x giganteus	3.35±0.56 g	2.87±0.35 l	2.76±0.59 m	2.44±0.40 o	2.06±0.20 p	1.90±0.50 r	2.56±0.64 g
Miscanthus sacchariflorus	4.42±1.39 c	3.87±0.86 e	3.40±0.72 g	3.04±0.83 j	2.56±0.77 n	2.44±0.73 o	3.29±1.05 c
Miscanthus sinensis	3.55±0.95 f	3.00±0.42 j	2.83±0.48 l	2.24±0.32 o	2.32±0.41 o	2.26±0.19 o	2.70±0.66 f
Spartina pectinata	3.38±0.45 g	3.10±0.38 i	3.09±0.45 i	2.73±0.08 m	2.62±0.10 m	2.58±0.12 n	2.92±0.40 d
Sida hermaphrodita	3.09±0.66 i	3.00±0.67 j	2.55±0.46 n	2.56±0.16 n	2.56±0.19 n	2.36±0.30 o	2.69±0.47 f
Helianthus tuberosus	5.26±2.07 a	4.71±1.12 b	3.95±0.53 d	3.15±0.44 h	3.12±0.40 h	3.02±0.33 j	3.87±1.23 a
Silphium perfoliatum	4.23±0.97 d	3.81±0.66 e	3.77±0.40 e	3.13±0.67 h	3.04±0.53 j	2.97±0.48 j	3.49±0.73 b
Reynoutria japonica	3.09±0.40 i	2.92±0.48 k	2.70±0.46 m	2.73±0.21 m	2.70±0.29 m	2.57±0.29 n	2.78±0.35 e
Reynoutria sachalinensis	2.82±0.36 l	2.94±0.68 k	2.77±0.22 m	2.66±0.26 m	2.54±0.15 n	2.54±0.14 n	2.71±0.33 f
Salix viminalis	1.52±0.13 u	1.49±0.24 u	1.52±0.18 u	1.60±0.08 t	1.53±0.16 u	1.51±0.16 u	1.53±0.20 i
Salix dasyclados	1.71±0.11 s	1.64±0.26 t	1.65±0.13 t	1.60±0.03 t	1.59±0.09 t	1.66±0.13 t	1.64±0.13 h
Mean	3.31±1.31 a	3.03±1.02 b	2.82±0.82 c	2.53±0.62 d	2.42±0.59 e	2.35±0.56 f	2.74±0.92

± standard deviation, a, b, c… homogenous groups, n = 9.

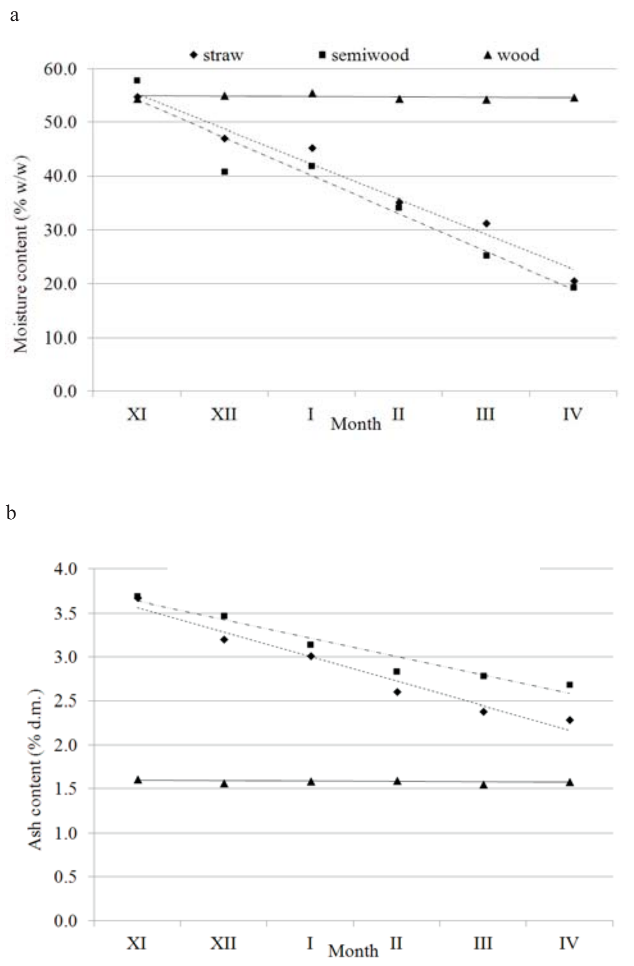

Fig. 1. Changes in the: a – water content, b – ash content in the three types of biomass at harvest, means for three harvest seasons (for wood biomass n = 18, for semi-wood biomass n = 45 and for straw biomass n = 36).

the environment is much weaker than that of annual agricultural crops (Borzęcka-Walker *et al*., 2008; Fernado *et al*., 2011).

Nonetheless, it should be emphasized that the present research was focused on the value of biomass produced by perennial crops, whereas proper selection of particular species suitable for given climatic and soil conditions so as to achieve optimal yields remains a separate issue. Apart from the biomass yield obtained in a given year, another important question is the total exploitation time of a whole plantation because it will determine the total biomass yield obtained from 1 ha of a perennial plantation during its life. It should also be emphasized that another key question is the cultivation and harvest technologies used for particular crop species. While the present study was conducted, it was observed that some of the species producing straw or semi-wood biomass tend to lodge in autumn and winter due to profuse snow and rainfalls or strong winds. The low resistance of crops to bad weather conditions is an extremely undesirable trait because it has a significant effect on the technical capabilities of biomass harvest, which in some extreme cases may become impossible.

At the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn, experiments on willows have been carried out since the 1990s, while studies on energy crops yielding semi-wood or straw biomass began in 2003. Over those years, we have found that native species of willow are fully tolerant to unfavourable weather conditions prevailing in north-eastern Poland. Among the species grown for semi-wood biomass, *Sida hermaphrodita, Reynoutria japonica* and *Reynoutria sachalinensis* are resistant to lodging, unlike *Helianthus tuberosus* and *Silphium perfoliatum* which can lodge soon after the first heavy precipitation that may occur as early as October. Among the tested straw crops, *Miscanthus x giganteus* seems to be most resistant to lodging. Over the ten years of observations, it lodged only once. The least lodging-resistant species is *Miscanthus sacchariflorus* which in practice is always lodged in November. Moreover, the analyzed straw species, as well as some other perennial species, are vulnerable to ground frosts in the spring and frost death in the winter. Thus, apart from the quality of biomass, the species which can be useful in agronomic practice should be the ones that are relatively easy to grow and produce reliable yields year after year. In the context of the above observations, whether made by the authors or reported by other researchers (Tworkowski *et al*., 2010), it may be concluded that harvesting grass species and some perennial crops for solid fuel, under the conditions present in NE Poland, can be either difficult or even impossible due to plant lodging. Therefore, it seems that the species yielding biomass in the form of wood *ie* willow, poplar or black locust are more reliable as crops producing solid biomass.

On the other hand, species diversity is what we need for improved biodiversity and in order to offer a somewhat continuous biomass supply 'line' for the energy generation sector and, more broadly, for integrated biorefineries and industry. The perennial crops tested in our study can be produced not only for solid biofuels but also as raw material for the production of liquid and gas fuels (Christian *et al*., 2008; Greenhalf *et al*., 2012; Somerville *et al*., 2010). Then, some of them can be harvested in two or even three cuts during one growing season instead of waiting for one harvest after they stop growing. Besides, the species *Helianthus tuberosus* grown as an energy or industrial crop can be harvested for both the aerial parts and tubers (Curt *et al*., 2006; Kondor and Dallos, 2010). Different species of perennial crops, beside providing biomass for industrial aims or energy generation, play an important role in the reclamation of contaminated land. Moreover, they can be fertilized with sewage sludge (Dimitriou and Rosenqvist, 2011). Thus, it is very important to continue studies on the selection of species adapted to the climatic and soil condi-

Table 4. Higher heating value (MJ kg^{-1} d.m.) and lower heating value (MJ kg^{-1} f.m.) of the biomass of the tested species in different months, means for three harvest seasons

Species	Month						Mean
	XI	XII	I	II	III	IV	
			Higher heating value				
Miscanthus x giganteus	19.10±0.19 d	19.05±0.11 e	19.09±0.11 d	19.01±0.08 e	19.12±0.26 d	19.18±0.18 d	19.09±0.15 c
Miscanthus sacchariflorus	18.82±0.29 f	18.82±0.08 f	18.87±0.20 f	18.99±0.14 e	18.97±0.34 e	19.05±0.22 e	18.92±0.21 f
Miscanthus sinensis	19.06±0.27 e	19.04±0.13 e	18.95±0.12 e	19.10±0.19 d	19.04±0.23 e	19.14±0.21 d	19.05±0.18 d
Spartina pectinata	19.16±0.20 d	18.93±0.13 f	19.14±0.07 d	19.20±0.03 d	19.09±0.11 d	19.09±0.10 d	19.10±0.13 c
Sida hermaphrodita	18.71±0.40 g	18.91±0.18 f	18.80±0.07 g	18.90±0.05 f	18.72±0.27 g	18.75±0.15 g	18.80±0.20 g
Helianthus tuberosus	18.45±0.45 i	18.25±0.60 j	18.58±0.28 h	18.66±0.13 h	18.63±0.30 h	18.54±0.20 h	18.52±0.33 i
Silphium perfoliatum	18.66±0.09 h	18.76±0.17 g	18.74±0.44 g	18.87±0.30 f	18.70±0.34 g	18.90±0.16 f	18.77±0.25 h
Reynoutria japonica	19.39±0.11 b	19.40±0.08 b	19.54±0.19 a	19.40±0.27 b	19.30±0.39 c	19.42±0.20 b	19.41±0.20 b
Reynoutria sachalinensis	19.03±0.18 e	18.95±0.20 e	19.05±0.24 e	19.03±0.14 e	18.90±0.27 f	19.02±0.13 e	19.00±0.18 e
Salix viminalis	19.56±0.12 a	19.45±0.14 b	19.40±0.17 b	19.59±0.28 a	19.51±0.21 a	19.56±0.10 a	19.51±0.16 a
Salix dasyclados	19.49±0.19 b	19.53±0.14 a	19.47±0.13 b	19.60±0.24 a	19.45±0.28 b	19.40±0.17 b	19.49±0.18 a
Mean	19.04±0.40 c	19.01±0.40 d	19.06±0.35 c	19.12±0.33 a	19.04±0.37 c	19.09±0.32 b	19.06±0.36
			Lower heating value				
Miscanthus x giganteus	6.53±0.79 p	7.73±0.42 kl	7.86±0.44 kl	9.86±1.00 h	11.12±1.15 fg	14.16±2.08 c	9.54±2.79 h
Miscanthus sacchariflorus	7.51±1.00 l	9.29±2.50 i	10.36±3.77 gh	13.75±1.23 d	13.50±3.68 d	15.01±1.86 a	11.57±3.52 b
Miscanthus sinensis	7.55±1.49 l	9.37±0.74 i	9.82±0.99 h	12.17±0.71 ef	13.58±2.84 d	15.05±2.24 a	11.26±3.02 d
Spartina pectinata	7.50±0.34 lm	9.17±0.96 i	9.06±2.31 ij	10.22±1.72 gh	11.13±1.17 fg	14.48±1.66 b	10.26±2.58 f
Sida hermaphrodita	9.67±0.97 hi	13.68±0.36 d	13.36±0.41 de	14.16±0.82 c	14.22±1.23 c	14.95±1.64 a	13.34±1.96 a
Helianthus tuberosus	5.20±1.08 s	10.15±1.45 gh	10.81±4.06 g	13.27±0.64 de	14.04±0.89 cd	14.78±1.22 ab	11.37±3.69 c
Silphium perfoliatum	6.55±1.33 p	11.12±2.81 fg	10.16±2.52 gh	10.48±1.42 g	13.35±1.75 de	14.95±1.52 a	11.10±3.18 e
Reynoutria japonica	5.63±2.21 r	7.62±2.92 l	6.70±0.47 o	8.55±1.14 jk	12.85±2.67 e	14.87±2.30 ab	9.37±3.88 i
Reynoutria sachalinensis	5.60±1.65 r	8.07±3.34 k	8.76±3.00 j	11.58±0.75 f	12.76±3.40 e	14.39±2.34 b	10.19±3.77 g
Salix viminalis	7.84±0.59 kl	7.61±0.03 l	7.47±0.16 lm	7.76±0.34 kl	7.74±0.36 kl	7.65±0.41 l	7.68±0.35 j
Salix dasyclados	7.29±0.08 n	7.22±0.19 n	7.12±0.45 n	7.44±0.34 m	7.44±0.40 m	7.36±0.49 m	7.31±0.32 k
Mean	6.99±1.58 f	9.18±2.42 e	9.22±2.63 d	10.84±2.43 c	11.98±2.90 b	13.42±3.19 a	10.27±3.29

Explanations as in Table 3.

Table 5. Content of carbon, hydrogen, and sulphur in the biomass of the tested species in different months, means for three harvest seasons (% d.m.)

Species	Month						Mean
	XI	XII	I	II	III	IV	
			Carbon				
Miscanthus x giganteus	46.55±2.24 l	49.19±2.97 f	47.78±1.64 i	50.64±3.16 b	49.80±3.27 d	50.43±3.50 b	49.06±2.84 b
Miscanthus sacchariflorus	46.76±2.27 l	47.61±3.07 i	48.26±2.16 h	50.96±2.84 a	48.61±2.37 g	49.60±2.46 e	48.63±2.56 d
Miscanthus sinensis	46.52±1.70 l	47.84±4.73 i	49.54±0.61 e	51.21±3.03 a	47.91±4.80 i	48.59±6.92 g	48.60±3.84 d
Spartina pectinata	46.75±2.19 l	49.24±1.48 f	48.79±0.63 g	50.52±2.89 b	48.29±2.48 h	49.17±2.70 f	48.79±2.19 d
Sida hermaphrodita	46.08±1.83 m	49.46±0.90 e	47.71±1.58 i	49.18±2.60 f	48.89±1.85 g	49.22±4.06 f	48.43±2.33 e
Helianthus tuberosus	44.83±1.93 n	46.23±1.16 m	46.69±0.48 l	48.10±2.97 h	46.75±2.48 l	46.98±1.99 k	46.60±1.96 g
Silphium perfoliatum	44.88±2.59 n	47.83±1.38 i	47.02±1.71 k	47.93±2.08 i	47.40±2.83 j	48.69±2.02 g	47.29±2.19 f
Reynoutria japonica	48.24±2.13 h	50.01±2.22 c	50.32±1.26 c	50.14±1.53 c	49.20±1.75 f	49.66±2.89 d	49.59±1.86 a
Reynoutria sachalinensis	47.78±2.70 i	48.07±1.98 h	49.01±1.65 f	49.98±1.83 d	49.21±2.62 f	49.32±3.28 e	48.90±2.17 c
Salix viminalis	48.03±2.80 h	49.11±1.17 f	49.40±0.53 e	50.98±2.17 a	49.59±2.31 e	50.28±2.42 c	49.57±1.71 a
Salix dasyclados	47.04±2.31 k	48.70±1.27 g	48.85±0.54 g	49.91±1.25 d	49.25±2.33 f	49.73±2.18 d	48.91±1.78 c
Mean	46.68±2.12 d	48.48±2.18 c	48.49±1.52 c	49.96±2.32 a	48.63±2.43 c	49.24±2.96 b	48.58±2.48
			Hydrogen				
Miscanthus x giganteus	5.47±0.31 de	5.65±0.32 cd	5.56±0.58 d	6.02±0.36 a	5.87±0.32 b	5.84±0.39 bc	5.74±0.38 c
Miscanthus sacchariflorus	5.53±0.28 d	5.48±0.38 de	5.68±0.27 cd	5.99±0.23 a	5.88±0.25 b	5.88±0.28 b	5.74±0.31 c
Miscanthus sinensis	5.51±0.18 d	5.48±0.62 de	5.81±0.20 bc	5.96±0.29 ab	5.67±0.13 cd	5.83±0.26 bc	5.71±0.33 c
Spartina pectinata	5.47±0.09 de	5.67±0.20 cd	5.77±0.21 c	6.02±0.31 a	5.88±0.33 b	5.79±0.25 c	5.77±0.27 b
Sida hermaphrodita	5.46±0.23 de	5.69±0.09 cd	5.71±0.18 cd	5.89±0.27 b	5.80±0.35 c	5.83±0.27 bc	5.73±0.25 c
Helianthus tuberosus	5.11±0.20 h	5.36±0.35 ef	5.54±0.47 d	5.79±0.32 c	5.67±0.36 cd	5.68±0.32 cd	5.52±0.37 f
Silphium perfoliatum	5.32±0.46 f	5.49±0.24 de	5.54±0.37 d	5.76±0.39 c	5.70±0.30 cd	5.84±0.41 bc	5.61±0.36 d
Reynoutria japonica	5.27±0.40 g	5.47±0.28 de	5.76±0.23 c	5.85±0.28 b	5.68±0.44 cd	5.66±0.36 cd	5.61±0.35 d
Reynoutria sachalinensis	5.41±0.24 e	5.40±0.23 e	5.47±0.33 dc	5.68±0.34 cd	5.72±0.23 cd	5.68±0.19 cd	5.56±0.26 e
Salix viminalis	5.67±0.18 cd	5.66±0.26 cd	5.71±0.32 cd	6.04±0.17 a	5.99±0.31 a	5.81±0.27 bc	5.81±0.28 a
Salix dasyclados	5.49±0.13 de	5.64±0.14 cd	5.72±0.35 cd	5.94±0.39 ab	5.94±0.35 ab	5.91±0.36 ab	5.77±0.31 b
Mean	5.43±0.27 e	5.55±0.28 d	5.66±0.30 c	5.90±0.28 a	5.80±0.29 b	5.80±0.27 b	5.69±0.32

Explanations as in Table 3.

T a b l e 5. Continuation

Species	Month						Mean
	XI	XII	I	II	III	IV	
	Sulphur						
Miscanthus x giganteus	0.040±0.004 cd	0.031±0.010 de	0.028±0.007 e	0.028±0.007 e	0.026±0.006 e	0.028±0.005 e	0.030±0.007 f
Miscanthus sacchariflorus	0.048±0.008 bc	0.056±0.004 b	0.058±0.001 b	0.050±0.010 bc	0.045±0.019 c	0.041±0.018 cd	0.050±0.012 b
Miscanthus sinensis	0.036±0.012 d	0.044±0.005 c	0.034±0.008 d	0.031±0.008 de	0.034±0.014 d	0.034±0.008 d	0.036±0.009 e
Spartina pectinata	0.069±0.032 a	0.068±0.016 a	0.057±0.016 b	0.056±0.008 b	0.058±0.018 b	0.054±0.012 b	0.060±0.017 a
Sida hermaphrodita	0.038±0.012 d	0.037±0.003 d	0.034±0.003 d	0.026±0.007 e	0.023±0.009 f	0.029±0.008 e	0.031±0.009 f
Helianthus tuberosus	0.050±0.031 bc	0.052±0.018 b	0.036±0.013 d	0.034±0.003 d	0.032±0.006 de	0.032±0.005 de	0.039±0.016 d
Silphium perfoliatum	0.041±0.012 cd	0.042±0.019 c	0.041±0.017 cd	0.035±0.008 d	0.036±0.010 d	0.034±0.002 d	0.038±0.011 d
Reynoutria japonica	0.036±0.007 d	0.045±0.011 c	0.032±0.006 de	0.035±0.011 d	0.030±0.010 de	0.033±0.010 d	0.035±0.009 e
Reynoutria sachalinensis	0.028±0.011 e	0.036±0.012 d	0.032±0.007 de	0.025±0.005 e	0.027±0.004 e	0.026±0.003 e	0.029±0.008 f
Salix viminalis	0.032±0.014 de	0.033±0.017 d	0.037±0.009 d	0.036±0.013 d	0.035±0.011 d	0.035±0.012 d	0.035±0.009 e
Salix dasyclados	0.040±0.009 cd	0.046±0.009 c	0.039±0.008 cd	0.039±0.013 cd	0.041±0.014 cd	0.038±0.013 d	0.041±0.010 c
Mean	0.042±0.017 b	0.045±0.014 a	0.039±0.012 c	0.036±0.012 d	0.035±0.014 d	0.035±0.011 d	0.039±0.014

Explanations as in Table 3.

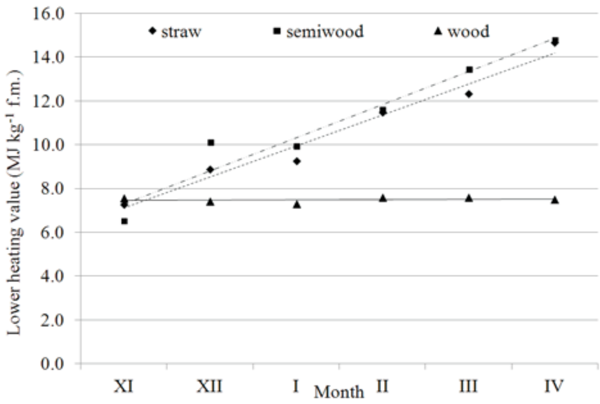

Fig. 2. Changes in the lower heating value of the three types of biomass at harvest, means for three harvest seasons. Explanation as in Fig. 1.

tions, on the evaluation of yield volume and on the biomass energy value and quality. It is extremely important because these factors will subsequently affect the energy and economic efficiency as well as the environmental impact of the production and use of biomass of different perennial crops -questions which will be investigated by the authors in their following studies.

CONCLUSIONS

1. The thermophysical and chemical properties of biomass are quite considerably differentiated by the crop species as well as by the harvest period and the weather conditions at harvest.
2. Virginia mallow produces the biomass of the best characteristics as solid biofuel. It has the lowest water content and the highest lower heating value.
3. The biomass of the other semi-wood or straw crop species tended to improve on later harvest dates. It contained less sulphur, ash and water, and had a higher lower heating value.
4. The quality of biomass obtained from willow plants in annual cycles did not change much depending on harvest dates. It was characterized by the lowest content of ash but its water content was high, which meant low lower heating value.

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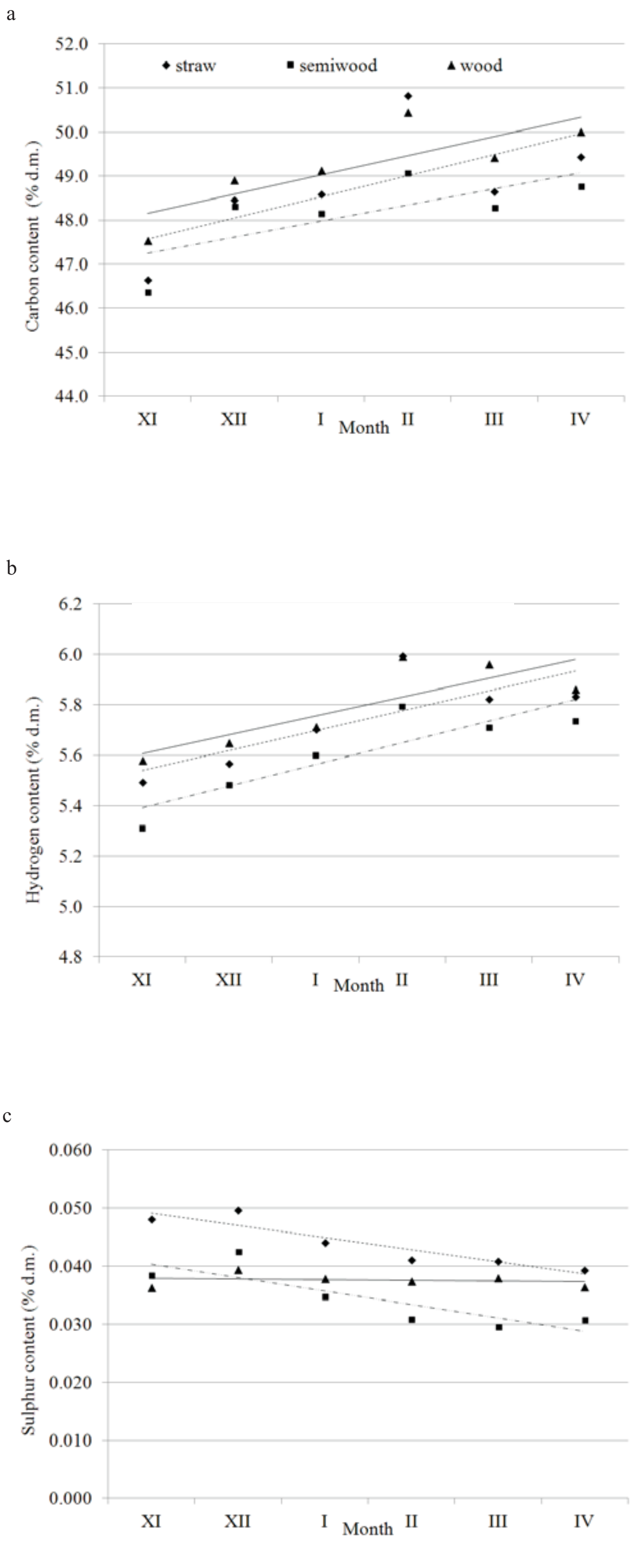

Fig. 3. Changes in the content of: a – carbon, b – hydrogen, and c – sulphur in the three types of biomass at harvest, means for three harvest seasons. Explanations as in Fig. 1.

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