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Reed canary grass cultivation's energy efficiency and fuel quality

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Abstract. The article discusses the energy yield and yield capacity of reed canary grass stands in semi-natural and cultivated meadows with edaphic conditions most favourable for species growing on fertile soil. Energy grass production yields have been assessed with respect to the issues of precipitation, sunshine, and frozen ground. In Estonia, a dried matter level of 4.2–8.5 t ha^{-1} of reed canary grass may produce 72.91–147.56 GJ ha^{-1} gross energy by using 1.48–3.06 GJ ha^{-1} input energy, which consequently nets 71.44–1,445.00 GJ ha^{-1}. The above finding indicates that 1 MJ input energy enables the production of 2.8 kg dry matter. The efficiency of energy production (ratio of energy returned on energy invested) depends on the amount of input energy used to grow and harvest reed canary grass. The input energy payback ratio for the given case was 48.2–49.4, which was higher than cases with lower and higher dry matter yield levels. Precipitation during the second part of the Estonian summer, heavy winter snow cover and a simultaneous frequent lack of frozen ground reduce the productivity of reed canary grass as energy hay because the winter or early spring harvest cannot be used.

Key words: bioenergy, energy payback ratio, fuel quality, harvest yield, *phalaris arundinacea*.

INTRODUCTION

Notwithstanding fossil fuels' price, the time of needing these fuels has passed. General energy needs to be used more sustainably now to replace fossil energy with alternative energy sources (wind, water, solar, and bioenergy) if possible. The use of fallow land left out of agricultural production to cultivate energy grass has become fashionable. The need to grow energy grass at any cost and in enormous quantities as opposed to confining production to the amount of herbaceous plants suitable for energy grass needs to be analysed. These plants are an inevitable by-product of production (straw from cereal and grass seed fields, stems of canola and melilot) and are obtained from natural grasslands, especially those that until now have often not been harvested, have been recovered from areas already harvested by natural protection and from grasslands not managed by farmers.

Reed canary grass (*Phalaris arundinacea* L.) is a more interesting energy grass culture for the studied conditions. In suitable edaphic conditions (on fluvisols and minerotrophic soils), the yield capacity of this species surpasses that of other species;

moreover, its lodging resistance also surpasses that of other species. Although reed canary grass does not perish even after 9 months of flooding (variety 'Pedja'), it does not tolerate high stagnant ground water levels (Espenberg, et al., 2016). It does not produce sufficient yields in acid wastelands, humus on mineral soils or acid, poor cutaway peat lands in exhausted milled peat fields (Heinsoo et al., 2011). As a natural species in flood meadow communities, reed canary grass has been extensively used in Estonian territories at least since the appearance of the scythe (from the middle or the third quarter of the first millennium AD) (Laul & Tõnisson, 1991). Due to spring flooding, reed canary grass has been used for late-summer single harvesting. Because of the distribution of floodplain use among many farmsteads, the late harvesting and the long distances among the farmsteads primarily prevented the use of the flood aftermath. This single harvesting of soils with good nutrient supplies, with floodwater providing additional nutrients, guarantees the productive longevity of reed canary grass. Reed canary grass is a rather newly cultivated plant. It was sown for the first time in England in 1813 (Vose, 1959). According to current knowledge, reed canary grass was sown for the first time in Estonia at Sangaste Manor in 1910 (EAA…, 2014).

The aim of our study was to evaluate the reed canary grass cultivation energy payback ratio based on the yield levels, yield quality and influence of cultivation conditions to assess the potential of Estonia as a northern country for bioenergy production.

MATERIALS AND METHODS

Placement and weather conditions in the experimental site

The study site (58.1279 N; 27.5268 E) was a polder field near Räpina in Estonia on the coast of Lake Peipsi. Based on the data of the Estonian Environment Agency (Estonian…, 2014) the climate in the region is semi-continental with an annual average temperature of 5.6 °C and precipitation of 646 mm over the past thirty years.

Base data of the experimental plots

The paper presents data (Table 1) on the reed canary grass herbage stands of five different yield levels. The first two (1.2 t $ha^{-1}$and 4.2 t ha^{-1}) are semi-natural herbage stands, the yields of which (1.5 t ha^{-1} and 5.0 t ha^{-1}) as hay have been calculated on a dry matter basis to be 1.2 and 4.2 t ha^{-1} (Krall et al., 1980). This work describes experiments carried out according to those outlined in one of the author's previous studies (Annuk, 1992). Three of the experiments were made with different fertilizer levels. The ferilizers and the achieved yields were:

a) N (0), P_2O_5 (0), K_2O (0) – 8.5 t ha^{-1};
b) N (0), P_2O_5 (60), K_2O (120) – 11.5 t ha^{-1};
c) N (200), P_2O_5 (120), K_2O (240) – 15.1 t ha^{-1}.

Energy determination of the grassland biomass

We determined the energy contained in the dry matter of reed canary grass (17.36 MJ kg^{-1}) using a macro-calorimeter, ELVI-MK-1 (Annuk et al., 1991). Notably, the dry matter energy concentration of the same material determined according the chemical composition with four different formulae in different countries was 4.6–6.0% higher than the one directly determined by the calorimeter (Annuk et al., 1991). This finding confirmed the of calorific value data for reed canary grass from Sweden (17.6 MJ kg^{-1}) (Burvall, 1997). The ash content of reed canary grass grown on peaty soil is slightly lower. Therefore, the energy contained in its dry matter is slightly higher than that of reed canary grass grown on mineral soil (Heinsoo et al., 2011).

To calculate the input energy of the yield from the semi-natural meadows, we solely considered the energy used for mowing, baling, and transport over a distance of 20 km. For cultivated meadows, we first calculated the energy cost of establishment (soil cultivation, fertilisers, fertiliser drilling, seeds, seeding, and meadow management). To calculate the cost of production, we considered the energy spent on establishment during the crop years within a range of 1/8, similar to financial expenses (EUR kg^{-1}) (Haabpiht, 2006). The input energy of the years of meadow use was obtained by adding the energy spent (fertiliser energy, fertiliser drilling, mowing, baling, and transport) during the years of use to the energy spent on establishment (1/8). To calculate the energy use of the input energy, we have taken the standards for energy values of different tasks and substances from works by the Finnish authors J. Ahokas and H. Mikkola (Ahokas & Mikkola, 2007; Mikkola & Ahokas, 2009; Mikkola & Ahokas, 2010; Ahokas et al., 2013).

RESULTS

The productivity of reed canary grass may vary considerably, as shown in Table 1. The yields are given as dry matter for ease of comprehension. The data background for Table 1 is described in the chapter of: Base data of the experimental plots. A large range of dry matter yields was sampled to better evaluate the energy parameters of the production of reed canary grass. The experiments for the last three samples in Table 1 were carried out in triplicate for the used fertilisers and cultivated land; therefore, increased yields were observed. According this table, the DM yield, input and output energy amounts increased. The net energy also simultaneously increased.

Table 1. Reed canary grass as energy grass (DM – dry matter of grass)

Grass stand	Harvested yield, (t DM ha^{-1})	Output (GJ ha^{-1})	Input (GJ ha^{-1})	Net energy Output- input (GJ ha^{-1})
	1.2	20.83	0.90	19.93
	4.2	72.91	1.48	71.44
	8.5*	147.56	3.06	144.50
	11.5*	199.64	6.31	193.33
	15.1*	262.14	19.27	242.86
*LSD $_{0.05}$	2.4			

LSD – least significant difference.

The difference in the interval between the DM yield of cultivated meadow reed canary grass fertilising experiments varieties exceeded the LSD value (2.4 t DM), which shows that the yield data are reliable to a confidence level of 0.05. These findings indicate that reed canary grass reacts to fertiliser containing phosphorus- potassium and nitrogen despite the high natural productivity (8.5 t DM ha^{-1}) of flood plain meadow soils.

Table 2 was compiled to better understand the output energy production in Table 1. The first column gives the reed canary grass DM yield and input energy amounts per ha. The second column gives the maximum possible DM amount per 1 MJ of input energy. The third column gives the energy payback ratio, which is the ratio of the output and input energies. The last column presents the input energy per ton. The marked three boxes of the table show (similarly) the input energy productivity and the advantage of yield levels 4.2 and 8.5 t ha^{-1} both over the lower (1.2 t ha^{-1}) and higher (11.5 and 15.1 t ha^{-1}) yield levels based on the production of 1 ton of dry matter.

Table 2. Input energy payback ratio and expense for the production of 1 ton dry matter

Yield (t DM ha^{-1}) / Input (MJ ha^{-1})	Productivity (kg DM MJ^{-1})	Energy payback ratio (output)/(input)	Input (MJ t^{-1} DM)
1.2 / 900	1.3	23.1	750
4.2 / 1,476	2.8	49.4	351
8.5 / 3,062	2.8	48.2	360
11.5 / 6,307	1.8	31.7	548
15.1 / 19,272	0.8	13.6	1276

In the best energy payback ratio conditions, a DM level of 4.2–8.5 t ha^{-1} reed canary grass (Table 1):

a) may produce 73.91–148.56 GJ ha^{-1} gross energy;
b) has been produced using 1.48–3.1 GJ ha^{-1} input energy;
c) will consequently produce 71.44–1,445.00 GJ ha^{-1} net energy.

The findings above indicate that 1 MJ of input energy allows the production of 2.8 kg dry matter (Table 2). In this case (4.2–8.5 t ha^{-1} DM) the input energy payback ratio is 48.2–49.4 which is higher than in the cases of the lower and higher dry matter yield levels. Thus, the input energy expense for the production of 1 t dry matter is lower (351–360 MJ t^{-1} DM).

Nevertheless, a trend towards single mowing performed in the spring following the yield year persists in energy grass production (Landström et al., 1996; Burvall, 1997; Hadders & Olsson, 1997; Paulrud & Nilsson, 2001; Lötjönen, 2008). The breeding of special reed canary grass varieties for energy grass is under way (Christian et al., 2006). Single mowing is necessary for the longevity of reed canary grass stands, which reduces the cost of machinery operation. In its semi-natural communities, reed canary grass has only been single-harvested throughout its period of use. Furthermore, it has produced high yields and been long-lived if double-harvested as a cultivated plant (Fig. 1). However, triple-harvesting during the summer for fodder production significantly diminished the yield level of the following years and the permanence of the grass stand. Reed canary grass is more sensitive to triple-harvesting than to higher harvesting frequencies (4, 5). The yield quantity, structure of the mown mass (leaves, stems), and the amount of harvesting loss may depend on the harvesting period of the grass stands consisting of mown graminaceous plants. Among other perennial graminaceous plants, reed canary grass has a lodging resistance that surpasses that of other species, granting less harvesting loss at mowing. The lodging resistance of reed canary grass is difficult to explain even with its physical characteristics (stem wall thickness, stem diameter, burst and shear strength) of the lower internodes of its stem compared to brome grass (*Bromus inermis* Leyss.). The lodging resistance of reed canary grass may possibly derive from the morphological peculiarities of the lower internodes of its stem or from the slightly higher crude fibre and lignin content of its lower internodes compared to that of brome grass (Strašil, 2012).

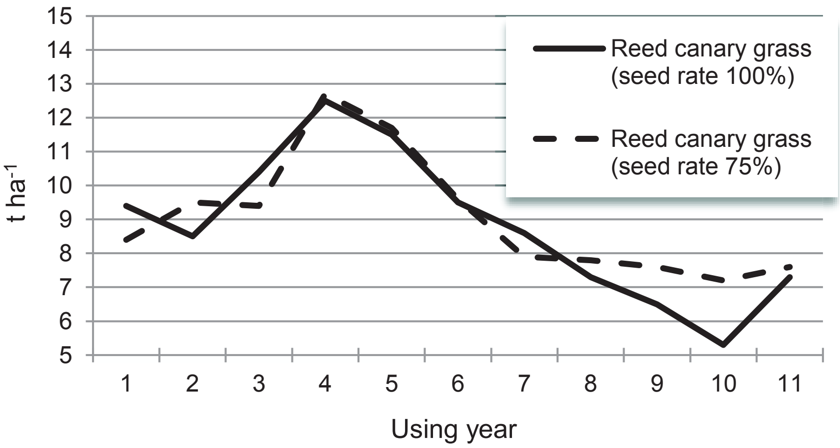

Figure 1. Hay yield (83% of DM).

The term 'winter loss' has been used at spring harvesting, which evidently involves leaf loss due to mowing and snow or gales as well as the leaching of mineral substances. At the spring harvesting of reed canary grass, the 'winter loss' of dry matter is 25% in southern Sweden and 15% in northern Sweden (Landström & Lomakka, 1996). At summer harvesting, more than 30% of the fresh weight of reed canary grass consists of leaves. Snow and large storms in winter result in a comparatively high leaf loss, which increases the stem ratio of spring harvested herbage mass (Hadders & Olsson, 1997). The quality of the chemical composition of fuel produced from spring-harvested stem-rich reed canary grass is higher than that of reed canary grass harvested in summer, as shown in Table 3 (Landström et al., 1996). Table 3 shows a decrease (20–25%) in the biomass ash content during spring harvesting. The ash content of herbaceous biomass is a critical problem during biomass burning (Fahmi et al., 2007); for example, the ash content in wood does not exceed 2% (Obernberger et al., 2006), while this figure is several times higher in herbaceous biomass (Table 3). According to Lewandovski & Schmidt (2006), the melting temperature interval of reed canary grass ash is 1,100–1,650 °C. Data gathered by Burvall (1997) on the melting temperature of reed canary grass ash also indicate the advantage of spring harvested (March–May, 1,404 °C) mass compared to summer harvesting (July–October, 1,074 °C). This difference may also be due to leaf loss and the leaching out of mineral substances. In late summer, the melting temperature of reed canary grass ash is 1,100 °C; however, it is 1,400 °C for spring harvesting (Hadders & Olsson, 1997).

Table 3. Nutrient and ash concentration (% of DM) in the leaf and stem of reed canary grass (Landström et al., 1996)

Harvest time	Element analysed	n	Leaf Mean	Leaf SE	Stem Mean	Stem SE
Summer (August)	N	21	2.32	0.07	0.62	0.05
	K	21	1.59	0.07	0.9	0.07
	P	21	0.25	0.01	0.11	0.01
	Ca	21	0.69	0.03	0.1	0.01
	Mg	21	0.26	0.02	0.06	0.01
	Cl	21	1.07	0.07	0.52	0.03
	Ash	21	8.51	0.31	4.21	0.23
Spring (April, May)	N	26	1.86	0.07	0.7	0.04
	K	26	0.35	0.05	0.24	0.03
	P	26	0.2	0.01	0.08	0.01
	Ca	22	0.35	0.02	0.12	0.01
	Mg	22	0.1	0.01	0.04	0
	Cl	22	0.1	0.02	0.11	0.02
	Ash	26	6.6	0.34	3.42	0.2

The given data indicates an up to six-fold decrease in the Cl and K contents during the winter and ten- and four-fold differences in Cl and K according to Table 3 (Landström et al., 1996). The Cl and K contents in the ash negatively correlate with the fuel quality (Obernberger et al., 1997). Therefore, the content of alkali metals and Cl in ash lowered the melting point of ash and caused slag formation on the boiler fender and fireplace surfaces (Obernberger et al., 2006).

DISCUSSION

The data in Table 1 show that reed canary grass can be produced under suitable edaphic conditions in a collection of dry matter that can reach the upper bound of the biological potential calculated for graminaceous plants in an Estonian climate (14.0–16.2 t ha^{-1} DM) (Tooming, 1988). However, the data in Table 1 question the necessity of gaining the maximum biological potential of herbaceous plants in production.

The energy return on investment depends on the amount of input energy (Zentner et al., 2011). Dry matter yields ranging from 4.2–8.5 t ha^{-1} are evidently sufficient. Approximately 70.00–145.00 GJ ha^{-1} of energy has been produced in the form of solid fuel. The lowest energy payback ratio was obtained for yield levels of 1.2 and 15.1 t DM ha^{-1} at 23.1 and 13.6, respectively. The energy payback ratio was maximised for yield levels of 4.2 and 8.5 t DM ha^{-1} at 49.4 and 48.2, respectively. The energy payback ratio of this cultivation process demonstrates an effective use of input fossil energy. The input fossil energy is inversely proportional to the energy payback ratio. Similar energy yields have been reported for graminaceous biomass (Heinsoo et al., 2010; Melts et al., 2013). The energy payback ratio fluctuates by harvest year (Ferraro, 2012), but this study evaluated the energy parameters as a function of the given input energy. This approach may or may not have included a small expense on the input energy for the establishment of the grassland. Fertilisers have either not been used at all, or only the aftereffects of the fertilisers have been observed (P_2O_5 at 60 and K_2O for the establishment of 120 kg ha^{-1}) in addition to the expenses of the input energy on harvesting. This type of energy can be produced if one can use either semi-natural or cultivated meadows of reed canary grass long-term; furthermore, annual establishment costs are either absent or low, and liming, sprinkler irrigation, large quantities of fertilisers, herbicides, or pesticides are not necessary. The existing machinery for fodder production can be used for harvesting. Although large quantities of mineral fertilisers allow the total energy output to be significantly increased, they also increase the amount of energy input used, which decreases the net energy (Tonn et al., 2009; Kukk et al., 2010; Kukk et al., 2011).

Fertilising, the mowing frequency, or the harvesting season has been claimed to minimally affect the energy value of herbaceous plants (Runge, 1973). We have also witnessed that the energy content of the dry matter of herbaceous plant varieties (clover and timothy grass) currently used for fodder do not differ significantly (Mikkola & Ahokas, 2010).

Producing quality energy grass in Estonia is difficult, the main obstacle being the unstable weather. The climate is characterised by a large number of rainy days (more than 200 a year) (Kirde, 1939) and a small number of sunny hours (fewer than 266 a year) (Russak & Kallis, 2003). The snow cover and the upper 10 cm of soil horizon melt simultaneously in spring. Extreme years (2010/2011) feature a thick snow cover and a complete lack of frozen ground. On average, the end of the snowmelt occurs between the 27th of March and 10th of April in Estonia. The soil melts from the surface to a depth of 10 cm between the 2nd and 12th of April (Kivi, 1976).

If energy grass that has reached the right quality cannot be harvested under the winter conditions, the possibility and need for using a single harvest grass stand are eliminated. Late single mowing will be useless, as the formed aftermath lacks practical use due to the low yield; moreover, the main crop also cannot be used without artificial drying because of the autumn precipitation. Separate buildings and high energy use will be necessary for the drying. For the favourable wintering of reed canary grass and with regard to next summer's yield, the last mowing during the vegetation period should be carried out when pre-winter aftermath formation is absent; i.e., the mowing should take place as late as October (Annuk, 1993; Pahkala, 2007). The only option for producing energy grass from reed canary grass is double-harvest, with the yield of the second mowing utilised for biogas production or only silage. The yield does not significantly depend on single-species sowing (100% reed canary grass in the seed mixture) or on its dominance in the seed mixture (75%) (Fig. 1). For double-harvest use, meadow foxtail (*Alopecurus pratensis* L.) and timothy grass (*Phleum pratense* L.) may be added to reed canary grass in approximately equal quantities. The first mowing accounts for 65–75% and the second mowing accounts for 25–35% of the gross summer yield (Bassam, 2010; Kallionen, 2012).

In addition to the research conducted in Finland on the transportation distances of reed canary grass as energy grass (Lindh et al., 2009), we cannot recommend the large-scale concentrated production of reed canary grass as an energy grass based on the potential quality of the reed canary grass as a fuel and the scarcity of suitable boiler houses for its direct use. The present-day land use of polders also does not favour large-scale energy grass production. Evidently, the use of reed canary grass as a supplementary fuel may be convenient when adding wood and peat in regional boiler houses (Ericsson, 2007). This scenario necessitates diffuse production and the use of reed canary grass as a fuel, similar to the recommendations for the use of common reed (*Phragmites australis* (car) Trin. Ex Steud) as a fuel (Aavik & Kask, 2010).

CONCLUSIONS

In the northern country of Estonia, the grass stand of reed canary grass is the highest-yielding stand for energy grass production. Growing reed canary grass as energy hay is reasonable at median yield levels to maximise the energy return on investment. The lowest energy efficiency was observed for yield levels of 1.2 and 15.1 t DM ha^{-1} at 23.1 and 13.6, respectively. The energy payback ratio was maximised for yield levels of 4.2 and 8.5 t DM ha^{-1} at 49.4 and 48.2, respectively. The energy payback ratio of this cultivation process demonstrates the effective use of input fossil energy. The input fossil energy is inversely proportional to the energy payback ratio.

The ideal result is hampered by the unstable climate in Estonia, which does not permit the single-mowing frequency and, thus, spring (post-winter) harvesting for reed canary grass production. The precipitation in the second part of the Estonian summer, heavy winter snow cover and simultaneous frequent lack of frozen ground reduce the use of reed canary grass productivity as energy hay because the winter or early spring harvest time cannot be utilised. The double-harvest of reed canary grass, in cooperation with biogas or fodder production, must be applied, using the first mowing for energy grass and the second mowing either for biogas or silage production.

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