Original scientific paper

Root Biomass and Morphological Characterization of Energy Willow Stumps

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Abstract

Energy willow plantations are used in cycles of 20–25 years. After such a period of use, or earlier, plantations should be liquidated. In the case of arable land, liquidation of a plantation also means restoration of the original production properties of the soil. In particular, this means: permanent elimination of the possibility of plant regrowth from the above-ground rootstock and root systems and disintegration and mixing of the above-ground rootstock and root systems. The present authors undertook the task of developing a technology for stump removal on energy willow plantations that would have the advantage of lower energy consumption and execution costs than the technologies used so far. The development of a new machine for the disintegration of the above-ground rootstock and root systems requires recognition of the variability of their morphological parameters and their biomass. For that purpose, a head for planting trees was used to sample rootstocks and extract them, and a number of biometric parameters were determined with the division into thickness fractions. The average biomass of the root system of an energy willow shrub with a butt-end of approx. 10 cm in height was 3.1 kg, of which the butt-end and roots with a diameter greater than 30 mm accounted for more than 73%. The vertical and horizontal range of thick roots, which should be ground during plantation liquidation, is small and amounts to approx. 26 and 29 cm, respectively. This justifies the use of machines that work along strips of land during plantation reclamation.

Keywords: biomass production, energy willow, land reclamation, stump removal, root system

1. Introduction

For several years the production and harvesting of the biomass of fast-growing species has been advocated as a new direction for agricultural production. However, the development of this new agricultural activity is largely determined by economic aspects (Faber et al. 2009, Günther 2005, Stolarski 2006). One of the barriers to the production of biomass from energy plants on a large scale is the large cost of that production. The processes of biomass production from perennial energy plants can be divided into the following stages: establishment of a plantation, use (running a plantation) and liquidation of a plantation (Grzybek 2010, Tworkowski et al. 2010). The costs of the establishment and liquidation of a plantation when related to its duration of use will enable an estimation of the average annual cost of running the plantation. Depending on the type of land on which it is planned to establish a long-term plantation, several different types of technological activities must be performed. All operations and associated activities are carriers of costs. The costs of production of biomass for energy purposes depend on: the yield size and its price, the area of a field, harvesting technology and organization of work, especially using multi-operational forestry machinery (Di Fulvio 2012, Spinelli et al. 2008, 2009). So far, various authors have described in detail the many aspects of willow plantation establishment costs which, according to various sources, amount to € 1224–2164 per ha (Kwaśniewski 2010, Matyka 2008, McKendry 2002, Szczukowski et al. 2004, 2012). Thus, the costs calculated per year, assuming that a plantation will be used for 25 years, will amount to € 49–87. This accounts for approximately 50% of the costs incurred in Nordic countries (Ericsson et al. 2006). Nearly 30% of the costs are accounted for by the preparation of seedlings and establishment of the crop. An interesting way to reduce energy and hence the cost of the above mentioned treatments, nearly by half, is an innovative method based on horizontal distribution of stems of a length of 1.2 m at a depth of 5–10 cm (Bergante et al. 2016).

The use of modern, high performance machinery, working in fields of higher acreage, can significantly reduce costs (Trzepieciński et al. 2016), as can the use of a single-stage harvest via balloting (Stolarski et al. 2015).

The estimated total area of plantations of energy willow in Poland is currently approx. 10–12 thousand hectares (Dubas 2010). These are plantations of varied areas: from small area ones (less than 1 ha) to large scale ones (several dozen hectares). Any long term crop cultivation must be liquidated and renewed or converted to another crop. The decision on liquidation depends on many factors. The most important of these are: the demand for a given raw material, the selling price, the yield per unit area and consequently, above all, the profits. In addition, plantation liquidation is also carried out due to the natural aging of the plants. In the literature, there is little information on the results of studies related to the liquidation of long term energy crop plantations. The information published on this subject in Poland consists of theoretical analyses unsupported by fieldwork. This is due to the fact that the vast majority of established plantations are relatively young (present only for a few years) and do not yet require liquidation (Kwaśniewski et al. 2010).

Plantations of energy willow have been in use for 20–25 years (Dubas et al. 2004, Larsson 2006, Lisowski 2010, Szczukowski et al. 2004). The optimum period of cultivation on a given site seems to be 22 years: the first year being an initial one, followed by seven three-year rotations (Szulc and Dach 2014). After that period, or earlier, a plantation should be liquidated. In the case of agricultural land, stump removal also means restoration of the original properties of the soil. In particular, this is done by:

⇒ permanent removal of the possibility of plant regrowth from the above-ground parts of the rootstocks and the root systems

⇒ fragmentation of the above-ground parts of the rootstocks and the roots.

One of the stump removal methods consists of full-surface grinding of rootstocks. Generally, this involves the use of soil cutters, with a working width of 2–2.5 m and a working depth of up to 0.3–0.45 m, mounted on and powered by a tractor with the power of 200–300 kW. The volume of soil which is ground and mixed with the cut portions of the root system amounts to 3–4.5 thousand m^3 per 1 hectare. The share of the mass of the root system is very small relative to the mass of the broken up soil and amounts to slightly more than 11%. The low working speed of the tractor machine set and the large energy inputs for the drive of working assemblies make fuel consumption and operation costs very large. Objective problems of field reclamation after the cultivation of energy willow provide a basis on which to formulate the conditions of the possibility to develop a plantation liquidation technology with lower energy consumption than the methods used so far. These conditions are as follows:

⇒ Limitation of the regrowth of willow stems is generally associated with the destruction of above-ground parts of rootstocks and the part that is directly below it – therefore, mechanical grinding of the root system throughout the surface of the field (aimed at reducing the possibility of shoot regrowth) is not necessary

⇒ Part of the field remaining after the plantation (where grinding the rootstock and the root system located underneath was performed only in strips) may be used for growing and mechanical harvesting of some plants (e.g. maize)

⇒ Leaving the unground root system (outside the strip of the ground rootstocks) for a few years is enough to weaken it (due to biodegradation) so as to allow for further liquidation with the use of less energy-intensive technologies, e.g. by using disk harrows.

Thus, it appears possible to reduce the energy inputs for the reclamation of plantation fields after cultivation of willow through the use of machines with a smaller working width, which will grind and mix with the soil only such strips of the field whose width corresponds to the main part of the willow root system. In contrast, those parts of the field where the root system is too underdeveloped to produce plant stems may be left intact. The aim of the study was to identify the morphology of the willow root system, which would be the basis for a determination of which part should be ground and which can remain intact. Allocation of the biomass of energy willow roots from the viewpoint of the future development of a machine for plantation restoration will constitute key information for design engineers.

2. Materials and methods

The biological material was obtained from a plantation area of approx. 3 ha, established in 2003, situ-

Fig. 1 Root ball of an energy willow extracted using a head for transplanting large trees

Fig. 2 A wrapped root ball – ready for transport

Fig. 3 Washing the soil off the root system using a pressure washer

Fig. 4 Cleaned root systems of energy willow

ated along the Vistula river in Kaniów (Silesian Voivodeship). Cuttings had been planted at every 0.5 m, with a spacing width of 0.75 m, with no separate tramline system; the planting amounted to approx. 26,600 plants/ha. The plantation was cultivated extensively: in subsequent years no treatments related to management and fertilization were performed, except for mechanical harvesting every 3 years. The current density is approx. 20,000 plants/ha.

After cutting the willow shoots using a saw, each item was labeled separately for later identification when measuring the amount of shoots and specifying their biomass. The willow rootstocks were collected together with lumps of soil by means of the hydraulic head of an OPTIMAL 1100, aggregated with a front loader, used for transplanting large trees (Fig. 1). The device has 4 hydraulic shovels moving along a curved trajectory, which enable complete separation of the root system from undisturbed soil (Tylek 2008). The applied head allowed for the extraction of root balls with repeated geometrical features, i.e. a volume of 0.34 m^3, a width of the upper part of 1.14 m and a depth of the blade range of 0.75 m. Then, after wrapping in burlap and a steel mesh (Fig. 2), the root balls were transported to a storage area where the root systems were cleaned using a pressure washer (Figs. 3 and 4). This allowed for determination of their mass in fresh state and their geometric parameters characterizing the distribution of willow roots in the soil.

Root biomass and allocation were measured by dividing the following fractions into diameters: fine roots bellow 2.0 mm, medium at 2–8 mm and coarse roots at 8–30 mm. Coarse roots were dug up and extracted by machine, washed, measured and weighed. In order to identify the biomass of fine roots, thirty soil monoliths distributed regularly across the experimental plot were collected using steel cylinders to the depth of 40 cm (Böhm 1985, Pietrzykowski et al. 2010, Pietrzykowski and Woś 2010). The collected monoliths were washed in the laboratory, and roots were extracted. Appropriate root fractions were selected by measuring with calipers to obtain fine root fractions, and then roots were weighed in fresh state, and reweighed after drying at 65°C to determine biomass.

3. Results and discussion

Fig. 5 presents characteristic parameters of the root system of energy willow, measured on the prepared roots (Juliszewski et al. 2015). Moreover, the biomass (in dry state) of the rootstocks and the roots themselves was determined after distinguishing the individual thickness of fractions (Fig. 6). Measurement results and characteristics of the above-ground parts of willow shrubs are summarized in Table 1. The height of shoots on the experimental plantation was very balanced, but the average height of 3 year old shrubs was relatively small: below 4.3 meters, which was caused by the very high surface density of the shrubs. With more than 20 thousand shrubs planted on one hectare, the dry biomass harvested had a weight of approx. 49 Mg ha^{-1} (16.3 Mg $ha^{-1}y^{-1}$). The obtained crops are slightly more abundant in relation to experimental results obtained in Denmark, Finland, Sweden, Lithuania, Latvia and Estonia, considering the number of shrubs per unit area of the plantation, and are comparable with experiments conducted in the USA (Wang and MacFarlane 2012, Mola-Yudego 2010, Sevel et al. 2012). In turn, the crops were slightly less abundant in Hungary when subjected to intensive mineral and organic fertilization (Mikó et al. 2014). In the above mentioned experiments, a close association was demonstrated between yields and soil properties,

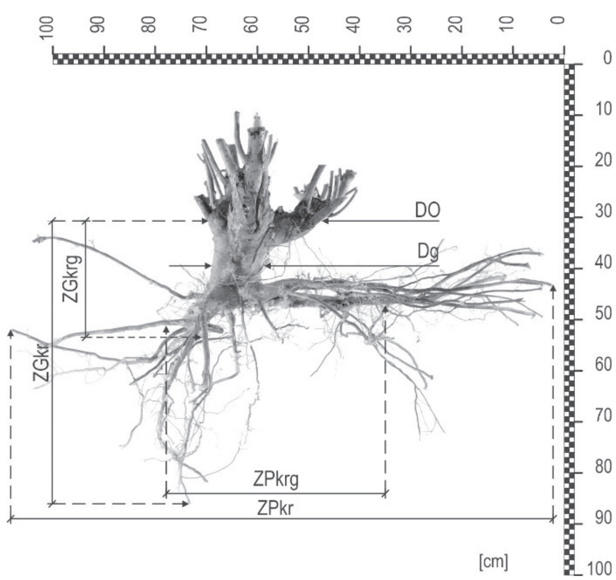

Fig. 5 Morphological parameters of the root system of energy willow, identified during the research; D0 –rootstock diameter at the root collar at ground level, Dg – main root diameter at its thickest point, ZGkrg – vertical range of thick roots, ZGkr – vertical range of roots, ZPkrg – horizontal range of thick roots, ZPkr – horizontal range of roots

Table 1 Characteristics of the morphology and biomass of energy willow shrubs

Parameter	Mean	Min.	Max.	$CV_{,\%}$
Shrub height, m	4.28	3.36	5.01	12.1
Number of offshoots, items	11.3	4	28	47.5
Rootstock diameter at the root collar at ground level, cm	18.00	6.45	30.25	33.0
Main root diameter at the thickest point, cm	6.68	3.45	11.50	22.2
Vertical range of thick roots, cm	26.32	16.50	61.50	30.7
Vertical range of roots, cm	48.59	22.50	83.00	24.6
Horizontal range of thick roots, cm	27.82	5.25	53.50	42.4
Horizontal range of roots, cm	71.24	48.75	90.25	14.5
Biomass of the above-ground part (shoots), kg	2.51	0.99	8.69	64,4
Biomass of the basal part (after cutting the shoots), kg	0.98	0.18	2.84	60.6
Biomass of very thick roots (diameter above 30 mm), kg	1.29	0.41	4.22	61.3
Biomass of thick roots (diameter of 8–30 mm), kg	0.36	0.10	1.35	62.4
Biomass of medium-sized roots (diameter above 2–8 mm), kg	0.36	0.13	0.66	39.1
Biomass of fine roots (diameter below 2 mm), kg	0.11	0.02	0.24	43.8

access to water and the type of maple willow. Differences may exceed 30% in extreme cases. In turn, appropriate fertilization may increase the abundance of crops even more than twofold. It should be emphasized that this plantation was carried out extensively and the location of the plantation along a large river ensured proper moisture conditions. The lack of treatments and chemical protection could have a significant impact on the height of shrubs and the number of shoots, which is usually directly translated into the amount of the yield (Schulz et al. 2016).

Small variation also characterized the rootstock diameter at the root collar, measured at the ground level, and the main root diameter measured at its thickest point. The coefficients of variation of these morphological parameters amounted to 33% and 22%, respectively. This is important information with respect to the choice or design of machines for plantation reclamation, as it is these fragments of the rootstock that should be ground the most precisely, while the demand for power to drive the working tools must be

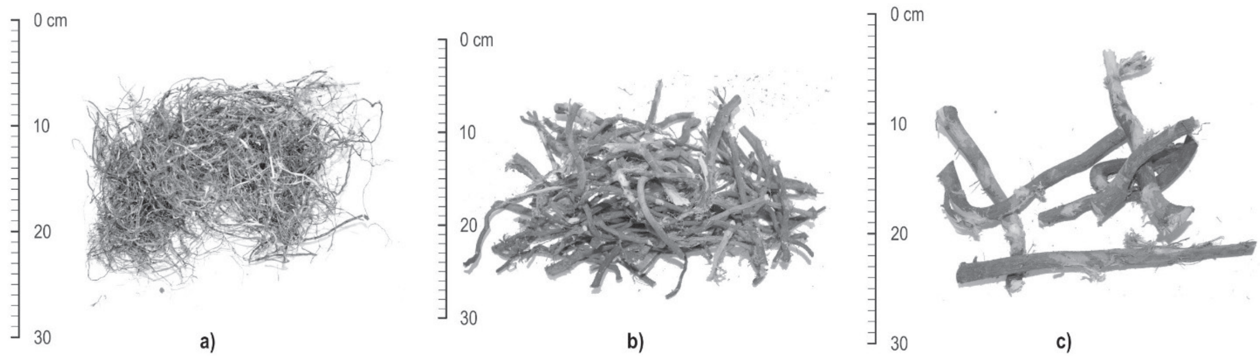

Fig. 6 Illustration of the root division into thickness fractions; a) up to 2 mm, b) 2–8 mm, c) 8–30 mm

adapted so as to destroy the structure of these very fragments. It is true that the recorded maximum diameters of rootstocks and main roots were approx. 70% greater than the average, but this applied only to individual items, growing only on the edge of the plantation or in gaps.

The vertical range of thick roots (with a diameter of 30 mm) averaged approx. 26 cm, and in an extreme case maximally 62 cm. Analogous values for the horizontal range are 28 cm and 54 cm, respectively. The results regarding the horizontal range of thick roots were similar to the results obtained from the experiment performed using the same method for age-equal plantations, but established on sandy soil. In turn, the vertical range of thick roots was almost 2-fold lower (Juliszewski et al. 2015).

This allows for the assumption that the idea presented in the project concerning the applicability of reclamation of strips of land after cultivation of energy willow may be correct. Although the average range of roots with a diameter of less than 8 mm is approx. 2–2.5 times greater, leaving them unground deep in the soil should not result in reduced efficiency of land reclamation.

Although the height of the plantation crops was regular, the number of offshoots of individual shrubs varied considerably and ranged from 4 to 28. Large variability in the number of shoots could result from the lack of treatments and protective actions (Schulz et al. 2016).

The coefficient of variation of the shoot biomass was very high: over 64%. Only a slightly lower degree of variation characterized the biomass of the underground parts of the shrubs. Despite the large variation, a high correlation was noted between the biomass of the above-ground and underground parts of the energy willow shrubs (Fig. 7).

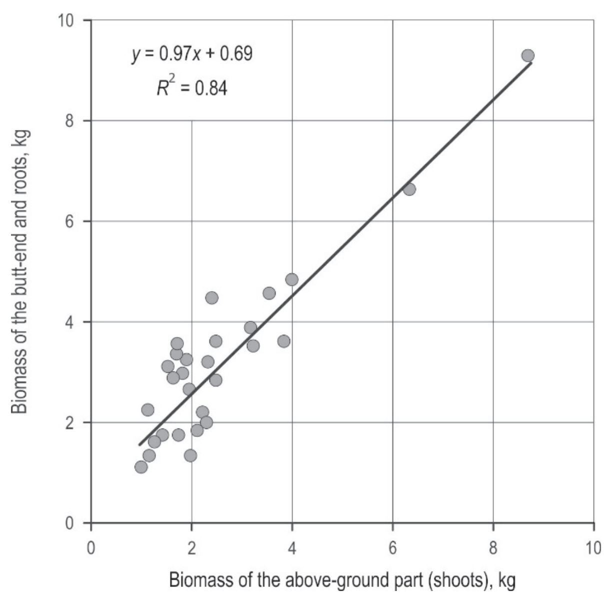

Fig. 7 Relationship between biomass of above-ground and underground parts of energy willow shrubs

The average biomass (in dry state) of the root system of an energy willow shrub with a butt-end of approx. 10 cm in height was 3.1 kg, of which over 73% was the basal part and roots with a diameter greater than 30 mm. Fig. 8 shows the allocation of biomass in different parts of the plant. In the case of wood harvesting after three growing seasons, shoots accounted for 45% of the biomass. Butt-ends accounted for as much as 18% of the biomass. It should be noted that cutting the plantation lower to the ground, i.e. leaving a butt-end of a height not greater than 5 cm, can increase the yield per hectare by up to approx. 10%. It should also be noted that such a shallow cut of shrubs requires the use of an appropriate tool, which is resistant to blunting in consequence of contact with inor-

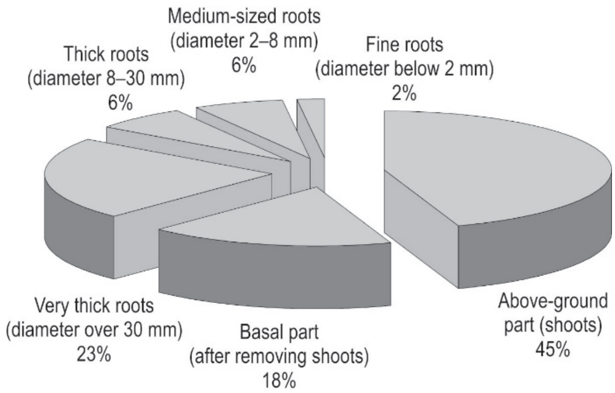

Fig. 8 Allocation of biomass (in dry state) on the energy willow plantation

ganic contaminants, e.g. a beater system. However, in this case, the danger of damage to a part of the below-ground rootstock should be taken into account (Stolarski et al. 2015).

The biomass remaining in the soil after harvest is approx. 58 Mg ha^{-1}; and the mass that should be ground during plantation reclamation (basal parts as well as thick and very thick roots) amounts to approx. 49 Mg ha^{-1}.

Mechanical liquidation of a plantation may consist of extracting the whole rootstocks from the ground. However, this raises another problem: how to deal with rootstocks largely covered with soil debris, at a rate of 10–15 thousand pieces per 1 ha. Experimental elimination of a 15-year old plantation was carried out based on a field experiment over an area of 0.4 hectares on the Kwidzyńska Plain in the Vistula glacial valley (Stolarski 2006, Stolarski 2009, Stolarski et al. 2008). The experiment had the following stages of work: harvesting energy willow in January (shoots were mowed close to the ground surface); spraying young plants with Roundup in the amount of 7 dm^3 ha^{-1} in the third decade of May; rootstock extraction using a plow in the third decade of July; double harrowing of the plowed field and manual removal of rootstock pieces from the field and their transportation. Harrowing was performed twice, in order to facilitate manual collection of rootstocks and their more precise removal. A similar process has been designed for technology based on spraying with Randap in the amount of 5 dm^3 ha^{-1} and the use of a heavy forestry mulcher, followed by a return to the production of grass plants after waiting at least one growing season (Caslin et al. 2015).

However, the chemical-mechanical technology requires multiple agrotechnical treatments, hard manual labor and the use of reinforced plows (preferably forest ones). It is, therefore, scarcely possible to regard this as a comprehensive mechanized technology.

Currently available economic analyzes of biomass production on willow crop plantations do not include the cost of liquidation of the plantation (Ericsson et al. 2006). Recognizing the morphology of root systems of willow will facilitate the development of a comprehensive, low-input technology for the elimination of the below-ground rootstock, in order to restore agricultural production.

4. Conclusions

The use of a head for transplanting large trees for the purpose of collecting energy willow rootstocks enabled standardized samples to be obtained containing complete butt-ends and thick roots, appropriate for the selection of the technology and equipment for plantation reclamation;

Due to the different number of offshoots (4–28), shrub biomass is characterized by high variability. The biomass of offshoots is strongly correlated with the biomass of the root system;

The mean rootstock diameter, when measured on the surface of the soil, amounts to 18 cm and this is three times greater than the diameter of the thickest root;

The vertical and horizontal ranges of thick roots (ones with a diameter of more than 8 mm), which should be ground during plantation liquidation, are small and amount to approx. 26 and 29 cm, respectively. This justifies the use of machines that work along strips of land during plantation reclamation;

The use of machines that leave lower basal parts (5 instead of 10 cm in height) for the harvesting of energy willow results in an approx. 10% increase in yield per hectare of plantation.

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