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The potential of Estonian semi-natural grasslands for bioenergy production

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ABSTRACT

High biodiversity of Estonian semi-natural grasslands can only be maintained through continuous management. One option for the usage of biomass from these areas is bioenergy production, if both the herbaceous biomass yield and the chemical characteristics of the cut meet the needs. In 2007 the largest average annual biomass yield per area was achieved in floodplain meadows (5.7 t dry mass/ha), which also have the highest potential for biomass production among Estonian semi-natural grasslands (more than 113,000 t dry mass). The area of mesic meadows is larger, but due to lower average yield per area (2.5 t dry mass/ha), the potential of this meadow type was less than half of that of floodplain meadows (53,000 t dry mass). The corresponding numbers for wooded meadows were 1.6 t dry mass/ha and 12,000 t dry mass, respectively. Chemical characteristics of herbaceous biomass from wooded meadows significantly differed from mesic and floodplain meadows, giving the highest values of Ca, K, Mg, crude protein and ash (1.3%, 2.4%, 0.3%, 10.9% and 9.5% of the dry biomass, respectively). The energetic value of the biomass from different meadow types varied between 18.1 kJ/g and 18.6 kJ/g. Therefore, various options for bioenergy conversion should be considered depending on the local plant community and restrictions to the harvest time.

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1. Introduction

Semi-natural grasslands (including wooded meadows, coastal meadows, alvars and floodplain meadows) have been formed and shaped by extensive human activities, mainly grazing and mowing. In Europe these plant communities are often the ecosystems with the highest biodiversity on both the micro- and wider landscape level (e.g. Van Dijk, 1991; Joice and Wade, 1998; WallisDeVries et al., 2002); hence the European Union's habitats directive (Council Directive, 1992) emphasises the need for their protection and subsequent management. In order to preserve and increase plant biodiversity, hay mowing and removal of the hay has been recommended rather than grazing (Hansson and Fogelfors, 2000; Sammul et al., 2000; Schaffers, 2002). The nature conservation value of semi-natural grasslands only persists when low intensity management is applied (Donath et al., 2004; Sammul et al., 2008). Intensification of semi-natural grassland management either by application of fertilizers, by more frequent mowing or by sowing more productive plant species will have detrimental effects on biodiversity (Schellberg et al., 1999). Changes in management can decrease the overall biodiversity of the habitat, affecting the number of typical grassland species (Berlin et al., 2000; Gustavsson et al., 2007). Therefore, in order to maintain the high biodiversity in semi-natural grasslands their seeding, fertilising or alteration of mowing period is not permitted in protected areas (e.g. NATURA sites). These are also the main criteria that distinguish these plant communities from other agricultural grasslands.

Throughout Europe the area covered by semi-natural grasslands has decreased considerably during the last century (Bakker, 1989; Van Dijk, 1991). In Estonia the area of semi-natural grasslands decreased almost fivefold from 1,571,000 ha in 1939 to 303,000 ha in 1981 (Kukk and Kull, 1997). The major factors contributing to this decrease were nationalization of private property in the 1940s and subsequent changes in land use practice towards mechanisation and intensification. Many of these areas reverted to forest through natural succession or were cultivated. More recently however, the active nature conservation policy in the EU and current subsidy systems for semi-natural grassland management have promoted the expansion of the area covered by these ecosystems (Sammul et al., 2008). In 2006 semi-natural grassland was estimated to cover 130,000 ha in Estonia, of which floodplain meadows (NATURA 2000 habitat type code 6450) covered 20,000 ha, wooded meadows (NATURA 2000 habitat type code *6530) 8000 ha and mesic meadows (NATURA 2000 habitat type codes 6210 and *6270) 21,000 ha (Kukk and Sammul, 2006). In order to promote grassland management and increase the benefits for farmers, alternative uses for the biomass are required without changing the traditional management principles (time of mowing, absence of fertilisers, etc.).

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Recently much attention has been paid to bioenergy production from various sources. As the typical woody biomass resources from forestry are exhausted in several countries, energy production from different agricultural products has also been considered. Data are available on the quality of several perennial grasses as special energy crops (Dien et al., 2006; Fahmi et al., 2007; Monti et al., 2008). Moreover, the availability of herbaceous biomass from cultivated grasslands and pastures for energy production has also been investigated (Florine et al., 2006; Amon et al., 2007; Jasinskas et al., 2008). Simultaneously a lot of attention is being paid to the biodiversity and landscape protection functions of semi-natural ecosystems (e.g. Mikhailova et al., 2000; Schaffers, 2002; Sammul et al., 2008), although data on the energy potential of herbaceous biomass from semi-natural meadows and its quality for different energy conversion methods is limited (for overview see Prochnow et al., 2009a).

Biomass from grasslands can be used as both feedstock for biofuel production and raw material for power and heat generation (Ahmed, 1994; McKendry, 2002). Benefits of the conversion of biomass to combustion, biogas, bioethanol or pyrolysis depend on the physical and chemical characteristics of the particular raw material. Today the use of grassland biomass for these latter two options is under large-scale investigation, but not yet implemented in practice (Prochnow et al., 2008). Hence, in the current paper we shall focus on the biomass characteristics required for heat and power generation, only. Besides calorific value the most important characteristics for biomass combustion efficiency are the content of moisture, ash and different organic compounds (Quaak et al., 1999). Among the organic compounds the two largest and most important fractions are the crude protein (CP) and neutral detergent fibre (NDF), both of which have been widely studied because of their importance for fodder quality. High protein content is favoured for both fodder and industrial biogas production, however, during combustion this material can cause problems because of NO_x emissions (Obernberger and Thek, 2004). Due to seasonal changes in CP content the combustion of herbaceous biomass harvested in late summer or spring is preferred (Jasinskas et al., 2008). The NDF group consists mainly of lignin, cellulose and hemicellulose. In general, this group is less biodegradable than proteins, but possesses high energy content. During the vegetation period, the NDF content of perennial grasses generally increases, while the CP content decreases (e.g. Bovolenta et al., 2008). In semi-natural grasslands, the harvesting period is restricted by nature conservation needs. Thus for these grasslands the selection criteria for suitable means of bioenergy conversion method should depend on the chemical characteristics of the biomass and not *vice versa*.

The aim of our study is to evaluate the energy potential of herbaceous biomass originating from some semi-natural grassland types that are valued in nature conservation. We focused on the suitability for bioenergy production of biomass from floodplain, mesic and wooded meadows. Wooded meadows typically have high biodiversity and are therefore considered to be priority habitats for nature conservation. Floodplain meadows were assumed to have higher nutrient and moisture inputs, which should result in higher herbaceous biomass yields. Mesic meadows are the most widely spread semi-natural grassland type in the North Temperate Zone. Furthermore, meadows of this type are easy to manage and, therefore, of great interest for new management approaches and associated land use practices. We estimated different quantitative and qualitative parameters of herbaceous biomass of these semi-natural grassland types in order to evaluate the suitability of this biomass for different energy conversion methods and to estimate the potential of these grassland types for bioenergy production.

2. Materials and methods

2.1. Location and weather conditions in the study area

The study was carried out on the Estonian mainland, located on the north eastern shore of the Baltic Sea between 57.3° and 59.5°N and 21.5° and 28.1°E. Fieldwork was carried out in 2007 between 1st and 20th of July. This period is a traditional harvesting time for semi-natural grasslands in Estonia. Earlier harvesting time is not suggested (and sometimes not allowed) due to nature conservation restrictions. Due to the late harvesting time and relatively small production per area, second harvest is very untypical in Estonian semi-natural grasslands. Estonian climatic conditions during the first 3 months of the vegetation period (April, May and June) in 2007 were not significantly different from the long-term (1992–2008) averages. The average daily temperature was 11 °C (long-term average 10.3 °C) and the average monthly precipitation was 50 mm (long-term average 55 mm/month) (Statistics Estonia, 2009).

2.2. Site selection

Fieldwork encompassed sampling from 19 different semi-natural grasslands typical in Estonian conditions (one harvest only, no seeding, fertilising or alteration of mowing has been carried out during last 10 years) (Fig. 1). Nine floodplain meadows, six mesic meadows and four wooded meadows were selected in those areas where the particular meadow type is most frequent. Only sites that had been harvested during at least last three preceding years were selected. Information about previous management was obtained from local authorities or landowners. For site selection, the database of semi-natural grasslands from the Estonian Seminatural Communities' Conservation Association was used. Only the sites determined by their previous inventory of plant communities and status and corresponding with NATURA 2000 habitat type codes 6450, *6530 or 6210 and *6270 were selected for the study. If possible, study sites with larger distance between each other were preferred. Estimates for the total area of each particular semi-natural grassland type in Estonia were taken from published sources (Kukk and Sammul, 2006).

2.3. Measurements of biomass physical characteristics

In each of the meadows studied, 17 round plots (area 0.18 m^2) were selected for biomass sampling. Plots were located along a transect; distance between the plots was at least 30 m. In each plot average herbage height was determined before harvesting. The aboveground biomass of plants rooted inside the circle was harvested manually with scissors just above the ground level and stored in mini-grip bags. Samples were weighed to determine fresh weight. Five samples from each studied meadow were dried for 48 h at 80 °C to determine dry weight. From the pooled data the linear correlation was calculated between dry and fresh weight for each grassland type studied. This correlation was used to calculate dry weight of the biomass from the rest of the plots of that particular grassland type.

2.4. Biomass chemical analyses

The biomass samples from each of the meadows studied were mixed and taken to the lab. The biomass content of crude protein (CP), neutral detergent fibre (NDF), ash and the concentrations of calcium (Ca), magnesium (Mg), and potassium (K) were measured in the Laboratory of Plant Biochemistry of the Estonian University of Life Science. Analyses of the organic compounds, K and ash were carried out according to standardised methods (AOAC, 1990). For

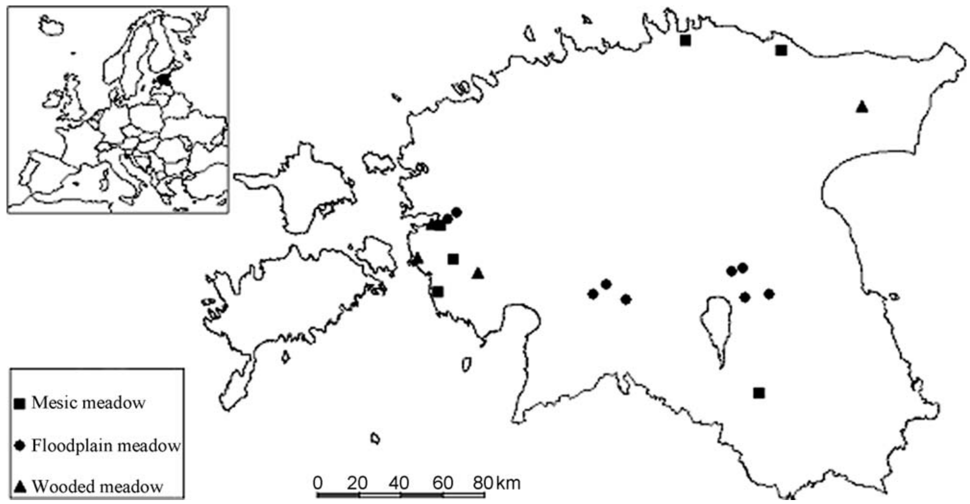

Fig. 1. Location of the studied sites.

Table 1
Parameters of a linear regression model for different meadow types (plant biomass dry weight = $a \times$ plant biomass fresh weight).

	R^2 of the correlation	Parameter a	Lower confidence limit of a	Upper confidence limit of a
Mesic meadow	0.91	0.31	0.28	0.33
Floodplain meadow	0.87	0.31	0.29	0.32
Wooded meadow	0.57	0.21	0.18	0.24

Kjeldahl Digest determination of Ca, and Titan Yellow Mg determination of Mg, a Fiastar 5000 was used (AN 5260 and ASTN90/92, respectively). Gross calorific value (CV) was measured with an IKA WERKE Calorimeter System C 5000 in the laboratory of the Department of Forest Industry of the same university.

2.5. Statistical analyses

Statistical analyses and correlations were performed with the software package SAS. To test the differences in plant biomass weight and in chemical characteristics between different grassland types, the Tukey's Honestly Significant Difference test (HSD) and Ryan–Einot–Gabriel–Welsch Multiple Range test (REGWQ) were used. Significance of different factors on the regressions between variables was detected with GLM Multiple Linear Regression test (MLR) Type I SS hypothesis. Co-variation of different chemical characteristics was studied with the Least Square Means test (LSM). The confidence level of all analyses was set at 95%.

3. Results

3.1. Biomass physical characteristics

The average fresh weight of herbaceous biomass in the floodplain meadows studied was twice as high as that of the mesic meadows and wooded meadows (1846 g/m^2, 818 g/m^2 and 750 g/m^2, respectively). The variability of fresh biomass weight was large in all meadow types resulting in significant differences between various sites of a particular type (SAS Tukey's HSD test). For example, average fresh weight differed more than fourfold between the mesic meadows studied. However, the large number of samples resulted in standard errors less than 8% of the average fresh biomass weight for all meadow types studied. The samples from wooded meadows had significantly higher water content as compared to those from floodplain and mesic meadows (SAS MLR, $p < 0.001$ for both type and site factors; for general data see Table 1). The calculated average dry weight of biomass also varied significantly between meadow types (Fig. 2). The highest average amount of dry biomass (737 g/m^2) was recorded from one of the floodplain meadows. The lowest value was recorded from a mesic meadow (86 g/m^2) (Fig. 2).

The mean value of the average herbage height was the highest (0.65 m) on floodplain meadows as compared to the wooded and mesic meadows (0.22 m and 0.26 m, respectively). However, the standard deviation of average herbage height estimated in the mesic meadows was larger compared with that of the wooded meadows. Even with the higher number of measurements in mesic meadows the relative standard error of the mean value remained the highest for this type (Table 2).

The linear regression model analyses showed that the dry weight could be described by the data of average grass height

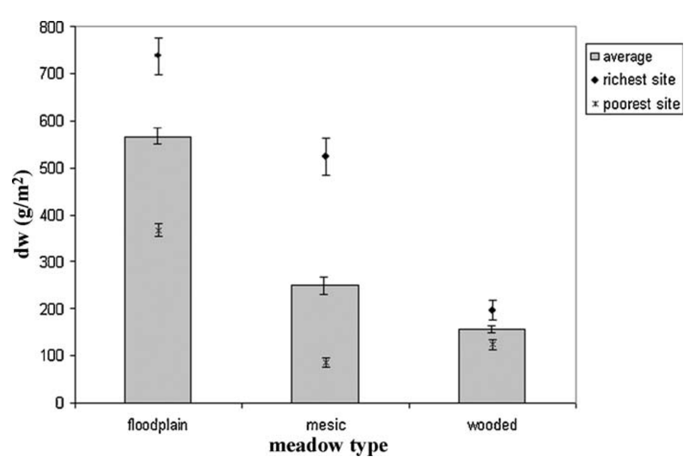

Fig. 2. Average dry weight of herbaceous biomass in different meadow types (mean of the means). Maximum and minimum are the averages of the dry weight of samples from the poorest and most productive study site per type, respectively. The vertical bars indicate the standard error of the mean values.

Table 2
Results of height estimation in different meadow types. x: arithmetic mean; n: sample size; SD: standard deviation; SE%: relative standard error.

Meadow type	n	Average height (m)		
		x	SD	SE%
Mesic	102	0.26	0.13	5.04
Floodplain	153	0.65	0.18	2.29
Wooded	68	0.22	0.07	3.61

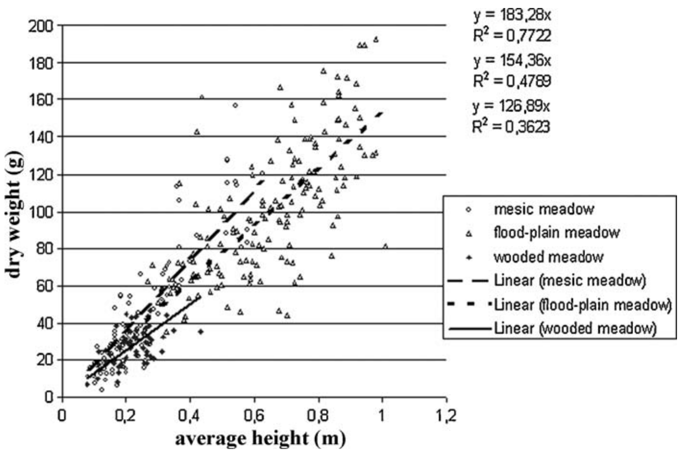

Fig. 3. Relationship between average herbage height and biomass weight for different semi-natural meadow types. The order of the trendline equations corresponds to the order of the data series in the legend.

($R^2 = 0.74$). The model benefited from including the factors of meadow type and site. The detailed analysis of the model showed that from a mesic meadow with a particular average grass height a larger amount of dry biomass can be expected than from other studied meadow types with the same average herbage height. The model showed that if the average height of the herbage was equal by grassland types, the least herbaceous dry biomass could be expected from a wooded meadow (Fig. 3).

3.2. Biomass chemical characteristics and energetic value

The concentrations of several components that determine biogas yield or combustion efficiency were measured. Most of the investigated parameters had approximately the same average value for floodplain meadows and mesic meadows (Table 3). The characteristics of the herbaceous biomass collected from the wooded meadows differed from those collected from other meadow types. In general, the herbaceous biomass from wooded meadows had higher protein content and lower fibre content compared to biomass from the other meadow types studied. The biomass samples with high total fibre content also had significantly higher ash content ($p < 0.001$). However, there was no correlation between the concentrations of proteins and ash content in the dry matter ($p = 0.39$). In general, lower ash content of the biomass resulted in higher heating values (SAS LSM, $p < 0.001$).

Analyses of the content of mineral elements also revealed differences between wooded meadows and the other meadow types (Table 3). The analysed biomass of wooded meadows contained higher amounts of K, Mg and Ca than that of the other meadow types studied, samples with higher Ca and Mg concentrations also had a significantly higher ash content ($p < 0.01$ for all cases). However, this correlation was not found between K concentration and ash content of the herbaceous biomass.

The energetic value of the biomass samples varied between 17.6 kJ/g and 19.1 kJ/g. The energetic value of the herbaceous biomass from mesic meadows was significantly higher than that from wooded meadows. The average values were 18.6 kJ/g, 18.4 kJ/g and 18.1 kJ/g for mesic, floodplain and wooded meadows, respectively (Table 3).

4. Discussion

4.1. Biomass yield estimations

The results of our study revealed that the average harvestable herbaceous biomass yield among different semi-natural grassland types in Estonia was the highest in floodplain meadows (5.7 t dry - weight/ha). Values for mesic meadows and wooded meadows were 2.5 t/ha and 1.6 t/ha, respectively. However, the analysis showed that there could be more than a fourfold difference in the biomass yield among the sites of the same meadow type. It is therefore especially important to evaluate the potentially harvestable biomass for any particular meadow in order to identify both the energetic and economic feasibility of biomass production. However, the data about average herbage height have only limited value to predict the production. Direct estimation of biomass weight, despite being time and equipment intensive, is considered the best option for site evaluation since the relation between average herbage height and yield was also found to be significantly site-specific. Particularly important is the direct estimation of biomass yield in mesic meadows. The higher relative standard error of the average height data in mesic meadows may indicate more variable edaphic conditions and water availability between different sites. This hypothesis was also supported by a larger variability of mean values of the average height per site in mesic meadows compared with other meadow types (data not shown). A larger amount of dry biomass at the same average plant height indicates that vegetation density is higher in the mesic meadows than in the other meadow types investigated.

4.2. Biomass suitability for energy conversion

The chemical analyses of herbaceous biomass samples revealed that there was a significant difference in the characteristics of the

Table 3
Chemical characteristics of the herbaceous biomass from different meadow types. The unit of calorific value (CV) is kJ/g, all the concentrations are represented in % dry weight. Statistically different average values of the same characteristic found with REGWQ are indicated by different letters.

Characteristic	Mesic meadow		Floodplain meadow		Wooded meadow	
	Mean value	REGWQ	Mean value	REGWQ	Mean value	REGWQ
CV	18.6	A	18.4	AB	18.1	B
Ca	1.0	A	0.8	A	1.3	B
K	1.8	A	1.5	A	2.4	B
Mg	0.2	A	0.2	A	0.3	B
NDF	54.1	A	59.7	A	45.3	B
CP	8.5	A	9.4	AB	10.9	B
Ash	7.0	A	6.1	A	9.5	B

cut from wooded meadows compared with the cut from other meadow types. The higher water content and protein concentration in the herbaceous biomass from wooded meadows may refer to the different phenological stage of the herbage as compared with other meadows. It can be assumed that due to tree shading, herbage on wooded meadows becomes senescent later than that on mesic meadows open to direct sunlight. The temporal variation in the content of mineral elements in perennial plants has previously been reported for different energy crops (Pahkala and Pihala, 2000; Lewandowski and Heinz, 2003; Prochnow et al., 2009a). The differences in chemical element content between the biomass of different meadow types may also reflect soil characteristics and associated differences in nutrient loads. Unfortunately, this hypothesis is very difficult to prove since each meadow type exists only on certain soil types. The last and the most obvious explanation for differences in herbaceous biomass chemical characteristics between meadow types studied is the variability of plant species composition. The chemical composition of various herbal species can differ significantly (Pahkala and Pihala, 2000; Bridgeman et al., 2007). However, more detailed studies are needed before general conclusions concerning the use of particular semi-natural meadow plant communities for bioenergy production can be drawn.

The high ash content of herbaceous biomass is a major problem when using this material in combustion (Fahmi et al., 2007; Khan et al., 2009). The current research proved that the ash content of meadow herbage was similar to that of briquettes from spring-harvested reed canary grass (*Phalaris arundinacea*) and switchgrass (*Panicum virgatum*) (Paulrud and Nilsson, 2001; Dien et al., 2006). A similar ash content is also characteristic of different species from naturalized grassland (Florine et al., 2006) and air-dried wheat straw (Zhu et al., 2008). Mg and K content in our samples was similar to that recorded from floodplain meadows in Germany (Donath et al., 2004), only Ca content in our samples was higher. The concentration of Ca and Mg in our study was comparable to data reported from special energy crops in Italy (Monti et al., 2008). The only element showing significantly higher concentrations in our study was K, although this was still less than half of the value (<7%) at which problems are reported to affect thermal utilization (Obernberger, 1998). This critical factor should still be kept in mind, however. Besides the usage of special combustion systems, mixing biomass from different sources can also help reduce these problems. In our study, several parameters (e.g. water content, metal concentration) were the most critical in the biomass from wooded meadows. Therefore, we consider this raw material to be less favourable for combustion and alternative conversion technologies should be preferred for this particular raw material. At the same time the impact of delayed harvest on the chemical characteristics of the grass of wooded meadows should be studied.

During the pasture management period in alpine meadows some grassland species have similar CP content to that recorded from our meadows (Bovolenta et al., 2008). Moreover, the CP content of floodplain meadows in our study was higher than that from floodplain meadows harvested in mid-June in Germany (Donath et al., 2004). On the other hand, the estimated CP values in biomass from our semi-natural grasslands were lower than the CP content in the biomass of semi-natural grasslands used for grazing heifers in Sweden (Hessle et al., 2008). Much higher CP values have also been reported for special cultivated forage crops (e.g. Miller, 1984; Fraser et al., 2005). Most likely, these differences were caused by variable species composition in different grassland types or by harvesting time. Usually there are special restrictions that limit the harvesting time of semi-natural grasslands in order to protect ground-nesting birds or to ensure the flowering of rare plants. Unfavourable timing of harvest can be a problem for fodder production from semi-natural grasslands and this may also influence the biogas production efficiency from this biomass. However, it has been demonstrated that the area-specific methane yield of grass species depends on the biomass yield rather than on the feedstock-specific methane yields (Prochnow et al., 2009b). Therefore, additional studies about the dynamics of the biomass yield and the CP concentration should be implemented to determine if these restrictions on harvesting time could be a problem in Estonian conditions. As semi-natural grasslands are valuable for their high biodiversity, and neither sowing of more protein-rich species nor changes of mowing time are to be favoured, biogas conversion operations need to be adapted to the raw material from semi-natural grasslands. Due to the higher CP concentration in the cut from wooded meadows, this plant community has the largest potential for biogas production among the grasslands studied.

4.3. Energetic potential

The calorific value of biomass from the semi-natural grasslands studied was similar to that of special energy crops (Dien et al., 2006; Fahmi et al., 2007; Jasinskas et al., 2008). However, the calculated energy potential of the semi-natural grassland was only 29, 47 and 104 GJ/ha for wooded, mesic and floodplain meadows, respectively. On average, our data are in the same range as those recorded for hay from low input grasslands in Germany (Rösch et al., 2009). On the other hand, these values are much lower than those of fertilized grains (Lewandowski and Kauter, 2003) or of cultivated plant mixtures in favourable years (Jasinskas et al., 2008). These differences are mainly the result of the lower biomass yield per hectare in semi-natural grasslands. It has been demonstrated that on more fertile soils it is possible to increase the energy yield achieved per hectare threefold with more intensive management of special energy crops (Rösch et al., 2009). However, the management of semi-natural grasslands also needs a much lower energy input when compared with sowed agricultural crop cultivation. Moreover, due to high biodiversity of semi-natural communities, a subsidy system exists in many countries to support the management of these areas (e.g. Council Regulation, 2005). These additional benefits should keep the management of semi-natural grasslands for bioenergy production economically reasonable for farmers. For instance, in Estonia the average subsidy for semi-natural grassland harvesting was 3000 EEK/ha in 2007. At the same time the average price for wood-chips used for heating was 114 EEK/m^3 (Eesti Statistika, 2009). According to rough calculations approximate cost of energy from this biomass is 47 EEK/GJ. Consequently, the subsidy covers losses in production amounting to ca. 65 GJ/ha. This places the income from the management of semi-natural grasslands in the same range as that from the intensive management of special energy crops with an energy yield of ca. 100 GJ/ha (Jasinskas et al., 2008; Rösch et al., 2009). The actual income may vary between different cases as the energy prices are changing and because of the small market for herbaceous biomass for combustion in Estonia today. Also the different management costs (sowing, fertilisation, multiple harvesting, etc.) of these two options are not included in this comparison.

It is also worth pointing out that this additional financial contribution is a significant tool in the support for farmers who want to pursue the sustainable management of semi-natural grasslands while also producing raw material for energy purposes. Hence this additional payment reduces also the risk for the intensification of grassland management.

A database is available to estimate the area and location of different semi-natural plant communities in Estonia (Kukk and

Table 4
Estimated annual potential biomass production and energetic value of different meadow types studied in Estonia. fw: biomass fresh weight; dw: biomass dry weight. Potential methane production was based on the assumption of 1 kg CP = 0.5 m^3 CH_4 (according to Wheatley, 1980).

Characteristic	Floodplain meadow	Wooded meadow	Mesic meadow
Yield (fw t/ha)	18.5	7.5	8.2
Yield (dw t/ha)	5.7	1.6	2.5
Total area in Estonia (ha)	20,000	8000	21,000
Theoretical grass yield (t fw)	369,216	60,025	171,831
Theoretical grass yield (t dw)	113,349	12,665	52,580
Theoretical energy content (GJ)	2,089,358	229,190	979,779
Theoretical methane production (m^3)	5,300,975	691,206	2,228,522

Sammul, 2006). Based on these data it is possible to make rough estimations concerning the potential herbaceous biomass available (Table 4). According to this database, the total theoretical energetic potential of the biomass from these three meadow types is 3.4×10^7 GJ, equivalent to 2% of the Estonian primary energy consumption. More than half of the biomass theoretically available for energy production is located on floodplain meadows and it can therefore be suggested as a major source for bioenergy consumption from Estonian semi-natural plant communities. However, due to seasonal flooding and location in the river basins, the access to the floodplain meadows for harvesting could be more difficult than that to other meadow types. Usage of this potential is even more complicated due to the uneven distribution of semi-natural grasslands in Estonia. A more detailed analyses taking into account the logistic details of these meadows (road access, distance to the destination point, management difficulties, etc.) is therefore required to assess the economically feasible potential of these meadows. Moreover, for the exploitation of biomass from wooded meadows it must be taken into account that approximately 30% of the area is usually covered with trees and therefore not available for grass production. Thus, for a detailed analysis of the energetic potential at a regional level, a model including more factors is required.

5. Conclusions

Considering the results of the current study we can conclude that

- among the Estonian semi-natural grasslands studied the highest biomass yield can be obtained from the floodplain meadows;
- the quality of the cut for bioenergy production depends on the meadow type. Therefore biogas conversion is suggested for relatively protein-rich biomass from wooded meadows, and combustion for other semi-natural grassland types, where the biomass has lower water, ash and metal content;
- semi-natural communities have a high potential for bioenergy production in Estonia. Theoretically, and without considering logistical problems, alternative hay usage possibilities or site-specific obstacles, about 2% of Estonian primary energy consumption could be provided by this type of raw material;
- by using the biomass yield from semi-natural grasslands it is possible to promote both the sustainable management of semi-natural grasslands and the achievement of nature conservation goals.

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References

Ahmed, K., 1994. Renewable energy technologies: a review of the status and costs of selected technologies. World Bank Technical Paper 240, Energy Series.
Amon, T., Amon, B., Kryvoruchko, V., Machmüller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Pötsch, E., Wagentristl, H., Schreiner, M., Zollitsch, W., 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. Bioresource Technology 98, 3204–3212.
AOAC, 1990. Official Methods of Analysis of the Association of Official Analytical Chemists, 15th ed. Association of Official Analytical Chemists, Washington, DC.
Bakker, J.P., 1989. Nature Management by Grazing and Cutting. Kluver Academic Publishers, Dordrecht.
Berlin, G.A.I., Linusson, A.C., Olsson, G.A., 2000. Vegetation changes in semi-natural meadows with unchanged management in Southern Sweden, 1965–1990. Acta Oecologica 21, 125–138.
Bovolenta, S., Spanghero, M., Dovier, S., Orlandi, D., Clementel, F., 2008. Chemical composition and net energy content of alpine pasture species during the grazing season. Animal Feed Science and Technology 140, 164–177.
Bridgeman, T.G., Darvell, L.I., Jones, J.M., Williams, P.T., Fahmi, R., Bridgwater, A.V., Barraclough, T., Shield, I., Yates, N., Thain, S.C., Donnison, I.S., 2007. Influence of particle size on the analytical and chemical properties of two energy crops. Fuel 86, 66–67.
Dien, B.S., Jung, H.J.G., Vogel, K.P., Casler, M.D., Lamb, J.A.F.S., Iten, L., Mitchell, R.B., Sarath, G., 2006. Chemical composition and response to dilute-acid pretreatment and enzymatic saccharification of alfalfa, reed canarygrass, and switchgrass. Biomass and Bioenergy 30, 880–891.
Donath, T.W., Hölzel, N., Bissels, S., Otte, A., 2004. Perspectives for incorporating biomass from non-intensively managed temperate flood-meadows into farming systems. Agriculture, Ecosystems and Environment 104, 439–451.
Council Directive 92/43/EEC, 1992. On the conservation of natural habitats and of wild fauna and flora. European Official Journal L 206 .
Council Regulation (EC) No. 1698/2005 of 20 September 2005 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD), 2005. Official Journal of the European Union L 277 (1) .
Eesti Statistika, 2009. Energy consumption and production. Annual Statistics (Accessed in September 2009)http://pub.stat.ee/px-web.2001/I_Databas/Economy/07ENERGY/07ENERGY.asp.
Fahmi, R., Bridgwater, A.V., Darvell, L.I., Jones, J.M., Yates, N., Thain, S., Donnison, I.S., 2007. The effect of alkali metals on combustion and pyrolysis of *Lolium* and *Festuca* grasses, switchgrass and willow. Fuel 86, 1560–1569.
Florine, S.E., Moore, K.J., Fales, S.L., White, T.A., Lee Burras, C., 2006. Yield and composition of herbaceous biomass harvested from naturalized grassland in southern Iowa. Biomass and Bioenergy 30, 522–528.
Fraser, M.D., Fychan, R., Jones, R., 2005. Comparative yield and chemical composition of two varieties of narrow-leafed lupin (*Lupinus angustifolius*) when harvested as whole-crop, moist grain and dry grain. Animal Feed Science and Technology 120, 43–50.
Gustavsson, E., Lennartsson, T., Emanuelsson, M., 2007. Land use more than 200 years ago explains current grassland plant diversity in a Swedish agricultural landscape. Biological Conservation 138, 47–59.
Hansson, M., Fogelfors, H., 2000. Management of a semi-natural grassland; results from a 15-year-old experiment in Southern Sweden. Journal of Vegetation Science 11, 31–38.
Hessle, A., Wissman, J., Bertilsson, J., Burstedt, E., 2008. Effect of breed of cattle and season on diet selection and defoliation of competitive plant species in semi-natural grasslands. Grass and Forage Science 63, 86–93.
Jasinskas, A., Zaltauskas, A., Kryzeviciene, A., 2008. The investigation of growing and using of tall perennial grasses as energy crops. Biomass and Bioenergy 32, 981–987.
Joice, C.B., Wade, P.M., 1998. Wet grasslands: a European perspective. In: Joice, C.B., Wade, P.M. (Eds.), European Wet Grasslands Biodiversity, Management and Restoration. John Wiley & Sons, Chistester, pp. 1–12.
Khan, A.A., de Jong, W., Jansens, P.J., Spliethoff, H., 2009. Biomass combustion in fluidized bed boilers: potential problems and remedies. Fuel Processing Technology 90, 21–50.
Kukk, T., Kull, K., 1997. Puisniidud. Estonia Maritima 2, 1–249.
Kukk, T., Sammul, M., 2006. Loodusdirektiivi poollooduslikud kooslused ja nende pindala Eestis. Eesti Looduseuurijate Seltsi aastaraamat 84, 114–159.

Lewandowski, I., Heinz, A., 2003. Delayed harvest of miscanthus—influences on biomass quantity and quality and environmental impacts of energy production. European Journal of Agronomy 19, 45–63.
Lewandowski, I., Kauter, D., 2003. The influence of nitrogen fertilizer on the yield and combustion quality of whole grain crops for solid fuel use. Industrial Crops and Products 17, 103–117.
McKendry, P., 2002. Energy production from biomass. Part I. Overview of biomass. Bioresource Technology 83, 37–46.
Mikhailova, E.A., Bryant, R.B., Cherney, D.J.R., Post, C.J., Vassenev, I.I., 2000. Botanical composition, soil and forage quality under different management regimes in Russian grasslands. Agriculture, Ecosystems and Environment 80, 213–226.
Miller, D.A., 1984. Forage Crops. McGraw Hill, New York.
Monti, A., Di Virgilio, N., Venturi, G., 2008. Mineral composition and ash content of six major energy crops. Biomass and Bioenergy 32, 216–223.
Obernberger, I., 1998. Decentralized biomass combustion: state of the art and future development. Biomass and Bioenergy 14, 33–56.
Obernberger, I., Thek, G., 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass and Bioenergy 27, 653–669.
Pahkala, K., Pihala, M., 2000. Different plant parts as raw material for fuel and pulp production. Industrial Crops and Products 11, 119–128.
Paulrud, S., Nilsson, C., 2001. Briquetting and combustion of spring-harvested reed canary-grass: effect of fuel composition. Biomass and Bioenergy 20, 25–35.
Prochnow, A., Heiermann, M., Idler, C., Plöchl, M., Venus, J., Amon, T., Langeveld, H., Hobbs, P.J., 2008. Grassland biomass to energy and materials—an overview. In: Proceedings of the 16th European Biomass Conference and Exhibition, Valencia, Spain, 2–6 June 2008, pp. 439–458.
Prochnow, A., Heiermann, M., Plöchl, M., Amon, T., Hobbs, P.J., 2009. Bioenergy from permanent grasslands—a review. 2. Combustion. Bioresource Technology 100, 4945–4954.
Prochnow, A., Heiermann, M., Plöchl, M., Linke, B., Idler, C., Amon, T., Hobbs, P.J., 2009. Bioenergy from permanent grasslands—a review. 1. Biogas. Bioresource Technology 100, 4931–4944.
Quaak, P., Knoef, H., Stassen, H., 1999. Energy from biomass. A review of combustion and gasification technologies. World Bank Technical Paper 422, Energy Series.
Rösch, C., Skarka, J., Raab, K., Stelzer, V., 2009. Energy production from grassland—assessing the sustainability of different process chains under German conditions. Biomass and Bioenergy 33, 689–700.
Sammul, M., Kull, K., Kukk, T., 2000. Natural grasslands in Estonia: evolution, environmental and economic roles. In: Viiralt, R. (Ed.), Conventional and Ecological Grassland Management. Comparative Research and Development. Proceedings of the International Symposium. Estonian Grassland Society, Tartu, pp. 20–26.
Sammul, M., Kattai, K., Lanno, K., Meltsov, V., Otsus, M., Nõuakas, L., Kukk, D., Mesipuu, M., Kana, S., Kukk, T., 2008. Wooded meadows of Estonia: conservation efforts for a traditional habitat. Agricultural and Food Science 17, 413–429.
Schaffers, A.P., 2002. Soil, biomass, and management of semi-natural vegetation. Part II. Factors controlling species diversity. Plant Ecology 158, 247–268.
Schellberg, J., Möseler, B.M., Kühbauch, W., Rademacher, I.F., 1999. Long-term effects of fertilizer on soil nutrient concentration, yield, forage quality and floristic composition of a hay meadow in the Eifel Mountains, Germany. Grass and Forage Science 54, 195–207.
Statistics Estonia, 2009. Weather. Retrieved February 2, 2009 from http://www.stat.ee.
Van Dijk, G., 1991. The status of semi-natural grasslands in Europe. In: Goriup, P.D., Batten, L.A., Norton, J.A. (Eds.), The Conservation of Lowland Dry Grasslands Birds in Europe. JNCC, Newbury, pp. 15–36.
WallisDeVries, M.F., Poschlpd, P., Willems, J.H., 2002. Challenges for the conservation of calcareous grasslands in northwestern Europe: integrating the requirements of flora and fauna. Biological Conservation 104, 265–273.
Wheatley, B.I., 1980. The gaseous products of anaerobic digestion. In: Stafford, D.A., Wheatley, B.I., Hughes, D.E. (Eds.), Anaerobic Digestion. Proceedings of the 1st International Symposium on Anaerobic Digestion, Cardiff, Wales, September 1979. Applied Science Publishers Ltd., London, pp. 415–428.
Zhu, W., Song, W., Lin, W., 2008. Catalytic gasification of char from co-pyrolysis of coal and biomass. Fuel Processing Technology 89, 890–896.