The Dependence of Reed Canary Grass (*Phalaris arundinacea* L.) Energy Efficiency and Profitability on Nitrogen Fertilization and Transportation Distance

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Abstract. The increased interest in bio-energy production forces us to consider production sustainability which in turn requires energy crop multi-criteria evaluations. The current study analyzes the dependence of reed canary grass (*Phalaris arundinacea* L.) energy use efficiency and production profitability on nitrogen fertilization and biomass transportation distance. The study used yield data from reed canary grass field experiments conducted in Estonia in 1968-1976. In reed canary grass production, nitrogen fertilization influences the biomass yield significantly and therefore has an impact on production energy efficiency. Although reed canary grass net energy yield increases continuously (0.15 GJ kg^{-1}) with increasing nitrogen application, the optimum energy use efficiency is reached with 117 kg N ha^{-1}. Increased reed canary grass transportation distance results in an average energy efficiency decrease of 7 MJ GJ^{-1} km^{-1}. Reed canary grass cultivation for bio-energy production could be considered at a break-even price of 1.5 EEK kg^{-1}, whereas production profit-loss in this instance depends on nitrogen application. Supplementing profitability analysis with transportation costs results in production net cost and therefore also an increase in break-even price. In the current economic situation the actual buying-up prices do not exceed the production net costs, which is why the negative profitability in reed canary grass bio-energy production must be considered. As the current study evaluated reed canary grass production efficiency on soils with low soil humus content, there is a necessity of extending the study to soils with different fertilizer requirements. The methodology of the current study could be used for evaluating bio-energy production optimization in general despite the results being based on one field experiment.

Key words: Reed canary grass, energy use efficiency, production profitability, biomass transportation

INTRODUCTION

The increased interest in bio-energy production during the last decades has forced scientific research to estimate biomass energy potential. Reed canary grass (*Phalaris arundinacea* L.) has been estimated to be a potential bio-energy crop in northern Europe (Hadders & Olsson, 1997; Lewandowski et al., 2003). It is generally agreed that sustainable bio-energy production requires multi-criteria evaluations. Therefore, economical analysis of production as well as further evaluation emphasizing an optimum resource usage should be performed. Studies have evaluated reed canary grass yields, duration period, winter losses (Landström & Wik, 1997; Pahkala & Pihala, 2000; Saijonkari-Pahkala, 2001; Lindh et al.,

2009) in the Northern conditions, but some comparisons have been made of economy, practical production value and energy efficiency characterizing environmental effects. Research has evaluated energy balances (Venturi & Venturi, 2003), also energy and nitrogen use efficiency (Lewandowski & Schmidt, 2006; Wrobel et al., 2009) in biomass production. Energy gain per hectare and consumption per output unit (e.g. energy use efficiency) are substantial indicators characterizing the environmental effect of production.

In biomass analysis the entire production chain (including transportation) should be considered. Perpiňá et al. (2009) performed a methodology based approach for biomass transport optimization. Studies have indicated dependence of optimum transportation distance on the truck's load capacity and the density of transported matter (Junginger et al., 2001; Lindh et al., 2009). Lindh et al. (2009) conclude that in the case of reed canary grass it is impossible to obtain the full load-bearing capacity of a lorry even with bales, therefore, not the maximum mass but the maximum volume may be the limiting factor in biomass transportation. In Finland the maximum cost-effective transportation distance of reed canary grass is estimated at 60km (Pahkala, 2007), but a detailed profitability analysis in Estonian conditions is lacking.

The aim of the current study was to analyze energy use efficiency (EUE) and the production profitability of growing reed canary grass as a bio-energy crop and its relation to nitrogen fertilization and distance of biomass transportation from the plantation.

MATERIALS AND METHODS

Net energy yield and energy use efficiency

Net energy yield (NEY) is calculated by subtracting the total energy input (EI) from total energy yields. Energy use efficiency (EUE) is the ratio of NEY to EI. The reed canary grass total biomass energy was calculated using a lower heating value of 16.6 MJ kg^{-1} (Burvall, 1997). As a delayed harvest is suggested in biomass energy production in Nordic conditions (Saijonkari-Pahkala, 2001), autumn harvested reed canary grass yields were estimated considering 40% yield losses for spring harvest (Lindh et al., 2009). A total energy input in the plantation was calculated annualizing the total consumed energy input of 12 production years (Landström & Wik, 1997), taking into account direct (fuel) and indirect (seed, fertilizers and field machinery) energy input. Machinery energy consumption included energy for manufacturing (86.7 MJ kg^{-1}) and for repair and maintenance (R&M) as suggested by Bowers (1992). In addition, consumed energy of 8.8 MJ kg^{-1} (Loewer et al., 1977) for transporting machines from plantation to farm was included. Energy input for diesel fuel considers a low heating value of 35.7 MJ l^{-1} (European Commission, 2004), whereas fuel consumption in different machinery operations originates from Rinaldi et al. (2005), Dalgaard et al. (2001) and Mikkola & Ahokas (2009). Field machinery operations included tillage, fertilization, harvesting, and biomass field transport. The total energy consumption in production of agricultural machinery and diesel fuel was evaluated for tillage (ploughing, cultivating and rolling), fertilization (twice a year), and harvesting (mowing and baling). Complete energy-related input for fertilization also included varying N and fixed PK application norms with energy input for the production of fertilizer N 35.3 MJ kg^{-1} (Appl, 1997), P 36.2 MJ kg^{-1} and K 11.2 MJ kg^{-1} (Kaltschmitt & Reinhardt, 1997). Additionally, 10 MJ ha^{-1} y^{-1} (Bullard & Metcalfe, 2001) of seed energy and biomass field transport energy was included in the analysis. As the current study assumed the production of cylindrical bales with a 1.2 m diameter, field transport considers the consumed energy to deliver small cylindrical bales to the field side for further hauling with a truck. For evaluating field transport energy consumption, relationship between the total energy input and harvested area was implemented. The total energy input for field transport included machinery and fuel energy as well as 59 MJ DM t^{-1} (Bullard & Metcalfe, 2001) of energy for biomass loading and unloading.

The transport distance calculation considered a semi-trailer with a useful size of 2.5×2.5×14 m. The capacity of the trailer is 88m^3, containing 44 small cylindrical bales as a full-load. The total energy input (diesel fuel, vehicle and maintenance) for truck transport was considered to be 2.3 MJ t^{-1} km^{-1} (Brindley & Mortimer, 2006), the consumption of full-load truck hauling reed canary grass biomass. Additionally, the energy input for loading and unloading small cylindrical bales to and from the truck was included.

Production costs and profitability

A profitability analysis was performed considering the same field machinery operations and general assumptions (including 40% yield losses) as in the energy analysis taking into account the available data of the current economic situation. The current study considered the average NPK fertilizer costs at 18, 50 and 15 EEK kg^{-1} and a seed cost at 100 EEK kg^{-1}. Price analyses for field machinery and operation service costs by the Agricultural Research Centre and output by the Estonian Research Institute of Agriculture were used. In profit evaluation, the authors included 1,108 EEK ha^{-1} of single area payments to the income and performed an analysis with varying buying-up prices of 0.4, 0.8, 1.2, 1.6 and 2 EEK kg^{-1}. In transport distance profitability analysis, the cost of 15 EEK km^{-1} and a loading/unloading cost was considered.

Description of field trial

The current analysis was performed using yield data from 1968-1976 (Rand & Krall, 1978) on reed canary grass field experiment established on an Albeluvisol soil with a sandy loam texture (soil Corg 12 g kg^{-1}, Ntot 1.2 g kg^{-1}) in Estonia (Olustvere, N 58°33′, E 25°33′). Fertilizers with an annual application of 0, 120, 240 and 360 kg N ha^{-1} were used, whereas 35 kg P ha^{-1} and 133 kg K ha^{-1} for N_0, N_{120}, N_{240} and N_{360} was applied additionally. Reed canary grass aboveground biomass was harvested and measured in autumn.

RESULTS AND DISCUSSION

The average reed canary grass DM yields increased continuously from 2.7 to 9.5 t ha^{-1} y^{-1} with an increase in N input (Fig. 1). Applying 80 kg N ha^{-1} results in a doubled average yield compared to biomass from unfertilized areas. Increasing N application to 240 kg ha^{-1} or 360 kg ha^{-1} resulted in a decline in yield increase. Previously reported high reed canary grass yields (7-8 t ha^{-1} on clay soils) (Saijonkari-Pahkala, 2001) could be achieved on soils with low nitrogen content using more than 200 kg ha^{-1} of fertilizers in which case environmental restrictions should also be taken into account.

On the other hand, the variation coefficient (CV, %) of reed canary grass biomass yield decreases rapidly when increasing N fertilization application to 120 kg ha^{-1}. A further increase in N supply resulted in a CV decrease of 0.02% kg^{-1} which verifies the fact that stable reed canary grass yields could be achieved on soils with low humus content by increasing the N supply. In Estonian conditions, reed canary grass variation coefficient could reach up to 44% depending on pedo-climatic conditions and fertilization (Rand, 1981; Eilart & Reidolf, 1987). The Pahkala & Pihala (2000) six-year-old field trial indicated higher biomass yield variability with autumn sowing compared to sowing in spring.

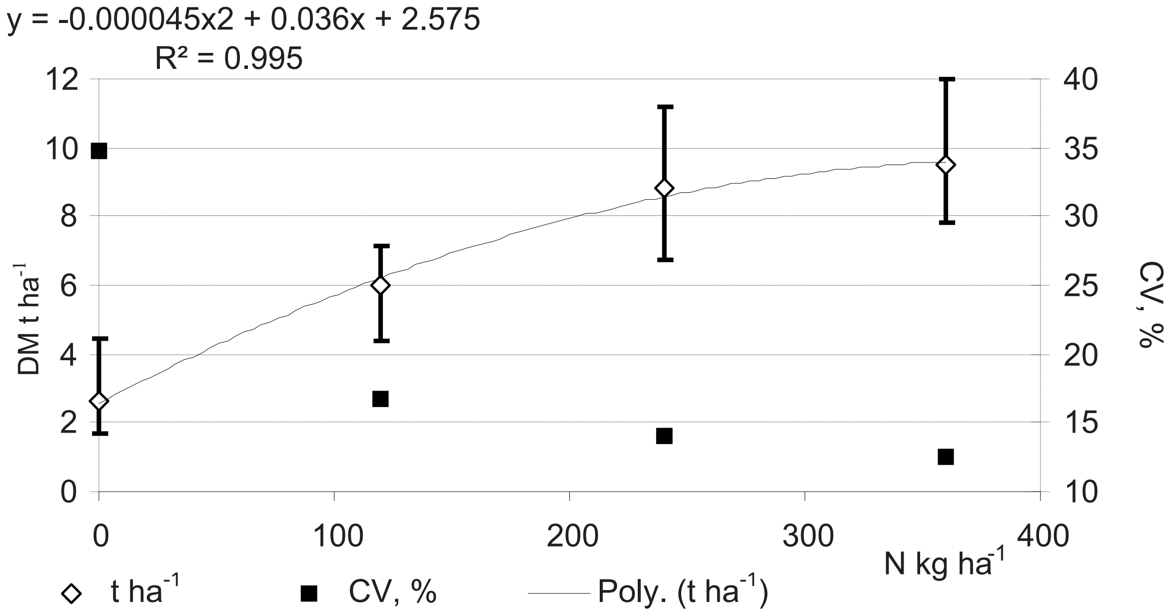

Fig. 1. Dependence of reed canary grass DM yield (t ha^{-1}) and variation coefficient on applied mineral nitrogen rates. Error bars indicate maximum and minimum values.

Energy consumption and production profitability

The average annual energy consumption per tonne of biomass varies with fertilization applications (Fig. 2). A nitrogen input of 140 kg N ha^{-1} results in minimum energy input for production (2.5 GJ t^{-1}). The share of fertilization in energy input increases with an increasing N supply, forming 75% to 89% of total consumption when applying 0-360 kg N ha^{-1}. Energy input for harvesting is the second largest input component in reed canary grass biomass production; as the yield increases, the energy input (GJ t^{-1}) of harvested biomass decreases. Sokhansanj et al. (2009) indicated switchgrass harvesting energy input (GJ t^{-1}) decreasing exponentially with the increasing yield. Biomass transport to the field side and tillage per tonne of production form altogether less than 10% of the total energy input.

The average annual net cost of reed canary grass production decreases from 3.3 to 1.9 EEK kg^{-1} with increasing N application to 238 kg ha^{-1} and increases with increasing N input afterwards. Fertilization costs per tonne of biomass form more than 80% of the total annual costs within all variants in the field experiment. Tillage, biomass transport to the field side and harvesting costs per unit mass altogether decrease with increasing fertilization application.

Production net cost and energy input per tonne of biomass indicate a positive linear relationship, whereas the increase in costs with additional energy consumption varies according to different fertilization norms. An additional energy input of 1 GJ results in a net cost increase of 1,200 EEK in unfertilized areas and 660 EEK with N application of 360 kg ha^{-1}, which indicates that production costs decrease 1.4 EEK kg^{-1} per energy input with increasing N application.

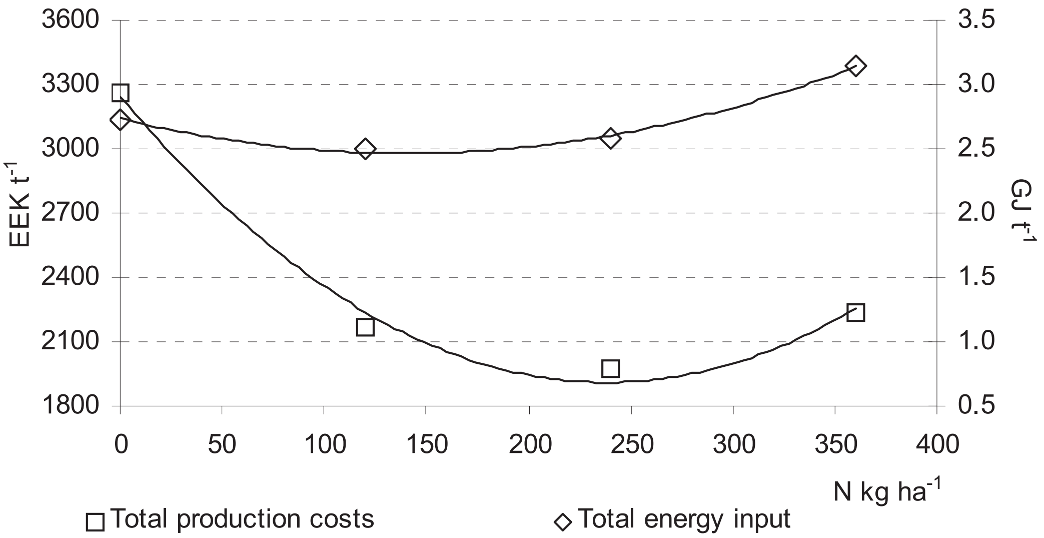

Fig. 2. Dependence of reed canary grass DM production net cost (EEK t^{-1}) and energy input (GJ t^{-1}) on applied mineral nitrogen rates.

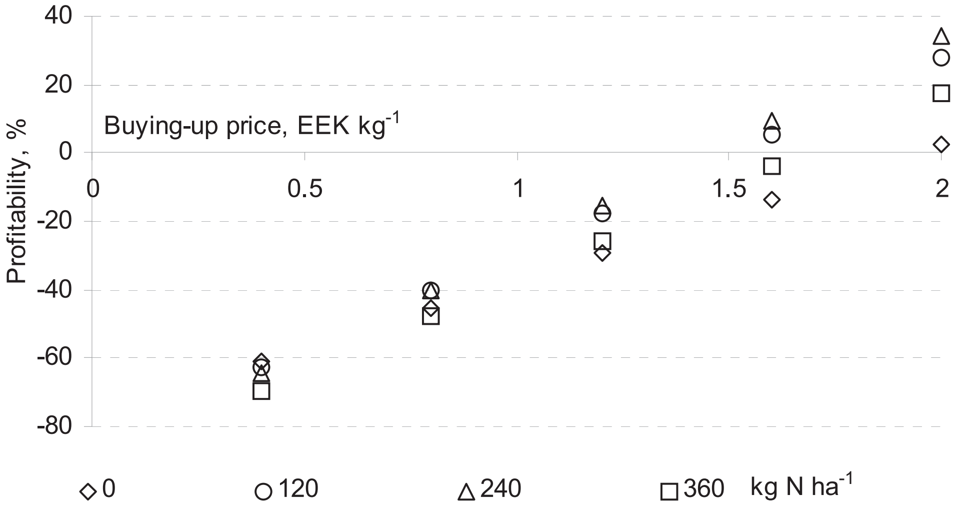

Fig. 3. Dependence of reed canary grass production profitability on applied mineral nitrogen rates and buying-up price (EEK kg^{-1}).

The profitability of reed canary grass production is highly dependent on the buying-up price of biomass and available subsidies. From an economic point of view, cultivation of reed canary grass for bio-energy production could be considered at a break-even price of 1.5 EEK kg^{-1}, although profitability differs within fertilization application norms (Fig. 3). The lowest profitability on Albeluvisols occurs when using high fertilization application rates (e.g. 360 kg N ha^{-1}) and biomass production without N fertilization. In the case of a buying-up price of 2 EEK kg^{-1}, a profit of 34% could be reached, using 210 kg N ha^{-1}. As the current evaluation was based on available data on recent production prices, it must be taken into account that biomass production costs and profitability varies according to different economic situations. Moreover, as the average buying-up price paid to biomass (straw) producers, according to the Estonian Institute of Economic Research, was 0.54 EEK kg^{-1} in January 2010 and the highest price, 1 EEK kg^{-1}, was paid in 2009, negative profitability in biomass production must be considered.

Dependence of energy efficiency and profitability on transportation distance

The average NEY production from fields increases 0.15 GJ kg^{-1} with increasing N applications from 0 to 360 kg ha^{-1}. Energy use efficiency (EUE), as a ratio of energy output to input, indicates the energy produced per unit of energy consumed. Boehmel et al. (2008) declared that EUE is an important criterion for evaluating the suitability of energy crop for bio-energy production. In the current study, average EUE decreased linearly with increasing transportation distance (Fig. 4). The influence of increasing N fertilizer application resulted in an average EUE increase reaching maximum efficiency and decreasing with increased energy input afterwards. An optimum reed canary grass efficiency (5.5 GJ GJ^{-1}), considering, for example, a hauling distance of 10km from the plantation, is achieved using

117 kg N ha^{-1}. The norm of fertilization for reaching optimum efficiency does not change significantly with increasing transportation distance. With an optimum N application, average EUE decreases 7 MJ GJ^{-1} km^{-1} as transportation distance increases. Applying a fertilization norm of 360 kg N ha^{-1} results in the lowest EUE, which indicates that yield decreases to 1 kg of applied fertilizer.

Transportation costs are linearly dependent on distance (Fig. 5). The average hauling costs increase by 1.64 EEK t^{-1} km^{-1} with increasing distance from the plantation. The results of the current study support previous evaluations of a linear relationship between driving distance and transportation costs (Tatsiopoulos & Tolis, 2003; Sokhansanj et al., 2009). Sokhansanj et al. (2009) indicated that in switchgrass production, truck transport is the least expensive option for biomass transportation for distances less than 160 km, but above this mileage the cheapest is rail when comparing four modes of transport. Although the current study considered a truck for biomass transportation with a load of 44 small cylindrical bales, biomass transportation costs could vary when using loads other than this. Lindh et al. (2009) presented an analysis indicating that load size and transport distance effect the formation of transportation costs. The costs of transporting bulk matter exceeded the costs of transporting bales, whereas cylindrical bales with a 1.2 m diameter had the highest costs compared to cylindrical bales with a 1.5 m diameter or large cubical bales.

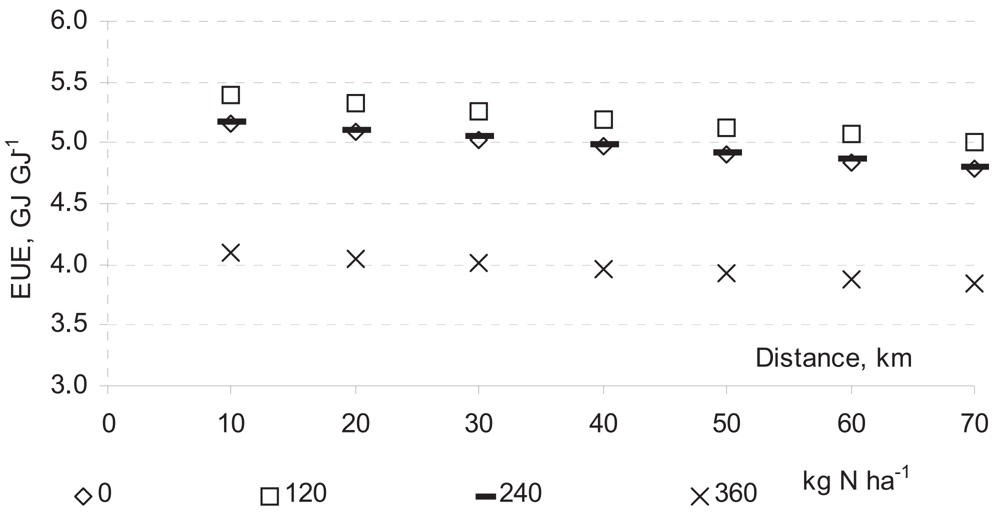

Fig. 4. Dependence of reed canary grass energy use efficiency (EUE) on applied mineral nitrogen rates and transportation distance.

In the current study transportation net costs, applying an optimum N norm of 238 kg ha^{-1}, increased with an increasing hauling distance approximately 2.1 to 2.2 EEK kg^{-1} (Fig. 5). Hauling net costs increased when applying 360 kg N ha^{-1} or 120 kg N ha^{-1} but were highest in plantations without N fertilization. The production of reed canary grass without applying N fertilizer results in an average net cost of 3.4 EEK t^{-1} with a transportation distance of 10 km. Reed canary grass hauling costs could be reduced when using large cubical bales instead of cylindrical bales, or when mixing reed canary grass with wood chips or peat before long-distance transport (Lindh et al., 2009). The advantage of this would be that trucks obtain a near full load-bearing capacity. When transporting reed canary grass, the truck's load is limited by load capacity and not weight. In the current study it was calculated that a trailer with an 88 m^3 capacity could carry 11 t^{-1} reed canary grass loads despite the fact that the truck's potential load capacity exceeds this amount.

Cost effective transportation distance is highly dependent on the buying-up price and applied subsidies. Considering a CAP payment of 1,108 EEK ha^{-1} and buying-up price 1.5 EEK kg^{-1}, negative profitability occurs within all fertilization application norms as the hauling distance increases. A buying-up price of 2.0 EEK kg^{-1} indicates negative profitability on the same terms in reed canary grass production without N fertilization. Pahkala (2007) has referred that an optimal distance for transporting reed canary grass biomass to power plants is less than 60 km. In the current study, if an optimum fertilization norm is applied for reed canary grass production, it will result in a cost effective driving distance of 50 km with buying-up price of 1.6 EEK kg^{-1} and CAP area payments of 1,108 EEK ha^{-1}. Although the profitability of biomass production occurs in aforementioned break-even price, the actual buying-up price in the current economic situation is less than 1.6 EEK kg^{-1} and therefore a negative profitability in reed canary grass production must be considered. The results of the current hauling distance evaluation confirm the statement by Junginger et al. (2001) that maximum transportation distances should not be adopted from literature, though they may provide a general idea on what is viable.

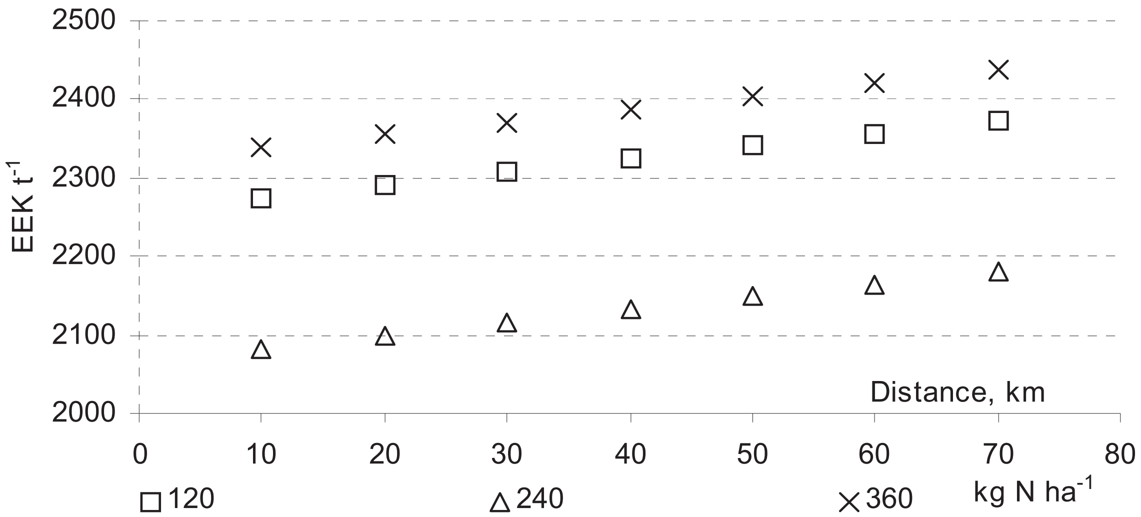

Fig. 5. Dependence of reed canary grass DM net cost (EEK t^{-1}) on applied mineral nitrogen rates and transportation distance.

Although the results of the current study indicate high fertilization application norms to obtain a minimum net cost, environmental restrictions in fertilization should be taken into account. Moreover, it must be considered that production costs and buying-up prices influencing the profitability of biomass production are dependent on the economic situation.

In the current study the output of the energy efficiency analysis indicated reverse results as compared to the output of the economic evaluation of reed canary grass. An optimum EUE could be achieved by reducing the N application norm by more than twice of the norm for reaching a production minimum net cost. Therefore, research must face the challenges of developing a methodology for taking into account several variables in evaluating the biomass production optimum input level. As the current reed canary grass energy efficiency and profitability analysis is performed on soils with low soil fertility, there is a necessity of extending the study to soils with different fertilizer requirements. In spite of the fact that the results presented are based on one field experiment, the methodology of the current original study could be used for evaluating the optimization of bio-energy production in general.

CONCLUSIONS

As the results of the current study indicate an inconsistency in the production of reed canary grass bio-energy, regarding the economical and environmental conditions, biomass multi-criteria evaluations should be emphasized. Although reed canary grass biomass production indicates positive energy efficiency within the applied mineral fertilizer norms, the output of the economic analysis confirms the importance of knowledge-based fertilization. The lowest profitability occurs when using excessive fertilization or when producing biomass without applying N fertilizers. Increasing the transportation distance results in a decrease in both the EUE and production profitability, whereas cost effective transportation distance is highly dependent on the buying-up price and applied subsidies. The current study verifies the importance of analyzing reed canary grass profitability and energy efficiency in local pedo-climatic conditions, whereas the results of the profitability analysis should be considered dependent on the economic situation. Although the results of this study describe production efficiency on a soil with low humus content, the developed methodology could be used for the evaluation of biomass production in general.

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