Eesti Maaülikool
Estonian University of Life Sciences

SITE-SPECIFIC ENERGY CROP PLANNING: POTENTIAL LAND RESOURCE, PEDO-CLIMATIC AND ECONOMIC RISKS

ASUKOHAPÕHINE ENERGIAKULTUURIDE PLANEERIMINE: POTENTSIAALNE MAARESSURSS, MULLASTIK-KLIMAATILISED JA MAJANDUSLIKUD RISKID

LIIA KUKK

A Thesis
for applying for the degree of Doctor of Philosophy
in Agricultural Sciences

Väitekiri
filosoofiadoktori kraadi taotlemiseks põllumajanduse erialal

Tartu 2012

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Institute of Agricultural and Environmental Sciences,
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II Kukk, L., Roostalu, H., Suuster, E., Rossner, H., Shanskiy, M., Astover, A. 2011. Reed canary grass biomass yield and energy use efficiency in Northern European pedoclimatic conditions. Biomass and Bioenergy 35(10):4407–4416.

III Kukk, L., Astover, A., Roostalu, H., Rossner, H., Tamm, I. 2010. The dependence of reed canary grass (*Phalaris arundinacea* L.) energy efficiency and profitability on nitrogen fertilization and transportation distance. Agronomy Research 8:123–133.

IV Alaru, M., Kukk, L., Olt, J., Menind, A., Lauk, R., Vollmer, E., Astover, A. 2011. Lignin content and briquette quality of different fibre hemp plant types and energy sunflower. Field Crops Research 124(3):332–339.

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III	**LK**	**LK**, AA, HR, HsR, IT	**LK**	**LK**
IV	MA	MA, RL, JO, AM	MA, **LK**, AA	MA, **LK**, JO, AM, EV

AA – Alar Astover; AM – Andres Menind; ES – Elsa Suuster; EV – Elis Vollmer; HR – Hugo Roostalu; HsR – Helis Rossner; IT – Indrek Tamm; JO – Jüri Olt; KS – Kalev Sepp; LK – Liia Kukk; MA – Maarika Alaru; MN – Merrit Noormets; PM – Peeter Muiste; RL – Ruth Lauk.

ABBREVIATIONS

ARIB – Agricultural Registers and Information Board
CAP – Common Agricultural Policy
CV – the coefficient of variation
DM – dry matter
EI – energy input
EU – European Union
EUE – energy use efficiency
EY – energy yield
FAO – Food and Agriculture Organization of United Nations
GIS – Geographic Information System
J – joule [kilo (k) 10^3; mega (M) 10^6; giga (G) 10^9; tera (T) 10^12; peta (P) 10^15; exa (E) 10^18; 1 kWh = 3.6×10^6 J]
K – potassium
N – nitrogen
NEY – net energy yield
Ntot – soil total nitrogen content (%)
Nüld – mulla üldlämmastiku sisaldus (%)
P – phosphorus
RCG – reed canary grass

1. INTRODUCTION

Population growth with limited land resource have emphasised the importance of considering land potential for all required (e.g. for agricultural, energy etc.) uses. The Food and Agriculture Organization of United Nations (FAO) has recognised that, in order to evaluate world`s land potential, data on soils and landforms must be combined with the analysis of climate (Bot et al. 2000). Studies have quantified agricultural land over large areas (Ericsson and Nilsson 2006; Rounsevell et al. 2006; Verburg et al. 2008) with Hoogwijk et al. (2005) and Ericsson and Nilsson (2006), for example, providing an analysis of different scenarios.

In recent decades, renewable energy production has become the focus of energy policy. Increasing the share of renewable energy has been set a target also in EU strategies. For example, Directive 2009/28/EC sets a target of reaching a 20% share of energy from renewable sources in the EU by 2020. In 2009, the share of renewable energy in gross final energy consumption in the EU27 was 11.7% (Eurostat 2012). Increase of renewable energy resources is also an aim in Estonia. On 26 November 2010, the Estonian government approved "The Action Plan of Renewable Energy in Estonia up to 2020", which includes targets for renewable energy and measures for reaching these targets (RT III, 30.11.2010, 3). For meeting the target of increasing the share of renewable energy, biomass use is claimed to be essential (Faaij 2006), i.e., land is considered as a resource for bio-energy production. However, the limitation of land resource addresses the possibility of competition between food, feed and bio-energy production. Therefore, potential land resource for renewable energy production should be allocated from abandoned land, since the use of these areas does not have a negative effect on food supply. Field et al. (2008) have estimated abandoned agricultural land at 386 Mha globally although they acknowledge that the uncertainty for this abandoned area estimate may be substantial. Tilman et al. (2001) proposes the expansion of global agricultural land during the next 50 years as human population increases. However, in Estonia, there is a need to plan for the use of abandoned agricultural areas since the aggregate area of arable land in 2006 was half that in use after the restoration of independence in 1991 (Astover et al. 2006[a]). Therefore potential land resource for bio-energy production and future perspectives of renewable energy should be assessed regionally.

Worldwide, biomass has been one of the main resources for renewable energy. Since the mid-1980s, there has been increasing interest in bio-energy crop production in the United States and Europe (Lewandowski et al. 2003). Biomass from dedicated energy crops has been used for decades. Studies have evaluated both positive (McLaughlin and Walsh 1998) and negative (Ledin 1998) environmental consequences of energy crop production. In addition, energy parameters describing the environmental impact have been included to provide a more complex approach. For instance, energy efficiency is considered as a criterion in evaluating crop suitability for bio-energy production. Nevertheless, multiple criteria (e.g. energy efficiency, economic feasibility etc.) should be included when evaluating crop suitability for bio-energy production.

Yield potential and quality are substantial indicators in bio-energy production for land-use decisions. Studies have analysed biomass potentials of dedicated energy crops in a wide geographical range (Richter et al. 2008; Ficher et al. 2010[a]; Jager et al. 2010; Wullschleger et al. 2010). Ericsson and Nilsson (2006) have analysed biomass supply and energy crop yield potential of large areas using statistical databases. More detailed bio-energy potential analyses in a region have been performed using Geographic Information System (GIS). Most of these studies have used coarse-scale databases (Voivontas et al. 2001; Stampfl et al. 2007; Hastings et al. 2009; Fischer et al. 2010[a]); however knowledge-based bio-energy production requires analysis made on as detailed a scale as possible. Many studies, as for example Richter et al. (2008) and Jager et al. (2010), have included meterological variables, soil water capacity and location in spatial yield analyses. However, studies considering yield dependence on soil properties are few. Furthermore, nationwide biomass production evaluations, taking into account field-specific soil information, do not currently exist. Therefore, regardless of thorough studies with dedicated energy crops, yield variation dependent on soil properties, i.e. site-specifity in spatial analyses has been insufficiently deliberated, being one of the challenges in bio-energy planning.

In the current dissertation, the bio-energy potential of abandoned agricultural land in Tartu County will be studied, as an example. Biomass yield dependence on pedo-climatic conditions and fertilisation will be analysed and evaluated on a detailed spatial scale. Also a multi-criteria analysis, i.e. energy efficiency and profitability as an example of reed canary grass (RCG) production will be performed.

2. REVIEW OF LITERATURE

2.1. Bio-energy potential

Hoogwijk (2004) has defined renewable energy sources as having theoretical, geographical, technical, economic and implementation potential. Several studies have analysed bio-energy geographical potential, i.e. production of primary biomass energy on available land areas (Fischer and Schrattenholzer 2001; Hoogwijk et al. 2003; Hoogwijk et al. 2005). Hakala et al. (2009) have indicated that the annual global energy potential of raw material from crop residues and bioenergy crops cultivated in the fields set aside varies at present from 47 to 133 EJ depending on diet. Hoogwijk et al. (2003) have proposed that total global geographical biomass potential, considering the timeframe up to 2050, is 33–1130 EJ year^{-1}, with dedicated energy crop production on agricultural land not needed for food or fodder production, is up to 988 EJ year^{-1}. Fischer and Schrattenholzer (2001) have estimated that for the year 2050, global bio-energy potential is 400 EJ. This variation in estimations of bio-energy potential is caused by different approaches, methodologies and assumptions. However, Sims et al. (2006) declare that approximately 46 EJ year^{-1} is currently derived from biomass, i.e. in the form of combustible biomass and wastes, liquid biofuels, renewable municipal solid waste, solid biomass/charcoal, and gaseous fuels. This indicates high global biomass (including bio-energy crops) potential in primary energy supply. In 2009, the consumption of primary energy in Estonia was 113 024 TJ (Statistikaamet 2012) and the share of renewable energy in gross final energy consumption formed 22.8% (Eurostat 2012). The majority of renewable energy consumption and production forms bio-energy (Estonian Institute of Economic Research 2011; Statistikaamet 2012). In 2009, 33,679 TJ of bio-energy was produced in Estonia of which energy from wood biomass formed 94% (Estonian Institute of Economic Research 2011). Bio-energy production from solid agricultural biomass of rapeseed (and turnip seed), perennial grasses, straw and grain formed 580, 19, 5 and 3 TJ, respectively. Since 99% of rapeseed (and turnip seed) bio-energy was exported, the consumption of solid agricultural biomass in Estonia, in 2009, was 30 TJ forming 0.13% of total bio-energy consumption (Estonian Institute of Economic Research 2011). Therefore, solid agricultural biomass production (incl. dedicated energy crops) may have higher potential for Estonia`s renewable energy resources.

Bio-energy potential is dependent on a variety of factors (Dornburg et al. 2010) with key parameters of land availability for bio-energy production and biomass productivity (Berndes et al. 2003; Smeets et al. 2007). Several studies have evaluated bio-energy potential in Europe (Ericsson and Nilsson 2006; Fischer et al. 2010[b]). Ericsson and Nilsson (2006), for example, provide a resource-focused approach in bio-energy potential assessment. However, precise analyses require assessments made on as detailed a scale as possible. Voivontas et al. (2001) have evaluated biomass potential on the island of Crete using site-specific statistical data. Förster et al. (2008) have performed even more detailed analysis of a rural district in the northeast lowlands of Germany by using soil parameters to assess land suitability for energy crop cultivation. The results of many studies (Lagacherie et al. 2000; Hoogwijk et al. 2003; Hoogwijk et al. 2005) confirm the statement of El Bassam (1998) that climate and local soil properties, i.e. pedo-climatic conditions, are the most important factors influencing the biomass productivity within a specific region. Although climate and soil data have been included in many studies covering large areas (Hoogwijk et al. 2003; Hoogwijk et al. 2005; Campbell et al. 2008; Fischer et al. 2010[a]), it has been pointed out that regional pedo-climatic conditions are ignored in many studies, which calculate bio-energy potentials (Smeets et al. 2007).

2.2. Bio-energy crops

The sources of bio-energy are agricultural and woody biomass (e.g. natural vegetation), crop residues, organic wastes, agricultural and forestry by-products or specially cultivated non-food crops, i.e. dedicated energy crops, for the purpose of converting their harvested biomass into bio-energy. A variety of plants are grown as dedicated energy crops, e.g., woody lignocellulosic crops (e.g., poplar, willow, and eucalyptus), herbaceous lignocellulosic crops (e.g., switchgrass, miscanthus) etc. (Haberl et al. 2010). Heaton et al. (2008) define dedicated energy crops as a long-term solution in bio-energy production and the use of energy stored in food and feed or lignocellulosic crop residues as shorter-term solutions. Of the wide range of energy crops tested in Europe, oilseed rape seed, eucalyptus, sunflower, willow, sugar beet, reed canary grass (RCG) and poplar have been cultivated more intensively, i.e. in thousands of hectares (Venendaal et al. 1997).

Based on photosynthesis, energy crops are specified as C3 or C4 plants. The first product of C3 and C4 species photosynthesis are 3-carbon and 4-carbon organic acid, respectively (El Bassam 1998). Many studies have stated that C4 species have higher nitrogen and water use efficiency compared with C3 species (Long 1983; Beadle and Long 1985). However, in cool regions where temperature limits the photosynthetic process (e.g. in Finland or in Estonia), C3 grasses perform better (Lewandowski et al. 2003). The review of Lewandowki et al. (2003) indicates that about 20 perennial grasses for bio-energy production in Europe have been tested, of which two C3 crops (RCG (*Phalaris arundinacea*) and giant reed (*Arundo donax*)) and two C4 crops (miscanthus (*Miscanthus* spp.) and switchgrass (*Panicum virgatum*)) have been chosen for more extensive research programs. Among local conditions, production techniques, pest and disease management, and mechanical cultivation and harvesting which should be included in crop selection in agronomic research (Morgan et al. 2010), high biomass productivity and favourable bioenergy characteristics are preferred in energy crop species decision-making (Förster et al. 2008). Of the large variety of plants that can be used for bio-energy production in northern Europe (Allison et al. 2010), RCG is proposed as a promising energy crop (Hadders and Olsson 1997). The cultivation area of RCG in Finland increased from 500 ha in 2001 to more than 17,000 ha in 2006 (Pahkala et al. 2008), and it is reported that the area of RCG could increase to 100,000 ha by the year 2015 (Lindh et al. 2009). In Estonia, it was possible to apply the subsidy for dedicated energy crop production during 2007–2009. The area used for dedicated energy crop production has increased from 11,512 to 23,964 ha during 2007–2009. Of the total dedicated energy crop area, 23,750 ha were used for rape and turnip, 135 ha for RCG, 77 ha for grain and 2 ha for willow production in 2009 (Estonian Institute of Economic Research 2011). In addition to the proposed potential energy crops suitable for cool regions, some alternative southern energy crops may also have bio–energy potential in Nordic conditions. Therefore, new alternative crops for energy production are studied in Estonian climatic conditions. Recently, fibre hemp and sunflower have been studied as energy crops in Estonia (Alaru et al. 2011[a]) although the cultivation of fibre hemp, as an example, has a very long tradition in Nordic conditions and has been studied also as a raw material for pulp and paper (Saijonkari-Pahkala 2001). Also, Jerusalem artichoke, Amur silver-grass, energy grass cultivar Szarvasi-1 and foxtail millet have been studied as energy crops in Estonian conditions (Alaru et al., 2011[b]).

2.3. Agricultural land resource

Studies have evaluated agricultural land resource and the change globally (Verburg et al. 2008), in Europe (Rounsevell et al. 2006; Verburg et al. 2008), within country (Peterson and Aunap 1998; Astover et al., 2006[a]) and on selected areas (Tappan et al. 2000; Semwal et al. 2004). Research analysing land use changes from the past to the present has to face challenges of which data collection is the most time consuming. However, there are several methodology-based studies proposing alternatives to overcome these difficulties. The use of satellite photographs (Tappan et al. 2000) or multitemporal Landsat Multispectral Scanner scenes imagery (Peterson and Aunap 1998) can aid analysis. Results considering land use change in the future are controversial. For example, Rounsevell et al. (2006) indicate a decrease in agricultural land use in Europe during next the 70 years but van Meijl et al. (2006) show that no drastic decrease in land for agricultural purposes is expected for the EU25 in the coming 30 years. Nevertheless, the common principle of all these studies is the knowledge that land use decisions are related to several factors and assumptions, e.g. production supply and demand, crop productivity etc. The political system and activity have a strategic impact on land use management. In China, estimation of the minimum quantities of food required have forced politicians to regulate the area per capita of cultivated land, i.e. to protect agricultural land resource (Skinner et al. 2001). Controversially, obligatory set aside land has been introduced to limit overproduction in European Union (Council Regulation No. 1782/2003). Future uncertainty is a reflection of the unforeseen tendencies of many factors, therefore land use change is commonly represented as scenarios (Ericsson and Nilsson 2006; van Meijl et al. 2006; Rounsevell et al. 2006). However, the main aspect, adequate land resource for food security, is primary and emphasised in all studies. The minimal cropland for a diverse diet is considered to be 0.5 ha per capita (Lal and Stewart 1990) but world cropland per capita in 2004 was 0.25 ha (Bringezu et al. 2009) and is expected to decrease in the future. The need to preserve the agricultural land resource is critical, for example in China, where the average national cultivated land area is only 0.08 ha per capita (Skinner et al. 2001). Analyses considering agricultural land resource indicate uncultivated fields globally (Field et al. 2008; Campbell et al. 2008) and on a regional scale (Astover et al., 2006[a]); many studies indicate abandoned land increases in Europe in the future (Rounsevell et al. 2006; Verburg et al. 2006; Verburg and Overmars 2009). However, the uncertainty of abandoned area estimates should be recognised as pointed out, for example, by Field et al. (2008). Abandoned agricultural land could be put to alternative use, as, for example, for bio-energy production. Peterson and Aunap (1998) estimated that one-third of the arable land in use in Estonia in 1990 had been abandoned by 1993. The use of abandoned agricultural areas does not have any negative affect on food supply. Several studies have proposed also energy crop production on degraded land (Makkar and Becker 2009; Offermann et al. 2011). Offermann et al. (2011) notices that there is the absence of clear delineation between the abandoned agricultural land and degraded land and substantial research has been performed calculating bio-energy potentials with overlaps of these areas. However, considering the definition of degraded areas as "areas where human activities have induced soil and/or vegetable degradation" (Hoogwijk et al. 2003), the overlap of abandoned and degraded land are not using these terms correctly. For example, Mottet et al. (2006) have pointed to socio-economic and bio-physical drivers in analysing land use change patterns.

2.4. Biomass production

Biomass potential depends on crop productivity. Lewandowski et al. (2003) compared crop productivity in different countries. Ewert et al. (2005) indicated that productivity of wheat, potatoes, sugarbeet and maize has increased in Europe over the period 1960–2000. Fischer et al. (2010[b]) noted aggregate crop yield increases during 1985–2002 in Western Europe with decreases in Eastern Europe. However, several studies propose yield increase within regions in following decades (Smeets et al. 2007; Fischer et al. 2010[b]). Ewert et al. (2005) have estimated crop productivity increase in Europe up to 163% with ranging between different scenarios and affected by climate change, increasing CO_2 concentrations and technology development. The effect of climate change on crops has been reported also in earlier studies (Rötter and van de Geijn 1999; Parry et al. 2004). Against the analyses of increased yields in the future, studies have emphasised the importance of considering lower yields on degraded land (Pinstrup-Andersen and Pandya-Lorch 1998; Tappan et al. 2000). Soil degradation includes changes in soil chemical, physical and biological properties (Lal et al. 1989; Lal 2001) with chemical deterioration denoted as the depletion of major plant nutrients, accumulation of salts and heavy metals in concentrations toxic to plant growth (Lal et al. 1989). Driessen and Konijn (1992) have generalised production as a reflection of the compounded sufficiency of all land characteristics and land qualities in a land-use system. Despite knowledge that some energy crop species are suitable on relatively unfertile (e.g. chemically degraded) soils (Makkar and Becker 2009; Sang and Zhu 2011), fertiliser application has been approved to increase yields of a variety of energy crops (Ercoli et al. 1999; Lewandowski and Schmidt 2006; Nikièma et al. 2011). Thus, soil properties, e.g. soil nutrient and water supply, is a fundamental indicator influencing biomass production. Wetzel and van der Valk (1998) have approved productivity dependence of selected perennial plant species on nutrient level, interspecific competition, soil moisture and interactions of all these factors using principal component analysis. In the study of Danalatos and Archontoulis (2010), N fertilisation did not affect crop growth and the authors suggested that this was due to the high fertility status of the soil. This indicates the importance of noting soil potential in biomass production. However, in bio-energy production analysis, uniform fertiliser applications are suggested as indicated in the review article of Lewandowski et al. (2003) while site-specifity in agronomic potential analysis is ignored. Only few studies, for example, that of Saijonkari-Pahkala (2001), have differentiated recommended fertiliser application separately for organic and mineral soil. Nevertheless, soil properties could differ substantially within mineral and organic soils (Batjes 1997). Since long-term field experiments of dedicated energy crops cultivated on various pedo-climatic conditions enable more accurate analysis, research has to face challenges in emphasising soil potential in biomass production.

2.5. The approaches of yield models

Many bio-energy potential studies have used the average yield approach in global or regional analysis (Ericsson and Nilsson 2006; Fischer et al. 2010[b]; Beringer et al. 2011). However, biomass production differs site-specifically and recent research has emphasised the importance of including yield variability in spatial analysis, e.g. in GIS (Richter et al. 2008; Jager et al. 2010). GIS is a database which could be used to store, modify, and analyse geographically distributed data and is a tool in a wide range of spatial applications (incl. biomass potential analysis). Field experiments allow presenting common principles of biomass dependence on many factors. Nevertheless, results of these studies are applicable in the same pedo-climatic conditions as in the field trials. This site-specific information, however, could be used for general, large areas covering analysis by using quantitative approaches, such as modelling. Crop models interpret results from different scientific disciplines and work as agronomic research tools for research knowledge synthesis (Steduto et al. 2009).

Different approaches have been used for crop yield modelling. These include: (i) statistical prediction models, (ii) crop growth simulation models (e.g. CERES, WOFOST, MACROS) (Jones and Kiniry 1986; van Diepen et al. 1989; Penning de Vries et al. 1989), (iii) cropping system simulation models (Wang et al. 2002; Jones et al. 2003) etc. Statistical models are based on field data and are usually applied in order to analyse how one variable depends on another continuous and/or categorical variable or variables. Regardless of the limitation of statistical prediction models – being applicable in the conditions for which it has been developed (McBratney et al. 2002) – Jager et al. (2010) argue the importance of using empirical models and emphasise their role in research.

Some models, i.e. simulation models that could have significant impact in scientific disciplines, are underexploited. Matthews et al. (2000) have identified the main limitations to the uptake and impact of the models and concluded that a major limitation is the lack of input data in spatial and temporal dimensions. To overcome model application difficulties (e.g. suitability for research objective), many studies have complemented and adapted previously developed models (Rosegrant et al. 2002; Pathak et al. 2003; Liu 2009) with Lagacherie et al. (2000) presenting an approach of including imprecise data for modelling crop yields over vast areas.

Many simulation models have been developed to be applicable over large areas (Potter et al. 1993; Nonhebel 1997; IMAGE-team 2001; Campbell et al. 2008; Liu 2009; Fischer et al. 2010[a]). In addition, scaling up site-based models to a region or down-scaling regional crop models to at fine-scale, as, for example, the studies of Paydar et al. (2009) and Therond et al. (2011), are commonly used approaches in research. Scaling up or down procedures could influence model reliability with the uncertainty surrounding the model input parameters (Denier van der Gon et al. 2000; Renschler 2003; Faivre et al. 2009) and model application may not be valid for spatial analysis. Regardless of many studies proposing strategies or methodologies to overcome or diminish this difficulty (Xiong et al. 2008; Ewert et al. 2009; Ewert et al. 2011), both the prediction as well as simulation models should be performed on as detailed a scale as possible, i.e. including site-specific information. The application of detailed scaled models, suitable in appropriate spatial scale, may still be restricted due to the limited data inputs. However, a methodological approach, the use of pedotransfer functions that predict soil characteristics from available data, as, for example, Richter et al. (2008), could be applied. Another methodological concept of models is prediction accuracy, i.e. the goodness of fit between observed and predicted values. Therefore, approaches in analysing prediction accuracy have been proposed. For example, Suuster et al. (2012) have compared some of the methods (i.e. the merits of the median approach, analysis of covariance, mixed models, and random forests) in order to evaluate differences of soil organic carbon concentrations based on the value of mean squared error between the methods.

With the increased interest of producing renewable energy from energy crops since the mid-1980s (Lewandowski et al. 2003) a development of biomass and bio-energy models occurred (Jebaraj and Iniyan 2006). Several studies such as those by Fischer and Schrattenholzer (2001) use robust and simplified crop models; however site-specificity in yield formation has been emphasised also in bio-energy research (Jager et al. 2010; Wullschleger et al. 2010). Furthermore, both Jager et al. (2010) and Wullschleger et al. (2010) applied empirical yield models in GIS. Energy crop yield models have used meterological (i.e. climatic) variables in yield analyses (Clifton-Brown et al. 2000; Wullschleger et al. 2010). Recent bio-energy studies have included also soil characteristics in yield analyses, i.e. performed assessments with several pedo-climatic variables (Hoogwijk et al. 2005; Hoogwijk et al. 2003; Hoogwijk et al. 2005; Richter et al. 2008; Jager et al. 2010). Yield models taking into account detailed pedo-climatic conditions contribute to risk assessment in agriculture and provide a foundation for knowledge-based decision making. However, knowledge of spatially variable soil properties influencing bio-energy production is still underexploited. Tenerelly and Carver (2012) have presented a methodological approach for analysing bio-energy potential by evaluating the suitability of land for energy crop growth. Di Virgilio et al (2007), inversely, have assessed spatial yield variability directly relating biomass to soil parameters. However, the models in the latter research were performed in a small field. While previous studies have analysed bio-energy production at either the site-specific (Förster et al. 2008) or regional level (Tenerelly and Carver 2012), nationwide biomass production evaluations considering field-specific soil information do not currently exist. Therefore, model application over large areas taking into account field-specific soil information is one of the challenges in bio-energy production.

2.6. Energy analysis

High yield is not commonly sufficient to evaluate species suitability as an energy crop (Bullard and Metcalfe 2001). Therefore energy parameters have been used to provide a more complex approach. Energy analysis may consist of several metrics. For example, many studies have included net energy yield (NEY), energy use efficiency (EUE) (Hetz and Sonesson 1993; Lewandowski and Schmidt 2006; Boehmel et al. 2008) and other energy indicators (e.g. energy productivity, specific energy) (Unakitan et al. 2010). The use of multiple characteristics enables assessment of a variety of aspects of production. For instance, EUE describes system efficiency and is approved to be dependent on energy input (Kuesters and Lammel 1999). NEY, on the contary, presents land use efficiency (Lewandowski and Schmidt 2006) with Rathke and Diepenbrock (2006) indicating NEY dependence primarly on energy output. The value of NEY is an important characteristic indicating the extent of competition between energy crops, food crops and native environments (Naylor et al. 2007) with the knowledge that higher values denote reduced land requirement to produce the same amount of energy as the crops with lower NEY values. The majority of studies have analysed the same energy parameters but defined these differently. For example, NEY is referred to also as primary net energy yield (Boehmel et al. 2008) and EUE as the ratio of energy output to energy input (Hülsbergen et al. 2001). However, the definition of energy parameters in some studies has not been unique. For example, EUE can be calculated as energy output/input ratio (Hülsbergen et al. 2001) as well as the ratio of NEY and energy input (Lewandowski and Schmidt 2006). This variability in methodologies limits the comparability of studies; the inconsistency leading to confusion and misleading conclusions have been stated in several studies (Bullard and Metcalfe 2001; Zegada-Lizarazu et al. 2010). However, studies have performed energy efficiency comparisons of crops and cropping systems. Boehmel et al. (2008) indicate that willow production had the highest EUE (72–99 GJ GJ^{-1}) in a comparison of six energy cropping systems. Venendaal et al. (1997) indicates large variation (from 1.1 up to 30 GJ GJ^{-1})

of energy ratios between crops. However, energy efficiency of a selected culture could also differ manyfold. For example, Prade et al. (2012) indicate that energy outputs and inputs are dependent on management alternatives, i.e. higher energy efficiency on baled biomass and lower in biogas production. Powlson et al. (2005) conclude that electricity generation from dedicated biofuels gives a slight benefit in terms of energy ratios compared to liquid biofuels (bioethanol, biodiesel). Lower energy output/input ratios in liquid biofuel production compared with solid biofuels (e.g. short rotation coppice, energy grasses) have been indicated also by Venendaal et al. (1997). Recently, new methodological approaches in energy efficiency analyses have been proposed. For example, Koukis and Sardo (2012) introduce a novel, bi-dimensional indicator ("Land and Energy Use Indicator") which combines both, land and energy use in crop systems. Despite many spatial scale bio-energy analyses (Förster et al. 2008; Hastings et al. 2009; Tenerelly and Carver 2012 etc.), the spatial analyses of energy efficiency has not been performed.

2.7. Economic analysis

Many bio-energy studies have been complemented with economic analysis (Förster et al. 2008; de Wit and Faaij 2010; Gómez et al. 2011). Economic feasibility has been used to assess biomass production profitability as well as an indicator of land use. For example, Walpole and Sinden (1997) include different soil, slope and land use categories in cost analysis to reflect the true condition of the land. However, the majority of studies apply methodology to evaluate final production sustainability. Furthermore, Smeets and Faaij (2010) have introduced a methodological approach to include sustainability criteria in the cost and potential analysis of bio-energy production.

Economic analysis may include a wide range of indicators depending on the objective of the research. These may include cost (de Wit and Faaij 2010), profitability (James et al. 2010) etc analysis or the combination of aforementioned indicators to supply curves (Graham and Downing 1995; Walsh 2000). Additionally, some supplemental parameters, as break-even price or break-even yield (Graham and Downing 1995; James et al. 2010; Monti et al. 2007) have been studied. Despite the diversity of economic indicators, the comparison of existing studies is complicated by the variety of methods used and the extent of documentation provided (Walsh 1998).

There is not a common knowledge in bio-energy crops economic analysis as in energy efficiency as pointed out by Bullard and Metcalfe (2001). Smeets and Faaij (2010) declare that biomass production for energy purposes at reasonable cost levels and meeting strict sustainability criteria at the same time is feasible. Ulgiati (2001), on the contrary, concludes that bioethanol production from maize is not viable on a large scale based on economic, energy and eMergy analysis. Different units used in research could impede the understanding of economic feasibility. For example, Brechbill and Tyner (2008) present production costs per tonne of production, Ericsson et al. (2009) per GJ and Monti et al. (2007) per hectare. However, valid conclusions are assured in studies using the same methodology. Therefore, results of Aravindhakshan et al. (2010) and James et al. (2010), which both apply a comparative approach, indicate comparable economical feasibility of selected energy crops.

The feasibility of bio-energy production is highly dependent on the promotion of renewable energy sources. In Estonia, financial support for the development of bio-energy has increased rapidly since 2007; total financial support for the development of bio-energy (incl. facilities, installations etc) has been 67 million euros during the period 2007–2010 (Estonian Institute of Economic Research 2011). However, the subsidy for dedicated energy crops production, which could have a significant influence on the profitability of bio-energy produced from solid agricultural biomass, can not be applied at present. Another factor influencing economical viability is economic and pedo-climatic variation that is a reflection of yield, input levels, prices etc (Walsh 1998). Therefore, economic assessments should be considered as a reflection of defined factors. De Wit and Faaij (2010) applied three methodologial steps in their study (available 'surplus' land quantification, productivity modelling and economic analysis) and concluded that there is large spatial variation in biomass production potential and costs in European countries. Förster et al. (2008) confirms economic variation site-dependency in the western part of the Federal State of Brandenburg. The influence of land quality to production economics has been approved by Azar and Larson (2000). Astover et al. (2006[b]) integrated agronomic and economic models on barley production as an example in GIS and approved profitability dependence on site-specific soil properties. Therefore site-specifity in economic analysis should be prioritised.

3. SET OF THE HYPOTHESES AND AIMS OF THE STUDY

The increase of renewable energy resources has become a focus of energy policy in the European Union as well as in Estonia. Since there has been a decrease in the use of agricultural areas after the restoration of independence in 1991 in Estonia, abandoned agricultural land resource may have a potential in increasing the share of bio-energy production. However, bio-energy sustainability (e.g. efficiency, profitability etc.) should be analysed. Furthermore, there is a need for site-specific bio-energy analyses.

The hypotheses of current study are following:

1) Abandoned agricultural land resource in Estonia has high theoretical bio-energy potential.
2) Bio-energy potential of abandoned areas is dependent on soil-crop suitability, i.e. abandoned agricultural land is not equally suitable for different energy crops production.
3) The production, energy efficiency and fertilisation efficiency of dedicated energy crops is dependent on pedo-climatic conditions.
4) Biomass production potential of dedicated energy crops varies in a detailed spatial scale.
5) Different criteria of multiple analysis (i.e. energy efficiency, profitability) contribute to the assessment of bio-energy production potential.

In order to study these hypotheses the aims of the study were:

- to develop a methodology for quantifying and locating abandoned agricultural areas and to analyse bio-energy potential on abandoned fields in Tartu County as an example (**I**).
- to model RCG yield dependence on soil N content and N fertilisation in relation to interannual variability (**II**).
- to analyse fertilisation and energy efficiency dependence on soil properties (**II, IV**).
- to analyse fibre hemp and energy sunflower biomass production grown on different nitrogen (N) treatments (**IV**).

- to compile multi-criteria analysis, i.e. energy efficiency (net energy yield, energy use efficiency; **II, III**) and profitability (**III**) of RCG production.
- to develop the methodology for site-specific yield analysis and to verify spatial variability of RCG yield potential in the agricultural land of Tartu County as an example (**II**).

4. MATERIAL AND METHODS

4.1. Potential land resource for bio-energy production (I)

We considered abandoned agricultural land as potential land resource for bio-energy production and quantified abandoned areas in Tartu County as an example. The study used a GIS environment, MapInfo Professional, to perform topology analysis. Abandoned field parcels were identified using the Estonian Basic Map (1 : 10,000), the field layer of the Agricultural Registers and Information Board (ARIB) and databases of the Common Agricultural Policy (CAP) payments in 2007. Abandoned areas were classed as 'entirely abandoned' or 'partially abandoned'. 'Entirely abandoned' areas were field parcels that did not have any applications for single-area payments; field parcels where area payments covered 50–99% of total area were classed as 'partially abandoned'. The study used an overlay comparison of the Estonian Basic Map and the ARIB field layers to identify agricultual areas excluded from ARIB's fields (i.e. not valid for CAP subsidy schemes), which we also classed as 'entirely abandoned'. Additionally visual and manual correction of area boundaries were performed to eliminate areas, which could not be used for agricultural purposes as being long narrow strips, emerged from using several map layers.

4.2. Analysis of bio-energy agronomic potential

4.2.1. A general analysis: the average yield approach (I)

In this thesis, the agronomic potential of bio-energy production was evaluated using general and detailed analysis. Bio-energy potential general analysis was performed to assess the total biomass potential of the region by (i) determining suitable areas from abandoned agricultural land in Tartu County for dedicated energy crop production applying soil-crop suitability analysis and (ii) using the average values of dry matter (DM) yields and calorimetry from previous field experiments (Rand 1981; Eilart and Reidolf 1987; Hovi 1995; Miles et al. 1995; Ross et al. 1996; Burvall 1997; Tullus et al. 1998; Uri 2000; Uri et al. 2002; Vares et al. 2003; Vares et al. 2005; Kryževiciene 2006; Meripõld 2006; Viil 2006; Lillak et al. 2007) (**I**).

The first phase in evaluating suitable areas for energy crop production was to identify the soils of abandoned land in Tartu County by using the Estonian Land Board's digital soil map (scale 1 : 10,000). Abandoned areas in Tartu County were then limited using soil-crop suitability analysis. The suitability of abandoned areas was assessed for short-rotation energy forestry and energy grasses depending on soil type and texture (Laas, 2004; Kõlli, 2006). Areas suitable for potential bio-energy production were evaluated using willow (*Salix sp*), grey alder [*Alnus incana (L.) Moench*], hybrid aspen (*Populus tremuloides Michx.* × *Populus tremula L.*), RCG (*Phalaris arundinacea L.*), and Caucasian goat's rue (*Galega orientalis Lam.*) as these crops are most studied in Nordic conditions. The energy output of the annual biomass yield for both separate plantations and combined land-use was calculated. A combined land-use was performed to provide the strategy of including all five selected energy crops in bio-energy potential analysis. In a combined land-use strategy it was considered that 30% of abandoned areas remain under natural conditions and 70% for energy grasses and short-rotation forestry. The land partition for energy crops of this strategy was based on the results of soil-suitability analysis considering relative area proportions suitable for each crop. Nevertheless, location-specific bio-energy potential evaluation presumes yield analysis made on as detailed a scale as possible.

4.2.2. A detailed analysis of agronomic potential (II, IV)

The agronomic potential of bio-energy production in a detailed analysis included the following: 1) yield prediction based on soil-specific parameters, i.e. the empirical regression-type statistical models (**II**) 2) yield analysis of energy crop plants on different N treatments (**IV**). Soil-specific analysis was evaluated for RCG and was based on soil N content (**II**). Data from previous Estonian RCG field experiments performed on Haplic Albeluvisol (data covering nine years) (Rand and Krall 1978), Fluvic Histosol (seven years) Annuk 1969; Annuk 1970; Annuk 1971; Annuk 1973) and Eutric Histosol (six years) (Jürgen 1971; Koitjärv 1976) were used. In this study, multiple regression models were developed to predict the yield and N fertilisation efficiency. Additionally, yield dependence on the rate of mineral N application were analysed. The model for evaluating RCG yield dependence on soil N content is defined as yield model and to analyse the average efficiency of mineral N fertiliser, the model is defined as efficiency model. In the yield model, we used probability (%)

to express climatic risk (interannual variability) and soil total N content (Ntot, %) as explanatory variables. In the efficiency model, the average efficiency of mineral nitrogen (kg DM kg^{-1} N^{-1}) was a function of the probability expressing climatic risk, Ntot and the annual rate of applied mineral nitrogen (kg N ha^{-1}). Normal distribution assumptions in both models were satisfied according to the Shapiro-Wilk test and Kolmogorov-Smirnov test. The normal distribution in the data allowed us to calculate probabilities for dependent variables on the principle of the Central Limit Theorem. The mean value of a dependent factor (i.e., RCG yield) equated to 50% probability, and values corresponding to other probabilities were found on the basis of normal distribution around the mean. In the case of approximate normal distribution, a certain proportion of data values remain within z standard deviations of the mean.

A field trial in 2008 to 2010 was conducted at the Instutute of Agricultural and Environmental Sciences to analyse the agronomic potential of selected energy crops on different N treatments (**IV**). Biomass productivity in DM was evaluated in fibre hemp (*Cannabis sativa* L.) and energy sunflower production (*Helianthus annuus* L.). The plants were grown on Stagnic Luvisol (IUSS Working Group WRB, 2006) soil (sandy loam surface texture, soil organic carbon content 1.12%, Ntot 0.12%, pH_{KCl} 5.6). The study estimated the effect of 100 kg N ha^{-1} on yield production with varying N treatments. The N treatments were as follows: without N (N0), mineral N fertiliser NH_4NO_3 (N100), municipal sewage sludge from Tartu (N100), vetch cv Carolina (N100) and cattle slurry (N100). The trial data were processed using Pearson's correlation, variance analyses (ANOVA) and descriptive statistics. Normal distribution assumptions were checked using the Shapiro-Wilk normality test. Tukey test was used as a post hoc test of significance differences between means. The means are presented with their standard errors. Significance is presented with $P < 0.05$. Statistical analyses were carried out using the statistical software R version 2.6.1 (R Development Core Team, 2011).

4.3. Bio-energy potential spatial analysis (II)

The yield model from soil-specific analysis was integrated to the Estonian large-scale digital soil map (scale 1:10,000) to calculate the average RCG yields dependent on soil N content in Tartu County. This approach enabled evaluation of site-specific biomass potential in the region using

GIS. The large-scale soil map does not contain direct values of soil nitrogen content. Therefore, we used the arable land evaluation database from the Estonian Land Board to assess the average soil organic matter (humus) content. The knowledge of humus content enabled determination of Ntot using pedo-transfer function provided by Roostalu (2008): Ntot = 0.047 * Humus + 0.0366 ($R^2 = 0.87$, $P < 0.01$), where Ntot is soil total nitrogen content (%), Humus is considered as a soil organic carbon content (%) determined by the Tjurin method and multiplied by 1.72. For Histic soils and Histosols, mean values of Ntot were used depending on the soil type and degree of peat decomposition. Pedo-transfer functions are widely used in soil sciences as being a method enabling the calculation of requested characteristics based on determined soil properties. The prediction of the yield model is illustrated in a grid thematic map of Tartu County which is produced by interpolating of an average (probability 50%) RCG productivity (inverse distance weighting interpolator). The GIS analysis was performed in MapInfo Professional (version 7.5).

4.4. Multi-criteria analysis (II, III)

Multi-criteria analysis considered energy efficiency general (**II**) and detailed (**III**) as well as economic (**III**) analysis of RCG production. Energy efficiency is defined as net energy yield (NEY) and energy use efficiency (EUE). Energy efficiency general analysis (**II**) was based on previous RCG field experiments on Haplic Albeluvisol by Rand and Krall (1978); on Fluvic Histosol by Annuk (1969), Annuk (1970), Annuk (1971), Annuk (1973); on Eutric Histosol by Jürgen (1971) and Koitjärv (1976). Detailed energy efficiency and economic (**III**) analysis was performed on the basis of RCG field experiment on Haplic Albeluvisol conducted by Rand and Krall (1978).

4.4.1. Energy efficiency analysis (II, III)

Net energy yield (NEY) and energy use efficiency (EUE) as environmental indicators of biomass production were supplemented in studies **II** and **III**). EUE, expressed as GJ GJ^{-1}, indicates the energy produced with an input unit and was calculated using the following formula:

$$EUE = NEY / EI$$

where NEY is net energy yield and EI is energy input.

NEY, expressed as GJ ha^{-1}, indicates net energy production of an area, i.e. land use efficiency and was calculated using the following formula:

$$NEY = EY - EI$$

where EY is energy yield (i.e. energy output; GJ ha^{-1}) and EI is total energy input (GJ ha^{-1}).

Additionally, NEY efficiency (**II**), which is a derivative from an NEY quadratic regression equation, was calculated. NEY efficiency describes the NEY of an additional input unit and was expressed as GJ GJ^{-1} EI^{-1}.

Total EY was calculated using a lower heating value of 16.6 MJ kg^{-1} (Burvall 1997). Autumn harvested RCG yields were estimated for delayed harvest considering 40% yield losses (Lindh et al. 2009). EI was calculated using the input of fertilisers (Table I in **II**) and generalised input of 3 GJ ha^{-1} adopted from the literature (**II**) or detailed annual energy input of total production years (**III**) (Table 1). Both 3 GJ ha^{-1} as well as total detailed energy input were considered as field energy consumption, i.e. the required energy input for field work of RCG biomass production. EI of fertilisers considered the input for the production of fertiliser N 35.3 MJ kg^{-1} (Appl 1997), P 36.2 MJ kg^{-1} and K 11.2 MJ kg^{-1} (Kaltschmitt and Reinhardt 1997). Total detailed energy consumption was calculated using EI for field machinery and for diesel fuel. Machinery EI included energy for manufacturing (86.7 MJ kg^{-1}) and for repair and maintenance as suggested by Bowers (1992). In addition, consumed energy of 8.8 MJ kg^{-1} (Loewer et al. 1977) for transporting machines from field to farm was included. Energy input for diesel fuel considers a low heating value of 35.7 MJ l^{-1} (Kavalov 2004), whereas fuel consumption in different machinery operations originates from Rinaldi et al. (2005), Dalgaard et al. (2001) and Mikkola and Ahokas (2009). In the detailed analysis, field work included tillage, fertilisation, harvesting, and biomass transport to the field side (i.e. field transport). Additionally, 10 MJ ha^{-1} y^{-1} of seed energy (Bullard and Metcalfe 2001) was included in the analysis. To evaluate field transport energy consumption, the 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 Mg^{-1} (Bullard and Metcalfe 2001) of energy for biomass loading and unloading.

Table 1. Energy inputs and outputs of general and detailed energy efficiency analyses.

	General analysis	Detailed analysis
Energy output	60% of total energy yield	60% of total energy yield
Energy input	NPK fertilisers	NPK fertilisers
	Generalised field energy of 3 GJ ha^{-1}	Detailed field energy for machinery and diesel fuel:
		1) tillage (ploughing, cultivating, rolling)
		2) fertilisation
		3) harvesting (mowing, baling)
		4) field transport

Detailed analysis of energy efficiency (**III**) was complemented with hauling distance consideration. To evaluate the transportation distance effect on EUE, a semi-trailer with a useful size of 2.5×2.5×14 m was considered in hauling cylindrical bales with a 1.2 m diameter. The capacity of the trailer is 88 m^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 Mg^{-1} km^{-1} (Brindley and Mortimer 2006), the consumption of full-load truck hauling RCG biomass. Additionally, the energy input for loading and unloading small cylindrical bales to and from the truck was included.

Additionally, a spatial analyses of RCG energy efficiency was performed. The spatial variability of mineral N efficiency and energy efficiency (i.e. NEY, EUE) in Tartu County was calculated to evaluate soil effect in efficiency formation. Energy and land use efficiency are calculated as weighted average of the county on the basis of the yield model. Energy analysis of Tartu County was performed considering the methodology (**II**) of general energy analysis.

4.4.2. Economic analysis (III)

A profitability analysis considered the same field machinery operations and general assumptions (including 40% yield losses) as the energy analysis of paper **III**. The profitability has been calculated as the ratio of profit to costs. The current study considered the average NPK nutrient costs at 1.15, 3.20 and 0.96 EUR kg^{-1} and a seed cost at 6.39 EUR 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 70.81 EUR ha^{-1} of single area payments to the income and performed an analysis with the potential varying buying-up prices of 0.03, 0.05, 0.08, 0.10 and 0.13 EUR kg^{-1}. In transport distance profitability analysis, the cost of 0.96 EUR km^{-1} and a loading/unloading cost was considered.

5. RESULTS

5.1. Potential land resource for bio-energy production (I)

Based on ARIB`s register, the agricultural area in Estonia in 2007 was 1.13 million hectares of which 123,187 ha were entirely abandoned areas and field parcels, where area payments covered 50–99%, formed 56,176 ha. In addition, 143,598 ha were abandoned agricultural areas excluded from ARIB's fields. Therefore, the total area of entirely abandoned fields in 2007 in Estonia was approximately 267,000 ha.

Of Tartu County`s total land resource of 308,900 ha, agricultural land in use formed 26%. The proportion of forest land was 38.9% that is, 12.6% less than in the country as an whole. Abandoned agricultural land in Tartu County covered a total of 26,351 ha of which 20,741 ha was 'entirely abandoned' and 5,610 ha was 'partially abandoned'. Abandonment rate differed spatially: the proportion of abandoned areas was highest near the city of Tartu, but was also high along the banks of the River Emajõgi and the shoreline of Lake Peipsi (Figure 1 in **I**).

The mean field area in Tartu County differed markedly between used and abandoned fields. The mean field size of used agricultural areas was 21 ha, 7-fold larger than the field size of abandoned areas. Therefore, field size could limit re-use of abandoned fields.

Soil composition in currently used and in abandoned agricultural areas are markedly different (Table II in **I**). The dominant soils from the total agricultural land resource are Stagnic Luvisols, Gleysols, Luvisols and Histosols of forming 33.5%, 20.6%, 18.9% and 8.8%, respectively. Therefore, these soils dominate also on agricultural land in use and on entirely abandoned areas with an exception of Histosols with an decreased area on land in use. The proportion of Albeluvisols and Histosols on abandoned areas account for more than twice the proportion of that in land use, and in the case of Fluvisols nearly 23-times this soil's landuse area. By contrast, Gleysols, Cambisols and Luvisols on land in use account for nearly twice the area of that on entirely abandoned areas.

5.2. Analysis of bio-energy agronomic potential

5.2.1. A general analysis of agronomic potential (I)

For bio-energy production general analysis, the current study limited abandoned areas in Tartu County using soil-crop suitability analysis. The suitability analysis of abandoned areas based on soil type and texture indicated that there are 11,951 ha, 15,914 ha or 13,140 hectares of entirely abandoned agricultural land in Tartu County suitable for growing willow, grey alder or hybrid aspen, respectively (Table III in **I**). On partially abandoned areas, willow is suitable for 2,757 ha, grey alder for 4,876 ha and hybrid aspen for 4,211 ha.

For energy grasses, 86% and 73% of total abandoned agricultural areas are suitable for growing RCG and Caucasian goat's rue, respectively. RCG could be grown on 17,433 hectares of entirely and 4,883 hectares of partially abandoned land and Caucasian goat's rue on 14,411 hectares of entirely and 4,486 hectares of partially abandoned agricultural land.

Identification of suitable areas of abandoned land, taking into account average yield, enabled evaluation of bio-energy potential in a region. For example, the cultivation of willow on Tartu County`s abandoned agricultural land would allow production of 71,242 tons of bio-energy with an energy value of 368 GWh. In comparison, the cultivation of grey alder or hybrid aspen on suitable areas in Tartu County`s on both the entirely and partially abandoned areas would result in energy production of 687 GWh or 538 GWh. Therefore, grey alder biomass production represents the highest bio-energy potential from selected energy forests. However, the energy potential of energy grasses is comparable or exceeds the bio-energy potential of grey alder. For example, RCG biomass production from abandoned areas could reach as high as 178,523 tons with an energy value of 823 GWh and Caucasian goat's rue as 132,280 tons with the production of 610 GWh.

As different crops are partially suitable to the same areas, causing overlaps in analysing soil suitability between selected crops, a combined land-use strategy could be used. In a combined land-use strategy 18,446 hectares of abandoned land could be re-utilised since we assumed that 30% of abandoned areas remains as natural grasslands (Table IV in **I**). The biomass of energy forests and grasses grown on abandoned fields in Tartu County would weigh 121,555 tons, of which 95,625 tons would come from entirely abandoned land and 25,930 tons from partially abandoned land. The total bioenergy production from these fields could be as high as 594 GWh, which in relation to separate plantations is lower than the energy production from RCG, Caucasian goat's rue, or grey alder but higher than that potentially from hybrid aspen or willow. Bio-energy potential of natural grasslands would be 15,811 tons with an energy value of 73 GWh. Therefore, biomass potential of a combined land-use strategy from total abandoned areas in Tartu County is as high as 667 GWh and could cover approximately a quarter of county's annual energy demand.

5.2.2. A detailed analysis of agronomic potential (II, IV)

5.2.2.1. Dependency of RCG yield on pedo-climatic conditions (II)

Studies have indicated the high biomass potential of RCG (e.g. 8 Mg ha^{-1} by Rand 1981). However, information on yield variability and dependence on pedo-climatic conditions is still lacking. The current study modelled RCG yield dependence on soil Ntot content and climatic conditions.

RCG yield model (Table II in **II**) indicates biomass variation of unfertilised areas from 0.9 to 6.9 Mg ha^{-1} depending on the Ntot content and the climatic conditions (probability, %) (Fig. I in **II**). The average (probability 50%) RCG yield on soils with an Ntot content of 0.1 to 3% increases from 2.1 to 5.6 Mg ha^{-1}. However, RCG yield without fertilisation on soils with an Ntot content 0.1% could be 0.9 Mg ha^{-1} as well as reach to 3.4 Mg ha^{-1} depending on climatic conditions. In comparison, RCG biomass on soils with a high soil N (Ntot 3%) as well as humus content (e.g. Histosols) could vary from 4.4 to 6.9 Mg ha^{-1}. The yields of 6–7 Mg DM ha^{-1} in the absence of N fertilisation are achievable within a few years on nitrogen-rich soils (Ntot ≥ 0.6%).

5.2.2.2. RCG yield dependency on N fertilisation (II)

RCG yield dependency on mineral N fertilisation varies between soil types (Fig. II in **II**). On Haplic Albeluvisol, the average RCG DM yields increase continuously from 2.7 to 9.5 Mg ha^{-1} y^{-1} with an increase in N input from 0 to 360 kg N ha^{-1}. RCG yield without additional mineral N application on Haplic Albeluvisol varies from 1.7 to 4.4 Mg ha^{-1}, with a variation coefficient (CV) of 35%. The CV decreases to a level of 23% with a doubled average biomass production (5.1 Mg ha^{-1} at 80 kg N ha^{-1}) and continues rapid decrease to a N fertilisation application of 120 kg ha^{-1} accounting for approximately half of the CV of unfertilised fields. A further increase in N supply results in a CV decrease of 0.02% kg^{-1} N^{-1} which verifies the fact that stable RCG yields could be achieved on soils with low humus content by increasing the N supply.

Response to an increase in N supply to both Fluvic Histosol and Eutric Histosol is in contrast to the CVs (i.e., production risks) to N fertilisation on Haplic Albeluvisol. Although RCG yields tend to increase with increasing mineral N application on Histosols, fertilisation efficiency is rather low. On Fluvic Histosols, the DM yield of unfertilised fields varies from 3.9 Mg ha^{-1} to 6.4 Mg ha^{-1} (5.1 Mg ha^{-1} on average). By contrast, the average yield from unfertilised Eutric Histosol reaches 5.8 Mg DM ha^{-1}.

The efficiency model (Table III in **II**) indicates that N fertilisation efficiency decreases with increasing soil N content and mineral N application (Fig. 1). An average (probability 50%) efficiency of 33 ± 6 kg DM kg^{-1} N^{-1} is achieved on soils with Ntot 0.1% when applying 100 kg N ha^{-1}. In comparison, the efficiency on soils with Ntot 1% is two-fold lower. Additionally, N fertilisation efficiency varies within different climatic conditions. For example, the probability of nitrogen fertilisation efficiency on soils with an Ntot of 0.1% when applying 100 kg N ha^{-1} is 25–41 kg DM kg^{-1} N^{-1} and on soils with an Ntot of 3% 6–22 kg DM kg^{-1} N^{-1}, respectively. Increasing both the rate of mineral N application and soil N content results in an increase in the variation of fertilisation efficiency.

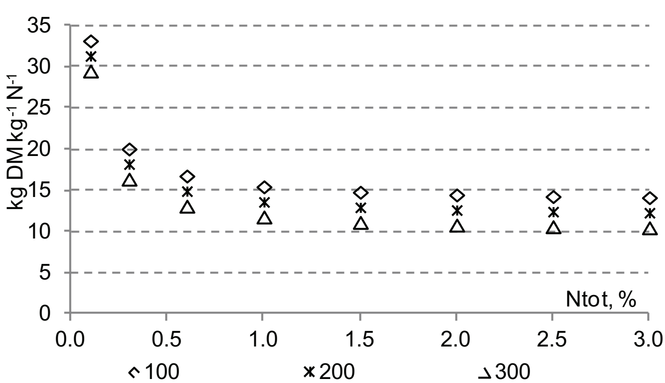

Fig. 1. The average (probability 50%) mineral nitrogen efficiency (kg DM kg^{-1} N^{-1}) of RCG.

5.2.2.3. Fibre hemp and energy sunflower yield depedence on N treatment (IV)

The yield of fibre hemp was significantly influenced by N treatment, cultivar and year with the proportion of variation 46%, 26% and 3%, respectively ($P < 0.001$ for all factors; Table IV in **IV**). Biomass of hemp plants was highest on N100 and sludge, followed by slurry treatment, with means and standard errors of trial years and cultivars of 6.05 ± 0.60, 6.61 ± 0.42 and 3.74 ± 0.33 Mg ha^{-1} (Fig. 2). Fibre hemp production on vetch treatment was the lowest although statistically the same as biomass produced on N0. The average yield of hemp plants varied over trial years. The temperature and precipitation data of 2008 and 2009 were similar to the long-term average (Figs. I and II in **IV**). However, in 2010, the temperature was higher than usual.

The most favourable treatment for sunflower biomass formation was sewage sludge. The yield of sunflower over trial years grown on the sewage sludge treatment was 13.53 ± 6.31 Mg ha^{-1}, which differed significantly from N0, N100, vetch and slurry treatments although the sunflower`s average yield on these treatments were statistically the same. The yield of both fibre hemp and energy sunflower was positively correlated with plant weight ($r = 0.64$, $P < 0.01$ for hemp; $r = 0.87$, $P < 0.01$ for sunflower).

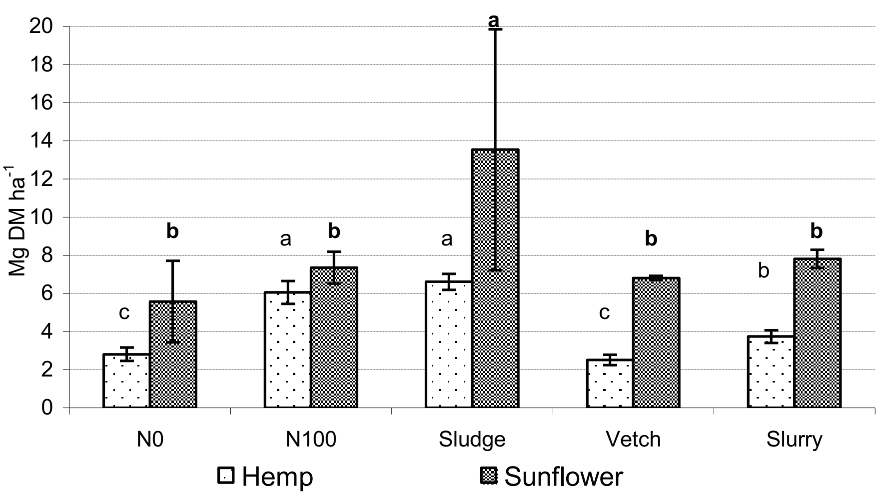

Fig. 2. The mean (± standard error) yield (Mg DM ha^{-1}) of fibre hemp and energy sunflower in 2008–2010. [a] Different letters indicate significant differences between treatments of hemp (letters not in bold) and sunflower (letters in bold) DM yield.

5.3. Bio-energy potential spatial analysis (II)

RCG biomass production varies spatially (Fig. 3). Approximately 81% (83,564 ha) of Tartu County`s agricultural area is capable of producing an average RCG yield (probability 50%) without fertilisation below 4 Mg ha^{-1}. Half of this area has the potential to produce yields within 2–3 Mg ha^{-1}. The majority of the lower levels of biomass production are formed in the southern part of the county. RCG annual DM yields of 4 to 6 Mg ha^{-1} are achievable in a limited number of fields. Application of 100 kg N ha^{-1} in Tartu County agricultural areas results in yields below 6 Mg ha^{-1} in nearly 65% of the area, and the yield potential of 9% of the area is 6.5 to 7 Mg ha^{-1}.

From the total agricultural areas in Tartu County, the NEY and EUE potentials of 65% of the area are 26 GJ ha^{-1} and 9 GJ GJ^{-1}, respectively, if 40% RCG winter losses are taken into account. The maximum EUE (17 GJ GJ^{-1}) without fertilisation could be achieved on 9% of the agricultural areas. Although application of 100 kg N ha^{-1} results in at RCG yield increase to 4.5 Mg ha^{-1}, the average EUE decreases to 9.6 GJ GJ^{-1}, that is 55% of the maximum efficiency of the unfertilised areas.

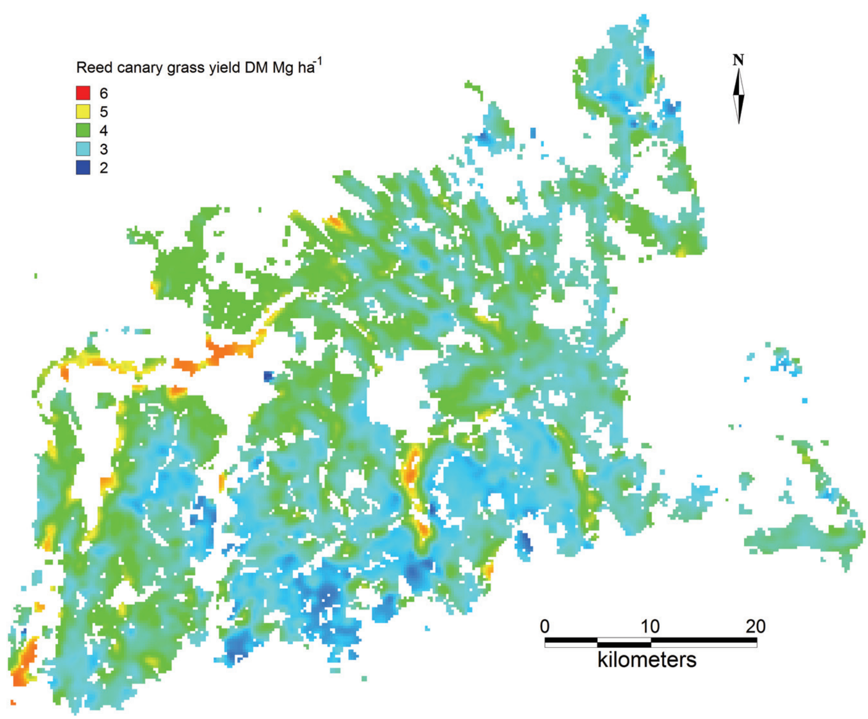

Fig. 3. The average (probability 50%) modelled RCG DM yield (Mg ha^{-1}) without fertilisation in Tartu County.

5.4. Multi-criteria analysis (II, III)

5.4.1. Energy efficiency general analysis (II)

On unfertilised plots of Haplic Albeluvisol, NEY varies from 11 to 38 GJ ha^{-1} and 60 to 101 GJ ha^{-1} in fields to which 360 kg N ha^{-1} were applied. The average NEY increases from 21 GJ ha^{-1} to 76 GJ ha^{-1} with increasing N application from 0 to 360 kg ha^{-1} (Fig. 4; Fig. III in **II)**.

On Fluvic Histosol, the average NEY increases continuously from 45 GJ ha^{-1} in unfertilised plots to 59 GJ ha^{-1} with an energy input requirement of 30 GJ ha^{-1}.

The average NEY on unfertilised plots of Eutric Histosol is 53 GJ ha^{-1}. Land use efficiency increases with increased energy input to 66 GJ ha^{-1} with the input requirement of 22 GJ ha^{-1}.

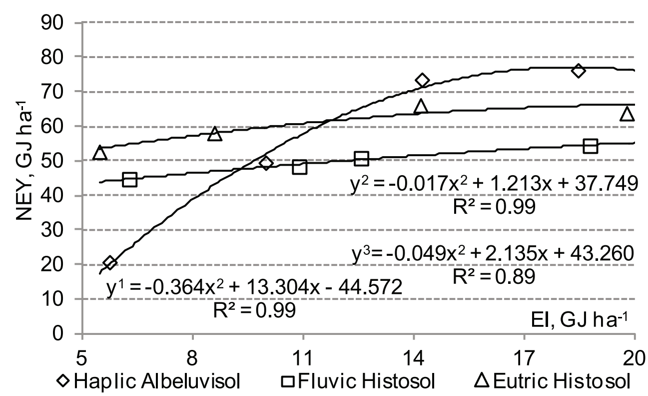

Fig. 4. RCG NEY (GJ ha^{-1}) on Haplic Albeluvisol (y^1), Fluvic Histosol (y^2) and Eutric Histosol (y^3) dependent on energy input.

NEY efficiency describing NEY of an additional input unit indicates a rapid decrease on Haplic Albeluvisol (Fig. 5; **II**); NEY efficiency decreases from 9 GJ GJ^{-1} at an input level of 6 GJ ha^{-1} to the level of producing no additional NEY with additional energy input at 18 GJ ha^{-1}.

On Fluvic Histosol and Eutric Histosol, NEY efficiency decreases from 1 to 0.6 and 1.5 to 0.4 GJ GJ^{-1} EI^{-1} at input levels of 6 to 18 GJ ha^{-1}, respectively. Therefore, additional energy input has a higher average effect to NEY on Eutric Histosol compared with on Fluvic Histosol of up to EI of 14 GJ ha^{-1}.

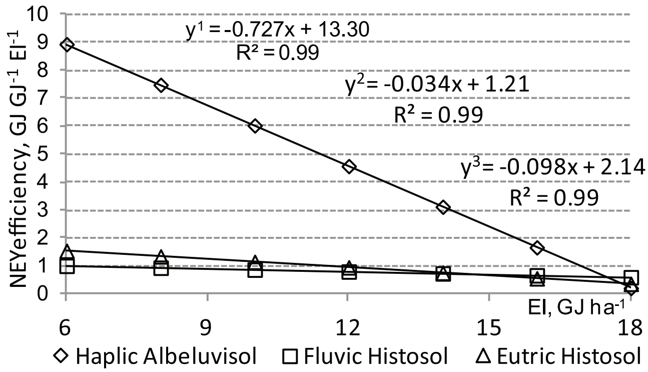

Fig. 5. NEY efficiency (GJ GJ^{-1} EI^{-1}) on Haplic Albeluvisol (y^1), Fluvic Histosol (y^2) and Eutric Histosol (y^3) dependent on energy input.

The average RCG EUE increases to an input level of 12.7 GJ ha^{-1}, reaching an efficiency of 5.2 GJ GJ^{-1}, and then decreases to a level of 4.1 GJ GJ^{-1} with total input of 18 GJ ha^{-1} on Haplic Albeluvisol (Fig. 6; Fig. III in **II**). To reach the optimum EUE level, N fertiliser inputs should be 198 kg ha^{-1}.

On Fluvic Histosol and Eutric Histosol, EUE decreases with increasing energy input. At input levels of 6 to 31 GJ ha^{-1}, EUE decreases from 7 to 2 GJ GJ^{-1} on Fluvic Histosol and from 9 to 2 GJ GJ^{-1} on Eutric Histosol. Fertilisation application of 90 kg N ha^{-1} should be used on Haplic Albeluvisol to achieve approximately the same NEY (45 GJ ha^{-1}) as on Fluvic Histosol without N fertilisation. Consequently, the average EUE on Fluvic Histosol exceeds the energy efficiency on Haplic Albeluvisol up to energy input of 10 GJ ha^{-1}.

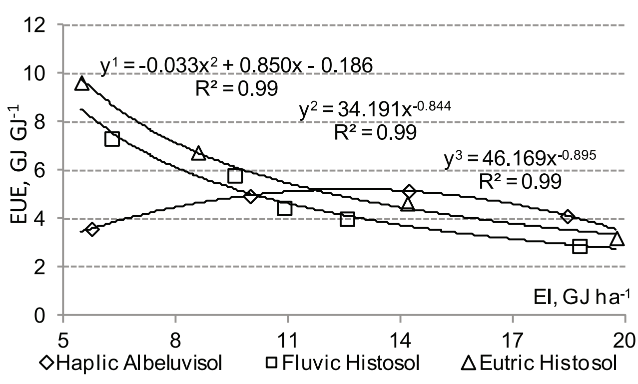

Fig. 6. RCG EUE (GJ GJ^{-1}) on Haplic Albeluvisol (y^1), Fluvic Histosol (y^2) and Eutric Histosol (y^3) dependent on energy input.

5.4.2. Energy efficiency detailed analysis (III)

Energy efficiency detailed analysis on Haplic Albeluvisol (**III**) indicated lower field energy input (i.e. total EI of field works) in comparison of energy analysis with generalised input (3 GJ ha^{-1} in **II**); field energy consumption in the efficiency detailed analysis were 30%, 12%, 6% and 4% lower on nitrogen treatment of N0, N120, N240 and N360, respectively. The decrease in energy consumption resulted from the differentiated energy input for biomass field transport and harvesting (i.e. baling). Lower energy input requirement increased proportionally the values of NEY and EUE (Figs. 7 and 8). Although NEY increases with increasing energy input in both general and detailed analysis, the optimum EUE in detailed analysis peaks at EI of 8 GJ ha^{-1}.

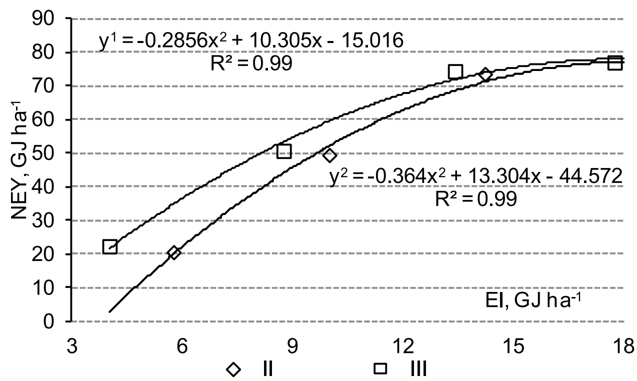

Fig. 7. The comparison of RCG NEY dependence on energy input general (**II**; y^2) and detailed (**III**; y^1) efficiency analysis.

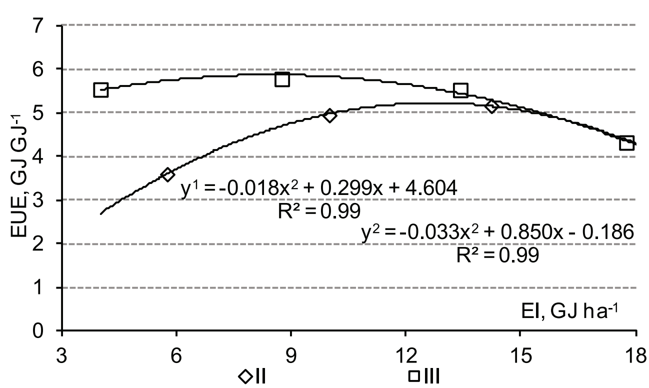

Fig. 8. The comparison of RCG EUE dependence on energy input general (**II**; y^2) and detailed (**III**; y^1) efficiency analysis.

In a detailed analysis NEY increases up to 77 GJ ha^{-1} (Table 2). However, NEY efficiency decreases with increasing EI and indicates that no additional energy yield of an additional input unit is produced when maximum NEY is reached. The share of total NPK fertilisation in energy input increases with an increasing N supply, forming 75% to 89% of total consumption when applying 0–360 kg N ha^{-1}. Harvesting is the second largest energy input component in RCG production; as the yield increases, the energy input per tonne (GJ Mg^{-1}) of harvested biomass decreases. Biomass transport to the field side and tillage per tonne of production form altogether less than 10% of the total energy input. The increase of transportation distance from the field side to the power plant decreases EUE (Fig. IV in **III**). With an optimum N application, average EUE decreases linearly 7 MJ GJ^{-1} km^{-1} as transportation distance increases.

Table 2. Energy input (EI, GJ ha^{-1}), energy output (GJ ha^{-1}), net energy yield (NEY, GJ ha^{-1}), NEY efficiency (GJ GJ^{-1} EI^{-1}) and energy use efficiency (EUE, GJ GJ^{-1}) of reed canary grass production on Haplic Albeluvisol.

N, kg ha^{-1}	Energy input (EI), GJ ha^{-1}			Energy output, GJ ha^{-1}	NEY, GJ ha^{-1}	NEY efficiency, GJ GJ^{-1} EI^{-1}	EUE, GJ GJ^{-1}
	N	Other	Total				
0	**0.0**	4.0	4.0	26.5	22.5	8	5.6
120	**4.2**	4.5	8.7	59.5	50.8	5	5.8
240	**8.5**	4.9	13.4	87.8	74.4	3	5.5
360	**12.7**	5.0	17.7	94.8	77.0	0	4.3

There is a significant negative correlation between EUE and EI per tonne of biomass ($r = -0.97$, $P < 0.001$). EUE decreases from 9.5 to 3.5 GJ GJ^{-1} with the increase of EI per tonne of biomass from 1.5 to 4 GJ Mg^{-1} (Fig. 9). The average annual energy consumption per tonne of RCG production varies with fertilisation applications (Fig. II in **III**). A nitrogen application of 140 kg ha^{-1} results in minimum EI for production (2.5 GJ Mg^{-1}). A minimum EI results EUE of approximately 6 GJ GJ^{-1} which is also the optimum EUE of a detailed analysis in Fig. 8.

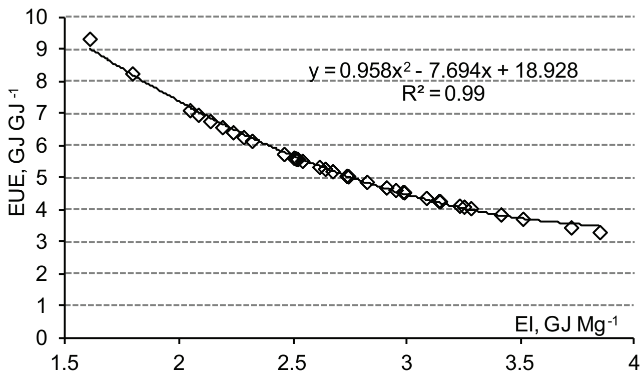

Fig. 9. Regression between EUE (GJ GJ^{-1}) and EI per tonne of RCG biomass (GJ Mg^{-1}).

5.4.3. Economic analysis (III)

The average net cost of RCG production on Haplic Albeluvisol decreases from 0.2 to 0.1 EUR kg^{-1} with increasing N application to 238 kg ha^{-1} and increases with increasing N input afterwards (Fig. II in **III**). Fertilisation costs per tonne of biomass account for more than 80% of the total annual costs within all variants in the field experiment. Soil tillage, biomass transport to the field side and harvesting costs per unit of biomass altogether decrease with increasing fertilisation application. Production net cost and energy input per tonne of biomass indicate a positive linear relationship. The increase in costs with additional energy consumption varies according to different fertilisation norms, i.e. net costs with GJ of additional energy input decrease 0.1 EUR kg^{-1} with increasing N application.

The profitability of RCG production is highly dependent on the buying-up price of biomass and available subsidies. From an economic point of view, cultivation of RCG on Haplic Albeluvisol for bio-energy production could be considered at a break-even price of 0.1 EUR kg^{-1}; however, it should be recognised that this break-even price applies in the case of optimum N application norm of 238 kg ha^{-1} (Fig. III in **III**) and biomass transportation to the power plant has not been taken into account. In addition, profitability could fluctuate according to the economic situation, i.e. the level of costs and available subsidies. Since the average buying-up price in the current economic situation paid to biomass producers, according to the Estonian Institute of Economic Research (2011), is approximately two to three times lower than the indicated break-even price on Haplic Albeluvisol soil, negative profitability in RCG biomass production must be considered. Furthermore, biomass transportation to the power plant increases considerably the production net costs and decreases profitability (Fig. V in **III**). The average haulage costs increase linearly by 0.1 EUR Mg^{-1} km^{-1} with increasing distance from the field. The transportation of RCG biomass in the current study is not profitable even when considering a CAP payment of 71 EUR ha^{-1} and buying-up price of up to 0.1 EUR kg^{-1}.

6. DISCUSSION

6.1. Potential land resource for bio-energy production and general bio-energy agronomic potential (I)

Biomass is expected to play a vital role in providing future renewable feedstocks (Fischer et al. 2010[b]). The estimation of potential land resource for bioenergy production requires consideration of multiple aspects with the main criteria, adequate land resource for food supply, highlighted in majority of land resource studies. This aspect is relevant also in Estonia since Estonia's agricultural self-sufficiency became negative in 1997 (Rask and Rask 2004). Many bio-energy studies have analysed energy crop potentials from areas not needed for food or fodder production (Smeets et al. 2007; Hoogwijk et al. 2003; Hoogwijk et al. 2005). However, information on the bio-energy potential of abandoned areas would have regional impact on both land-use decisions as well as renewable energy production. Furthermore, spatially quantified abandoned agricultural land resource forms a solid basis for further bio-energy production analysis. Although research has proposed various land-use scenarios (Ericsson and Nilsson 2006; van Meijl et al. 2006; Rounsevell et al. 2006), planning of dedicated energy crop production requires decisions made on as detailed a scale as possible. Van Dam et al. (2007) have quantified land resource available for energy crop production in Central and Eastern Europe indicating wide variation in land-use scenarios for Estonia up to 2030. Since the uncertainity of available area for bio-energy production could be surpassed with location-specific analysis, the current study quantified abandoned agricultural land as available area for energy crop production in a detailed spatial scale in Estonia in Tartu County as an example.

The increase of abandoned areas since the restoration of independence in 1991 (Astover et al. 2006[a]) indicates also a neccessity for the planning of abandoned agricultural land. In 2007, entirely and partially (payments covered 50–99%) abandoned agricultural land in Estonia formed 25% of the total agricultural area. In Tartu County, the proportion of abandoned fields was smaller than in Estonia forming 26,351 ha of the total Tartu County`s agricultural area of 111,143 ha. However, total abandoned land is not potentially available for agricultural production. An analysis with cadastrial land classes indicated that approximately 4% of the entirely abandoned ARIB`s fields in Tartu County are classified as residential, i.e. field is in ARIB`s database but it's actual land use has changed. Furthermore, a visual interpretation of abandoned ARIB`s fields in Tartu County indicated that 0.5% are covered with underwood. Therefore limitations in planning abandoned agricultural land should be recognised.

Also, a limited number of unused fields may be now again be in use mainly due to increased subsidies; i.e. the maintenance of these agricultural areas for the application of subsidies. The current study clarified that approximately 51,000 ha and 3,290 ha of agricultural land of ARIB`s fields in Estonia and in Tartu County were in use as grasslands, irrespective of there being no livestock unit for an area.

The density of abandoned fields in Tartu County differs regionally with higher abandonment near the county's biggest urban area partly because of urban sprawl. Limited accessibility and unsuitable soils for traditionally cultivated crops could be the reasons for the high proportion of abandoned areas along the banks of the River Emajõgi and the shoreline of Lake Peipsi. The average size of abandoned field parcels in the study area is relatively small (by a factor of about seven compared with used fields), they are often fragmented and dispersed around the county. Hence, the re-use of abandoned areas could have several technical and economical limitations and must be included in further analysis.

Land resource soil analysis indicated a clear tendency of soil effect on land-use decisions. The proportion of abandoned areas in Tartu County is higher on soils with low soil fertility. The swaths of Albeluvisols and Histosols in abandoned areas account for twice the area of land in use that is composed of these two soils, and Fluvisols in abandoned land equate to nearly 23 times this soil's aggregate land-use area. Whereas Astover et al. (2006[a]) verified a higher abandonment rate in regions with lower soil quality at the level of municipalities, our research provides, for the first time, evidence of this phenomenon at a detailed spatial scale (the level of mapped soil polygons 1:10,000). Therefore, planning biomass crop cultivation on abandoned fields requires consideration of site-specific soil information for a complex bio-energy analysis that can be used when evaluating agronomic potential.

Total abandoned areas are not suitable for energy crop production. Therefore the current study limited abandoned areas in Tartu County using soil-crop suitability analysis based on soil type and texture. However, soil-crop suitability has been analysed also by the use of GIS-models (Förster et al. 2008; Tenerelly and Carver 2012). Suitability analysis in the current study enabled estimation of the agronomic potential of selected energy grasses and short-rotation forestry with a conversion of the land potential to a bio-energy potential. The use of diverse land-use strategies, i.e. separate plantations and combined land-use, provides comparative general analysis of the county`s bio-energy agronomic potential. In the case of a combined land-use strategy, potential bio-energy production could provide approximately a quarter of county's annual energy demand whereas RCG could provide 24%, grey alder 20%, Caucasian goat's rue 18%, hybrid aspen 16%, willow 11%, and natural grassland 11% to the energy grid. The relative significances of these different crops must be handled provisionally because they depend on soil-crop suitability and some fixed assumptions (i.e., 30% of abandoned land will remain as natural grassland; partition of energy crops are calculated based on relative area proportions suitable for each crop from soil-crop separate plantation analysis). However, considering soil-crop suitability as separate plantations, RCG and grey alder represent highest re-use potential of abandoned parcels with each re-using more than 80% of the available abandoned land in Tartu County. The annual energy potential of RCG and grey alder is comparable with the energy potential of combined land-use strategy in Tartu County and would therefore cover approximately the same proportion of the county`s annual energy demand. Nevertheless, the results of Suuster et al. (2008) provide evidence that some dedicated energy crops suitable for abandoned areas in Saare County in Estonia could cover the county`s total annual energy demand. Since previous research covering large areas have emphasised climate effect on energy crop suitability (Tuck et al. 2006; Bellarby et al. 2010), further studies should include, in addition to soil properties, also climatic risks in bio-energy potential analysis. Furthermore, as bio-energy potential general analysis in the current study provides overall assessments depending on productivity and energy values presented in the literature, a detailed analysis of biomass production is required.

6.2. A detailed bio-energy agronomic potential (II, IV)

Reed canary grass (RCG)
Information on biomass production and its variability provides the basis of agricultural risk management. Although perennial grasses as energy crops have been cultivated for decades (Lewandowski et al. 2003), there has been little research to evaluate the dependence of bio-energy crops yields on site-specific characteristics. Nor research on site-specifity of RCG cultivation has been reported despite it being a promising bio-energy crop in Nordic conditions (Hadders and Olsson 1997). Therefore, the current study provides a model for evaluating RCG yield dependence on soil N content and the model of N fertiliser average efficiency with both in relation to climatic risks, i.e. probability. However, as soil N stock is reported to be a better predictor for nutrient availability (i.e. crop productivity) than soil N content (Ertsen et al. 1998), it would be worthwile to perform a yield model with soil N stock and to compare different methodologies, such as ANCOVA, mixed-models etc. In addition, the statistical models of the current study could be complemented with the inclusion of additional variables (e.g. a variety of soil nutrient stocks, meterological variables). The interactions of variables could be also included in modelling. Pathak et al. (2003), for example, have considered the interactions of N, P and K in assessing nutrient requirements and fertiliser recommedations for a target yield.

The yield model indicated that RCG yield is significantly influenced by soil N content and probability ($P<0.0001$). High RCG biomass potential is achievable from areas with a sufficient soil N supply. For example, the average (probability 50%) RCG yield on soils with high soil N as well as humus content (e.g. Histosols) exceeds the yields on mineral soils with low soil N content by a factor of 3. However, N fertiliser average efficiency decreases and the variation of efficiency increases with increasing soil N content. In addition, an increase of N fertiliser application results in a decrease in fertilisation efficiency in agreement with the results of Lewandowski and Schmidt (2006). There are different approaches to analyse fertilisation efficiency. For example, Zhang and Tillman (2007) modelled nitrogen fertiliser efficiency in pasture production using a decision tree approach. However, both the results of Zhang and Tillmann (2007) as well as of Lewandowski and Schmidt (2006) indicate a non-linear relationship between fertilisation efficiency and N application rate.

Hermanson et al. (2000) found a decrease in the incremental yield increase per unit of N input with increasing N supply. RCG biomass potential and fertilisation efficiency could be influenced also by factors other than included in the current study. For example, the study of Wetzel and van der Valk (1998) indicated a proportion of variance of several factors (e.g. nutrient level, interspecific competition, soil moisture) explained by the productivity for selected perennial plant species (incl. RCG). Therefore, besides meteorological variables also soil available water have been considered in bio-energy crop yield modelling (Richter et al. 2008, Price et al. 2004). Ericsson and Nilsson (2006) pointed out that the rationale for estimating water-limited yields is that often water is recognised as being the major limiting factor for crop growth, both in Southern Europe as well as in Denmark and Southern Sweden. In the current study, high biomass data used for RCG yield modelling were achieved on soils that had high soil N content and available water capacity. Therefore, we can infer that these soils also had a sufficient supply of water in most years.

To reach competitive and stable RCG yields on soils with low humus content, high rates of fertiliser application should be used, in which case, environmental restrictions must also be taken into account. However, on soils with a high soil N content (e.g. Histosols), RCG yield variability, i.e. production risks, increases with increasing fertiliser application. Furthermore, as Höper (2002) indicated, N mineralisation in fen soils could even exceed the N uptake by field plants, and an excessive use of N fertilisers should be avoided. Therefore, the mineral N application norm in RCG biomass production should not be generalised but assessed on a soil specific manner.

Fibre hemp and energy sunflower

Despite their potential to produce high yields (Hu 2008; Mankowski and Kolodziej 2008), the yield of fibre hemp and energy sunflower was not as high as reported from Southern areas. Furthermore, the mean yield of sunflower over the trial years grown on the sewage sludge treatment exceeded the mean yield of fibre hemp plants by a factor of 2. However, it should be recognised that the current study used N100 and further N application increase may also increase the mean yield of fibre hemp as indicated, for example, by Amaducci et al. (2002). The mean yield of fibre hemp of the treatment N0 is comparable with the yield of RCG yield model with low soil N content. The average yield of fibre hemp on

N0 treatment is 2.81±0.35 Mg ha^{-1} in comparison of RCG yield which could vary from 0.9 Mg ha^{-1} up to 3.4 Mg ha^{-1} depending on climatic conditions on nitrogen-poor soils. Therefore, climatic variability should be recognised in yield analysis.

Irrespective of fertiliser application rates, N treatment may affect energy crop yield thorough rhizome biomass as indicated by Xiong et al. (2009). Therefore, the current study analysed the yield of fibre hemp and energy sunflower plants grown on different N treatments and approves treatment significant influence on yield. The more favourable treatment for both fibre hemp and energy sunflower biomass formation was sewage sludge. The yield of fibre hemp was positively correlated with plant weight which was, in turn, significantly influenced by N treatment, i.e. highest on sewage sludge treatment due to lowest emergence on sludge. However, the emergence of energy sunflower plants did not differ significantly between treatments.

6.3. The spatial analyses of bio-energy potential (II)

Many bio-energy studies have analysed the potential of energy crops spatially, i.e. with the use of GIS (Förster et al. 2008, Panichelli and Gnansounou 2008, Shi et al. 2008 etc.). However, only few, as for example Förster et al. (2008), include soil properties and plant requirements in their analysis. Taking into account site-specific soil information enables assessment of biomass agronomic potential at a detailed scale. Previous studies have analysed bio-energy potential covering large areas with the use of coarse-scale databases (Fischer et al. 2010[a]; van Dam et al. 2007) or covering small areas with the use of site-specific data (Förster et al. 2008). Site-specific analysis covering large areas, however, is one of the challenges in bio-energy planning. In the current study, the average bio-energy potential of RCG dependence on soil N content in Tartu County were analysed as an example. This methodology could be applied nationwide as the required input, large-scale soil databases, are available for the whole country. Since the taxonomic large-scale soil map does not contain data of soil N content, a pedo-transfer function was used. In comparison, Lagacherie et al. (2000) have proposed a methodology, the qualitative description of the soil taxonomic units, as an alternative for considering imprecise soil data in crop models. The application of the yield model in the current study approved spatial variability of RCG biomass production within the county. Therefore, scaling up the results to a region enables areas with higher and lower biomass potential to be distinguished, i.e. the majority of low yield areas are located in the southern part of Tartu County and a higher yield potential is predicted along the banks of the county`s largest river (Emajõgi). Hence, biomass production spatial variability is a reflection of soil properties (i.e. soil Ntot in the current study).

Information on biomass agronomic potential of a region provides the basis for further analysis, as for example, energy efficiency evaluation. Furthermore, based on the results of the current study, where the EUE potential in 65% of Tartu County's agricultural areas is 9 GJ GJ^{-1}, and in a number of limited fields, is 17 GJ GJ^{-1}, it can be concluded that production efficiency should be assessed locally. However, as the current study did not take into account biomass variability in energy efficiency analysis and used weighted average yields with some fixed assumptions (e.g. 3 GJ ha^{-1} as an fixed input), further analysis is required to take into account detailed location-specific information. Also, as previous bio-energy research has not evaluated energy efficiency either locally or in GIS, site-specificity and methodology should be recognised in comparative studies.

6.4. Multi-criteria analysis (II, III)

Energy efficiency could be analysed also as a criterion in multi-criteria analysis. Several bio-energy studies have discussed multi-criteria analysis as the basis of decision-making (Rozakis et al. 2002; van Orshoven et al. 2011). The current study includes NEY, EUE and profitability of RCG production in multiple criteria analysis. Despite NEY and EUE being calculated using the same energy inputs and outputs, these characteristics represent energy efficiency of different categories, i.e NEY is an indicator of land use efficiency and EUE describes system efficiency. Both the average NEY as well as the average yield of RCG on Haplic Albeluvisol, Fluvic Histosol and Eutric Histosol increased with increasing fertiliser input. However, NEY efficiency on Haplic Albeluvisol, different from Histosols, indicated a rapid decrease. Therefore, the effect of an additional energy input to NEY on Haplic Albeluvisol exceeded the effect on Fluvic Histosol and Eutric Histosol several fold.

EUE has been proposed to be an important criterion for evaluating energy crop suitability in bio-energy production since, in addition to system efficiency, EUE describes also an environmental impact of the production. Studies have indicated that the output of EUE varies between cultures (Lewandowski and Schmidt 2006) and cropping systems (Boehmel et al. 2008), while efficiency decreases continuously with increasing energy input. For example, Lewandowski and Schmidt (2006) indicate a continuous decrease in EUE with RCG, miscanthus and triticale whereas RCG had the lowest EUE values. Our analysis of the efficiency in RCG production verifies an efficiency decrease on Histosols, but on humus-poor soils, a quadratic curve relationship between energy input and EUE occured. Therefore, the current study provides the first evidence of an EUE curve dependent on soil N content in RCG production. In the case of continuous decrease in EUE, the increase in energy input exceeds the yield increase attained with nitrogen fertilisation, i.e. soils with a higher soil N content had lower N fertilisation efficiency. The results of the general energy efficiency analyses indicated that regardless of a rapid NEY increase on Haplic Albeluvisol, EUE increases to an input level of 12.7 GJ ha^{-1}, reaching an efficiency of 5.2 GJ GJ^{-1}, and decreases with an increasing input afterwards. To reach the optimum EUE level, nitrogen fertiliser inputs should be 198 kg ha^{-1}. Therefore, lower EUE in comparison to Fluvic Histosols of up to 10 GJ ha^{-1} is caused by increased EI to achieve the same NEY on Haplic Albeluvisol as on Histosols. However, EI could be decreased with N-fixation by legumes when grass-legumes mixtures are used. Kryževičienė et al. (2008) indicates that legumes had a positive impact on the yield of grass-legume mixtures and EI of pure grass stands formed twice the EI of mixtures. Therefore, biological N-fixation could be an alternative for the use of N fertilisers to some extent.

In bio-energy production, high yields with low EI levels are preferred. Therefore, factors influencing EI should be recognised. The general energy efficiency analysis indicated fertilisation efficiency since the study used fixed input of 3 GJ ha^{-1}. However, a detailed energy efficiency was performed to quantify the EI of field production. The comparison of general and detailed efficiency analysis indicated lower energy input in field production which increased the values of both NEY and EUE. The decrease in energy consumption was not uniform between N application rates. Since the energy consumption for fertilisation accounted for the majority of the total EI, an optimum N fertilisation rate, i.e. 140 kg N ha^{-1} on Haplic Albeluvisol in the current study, should be applied. However, analysis of energy efficiency on nitrogen-rich soils, i.e. on Histosols, suggests a low fertiliser requirement is desirable to reduce energy inputs and increase EUE. Since a significant negative correlation between EUE (GJ GJ^{-1}) and EI per tonne of biomass occurred, the energy efficiency analysis of the current study approves EUE dependency on EI as indicated also by Kuesters and Lammel (1999).

An increase in transportation distance from field side to power plant decreases both the EUE as well as production profitability. The current analysis, as well as, for example, the study of Lindh et al. (2009) conclude that, in the case of RCG the maximum volume rather than the maximum mass may be the limiting factor in biomass transportation. However, increased interest in bio-energy production indicates the need to evaluate also field production costs. As in energy efficiency analysis, fertiliser costs per tonne of biomass account for most of the total annual costs within all variants of the field experiment. Furthermore, production net cost and energy input per tonne of biomass indicate a positive linear relationship. The lowest profitability occurs when using excessive fertilisers or when producing biomass without applying N fertilisers. The minimum average net cost of RCG biomass production is 0.1 EUR kg^{-1} at 238 kg ha^{-1}. Although the results of the current study indicate high fertiliser application norms to obtain a minimum net cost, environmental restrictions in fertiliser use should be taken into account. The comparative study of EUE and profitability of RCG production indicated that an optimum EUE could be achieved by reducing the N application norm twofold to reach a production minimum net cost. This inconsistency in the production of RCG regarding the economical and environmental conditions emphasises the importance of multi-criteria analyses. Further analysis of production profitability could include also the costs of land and risk as included in the production costs analysis by Ericsson et al. (2009). However, considering the subsidy of 70.81 EUR ha^{-1} and the costs designated in economic analysis on Haplic Albeluvisol soil, a negative profitability of RCG production should be considered since production net costs exceed the potential buying-up price. Therefore, additional subsidies are required for sustainable bio-energy production from perennial grasses and, in perspective to increase the share of bio-energy from energy grasses, appropriate measures should be implemented in Estonia`s renewable energy policy. Moreover, as the current study used fixed assumptions, it must be considered that production costs and buying-up prices influencing the profitability of biomass production are dependent on the economic situation and profitability may vary on soils with different fertiliser requirement.

7. CONCLUSIONS

In accordance with the main objectives of the study, the following conclusions are presented:

1. Abandoned agricultural land which is the potential land resource for bio-energy production forms nearly a quarter of the total agricultural area of Tartu County. However, the average size of abandoned field parcels is relatively small; they are often fragmented and dispersed around the county. Therefore, the re-use of abandoned areas could have several technical and economic limitations. The density of abandoned fields in Tartu County differs regionally with higher abandonment near the county's biggest urban area partly because of urban sprawl. However, land resource soil analysis approved also the soil effect on land-use decisions. The proportion of abandoned areas in Tartu County is higher on soils with low soil fertility. For example, the swaths of Albeluvisols and Histosols in abandoned areas account for twice the area of land in use that is composed of these two soils, and Fluvisols in abandoned land equate to nearly 23 times this soil's aggregate land-use area. Therefore, limited accessibility and unsuitable soils for traditionally cultivated crops could also be reasons for the high proportion of abandoned areas.

2. Total abandoned areas are not suitable for energy crop production. Soil-crop suitability analysis indicated that RCG and grey alder have the highest re-use potential for abandoned parcels of selected dedicated energy crops (i.e. RCG, Caucasian goat's rue, willow, grey alder, hybrid aspen) with each re-using more than 80% of the available abandoned land in Tartu County. As these crops are partially suitable to the same areas, a combined land use strategy was presented. In the case of a combined land-use strategy, the bio-energy potential of selected energy crops could cover approximately a quarter of county's annual energy demand.

3. The yield model approves high interannual variability of RCG yield and its dependence on soil N content. High RCG biomass potential is achievable from areas with a sufficient soil N supply. In Estonian conditions, RCG DM yields of 6–7 Mg ha^{-1} in the absence of N fertilisation are achievable within a few years only on nitrogen-rich soils (Ntot $\geq$ 0.6%). N fertilisation increases the yield and decreases yield variability of RCG on soils with a low soil N content. By contrast, on soils with a high soil

N content, RCG yield variability, i.e. production risks, increases with increasing fertiliser application. The current study proves the relationship between soil N supply and fertilisation efficiency. The efficiency model indicates that N fertiliser average efficiency decreases and the variation of efficiency increases with increasing soil N content. In addition, the increase of N fertiliser application results in a decrease in fertilisation efficiency.

4. The biomass production of fibre hemp and energy sunflower is significantly influenced by N treatment. The more favourable treatment for biomass formation in both crops was sewage sludge. Despite their high yield potential, the yields of fibre hemp and energy sunflower were not as high as reported from Southern areas. However, as the current study applied fertiliser at 100 kg N ha^{-1}, an increase in the N applied may also increase the mean yield.

5. The integration of the yield model to the Estonian large-scale soil database approves spatial variability of RCG biomass production in Tartu County. Scaling up the results to a region enabled areas with higher and lower biomass potential to be distinguished; based on soil Ntot content, most of the lower levels of biomass production potential are formed in the southern part of Tartu County. Therefore, biomass production should not be generalised but assessed on a site-specific manner. The methodology of biomass potential analysis could be applied nationwide as the required input, large-scale soil databases, are available for the whole country.

6. RCG energy efficiency differs between soils with varying soil N content. The average NEY of RCG on Haplic Albeluvisol, Fluvic Histosol and Eutric Histosol increases with increasing N fertiliser input. However, EUE decreases on Histosols, and on humus-poor soils, a quadratic curve relationship between energy input and EUE occurs. Therefore, the current study provides the first evidence of an EUE curve dependent on soil N content in RCG production. Detailed analyses on Haplic Albeluvisol indicated that an optimum EUE could be achieved by reducing the N application norm twofold to reach a production minimum net cost. Furthermore, the economic analyses on Haplic Albeluvisol soil indicated that even with the minimum average annual net cost of 0.1 EUR kg^{-1} at 238 kg ha^{-1}, a negative profitability in RCG biomass production on soils with low soil fertility should be considered since the average buying-up

price in the current economic situation is two to three times lower than the net costs of RCG production. Therefore, additional subsidies are required for sustainable bio-energy production from perennial grasses and appropriate measures should be implemented in Estonia`s renewable energy policy. By contrast, considering the environmental impact of RCG production, a positive energy efficiency occurred. Therefore, the inconsistency in the production of RCG regarding the economical and environmental conditions confirms the importance of considering multiple characteristics in bio-energy analysis.

Future research aims and application of the study results

The current study provides the methodology for quantifying abandoned agricultural land resource and modelling of biomass potential in GIS. As it analysed soil-crop suitability based on previously composed suitability assessments, a model application in suitability analysis could be performed and energy crop suitability in GIS presented. The application of statistical models performed in this thesis indicate the importance of considering site-specific information (e.g. soil N content, N fertilisation efficiency etc) in bio-energy planning. However, the statistical models applied could be complemented with the inclusion of additional variables and different methodological approaches (e.g ANCOVA, mixed models etc). The inconsistency regarding the economical and environmental conditions in the current study emphasises the importance of multiple criteria analyses. However, as the latter was assessed on soils with low soil N content, multi-criteria analyses also on soils with soil properties other than indicated in the current thesis should be performed.

The results of the current study are applicable to bio-energy planning processes and sustainability evaluation. However, the methodology of soil-crop suitability analyses, prediction model approaches and multi-criteria assessments could be used for analysing crop production in general.

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SUMMARY IN ESTONIAN

ASUKOHAPÕHINE ENERGIAKULTUURIDE PLANEERIMINE: POTENTSIAALNE MAARESSURSS, MULLASTIK-KLIMAATILISED JA MAJANDUSLIKUD RISKID

Sissejuhatus

Eesti taasiseseisvumisest alates on avalikes aruteludes tähtsal kohal olnud riigi energiaga varustatuse tagamine, keskkonnasõbraliku energeetika arendamine ja energiatõhususe suurendamine. Samas on Euroopa Liidus vastu võetud direktiiv (2009/28/EC), mille kohaselt 2020. aastaks peab liikmesriikides taastuvenergia moodustama 20% energia lõpptarbimisest. 2010. aastal kinnitas Eesti Vabariigi Valitsus "Eesti taastuvenergia tegevuskava aastani 2020", milles püstitatakse taastuvenergiaga seotud eesmärgid ja meetmed nende saavutamiseks (RT III, 30.11.2010, 3). Taastuvenergia osakaalu suurendamises on lähitulevikus tõenäoliselt oluline roll biomassi kasutamisel energia tootmiseks (Fischer et al. 2010[b]). Paljudes uuringutes on analüüsitud bioenergia geograafilist potentsiaali, sh biomassil põhineva energia tootmist aladel, mida ei vajata näiteks toidu ega sööda tootmiseks (Fischer ja Schrattenholzer 2001; Hoogwijk et al. 2003; Hoogwijk et al. 2005). Bioenergia tootmisel tuleb arvestada mitmeid aspekte, sh piisav maaressurss, mis tagaks riigi isevarustatuse toiduga. Põllumajanduslikust kasutusest väljajäänud alad on potentsiaalne maaressurss bioenergiakultuuride kasvatamiseks. Paljud uuringud on näidanud, et niihästi globaalselt (Field et al. 2008; Campbell et al. 2008) kui ka Eestis (Peterson ja Aunap 1998; Astover et al. 2006[a]) on kasutamata põllumajandusmaid. Kasutusest väljajäänud põllumajandusmaade taaskasutuselevõtu üks võimalusi on nendel aladel bioenergiakultuuride kasvatamine.

Bioenergiakultuuride kasvatamise planeerimisel on olulisteks indikaatoriteks saagipotentsiaal ja saagi kvaliteet. Enamik uuringuid, milles on hinnatud eri regioonide bioenergia tootmise potentsiaali, põhineb väikesemõõtkavalistel kaartidel (Voivontas et al. 2001; Stampfl et al. 2007; Hastings et al. 2009; Fischer et al. 2010[a]). Samas nõuab teadmistepõhine energiakultuuride planeerimine võimalikult detailse asukohapõhise informatsiooni kasutamist. Energiakultuure käsitlevates uuringutes on mullastik-klimaatiliste iseärasuste arvestamine kultuuride planeerimisel, kasvatamisel ja väetamise efektiivsuse hindamisel olnud seni ebapiisav.

Käesolev doktoritöö keskendub Tartu maakonna näitel kasutamata põllumajandusmaade bioenergia tootmise potentsiaali hindamisele. Detailsemalt analüüsitakse bioenergia tootmise potentsiaali ja energiakasutuse efektiivsuse sõltuvust mulla omadustest ning lämmastikuga väetamisest.

Töö hüpoteesid on järgmised:

1) Kasutamata põllumajandusmaal on Eestis arvestatav teoreetiline potentsiaal bioenergia tootmiseks.
2) Kasutamata maade bioenergeetiline potentsiaal sõltub mulla kasutussobivusest, s.t kasutamata põllumajandusmaa ei ole võrdselt sobiv erinevate bioenergiakultuuride kasvatamiseks.
3) Energiakultuuride saagikus ning energiakasutuse ja väetamise efektiivsus sõltub mullastik-klimaatilistest tingimustest.
4) Bioenergiakultuuride biomassi potentsiaal varieerub piirkonniti.
5) Mitut hindamiskriteeriumi (nt mitmesugused energiaparameetrid, majanduslik tasuvus) sisaldav analüüs võimaldab bioenergia tootmise potentsiaali täpsemalt hinnata.

Tulenevalt püstitatud hüpoteesidest on doktoritöö eesmärgid järgmised:

- välja töötada metoodika, mille abil saaks hinnata kasutusest väljajäänud põllumajandusmaa ressurssi ja selle bioenergeetilist potentsiaali Tartu maakonna näitel (**I**);
- modelleerida päideroo saagikuse sõltuvust mulla lämmastikusisaldusest ja lämmastikuga väetamisest, arvestades aasta mõju (**II**);
- analüüsida päideroo väetamise ja energiakasutuse efektiivsuse seost mulla omadustega (**II**, **IV**);
- analüüsida erinevate lämmastikväetiste mõju kiukanepi ja energiapäevalille saagi kujunemisele (**IV**);
- koostada päideroo kasvatamise energiaparameetrite (energiasaagis, energiakasutuse efektiivsus; **II**, **III**) ja majandusliku tasuvuse (**III**) võrdlev analüüs;
- välja töötada päideroo asukohapõhise saagipotentsiaali analüüsi metoodika ja rakendada seda Tartu maakonna põllumajandusmaade näitel (**II**).

Metoodika

Tartu maakonna kasutamata põllumajandusmaade kindlakstegemiseks rakendati ruumianalüüsi kasutades Maa-ameti põhikaarti, Põllumajanduse Registrite ja Informatsiooni Ameti (PRIA) põllumassiivide kaardikihti ja 2007. aasta ühtse pindalatoetuse taotluste (ÜPT) andmebaase. Leitud põllumajandusmaade mullastikust ülevaate saamiseks kasutati digitaalset mullastikukaarti mõõtkavas 1 : 10 000 ning hinnati määratud muldade kasutussobivust valitud bioenergiakultuuride (päideroog, ida-kitsehernes, paju, hall lepp, hübriidhaab) kasvatamiseks. Töös määrati valitud energiakultuuride bioenergeetiline potentsiaal kasutamata põllumajandusmaadel ning koostati nende kombineeritud maakasutuse strateegia. Kombineeritud maakasutuse strateegia puhul arvestati, et 30% kasutamata maadest jääb looduslikuks rohumaaks ja 70% maast on potentsiaalne ressurss energiakultuuride kasvatamiseks. Kasutamata maade jaotuvuse hindamisel lähtuti kombineeritud strateegias iga kultuuri proportsionaalsest sobivusest kasutamata põllumajandusmaadele. Tartu maakonna kasutamata põllumajandusmaade üldistatud agronoomilise potentsiaali leidmisel lähtuti kirjanduses toodud saagikuse ja kütteväärtuse keskmistest näitajatest.

Detailne agronoomiline analüüs hõlmab: 1) statistilisi mudeleid (saagimudel ja lämmastiku efektiivsuse mudel) ning 2) erinevate lämmastikväetiste mõju uurimist energiakultuuride saagi kujunemisele. Statistilised mudelid põhinevad kirjanduses avaldatud katseandmetel päideroo kohta (Annuk 1969; Annuk 1970; Annuk 1971; Jürgen 1971; Annuk 1973; Koitjärv 1976; Rand ja Krall 1978). Erinevate lämmastikväetiste mõju uurimiseks tehti 2008.–2010. aastal katse kiukanepi- ja energiapäevalillega. Katses kasutatud lämmastikväetiste variandid olid kontrollvariant (0 kg N ha^{-1}), NH_4NO_3 (100 kg N ha^{-1}), Tartu linna reoveesete (100 kg N ha^{-1}), vikk segukülvis kanepi või päevalillega (100 kg N ha^{-1}) ja veiseläga (100 kg N ha^{-1}). Asukohapõhise saagivarieeruvuse hindamiseks rakendati käesolevas töös koostatud päideroo statistilisi mudeleid digitaalsel mullastikukaardil ning koostati teemakaart Tartu maakonna näitel.

Energiakultuuride kasvatamise energiaparameetrite ja majandusliku tasuvuse analüüs põhineb kirjandusallikates avaldatud katseandmetel päideroo kohta (Annuk 1969; Annuk 1970; Annuk 1971; Jürgen 1971; Annuk 1973; Koitjärv 1976; Rand ja Krall 1978). Kasutatud on teaduskirjanduses või teistes allikates (nt. teenustööde hinnakiri) avaldatud energia- ja majandusnäitajate arvandmeid.

Tulemused ja arutelu

Põllumajandusliku tegevuse vähenemise tõttu viimastel aastakümnetel on kasutamata põllumajandusmaa pind suurenenud nii Eestis tervikuna kui ka käesolevas töös põhjalikumalt uuritud Tartu maakonnas. Põllumajanduslikust kasutusest väljajäänud maa on potentsiaalne ressurss bioenergiakultuuride kasvatamiseks. Tartu maakonnas oli 2007. aastal täielikult kasutamata põllumajandusmaid 20 741 ha. Peale selle oli osaliselt põllumajanduslikust kasutusest väljajäänud maid, s.t kus ühtset pindalatoetust taotleti 50–99% ulatuses kogu põllumassiivist, 5610 ha. Põllumajanduslikust kasutusest väljajäänud maade pind oli piirkonniti erinev: rohkem oli selliseid maid Tartu linna ümbruses ning Emajõe ja Peipsi järve kaldal. Kasutamata põllumajandusmaad paiknevad väga killustatult ja põldude keskmine suurus on võrdlemisi väike: Tartu maakonnas ületas põllumajanduslikus kasutuses olevate põllumassiivide keskmine suurus kasutamata massiivide suurust seitse korda.

Põllumajanduslikus kasutuses olevate ja kasutamata maade mullastikus on olulised erinevused. Kasutamata põllumajandusmaad on kasutuses oleva maaga võrreldes üldiselt väiksema viljakusega ning piiratuma kasutussobivusega. Leetunud ja turvasmuldi on Tartu maakonna kasutamata maadel kaks ning lammimuldi 23 korda rohkem kui põllumajanduslikus kasutuses olevatel maadel keskmiselt. Samas ületab glei-, leostunud ja leetjate muldade levik kasutuses oleval põllumajandusmaal kahekordselt nende muldade leviku täielikult kasutamata põllumajandusmaal.

Kogu kasutamata põllumajandusmaa ei sobi võrdväärselt analüüsitud energiakultuuride kasvatamiseks. Mulla omaduste poolest sobib Tartu maakonna kasutamata põllumajandusmaast 14 708 ha paju kasvatamiseks, 20 790 ha halli lepa, 17 351 ha hübriidhaava, 22 315 ha päideroo ja 18 897 ha ida-kitseherne kasvatamiseks. Arvestades energiakultuuride kasvatamiseks sobivate kasutamata põllumajandusmaade pinda, kultuuride keskmist saagikust ning kütteväärtust, on paju, halli lepa ja hübriidhaava kasvatamisega võimalik aastas toota vastavalt 368 GWh, 687 GWh ja 538 GWh energiat. Päideroo ja ida-kitseherne kasvatamise potentsiaalne bioenergiatoodang on vastavalt 823 GWh ja 610 GWh aastas. Paju, halli lepa, hübriidhaava, päideroo ja ida-kitseherne kombineeritud maakasutuse bioenergeetiline potentsiaal on 667 GWh, mis moodustab veerandi maakonna aastasest energiatarbest.

Selleks et hinnata saagipotentsiaali sõltuvust mullastik-klimaatilistest tingimustest, koostati päideroo saagikuse ja lämmastikuga väetamise efektiivsuse mudel. Saagimudelist järeldub, et päideroo kuivaine biomass väetamata mullal varieerub mulla lämmastikusisaldusest ja aastast olenevalt vahemikus 0,9–6,9 Mg ha^{-1}. Muldadel, mille lämmastikusisaldus on 0,1–3%, on aastate keskmine (tõenäosus 50%) päideroo saagikus 2,1–5,6 Mg ha^{-1}. Väetamise efektiivsus väheneb mulla lämmastikusisalduse ja väetisnormi suurenedes. Näiteks on lämmastikuvaestel muldadel (Nüld 0,1%) 100 kg mineraalse lämmastiku lisamisel keskmine efektiivsus 33 ± 6 kg kg^{-1} N^{-1}, samal ajal kui lämmastikurikastel mineraalmuldadel (Nüld>1%) on see kaks korda väiksem. Väikese lämmastikusisaldusega muldadel (Nüld 0,1%) päideroo saagi varieeruvus lämmastikväetiste andmisel väheneb; seevastu lämmastikurikastel turvasmuldadel saagi varieeruvus lämmastikuga väetamisel suureneb.

Aastate keskmine (± standardviga) kiukanepi ja energiapäevalille kuivaine saagikus reoveesettel – vastavalt 6,61 ± 0,42 ja 13,53 ± 6,31 Mg ha^{-1} – oli väiksem kui soojema kliimaga piirkondades keskmiselt (Hu 2008; Mankowski ja Kolodziej 2008). Samas tuleb arvestada, et käesolevas töös kasutati väetisnormi 100 kg N ha^{-1} ja selle suurendamine võib nii kiukanepi kui energiapäevalille saagikust oluliselt suurendada.

Peale lämmastikväetise koguse võib saagikust mõjutada ka väetise liik. Käesolevas doktoritöös uuriti kiukanepi ja energiapäevalille biomassi kujunemist mineraal- ja orgaaniliste väetiste kasutamisel. Nii kiukanepi kui energiapäevalille saagikus sõltus kasutatud lämmastiku allikast. Suurim kiukanepi maapealse biomassi saak saadi mineraalse lämmastikväetise ja reoveesette kasutamisel ning suurim energiapäevalille saak reoveesette kasutamisel. Kiukanepi ja energiapäevalille saagikuse ja taime massi vahel esines positiivne korrelatiivne seos. Erinevalt energiapäevalille taime massist mõjutas kiukanepi taime massi tärkamine. Kiukanepi taimik tärkas halvemini reoveesette kasutamisel.

Päideroo saagimudeli rakendamine Eesti suuremõõtkavalisel mullastikukaardil tõestab saagi suurt ruumilist varieeruvust Tartu maakonnas. Ligikaudu 81% Tartu maakonna põllumajandusmaadest tagab väetamata mullal potentsiaalse keskmise päideroo kuivaine saagikuse alla 4 Mg ha^{-1}, kusjuures ligikaudu pooltel nendest aladest on potentsiaalne keskmine saagikus kõigest 2–3 Mg ha^{-1}. Mulla väiksema üldlämmastikusisalduse tõttu on päideroo saagipotentsiaal väiksem Tartu maakonna lõunaosas. Väetisi kasutamata on päideroo keskmine potentsiaalne saagikus 4–6 Mg ha^{-1} saavutatav vaid üksikutel põldudel. Analüüsi tulemus osutab vajadusele hinnata bioenergiakultuuride saagipotentsiaali võimalikult asukohapõhiselt.

Päideroo netoenergiasaak ehk energiasaagis ja energiakasutuse efektiivsus sõltub väga palju mulla lämmastikusisaldusest. Päideroo energiasaagis suureneb lämmastikväetiste andmisel rohkem lämmastikuvaestel mineraalmuldadel ja vähem turvasmuldadel. Turvasmullal vähendab lämmastikuga väetamine päideroo energiakasutuse efektiivsust, kuid näivleetunud mullal suureneb see kuni annuseni 198 kg N ha^{-1} ning väheneb suuremate väetisannuste korral. Käesolev töö esitab kvantitatiivse seose energiakasutuse efektiivsuse ja mulla lämmastikusisalduse vahel. Päideroo energiaparameetrite detailne analüüs näivleetunud mullal tõendab mitme hindamiskriteeriumi arvestamise tähtsust energiakultuuride planeerimisel. Optimaalne energiakasutuse efektiivsus saadakse ligikaudu kaks korda väiksema lämmastikunormiga kui see on vajalik toodangu väikese omahinna saamiseks. Päideroo kasvatamine väikese lämmastikusisaldusega muldadel ei ole tasuv, sest tootmise arvestuslik omahind on kaks kuni kolm korda kõrgem kokkuostuhinnast. Seetõttu ei saa energiaheinapõhine bioenergia tootmine toimida ilma lisatoetuseta.

Kokkuvõte

Kasutusest väljajäänud põllumajandusmaa on potentsiaalne maaressurss bioenergiakultuuride kasvatamiseks. Mulla kasutussobivust arvestades on Tartu maakonna kasutamata põllumajandusmaadel viiest uuritud energiakultuurist suurim potentsiaal päiderool ja hallil lepal. Paju, halli lepa, hübriidhaava, päideroo ja ida-kitseherne kombineeritud maakasutus võimaldaks katta veerandi maakonna aastasest energiatarbest. Bioenergia tootmise planeerimisel tuleb arvestada paljusid kriteeriume ja lähtuda võimalikult asukohapõhisest informatsioonist. Käesolevas töös koostatud päideroo energiaparameetrite ja majandusliku tasuvuse võrdlev analüüs tõestas, et tootmine võib küll olla energeetiliselt efektiivne, kuid majanduslikult mittetasuv. Koostatud päideroo saagi- ja lämmmastikväetise efektiivsuse mudeli rakendus digitaalsel Eesti suuremõõtkavalisel mullastiku kaardil tõestab suurt saagipotentsiaali varieeruvust sõltuvalt mullastik-klimaatilistest tingimustest.

Edasist uurimist vajavad küsimused ja uurimistöö tulemuste kasutamine

Käesolevas doktoritöös töötati välja metoodika, mille alusel saab asukohapõhiselt kindlaks teha kasutamata põllumajandusmaa ressursi. Bioenergeetilise potentsiaali hindamise aluseks olid varem kogutud andmed muldade kasutussobivuse kohta. Edasist uurimist vajab aga mudelite kasutamine kultuuride kasutussobivuse hindamisel. Käesolevas töös koostatud statistiliste mudelite rakendusest ilmneb asukohapõhise informatsiooni kasutamise tähtsus bioenergia tootmise planeerimisel. Koostatud mudeleid saab täiendada parameetrite lisamisel ja nende koosmõju hindamisel. Uusi võimalusi töös käsitletud andmete analüüsiks pakub mitmesuguste statistiliste meetodite (nt ANCOVA, segamudelid jt) rakendamine. Käesolevas doktoritöös koostatud energiaparameetrite ja majandusliku tasuvuse võrdlevast analüüsist järeldub mitme hindamiskriteeriumi arvestamise olulisus kultuuride planeerimisel. Kuna energiakasutuse efektiivsust ja majanduslikku tasuvust võrreldi valitud energiakultuuri kasvatamisel lämmastikuvaesel mineraalmullal, tuleks analüüsi laiendada ka teistele muldadele.

Käesoleva doktoritöö tulemused on rakendatavad energiakultuuride tootmise planeerimisel. Samas võimaldab töös kasutatud metoodikate rakendamine analüüsida muldade kasutussobivust ja hinnata asukohapõhist saagipotentsiaali ning tootmise jätkusuutlikkust ka teiste kultuuride kasvatamisel.

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I

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ORIGINAL ARTICLE

Assessment of abandoned agricultural land resource for bio-energy production in Estonia

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Abstract
The current study locates and quantifies abandoned agricultural areas using the Geographic Information System (GIS) and evaluates the suitability of abandoned fields for bio-energy production in Tartumaa (Tartu County) in Estonia. Soils of abandoned areas are generally of low quality and thereby limited suitability for crop production; as a result soil–crop suitability analyses could form the basis of knowledge-based bio-energy planning. The study estimated suitable areas for bio-energy production using willow (*Salix sp*), grey alder [*Alnus incana (L.) Moench*], hybrid aspen (*Populus tremuloides Michx.×Populus tremula L.*), reed canary grass (*Phalaris arundinacea L.*), and Caucasian goat's rue (*Galega orientalis Lam.*) in separate plantations. A combined land-use strategy is also presented as these crops are partially suitable to the same areas. Reed canary grass and grey alder have the highest energy potentials and each would re-use more than 80% of the available abandoned agricultural land. Energy grasses and short-rotation forestry in combined land-use strategy represents the opportunity of covering approximately a quarter of county's annual energy demand. The study estimates only agronomic potential, so further bio-energy analysis should take into account technical and economic limitations. Developed framework supports knowledge-based decision-making processes from field to regional scale to achieve sustainable bio-energy production.

Keywords: *Abandoned fields, biomass energy potential, GIS, location-specific analysis, soil–crop suitability.*

Introduction

Since the last decades of the 20th century interest in the production and utilization of bio-energy has increased. The main reasons are a combination of diminishing fossil fuel reserves and increasing environmental protection awareness. European Union (EU) energy policy priorities are, as per Directive 2006/32/EC (European Union, 1995), greenhouse-gas-emission limitation and energy-supply efficiency. Increased use of renewable energy sources enables these targets to be met. During recent decades studies in Europe have examined renewable energy opportunities at the national level and provided detailed information about available renewable energy sources (Voivontas et al., 2001; Batzias & Sidiras, 2005) and about bio-energy policy-promotion tools (Streimikiene & Klevas, 2007). Effective energy utilization has maintained a central role in Estonia's public debates since 1991. The widely held conjecture is that the reserves of the most important natural resource in Estonia, oil shale, will estimably last only for a further 60 years (Valgma, 2003). Increasing the share of renewable resources in energy production is, therefore, important. A rapid decline in agricultural land use has occurred in Estonia since the restoration of independence in

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1991. The aggregate area of arable land in 2006 is half of that in use fifteen years earlier (Astover et al., 2006). The scale of this decrease in arable land was the most drastic in the whole of Europe and was, by a factor of 3.9, higher than other post-Soviet European countries (Astover et al., 2006). There is necessity in Estonia for the planning of abandoned agricultural land, and the field-specific soil databases developed in this study provide a solid basis for a knowledge-based allocation of bio-energy production. The databases are sufficiently flexible to allow the results from field level to be scaled up for regional-level analysis. Increasing bio-fuel production, as a result of increasing energy demands and mindful of policies on climate change, takes up a significant area of land in many scenarios and prevents substantial abandonment of agricultural land (Bush, 2006). The use of abandoned agricultural areas is one potential way of increasing bio-energy production. Environmental awareness has forced scientific research to estimate the impacts related to bio-energy production. Studies have referred to some positive influences (McLaughlin & Walsh, 1998) but also negative ones during the process of bio-energy production (Ledin, 1998). Also, a number of farm-related factors influencing bio-energy adoption have been indicated (Roos et al., 2000). The importance of making precise estimates of the environment at both regional and local levels is therefore important. The decline in arable-land use in Estonia was regionally variable and especially high in marginal districts with low soil quality (Astover et al., 2006). Therefore the planning of bio-energy production on abandoned areas requires precise location-specific analysis. The aim of the present study was to locate, quantify, and estimate the suitability of abandoned agricultural areas for bio-energy production using Tartumaa (Tartu County) in Estonia as an example.

Material and methods

Tartu County is situated in the south of Estonia between the shores of Lake Võrtsjärv (western side of the county) and Lake Peipsi (eastern side of the county) and straddles the River Emajõgi which flows between the two lakes. The county covers 308 900 ha, which is 7.1% of Estonia's land surface of 4 369 800 ha. In 2007, agricultural land in use formed 26% of the county's total area and 9% of Estonia's agricultural land. The proportion of forest land (38.9%) in Tartu County is smaller than that in the country as a whole (51.5%).

The study identified abandoned field parcels in Tartu County, using the Estonian Basic Map (1:10 000) and the field layer of the Agricultural Registers and Information Board (ARIB) and databases of Common Agricultural Policy (CAP) payments in 2007. We considered field parcels that did not have any applications for single-area payments as 'entirely abandoned' and field parcels where area payments covered 50–99% of total area as 'partially abandoned'. The study used an overlay comparison of the Estonian Basic Map and the ARIB field layers to identify agricultural areas excluded from ARIB's fields (i.e. not valid for CAP subsidy schemes), which we also tagged as 'entirely abandoned'. We then used visual and manual correction of area boundaries based on ortho-photos to eliminate any of the remaining agricultural areas on the Basic Map that did not fit the following topographical parameters and were thus unsuitable for either bio-energy production or further analysis: (i) areas less than 0.3 ha, and (ii) areas with perimeter:area ratio over 5:1. The total agricultural land in Tartu County included for analysis in the study was 111 143 ha (103 166 ha ARIB fields and 7977 ha from Basic Map) which forms 36% of the county's total land area. The study used a GIS environment, MapInfo Professional, to perform topology analysis of the field layers and the soil map polygons. We identified the soils of abandoned land using the Estonian Land Board's digital soil map (scale 1:10 000) and depending on the soil type and texture assessed the suitability of these areas for short-rotation energy forestry and energy grasses (Laas, 2004; Kõlli, 2006). Reintam et al., (2003) provide detailed overviews about the Estonian large-scale soil map and crop-specific suitabilities. We evaluated areas suitable for potential bio-energy production using willow (*Salix sp*), grey alder [*Alnus incana (L.) Moench*], hybrid aspen (*Populus tremuloides Michx.* × *Populus tremula L.*), reed canary grass (*Phalaris arundinacea L.*), and Caucasian goat's rue (*Galega orientalis Lam.*). These crops are the most studied energy cultures under Nordic conditions (Ross et al., 1996; Uri et al., 2002; Vares et al., 2003; Lillak et al., 2007; Pahkala, 2007).

Conversion of the land potential to a bio-energy potential

The estimated abandoned land was further planned by consideration of factors ranging from soil-suitability analysis to potential energy-crop production. We calculated, for each of the five selected energy crops, the energy output of the annual biomass yield for both separate plantations and combined land-use strategies. We considered in combined land-use strategy that 30% of abandoned areas remains under natural conditions [biomass yield for natural grassland 2.0 t dry matter (DM)/ha] and 70% for energy grasses and short-rotation forestry. The land partition for energy crops was based on the results of soil-suitability analysis considering relative area proportions suitable for each crop.

Annual DM productivity forms the basis of the bio-energy potential of a plant for which reason the study needed to know the relevant values for the five selected bio-energy plants. We used the results of previous studies and calculated average annual productivity of DM as well as the calorimetric value in megajoules (MJ) for each of the study's selected plants (Table I). Willow's annual DM production was considered as 4.4 t ha^{-1} in gleyic soils and Gleysols, and 5.9 t ha^{-1} in histic soils and Eutric Histosols. Annual willow production varies by a factor of 4–5 depending mostly on soil water regime and nutrient sufficiency (Ross et al., 1996). The potential bio-energy production for grey alder was taken as 6.4 t ha^{-1} and that for hybrid aspen as 6 t ha^{-1}. The main parameters influencing plantation production of grey alder and hybrid aspen coppice are age and soil. Soil parameters can influence the growth of these two types of plantations by a factor of two (Vares, 2005). The annual DM biomass yields were calculated for reed canary grass at 8 t ha^{-1} and for Caucasian goat's rue at 7 t ha^{-1}. Reed canary grass is one of the highest-yielding perennial herbaceous grasses (Wrobel et al., 2009). Under Estonian conditions the variation coefficient of reed canary grass and Caucasian goat's rue production is accordingly 44 and 24% depending on pedo-climatic conditions and also, in the case of reed canary grass, fertilization (Rand, 1981; Eilart & Reidolf, 1987; Meripõld, 2006; Viil, 2006). The higher the soil nutrient supply is, the more stable are reed canary grass yields. In the instance of soils with low humus content (2%), the use of high levels of fertilizer ($N_{200}P_{35}K_{130}$) can result in a DM yield of 8 tha^{-1}. In this instance the variation coefficient was 14%. Lowering the fertilization norm by a factor of 1.5–3 can result in the same DM yield (8 tha^{-1}) on histic soil and Histosols (Rand, 1981; Eilart & Reidolf, 1987).

Table I. Annual dry-matter productivities (DM, t ha^{-1}) and calorimetric values (MJ kg^{-1}) of bio-energy crops applied in calculation of bio-energy production potential.

Crop	Annual productivity (DM t ha^{-1})	Calorimetric value (MJ kg^{-1})
Reed canary grass	8[1]	16.6[6]
Caucasian goat's rue	7[2]	16.6[7]
Grey alder	6.4[3]	18.6[8]
Hybrid aspen	6[4]	18.6[9]
Willow		
Gleyic soils and Gleysols	4.4[5]	18.6[10]
Histic soils and Histosols	5.9[5]	18.6[10]

Sources: 1 – Rand (1981); Eilart & Reidolf (1987); Kryževiciene (2006). 2 – Meripõld (2006); Viil (2006); Lillak et al. (2007). 3 – Uri (2000); Uri et al. (2002). 4 – Vares et al. (2003). 5 – Ross et al. (1996). 6 – Burvall (1997). 7 – Hovi (1995). 8 – Tullus et al. (1998). 9 – Vares et al. (2003); Vares et al. (2005). 10 – Miles et al. (1995).

Results

Abandoned agricultural land in Tartu County covers a total of 26 351 ha of which 20 741 ha is 'entirely abandoned' and 5610 ha is 'partially abandoned'. Abandoned field parcels are distributed homogeneously all over the county, although the density varies (Figure 1). The proportion of abandoned fields is highest near the county's biggest urban area, Tartu, but also relatively high along the banks of the River Emajõgi and the shoreline of Lake Peipsi. The mean field area differs significantly between used (21 ha) and abandoned fields (2.9 ha).

Stagnic Luvisols form on 33.5% of the total analysed agricultural land and Gleysols 20.6% (Table II). Luvisols and Cambisols form altogether 25% and are distributed as 29.5% from used parcels and 16% from entirely abandoned fields. In the case of Histosols and Albeluvisols abandoned areas form more than twice the area of that in land use, and in the case of Fluvisols nearly 23-times this soil's land-use area.

The following analyses represent six different concept strategies for producing biomass from abandoned agricultural land in Tartu County; three of them concern short-rotation forestry, two energy grasses (Table III), and one combined bio-energy land-use strategy (Table IV).

Short-rotation forestry

Gleyic soils, histic soils, Gleysols, and Eutric Histosols are most suitable for growing willow. There are 11 951 hectares of entirely abandoned agricultural land in Tartu County which are suitable for growing willow. Gleyic soils and Gleysols form 69% and histic soils and Eutric Histosols 31% of these areas. The total quantity of willow dry wood, if grown in all of the entirely abandoned areas, would weigh 58 087 metric tonnes with an energy value of 300 GWh. There are also 2757 hectares of partially abandoned field parcels which are suitable for growing willow. The total production of willow dry wood in the aggregate of the partially abandoned areas would be 13 155 metric tonnes with an energy value of 68 GWh.

Grey alder is most productive on high-fertility Cambisols and Luvisols but satisfactory productivity also occurs on Stagnic Luvisols and Albeluvisols.

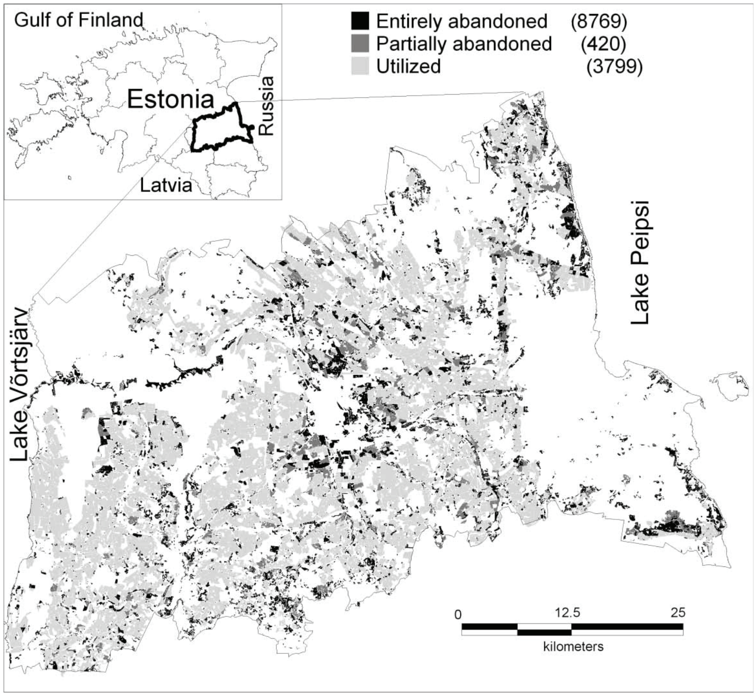

Figure 1. The location of used and abandoned agricultural areas in Tartu County. Number of field parcels shown in brackets.

Grey alder could be cultivated on 15 914 hectares of entirely abandoned agricultural land. The potential bio-energy production of these fields is as high as 526 GWh. There are 4876 hectares of partly abandoned areas where grey alder cultivation could potentially produce an energy value of 161 GWh. Grey alder biomass production represents the highest re-use potential of abandoned parcels (80% in total) by the three energy forests.

Hybrid aspen's soils requirement coincides mostly with that of grey alder; the most suitable soils are moderately moist soils, gleyic loamy sand, and loam soils. There are 13 140 hectares of entirely abandoned and 4211 hectares areas of partially abandoned agricultural land that are suitable for growing hybrid aspen as energy forest. The potential energy values of these areas are accordingly 407 GWh and 131 GWh.

Table II. Soil distribution (percentage of area) on agricultural land of Tartu County.

Soil reference group by WRB[1]	Total (%)	Land in use (%)	Entirely abandoned areas (%)
Fluvisols	1.6	0.3	6.8
Eroded soils	2.0	1.4	2.9
Deluvial soils	3.0	2.5	3.4
Gleysols	20.6	23.5	12.3
Histosols	8.8	6.9	13.9
Cambisols	6.2	7.4	4.4
Luvisols	18.9	22.1	11.9
Stagnic Luvisols	33.5	31.7	34.8
Albeluvisols	5.3	4.0	9.4
Other	0.2	0.1	0.2

[1]World Reference Base 1998.

Table III. Potential annual biomass and energy production from suitable abandoned areas in Tartu County using separate willow, grey alder, hybrid aspen, reed canary grass, or Caucasian goat's rue plantations.

	Entirely abandoned agricultural land			Partially abandoned agricultural land		
Crop	Area (ha)	Total yield[1] (t)	Total energy[2] (GWh)	Area (ha)	Total yield[1] (t)	Total energy[2] (GWh)
Reed canary grass	17 433	139 462	643	4883	39 060	180
Caucasian goat's rue	14 411	100 877	465	4486	31 403	145
Grey alder	15 914	101 850	526	4876	31 205	161
Hybrid aspen	13 140	78 842	407	4211	25 265	131
Willow						
Gleyic soils and Gleysols	8283	36 445	188	2076	9133	47
Histic soils and Eutric Histosols	3668	21 643	112	682	4022	21

[1]Total potential yield from suitable abandoned areas in tonnes. [2]Total potential energy production from suitable abandoned areas in gigawatt hours.

Energy grasses

Reed canary grass could be grown in 17 433 hectares of entirely abandoned areas, which forms almost 86% of these fields. Biomass production from these areas could reach as high as 139 462 metric tonnes with an energy value of 643 GWh. There are also 4883 hectares of partly abandoned fields which are suitable for growing reed canary grass. The potential energy production in these fields is as high as 180 GWh (Table III).

The potential bio-energy production of cultivating Caucasian goat's rue on both the entirely and partially abandoned agricultural land (18 897 hectares) is 132 280 metric tonnes of dry biomass with an energy value of 610 GWh.

Combined land-use strategy

Soil-suitability analysis for each of the selected crops indicated there were overlaps in soil suitability between the five crops. We decided therefore to compile a combined land-use strategy for evaluating potential bio-energy production from total abandoned areas using all five available crops. Since we had previously declared that 30% of abandoned areas would remain as natural grasslands the data for this category of abandoned land are included. The biomass of energy forests and grasses grown on abandoned fields in Tartu County would weigh 121 555 tons, of which 95 625 tons would come from entirely abandoned land and 25 930 tons from partially abandoned land (Table IV). The total bio-energy production from these fields could be as high as 594 GWh, which in relation to separate plantations is lower than the energy production from reed canary grass, Caucasian goat's rue, or grey alder but higher than that potentially from hybrid aspen or willow. Biomass production from natural grasslands would form 15 811 tons with an energy value of 73 GWh. Potential bio-energy production from total abandoned areas in Tartu County is as high as 667 GWh.

Discussion

Several studies have estimated agricultural land resource potential for bio-energy at global, EU, and national scales (Voivontas et al., 2001; Edwards et al., 2005; Hoogwijk et al., 2005) but investigations at a more detailed spatial level are few (Förster

Table IV. Potential annual biomass and energy production in Tartu County in the case of combined land-use strategy.

	Entirely abandoned agricultural land			Partially abandoned agricultural land		
Crop	Area (ha)	Total yield[1] (t)	Total energy[2] (GWh)	Area (ha)	Total yield[1] (t)	Total energy[2] (GWh)
Reed canary grass	3484	27 876	129	903	7226	33
Caucasian goat's rue	2904	20 326	94	825	5773	27
Grey alder	3194	20 442	106	903	5781	30
Hybrid aspen	2613	15 680	81	785	4713	24
Willow						
Gleyic soils and Gleysols	1603	7053	36	383	1685	9
Histic soils and Eutric Histosols	720	4249	22	128	753	4
Natural grassland	222	12 445	57	1683	3366	16
Total	20 741	108 070	524	5610	29 296	142

[1]Total potential yield from suitable abandoned areas in tonnes. [2]Total potential energy production from suitable abandoned areas in gigawatt hours.

et al., 2008). Sustainable bio-energy planning recommendations and related land-use decisions must be made on as detailed a scale as possible. Our field-scale GIS approach contributes knowledge and methodology which can be easily applied nationwide as the required input data for analysis are available. Owing to this we were able to avoid the main reason for the lack of many spatial-decision support systems that input data for models are unavailable, expensive, or difficult to collect. The study used GIS to store, modify, and analyse geographically distributed data. GIS has also been used for spatial-distribution estimation of biomass including available forest and agricultural crops residuals (Panichelli & Gnansounou, 2008; Shi et al., 2008) and cultivated energy crops (Förster et al., 2008). Since Mitchell (2000) analysed different computer models of bio-energy systems and suggested decision-support systems' development should be aimed towards bio-energy application, development of more complex biomass-management tools has occurred (Batzias & Sidiras, 2005). Any decisions about the cultivation of appropriate energy crops for a given area are best taken at a regional or local level (Fischer et al., 2005), which the results of our paper support. The application of a large-scale soil map with the combination of soil–crop suitability models provided the framework for spatial bio-energy planning.

The density of abandoned fields in Tartu County is higher near the county's biggest urban area partly because of urban sprawl. Limited accessibility and unsuitable soils for traditionally cultivated crops could be the reasons for the high proportion of abandoned areas along the banks of the River Emajõgi and the shoreline of Lake Peipsi. The compositions of soils in currently used and in abandoned agricultural areas are remarkably different (Table II). The proportion of soils with low quality and limited suitability is higher in abandoned areas compared with used fields. Whereas Astover et al. (2006) verified a higher abandonment rate in regions with lower soil quality (at the level of municipalities), our research provides, for the first time, evidence of this phenomenon at a detailed spatial scale (the level of mapped soil polygons 1:10 000). This peculiarity indicates the necessity to consider site-specific soil information. In Estonia, the large-scale digital soil map is available for the entire land surface, but is still rather rarely used in the decision-making process because of the complexities of the decision-support systems and the limited knowledge of the decision makers. The development of GIS-based decision-support systems where specific soil criteria will be converted for stakeholders to more understandable format (i.e., to functional suitability maps) can contribute to overcoming this shortcoming. For instance, Förster et al. (2008) developed a site-optimized suitability model where a medium-scale soil map was the basis for biomass-production analysis. We used suitability models to estimate the agronomical and biological potential of energy grasses and short-rotation forestry on various soils. We could, thereafter, calculate the possible energetic value of the biomass potential from abandoned areas. We calculated the energy production of the selected energy grasses and energy forestry using the average yields but analysing bio-energy production in detail, yielding variation based on soil texture, water content, nutrient sufficiency, climatic conditions, and plantation age, should be taken into account. In the case of combined land-use strategy potential bio-energy production could cover approximately 20–25% of total energy consumption in the study area whereas reed canary grass could provide 24%, grey alder 20%, Caucasian goat's rue 18%, hybrid aspen 16%, willow 11%, and natural grassland 11% to the energy grid. The relative significances of these different crops must be handled provisionally because they depend on some fixed assumptions (i.e., 30% of abandoned land will remain as natural grassland) and on soil–crop suitability. However, for more complex analysis several additional criteria should be included to the suitability analysis – technical, economical barriers, policy impulses, environmental restrictions, ethical values, etc. As these parameters influence bio-energy implementation, EU structural funds could be used to relieve some, for example, economic barriers (Streimikiene & Klevas, 2007).

Structural and communion funds considerably prioritize subsidizing energy production from renewable (including biomass) and alternative energy sources. Estonia's government has also adopted legislative measures (for example, excise tax exemptions for biofuels and biomass, CO_2 tax for combustion installations, etc.) for supporting bio-energy implementation. Psychological barriers include public awareness about bio-energy cultures and farmers' hesitancy towards bio-energy profitability.

The average size of abandoned field parcels in the study area is relatively small (by a factor of about seven compared with used fields), they are often fragmented and dispersed around the county. Hence the re-use of abandoned areas could have several technical and economical limitations and must be included in further analysis. Increased interest in bio-energy production indicates the necessity of evaluating production costs. Since Noon & Daly (1996) pointed out the importance of choosing power-plant location, further studies include distance calculations (Voivontas et al., 2001; Panichelli & Gnansounou, 2008; Shi et al., 2008).

The maximum cost-effective transportation distance in Finland in the case of reed canary grass is estimated at 60 km (Pahkala, 2007). Our research does not include any distance calculations of potential plantations to available power plants. Therefore the further planning process of bio-energy production on abandoned areas in Estonia should be supplemented with distance calculations and economic criteria.

The precise spatial determination of abandoned agricultural land resource forms a solid basis for further bio-energy suitability analysis without reducing existing food and fibre production. This is especially important for Estonia and also for other Eastern European countries with a high proportion of abandoned land. The current study concerning the allocation of suitable areas for bio-energy crops considers only the use of abandoned fields, because use of these areas does not have any negative effect on Estonia's level of food self-sufficiency. This is an important consideration since Estonia's agricultural self-sufficiency became negative in 1997 (Rask & Rask, 2004) and is currently caused also by low productivity. Increased land-use efficiency and crop productivity from utilized fields would be the basis for decreasing negative self-sufficiency. The use of abandoned agricultural areas for bio-energy production can help to improve the overall profitability of the agricultural sector and promote the economic stabilization of rural regions. Re-using abandoned agricultural areas could also ease the level of unemployment in rural areas (Streimikiene & Klevas, 2007) since the employment rate between 1990 and 2005 decreased in Estonia's agriculture and hunting sectors from 16.6 to 3.9%.

Soil–crop suitability analyses serve the basis for knowledge-based allocation of bio-energy production. As the soils on abandoned fields have a lower quality with limited suitability, the consideration of local pedological conditions is crucial. Our study provides a basis and framework to develop GIS-based decision-support systems for multi-criteria site-optimized bio-energy planning.

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II

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Reed canary grass biomass yield and energy use efficiency in Northern European pedoclimatic conditions

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ABSTRACT

Reed canary grass is a potential bio-energy crop in Northern Europe. As plantation biomass production depends on local pedoclimatic conditions, it is important to evaluate yield in the context of soil-specific characteristics. The current study used regression models to evaluate reed canary grass yield variability in the context of soil nitrogen (N) content and in applied mineral N fertilisers. Reed canary grass bio-energy potential was evaluated in a soil-specific manner to calculate the production and energy use efficiency. Soils with low N content produce yields of almost 1 Mg ha^{-1} in years with unsuitable weather conditions for plant growth. The average dry matter yield of 6–7 Mg ha^{-1} is achievable within limited years on soils with N contents of more than 0.6%. Fertilisation increases the yield and decreases yield variability in humus-poor soils, but on soils with high N content, production risks increase with increasing N fertiliser applications. Energy use efficiency decreases with increasing input on Histosols; increasing the input from 6 to 31 GJ ha^{-1} results in energy use efficiency decreasing from 9 to 2 GJ GJ^{-1}. As a consequence of energy use efficiency, a diminishing return occurs on Haplic Albeluvisol, as optimum efficiency peaks at 5.2 GJ GJ^{-1} using 198 kg N ha^{-1}. The current study integrated the developed models in the soil Geographic Information System and calculated the energy use efficiency of selected areas. This approach enables researchers to evaluate production risks in the region and provides a framework for knowledge-based bio-energy production.

1. Introduction

Increasing the proportion of alternative energy resources has become more pertinent in recent decades. Studies have broadly suggested potential bio-energy cultures suitable for particular pedoclimatic conditions. Reed canary grass (RCG) (*Phalaris arundinacea* L.) is a promising bio-energy crop [1] and potential non-wood crop for industrial uses (e.g., paper-making) [2,3]. Studies have evaluated RCG's yields, duration periods and winter losses [4–6], but there are little data evaluating large-scale RCG biomass production. Research has been done assessing the land suitability [7] and biomass potential [8] in bio-energy production using small-scale geographic databases, but a larger scale evaluation is

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required in terms of practical planning and land usage decisions. In Estonia, large-scale (1:10,000) soil maps covering the entire country have been digitised since 2001. There are also soil databases available that are sufficient for various outputs, including the evaluation of bio-energy production.

Biomass production depends on plantation management and production risks related to climate and soil. Several studies have indicated that the site, year and nitrogen (N) fertilisation influence RCG yields significantly [3,9]. Risk management in agriculture assumes decision making based on the available data. Studies have analysed risk management of biomass production from county to field level [10] and field to region level [11]. Long-term field experiment data can be used for modelling and analysing yield production and risks in a variety of land-use applications. Yield models taking into account detailed pedoclimatic conditions contribute to risk assessment in agriculture and provide a foundation for knowledge-based decision making. Depositing results in the Geographic Information System (GIS), as Förster et al. [12] did in their comparison of the suitability of evaluation methods for bio-energy crops, enables all stakeholders to visualise and analyse the outcomes. Although previous studies have performed bio-energy production analyses at either the site-specific [12] or regional level [11], nationwide biomass production evaluations taking into account field-specific soil information do not currently exist.

Sustainable bio-energy production within the constraints of limited usage of fossil fuels and the increasing global population requires a breadth of information for decision making. One possible method for informing these decisions is the estimation of bio-energy production using energy efficiency characteristics. Studies have evaluated energy balances [13] and energy and nitrogen use efficiency [14] to analyse biomass production efficiencies. Although various cultures [14] and cropping systems [15] in energy use efficiency analyses have been considered, there is an absence of comparative analysis emphasising soil effects in efficiency. Finally, as bio-energy yield is not linearly correlated with energy input [13], research has to address the challenges of evaluating production efficiency dependent on the input level.

The aim of the current study is to analyse RCG yield variability and biomass production in a site-specific manner without fertilisation as well as with the application of mineral N in relation to bio-energy efficiency.

2. Materials and methods

2.1. Description of field trials

We gathered and used data from previous Estonian RCG field experiments performed on Haplic Albeluvisol, Fluvic Histosol and Eutric Histosol (Table 1). The longest perennial field experiment (nine years) was performed by Rand and Krall [16] on Haplic Albeluvisol. The duration of the field experiments performed on the Histosols was three to four years. Soil total N content (Ntot) on Haplic Albeluvisol was 1.2 g kg^{-1}, much less than that in the Histosols. On Haplic Albeluvisol and Eutric Histosol, phosphorus (P) and potassium (K) rates applied in the field trials are shown in Table 1. On Fluvic Histosol, P and K norms of Annuk [17–19] were calculated as an average of the duration period (26 kg P ha^{-1} and 100 kg K ha^{-1} in the first year; 52 kg P ha^{-1} and 199 kg K ha^{-1} in following years). The P and K applications of Annuk [20] were indicated as the average of the field trial. Aboveground biomass was measured in the autumn in all of the field experiments.

Table 1 – The experimental design, soil characteristics and duration of reed canary grass field experiments used in the current study.

	N	P	K	Duration	Source
Haplic Albeluvisol, Ntot 1.2 g kg^{-1}	0	35	133	1968–1976	[16]
	120	35	133		
	240	35	133		
	360	35	133		
Fluvic Histosol, Ntot 21 g kg^{-1}	0	43	166	1968–1970	[17–19]
	85	43	166		
	170	43	166		
	340	43	166		
	680	43	166		
	0	39	150	1969–1972	[20]
	136	39	150		
	340	52	199		
Eutric Histosol, Ntot 30 g kg^{-1}	100	26	100	1973–1975	[21]
	200	52	199		
	300	78	299		
	500	131	498		
	0	39	149	1966–1968	[22]
	60	39	149		
	180	39	149		

2.2. Reed canary grass yield modelling

In the current study, statistical regression models of RCG biomass yield were performed on the basis of data from field trials conducted on Haplic Albeluvisol (data covering nine years), Fluvic Histosol (seven years) and Eutric Histosol (six years). Multiple regression models were developed to predict the following: 1) the yield – RCG dry matter yield of aboveground biomass (Mg ha^{-1}) harvested in the fall depending on soil productivity (control plots from field experiments without additional nitrogen fertilisers), and 2) the efficiency – average efficiency of mineral nitrogen fertilisers. The data gathered on RCG allows for analysis of the dependence of the yield on the soil total nitrogen content (Ntot, %) and N fertilisation because the application rates of mineral P and K were comparable and non-limiting factors. In the yield model, we used probability (Pr, %) to express climatic risk and Ntot as explanatory variables. An increased growth of vegetative grass crops occurs in nitrogen-rich soils [23], but the relationship between soil nitrogen and biomass yield is non-linear. Therefore, inverse values of soil Ntot were used as a model variable. The output of the yield model was used to estimate the pedoclimatic potential and the risks of RCG productivity in the case of an unfertilised management strategy.

In the second regression model (efficiency), the average efficiency of mineral nitrogen (kg DM kg^{-1} N^{-1}) was a function of the probability (Pr, %) expressing climatic risk, Ntot and the annual rate of applied mineral nitrogen (kg N ha^{-1}). Normal distribution assumptions in both models were checked using the Shapiro–Wilk test ($W = 0.93$, $P = 0.158$) and Kolmogorov–Smirnov test ($D = 0.15$, $P = 0.593$). The normal distribution in the data allowed us to calculate probabilities for dependent variables on the principle of the Central Limit Theorem. The mean value of a dependent factor (e.g., RCG yield) equated to 50% probability, and values corresponding to other probabilities were found on the basis of normal distribution around the mean. In the case of approximate normal distribution, a certain proportion of data values remains within z standard deviations of the mean. For example, for probabilities of 5% and 95%, the standard deviation was multiplied by 1.96 and either added or subtracted from the mean value. Whereas a yield model estimates the natural productivity of soils, an efficiency model gives the potential yield increase from fertiliser addition. Combining the outputs from both models enabled us to evaluate RCG yield depending on the pedoclimatic conditions and nitrogen fertilisation.

2.3. *Energy and land use efficiency*

Total energy yield (GJ ha^{-1}) was calculated using the RCG lower heating value of 16.6 MJ kg^{-1} [24]. Energy output was estimated for a delayed harvest while it was propagated in Nordic conditions [3], and yield loss compared to autumn harvest was considered to be 40% [6]. Total energy input (EI, GJ ha^{-1}) was calculated using the input for the production of fertiliser N 35.3 MJ kg^{-1} [25], P 36.2 MJ kg^{-1} and K 11.2 MJ kg^{-1} [26]. Other annualised energy inputs (establishment, harvesting, etc.) were taken as 3 GJ ha^{-1} [14,27,28]. In the current energy analysis, we calculated net energy yield (NEY), which was measured as GJ ha^{-1}, NEY efficiency as GJ GJ^{-1} EI^{-1} and energy use efficiency (EUE) as GJ GJ^{-1}. We calculated NEY describing land use efficiency as the difference between total energy yields and total energy input (EI). We calculated NEY efficiency as a derivative from an NEY quadratic regression equation describing energy yield efficiency of an additional input unit. EUE is the ratio of NEY to EI. The current study does not include any detailed nitrogen use efficiency (NUE) analysis, although the possibility of its parallel development with EUE as indicated by Lewandowski and Schmidt [14].

2.4. *The potential yield of RCG in Tartu County*

Studies [29,30] have commonly scaled up yield models on a regional basis for evaluating yield potential over large areas. For evaluating RCG biomass production in a region, we used Tartu County as an example. Tartu County is located in southern Estonia, covering 7.1% (308,900 ha) of Estonia's land surface. We conducted the study with GIS using the field layer of the Agricultural Registers and Information Board (ARIB) and the Estonian large-scale digital soil map (scale 1:10,000). ARIB's field layer data enabled us to quantify agricultural areas in Tartu County (database of 2007), and soil data were the basis for calculating RCG yields from developed models dependent on soil N content and fertilisation. The large-scale soil map does not include any direct values of soil nitrogen content. The qualitative nature of the initial soil map prohibits quantitative modelling. Thus, we used the arable land evaluation database of Tartu County from the Estonian Land Board (comprising 950 sq km and 31,226 fields). In each field, the soil type was assessed separately, and the average soil organic matter (humus) content grouped by texture was derived and embedded in the soil map's polygons. The next stage was to calculate the Ntot concentrations of mineral soils using a linear regression equation provided by Roostalu [31]: Ntot = 0.047 * Humus + 0.0366 ($R^2 = 0.87$, $P < 0.01$), where Ntot is soil total nitrogen content (%), Humus is soil organic carbon content (%) determined by the Tjurin method and multiplied by 1.72. For Histic soils and Histosols, mean values of Ntot were calculated depending on the soil type and degree of peat decomposition.

Tartu County's agricultural area yield analysis was performed considering the average (Pr = 50%) RCG yield production. Probability (Pr, %) expresses the yield variability in different years. We created a grid theme using inverse distance weighting (IDW) as an interpolator for visualising RCG biomass production in 50% probability. The results of Tartu County's energy and land use efficiency analysis are calculated as the weighted average of the county considering the methodology of the current study's general energy analysis.

3. Results

3.1. *Dependency of RCG yield on soil N content*

The explanatory variables of the yield model are indicated in Table 2. The standard error of the model estimate is 0.23 Mg ha^{-1}. The effect of 1/Ntot to RCG yield is non-linear.

The modelled dry matter (DM) yield of RCG in unfertilised areas varies from 0.9 to 6.9 Mg ha^{-1} depending on the Ntot content and the climatic conditions (Pr, %) (Fig. 1). Modelled yield estimation indicates that biomass production on soils with an Ntot content of 3% range from 4.4 to 6.9 Mg ha^{-1}. RCG yield on soils with low Ntot content is as low as 1 Mg ha^{-1} in years with unsuitable weather conditions for plant growth. The average (Pr = 50%) RCG yield on soils with an Ntot content of 0.1–3% increases from 2.1 to 5.6 Mg ha^{-1}. In Estonian pedoclimatic conditions, yields of 6–7 Mg DM ha^{-1} in the absence of nitrogen fertilisation are achievable within a few years on soils with an Ntot content greater than 0.6%. Establishing RCG plantation on soils with an Ntot content greater than 1% enables the production of biomass of at least 5 Mg ha^{-1} in seven out of ten years.

3.2. *RCG yield dependency on nitrogen fertilisation*

The N fertilisation efficiency model goodness of fit is lower compared with the yield model (Table 3). The model indicates

Table 2 – Regression model of RCG dry matter yield (Mg ha^{-1}) without nitrogen fertilisers (adjusted $R^2 = 0.97$, $P < 0.000$, SE of estimate = 0.23).

	Coefficient	SE of coefficient	P-value
Intercept	7.7126	0.2527	<0.0001
Pr	−0.0837	0.0178	<0.0001
Pr^2	0.0010	0.0003	0.002
Pr^4	5.938-E08	0.0000	0.002
1/Ntot	−0.3613	0.0121	<0.0001

Pr – probability, %; Ntot – soil total nitrogen, %; SE – standard error.

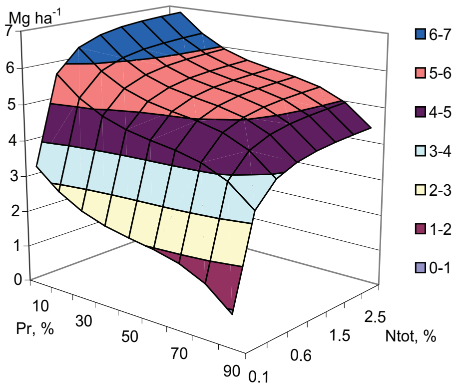

Fig. 1 – The probability (%) of RCG modelled DM yield ($Mg\ ha^{-1}$) dependent on soil N content.

that N fertilisation efficiency decreases and efficiency variability increases with increasing soil N content (data not presented). An average (Pr = 50%) efficiency of 33 ± 6 $kg\ DM\ kg^{-1}\ N^{-1}$ is achieved on soils with Ntot 0.1% in applying 100 $kg\ N\ ha^{-1}$. In comparison, the efficiency on soils with Ntot 1% is two times lower. The probability of nitrogen fertilisation efficiency on soils with an Ntot of 3% in applying 100 $kg\ N\ ha^{-1}$ is 6–22 $kg\ DM\ kg^{-1}\ N^{-1}$. Increasing the rate of mineral N application results in a decrease in overall fertilisation efficiency and an increase in the variation of fertilisation efficiency.

RCG dry matter yield without additional mineral N application on Haplic Albeluvisol varies from 1.7 to 4.4 $Mg\ ha^{-1}$, with a variation coefficient of 35% (Fig. 2, Table 4). While the average biomass production increases continuously with increasing N supply, doubling at 80 $kg\ N\ ha^{-1}$, the CV decreases rapidly (23% at 80 $kg\ N\ ha^{-1}$).

On Fluvic Histosols, the DM yield of unfertilised fields varies from 3.9 $Mg\ ha^{-1}$ to 6.4 $Mg\ ha^{-1}$ (5.1 $Mg\ ha^{-1}$ on average). By contrast, the average yield from unfertilised Eutric Histosol reaches 5.8 $Mg\ DM\ ha^{-1}$. RCG yields as well as CVs (i.e., production risks) increase with an increase in N supply in both Fluvic Histosols and Eutric Histosols.

Table 3 – Regression model for average nitrogen efficiency ($kg\ DM\ kg^{-1}\ N^{-1}$) (adjusted R^2 = 0.70, P < 0.000, SE of estimate = 6.04).

	Coefficient	SE of coefficient	P-value
Intercept	25.2248	2.0613	<0.0001
1/Ntot	1.9684	0.1903	<0.0001
Pr	–0.1968	0.0247	<0.0001
N_{min}	–0.0183	0.0046	<0.0001

Pr – probability, %; Ntot – soil total nitrogen, %; N_{min} – rate of mineral nitrogen, $kg\ ha^{-1}$, SE – standard error.

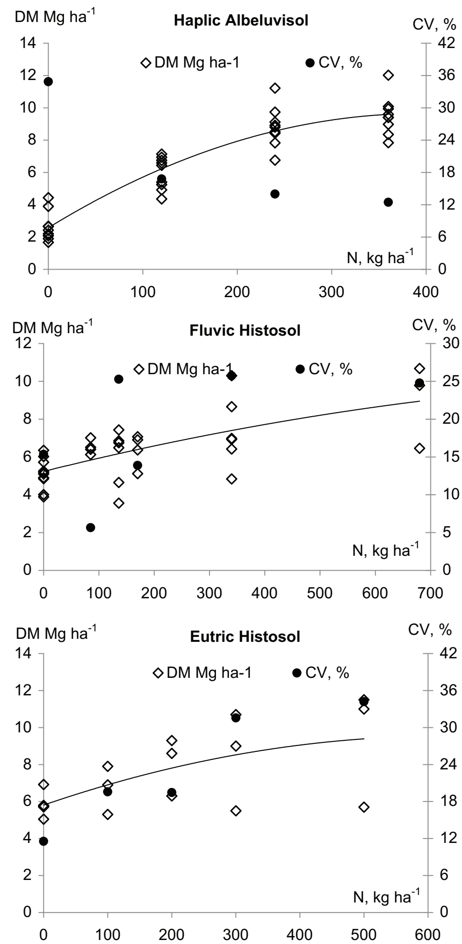

Fig. 2 – RCG DM yield ($Mg\ ha^{-1}$) and variation coefficient (%) on Haplic Albeluvisol, Fluvic Histosol and Eutric Histosol dependent on N fertilisation.

3.3. *Energy and land use efficiency of RCG dependent on energy input*

NEY describes land use efficiency. The average NEY on unfertilised plots of Haplic Albeluvisol is 21 $GJ\ ha^{-1}$ (Fig. 3, Table 4). Increasing the input level to 18 $GJ\ ha^{-1}$ with applied N of 360 $kg\ ha^{-1}$ results in the average NEY increasing to 76 $GJ\ ha^{-1}$. NEY efficiency (data not shown) decreases rapidly from 9 $GJ\ GJ^{-1}\ EI^{-1}$ at an input level of 6 $GJ\ ha^{-1}$ to the level of producing no additional NEY with additional energy input at 18 $GJ\ ha^{-1}$. The average EUE increases to an input level of 12.7 $GJ\ ha^{-1}$, reaching an efficiency of 5.2 $GJ\ GJ^{-1}$, and then

Table 4 – Regression equations of RCG dry matter (DM) yield (Y, Mg ha^{-1}), net energy yield (NEY, GJ ha^{-1}) and energy use efficiency (EUE, GJ GJ^{-1}) with explanatory variables N application (kg ha^{-1}) or energy input (GJ ha^{-1}).

Dependent factor	Independent factors, x_1: N application (kg ha^{-1}); x_2: energy input (GJ ha^{-1})	
	Equation	R^2
Haplic Albeluvisol		
DM yield (Y)	$Y = -0.00005x_1^2 + 0.0359x_1 + 2.5758$	0.87
Net energy yield (NEY)	$NEY = -0.364x_2^2 + 13.304x_2 - 44.572$	0.99
Energy use efficiency (EUE)	$EUE = -0.0334x_2^2 + 0.8504x_2 - 0.1863$	0.99
Fluvic Histosol		
DM yield (Y)	$Y = -0.000003x_1^2 + 0.0073x_1 + 5.2375$	0.45
Net energy yield (NEY)	$NEY = -0.017x_2^2 + 1.213x_2 + 37.749$	0.99
Energy use efficiency (EUE)	$EUE = 34.191x_2^{-0.844}$	0.99
Eutric Histosol		
DM yield (Y)	$Y = -0.00001x_1^2 + 0.0119x_1 + 5.8089$	0.39
Net energy yield (NEY)	$NEY = -0.049x_2^2 + 2.135x_2 + 43.260$	0.89
Energy use efficiency (EUE)	$EUE = 46.169x_2^{-0.895}$	0.99

decreases to a level of 4.1 GJ GJ^{-1} with the highest energy input. To reach the optimum EUE level, nitrogen fertiliser inputs should be 198 kg ha^{-1}.

On Fluvic Histosol, the average NEY increases continuously from 45 GJ ha^{-1} in unfertilised plots to 59 GJ ha^{-1} with an energy input requirement of 30 GJ ha^{-1}. NEY efficiency decreases from 1 to 0.2 GJ GJ^{-1} EI^{-1} at input levels of 6 to 30 GJ ha^{-1}, respectively. The average NEY on unfertilised plots of Eutric Histosol is 53 GJ ha^{-1}. Land use efficiency increases with increased energy input to 66 GJ ha^{-1} with the input requirement of 22 GJ ha^{-1} and then decreases to 63 GJ ha^{-1}. RCG EUE decreases with increasing energy input in both Fluvic Histosol and Eutric Histosol. At input levels of 6–31 GJ ha^{-1}, EUE decreases from 7 to 2 GJ GJ^{-1} on Fluvic Histosol and from 9 to 2 GJ GJ^{-1} on Eutric Histosol.

3.4. *The potential yield and energy use efficiency of RCG in Tartu County*

The total agricultural area in Tartu County is 103,166 ha. Although 81% (83,564 ha) is capable of producing an average RCG yield (Pr = 50%) without fertilisation below 4 Mg ha^{-1}, approximately half of this area has the potential to produce yields within 2–3 Mg ha^{-1} (Fig. 4). The majority of the lower levels of biomass production are formed in the southern part of the county. RCG annual DM yields of 4–6 Mg ha^{-1} are achievable in a limited number of fields. Applying 100 kg N ha^{-1} in Tartu County agricultural areas results in yields of 5.5–6.5 Mg ha^{-1} in nearly 90% of the area, and the yield potential of 9% of the area is 6.5–7 Mg ha^{-1}.

The NEY and EUE increase with increasing biomass production. From the total agricultural areas in Tartu County, the NEY and EUE potentials of 65% of the area are 26 GJ ha^{-1} and 9 GJ GJ^{-1}, respectively, if 40% RCG winter losses are taken into account. The maximum EUE (17 GJ GJ^{-1}) without fertilisation could be achieved in 9% of the agricultural areas. Although applying 100 kg N ha^{-1} results in the RCG yield increasing to 4.5 Mg ha^{-1}, the average EUE decreases to 55% of the maximum efficiency of the unfertilised areas.

4. Discussion

The knowledge of biomass potential and its variability over several years contributes to assessing the risks in agricultural production. In bio-energy production, high biomass yields and minor yield variability are essential. As RCG biomass yields in Estonian conditions on soils with low Ntot content can be as low as 1 Mg ha^{-1} in unfavourable years for plant growth, soil-specific bio-energy planning is essential. Studies such as those by Kukk et al. [32] indicate the importance of bio-energy production from abandoned agricultural areas, as these areas do not affect food self-sufficiency. In their study [32], they showed that swaths of Albeluvisols and Histosols in abandoned areas account for twice the area of land in use that is composed of these two soils, and Fluvisols in abandoned land equate to nearly 23 times this soil's aggregate land-use area. Therefore, planning biomass crop cultivation on abandoned fields requires complex bio-energy analysis that can be used for evaluating agronomic potential.

Contrary to low yields, the potential of 6–7 Mg DM ha^{-1} from unfertilised areas could be achieved on soils with a high soil N content in suitable weather conditions for plant growth. The yield potential of soils with a N content of more than 1% is higher than 5 Mg DM ha^{-1} in most years. Therefore, high RCG biomass potential is achievable from areas with a sufficient soil N supply. The results of the yield analysis of this study are applicable in cases when RCG P and K requirements are guaranteed. The rates of mineral P and K applied in the field experiments were comparable and non-limiting factors in RCG yield formation. This aspect is particularly important in high-yield production on Histosols, which commonly have low P and K content [33].

Research evaluating RCG yields dependent on site-specific characteristics has not been reported. Previous research on bio-energy crop yield modelling (e.g., Miscanthus) considered meteorological variables and soil available water [29,30]. Richter et al. [29] argued that more detailed soil variability should be considered in yield analysis through its effect on water availability. Price et al. [30] analysed the dependence of

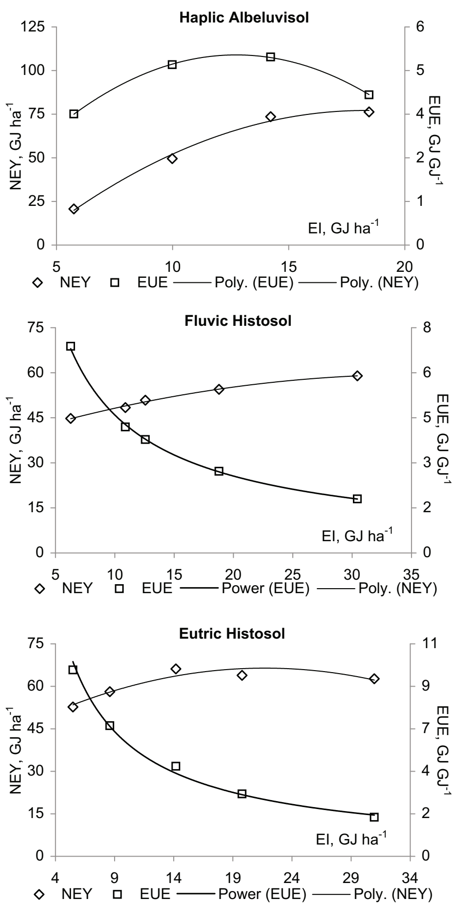

Fig. 3 – RCG NEY (GJ ha^{-1}) and EUE (GJ GJ^{-1}) on Haplic Albeluvisol, Fluvic Histosol and Eutric Histosol dependent on energy input.

perennial grass yield variability on weather conditions over a 30-year period, and their work emphasised the importance of considering climatic risk in biomass yield analysis. As Richter et al. [29] have indicated the importance of yield analysis through its effect on water availability, further studies should be conducted to clarify the effect of soil moisture regimes on RCG yield. High biomass data used for RCG yield modelling in the current study were achieved on soils that had high soil N content and available water capacity. Therefore, we can infer that these soils also had sufficient water supply in the majority of the growing years.

Although soil N content enables us to evaluate soil potential in yield production, the availability of N for plants depends on its mineralisation rate. Mineralisation of N depends significantly on soil type and on aeration status [34]. Updegraff et al. [35] demonstrated the effect of aeration on N mineralisation in peat soil (e.g., Histosol). Bridgham et al. [34] emphasised evaluating N mineralisation per unit of soil volume, not per mass of dry soil, and proved that higher N mineralisation occurs in more minerotrophic than ombrotrophic peatlands. In crop production, N mineralisation rates in minerotrophic fen soils exceed the mineralisation rates in automorphic soils [36]. Based on this, we can conclude that Fluvic and Eutric Histosols, which have a high soil N content (>2% in the current study), also have the potential for high N mineralisation and could, therefore, produce sufficient available N for plant production. Furthermore, the overview by Höper [36] indicated that mineralised N in fen soils could even exceed the N uptake by field plants. Hence, to prevent excessive N mineralisation, sustainable usage of Histosols should be considered. Kõlli et al. [37] found that among other soil protection aspects, sustainable usage of drained peat soils includes perennial grasslands but not annual crop production. Therefore, the usage of peat soils should also be considered for sustainable management, although mineralised N could be sufficient for crop production without applying N fertilisers.

Although knowledge about soil potential in yield production is essential, the awareness of risk management in applying fertilisers forms the basis of complex bio-energy production evaluation. Studies, by Lewandowski and Schmidt [14], for example, have modelled NUE, which considers both soil N and N fertiliser application in analysing the yield per unit of N supplied. Studies of N fertiliser efficiency in bio-energy production are rather rare, especially in RCG production, and have not been performed in the context of soil N content and climatic conditions. Nevertheless, there are different approaches in analysing fertilisation efficiency. For example, Zhang and Tillman [38] modelled nitrogen fertiliser use efficiency in pasture production using a decision tree approach.

The application of the efficiency model in the current study indicated that fertilisation efficiency decreases with increasing mineral nitrogen rates, in agreement with the results of Zhang and Tillman [38]. Furthermore, a non-linear relationship in nitrogen fertiliser use efficiency and N application rate occurred [38]. Hermanson et al. [39] found that a decrease in the incremental yield increase per unit of N input with increasing N supply is explained by Mitscherlich's Law. As a result, NUE invariably decreases at high levels of N input [39]. The N fertilisation efficiency model in the current study indicated that the increase in mineral N application rate results in increased variation of fertilisation efficiency. Furthermore, N fertilisation efficiency decreases and efficiency variability increases with increasing soil N content.

Yield analyses indicated that fertilisation increases the yield and decreases the variability in humus-poor soils. The variation coefficient in unfertilised plots exceeds the variation in the areas with increased fertiliser input, which validates the argument that higher levels of soil nutrient supply in areas with low soil nitrogen and low humus content leads to more stable RCG yields. Therefore, planning RCG plantation on soils with low N content requires increased fertiliser input for achieving high yields with minor variability. The results of the current study prove that previously estimated high RCG yields (7–8 Mg ha^{-1} on clay soils in Finland) [3] could be reached on

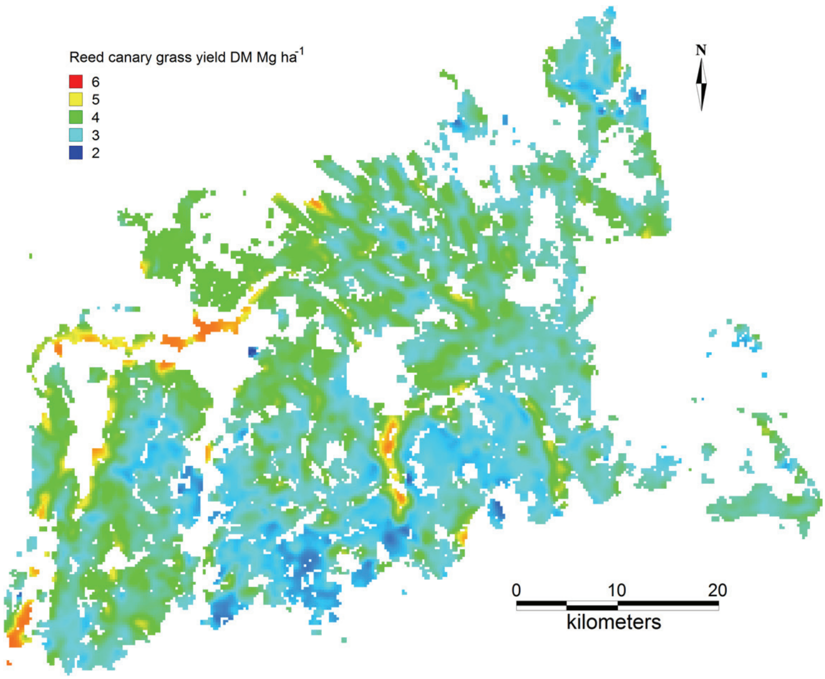

Fig. 4 – The average (Pr = 50%) modelled RCG DM yield (Mg ha^{-1}) without fertilisation in Tartu County.

soils with low humus content using fertilisers at more than 200 kg ha^{-1}, in which case, the environmental restrictions should also be taken into account. In the instance of soils with low humus content, the use of high levels of fertiliser ($N_{200}P_{35}K_{130}$) can result in a DM yield of 8 Mg ha^{-1}. Lowering the fertilisation norm by a factor of 1.5–3 can result in the same DM yield (8 Mg ha^{-1}) on histic soils and Histosols [40,41]. Furthermore, the current study proved that production risks on soils with high humus content increase with increasing N fertiliser application norms. As natural waterlogged peatlands are considered to be reservoirs of C and N [42], drainage for crop production may lead not only to increased mineralisation [35] but also to elevated N_2O emissions [43]. Organic soils are therefore potential targets in evaluating measures to mitigate greenhouse gas emissions from agriculture [44]. Hence, we can assume that N fertilisation of peat soils could even increase N_2O emission. Augustin et al. [45] concluded that N fertilisation in minerotrophic fen stimulates N_2O release with very high N applications (480 kg ha^{-1}), but with low and moderate N supplies (60 and 120 kg ha^{-1}), only a slight increase occurs. Therefore, rather low N fertilisation in peat grassland is advised for reducing N_2O emission [45]. Furthermore, Hyvönen et al. [46] indicated that perennial bio-energy crop (e.g., RCG) production on some organic soils, such as peat extraction sites, is possible without high N_2O emissions. As the emission of N_2O also depends on ground water tables, temperatures and other variables [43], complex analysis of greenhouse gas emissions on different organic soils should be performed.

In the RCG biomass yield analysis, we did not take into account winter losses because soil potential and additional fertilisation in biomass production form the basic framework for further analysis. Winter yield losses are considered in the RCG energy evaluation, as EUE, which describes production and environmental impact, is also an important criterion for evaluating energy crop suitability in bio-energy production.

Studies have indicated that the output of EUE varies between cultures [14] and cropping systems [15], while the efficiency decreases continuously with increasing energy input. Our analysis of the efficiency in RCG production verifies an efficiency decrease on Histosols, but on humus-poor soils, a quadratic curve relationship between energy input and EUE occurs. Therefore, the current study provides the first evidence of an EUE curve dependent on soil N content in RCG production. The difference of efficiencies could be explained with the lower N fertilisation efficiency on soils with a higher soil N content. Although EUE minimum values of 2 GJ GJ^{-1} using an input level of 31 GJ ha^{-1} on Histosols indicates double NEY values of applied input, the outcome also forces us to consider environmental restrictions and effective energy usage. As the current study evaluated RCG energy use efficiency in biomass direct combustion, EUE could differ using biomass management alternatives. In general, Hetz and Sonesson [47] concluded that RCG EUE in direct combustion systems is relatively high compared with integrated gasification.

Knowledge-based bio-energy production presumes land use decisions made on as detailed a scale as possible. Detailed soil information can be converted using models containing soil-specific characteristics. The combined databases of previous RCG field experiments enabled us to perform yield models dependent on soil N content and fertilisation. The integration of the models with the Estonian large-scale soil database contributes to assessing the agronomic and environmental risks in the selected area. In bio-energy potential GIS evaluations, previous studies have used small-scale soil databases [7,48], but planning decisions should follow a more bottom-up approach. Although detailed soil GIS analyses have been performed [12], scaling up the results for a region is rare. Förster et al. [12] used comparative analysis of site-optimised suitability and conventional suitability to evaluate biomass yield for three example biomass crops. Site-optimised suitability analyses took into account such soil parameters as moisture, depth and cation exchange capacity for evaluating bio-energy crop requirements and the suitability of various soils. Our analysis of RCG modelled yields in Tartu County, which depended on soil nitrogen content and fertilisation, calculated the average yield potential in the region. The regional analysis indicated that the yield potential of cultivating RCG as a bio-energy crop in Tartu County without fertilisation was less than 4 Mg ha^{-1} on average (probability 50%) in the majority of the region. A higher biomass potential was predicted in the region along the banks of the largest river (Emajõgi) in Tartu County. We can assume that these areas are being submerged by springs. Kõlli et al. [37] suggested that either surface or ground water or both could cause the paludification of mineral lands on low wetlands areas. Gorham [49] indicated that high organic matter soils are formed under permanently waterlogged conditions. Therefore, we can conclude that higher RCG biomass yields in this area are site-specific and achievable on the basis of accumulated soil organic matter and, consequently, higher soil N content.

A site-specific approach to biomass production that takes into account pedoclimatic conditions forces planners to consider low biomass yields without fertilisation. In addition, producers have to account for winter losses in delayed harvests in the spring because losses occur in perennial bio-energy crop production [3,5,50]. Studies have estimated RCG winter losses to be 15–30% [9,51], but it may be as high as 50–60% [6]. Winter losses of 40% results in yields of less than 2 Mg ha^{-1} (probability 50%) in 65% of agricultural fields in Tartu County, and yield potentials of 3.0–3.5 Mg ha^{-1} are reached only in 9% of the area. By comparison, a spring harvest with 60% of losses results in yields of less than 2.5 Mg ha^{-1} throughout the county's agricultural areas. Therefore, an analysis of energy crops' winter losses must take into account local pedoclimatic conditions. As RCG yields of 3.0–4.0 Mg ha^{-1} (including 40% winter losses) could be achieved in the majority of the region by applying 100 kg N ha^{-1}, the current analysis verifies that intensive N fertilisation decreases production dependence on soil properties.

Energy efficiency analyses have indicated that the EUE of solid fuel crops grown in Europe vary from 14 to 30 GJ GJ^{-1} [52], whereas the RCG energy ratio ranges from 14 GJ GJ^{-1} [52] to 20 GJ GJ^{-1} [27]. Based on our results, where the EUE potential in 65% of Tartu County's agricultural areas is 9 GJ GJ^{-1}, and in a number of limited fields, it is 17 GJ GJ^{-1}, we conclude that production efficiency should be assessed locally. The values of energy and land use efficiency could differ between years, however the current example used the average yield and did not take into account biomass variability. Additionally, as the current study used a fixed input of 3 GJ ha^{-1}, further analysis is required to take into account detailed location-specific information and consider the plantation distance from the site of production to the power plant. This last issue is particularly important, as Hetz and Sonesson [47] concluded that bale handling and transportation is the most energy expensive operation in RCG production system.

Although the current analysis evaluated RCG's suitability in Tartu County's agricultural areas, the methodology can be easily applied nationwide as soil information is available for the entire country, and the models performed in this study are applicable in RCG-planning processes. Bio-energy production evaluations from the field level to the regional level form the basis of sustainable bio-energy planning. In addition to the analysis presented here of the biomass agronomic potential, further studies are necessary to understand the economic and environmental factors contributing to knowledge-based bio-energy production.

5. Conclusion

Long-term field experiment data are a valuable resource for yield modelling. The output of this analysis contributes to risk assessment in agriculture and provides a foundation for knowledge-based decision making. The RCG yield model of soil productivity in biomass production in the current study enables researchers to evaluate yield potential in an unfertilised management strategy. As RCG biomass potential without mineral N application is not achieved on soils with a low soil N content, producing high yields with minor variability in these areas requires increased fertiliser input. Yield variability increases on soils with a high soil N content and decreases on soils with a low humus content. Therefore, the mineral N application norm in RCG biomass production should not be generalised but assessed in a soil-specific manner. As biomass is the basis of evaluating production energy output, RCG bio-energy efficiency differs between soils with varying soil N content. Our yield and energy use efficiency analyses in relation to soil-specific characteristics allows for evaluation of the region's biomass potential using a bottom-up approach. Considering the availability of large-scale soil information covering the whole of Estonia, the country's actual site-specific bio-energy potential could be assessed. Therefore, the outcome of this study contributes to knowledge-based RCG biomass production evaluation.

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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.

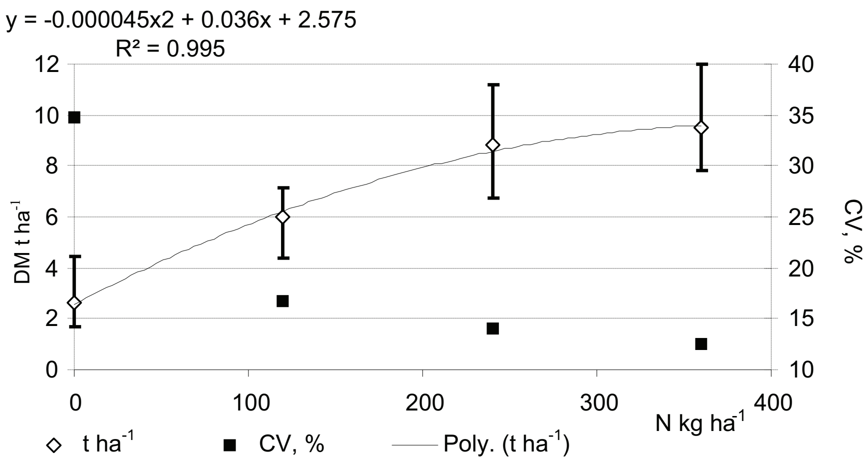

Fig. 1. Dependence of reed canary grass DM yield (t ha^{-1}) and variation coefficient on applied mineral nitrogen rates. Error bars indicate maximum and minimum values.

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.

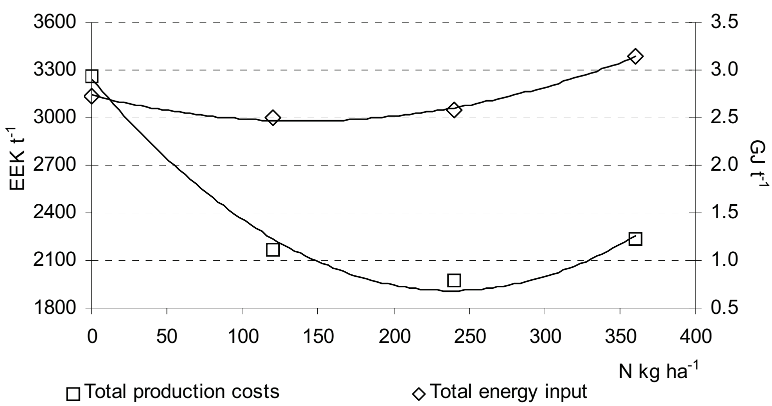

Fig. 2. Dependence of reed canary grass DM production net cost (EEK t^{-1}) and energy input (GJ t^{-1}) on applied mineral nitrogen rates.

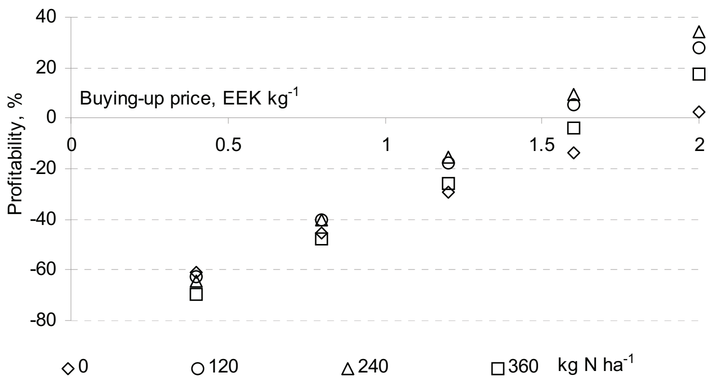

Fig. 3. Dependence of reed canary grass production profitability on applied mineral nitrogen rates and buying-up price (EEK kg^{-1}).

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.

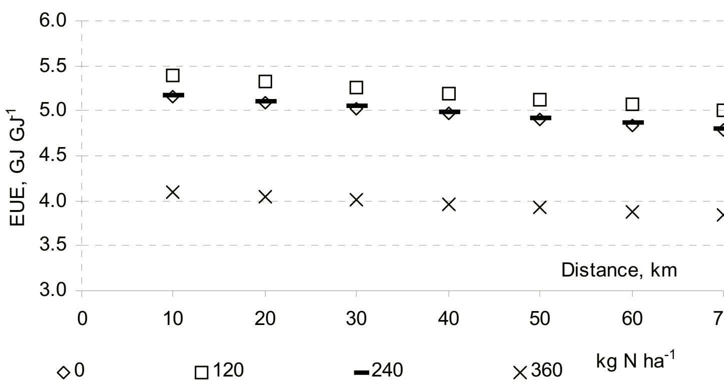

Fig. 4. Dependence of reed canary grass energy use efficiency (EUE) on applied mineral nitrogen rates and transportation distance.

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.

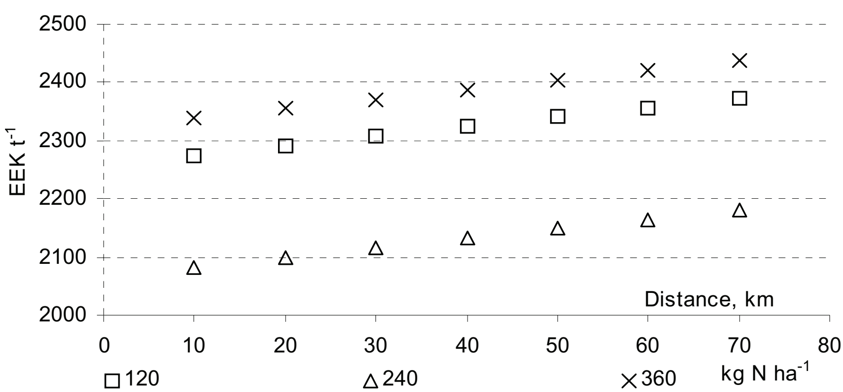

Fig. 5. Dependence of reed canary grass DM net cost (EEK t^{-1}) on applied mineral nitrogen rates and transportation distance.

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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IV

Alaru, M., **Kukk, L.**, Olt, J., Menind, A., Lauk, R., Vollmer, E., Astover, A. 2011. LIGNIN CONTENT AND BRIQUETTE QUALITY OF DIFFERENT FIBRE HEMP PLANT TYPES AND ENERGY SUNFLOWER. Field Crops Research 124(3):332–339.

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Lignin content and briquette quality of different fibre hemp plant types and energy sunflower

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ABSTRACT

Fibre hemp and energy sunflower are potential energy crops for production of solid biomass as renewable energy. The current study estimated (i) the lignin content of fibre hemp and energy sunflower plants grown on different nitrogen treatments and (ii) the quality of the briquettes made from different plant types of fibre hemp (i.e. monoecious and dioecious), energy sunflower and the combination of fibre hemp and energy sunflower. The monoecious and dioecious fibre hemp cultivars (Chameleon, Finola and Santhica-27, USO-31, respectively) and the energy sunflower cultivar Wielkopolski were grown in the experimental field in 2008–2010 on Stagnic Luvisol soil. The plants were grown on N treatments of N0, mineral nitrogen (100 kg N ha^{-1}), cattle slurry (100 kg N ha^{-1}), sewage sludge (100 kg N ha^{-1}) and vetch (100 kg N ha^{-1}). Calorific values (16.6–17.4 MJ kg^{-1}) of briquettes pressed from different materials did not differ significantly and had relatively low sulphur (<0.05%) and chlorine content (0.03–0.37%). Briquettes with higher compactness were made from the sunflower and the dioecious hemp. Dioecious hemp had significantly higher lignin content. The dioecious hemp needs lower GDD values for maturating, its stems lignin content was higher than of monoecious hemp by harvest time and therefore this plant type is more suitable for briquetting in Nordic climatic conditions. Comparison of the different N treatments indicated that application of sewage sludge decreased the emergence and density of the fibre hemp plants and the lignin content per kg of DM.

1. Introduction

Energy production from biomass is being increasingly promoted as an alternative resource and as a substitute for fossil fuels. At present in Estonia, and as well as in Finland, the major part of bioenergy is produced from wood. According to the data of Roostalu et al. (2008) over 283,000 ha of agricultural land in Estonia is currently unused which is the potential land resource for energy crops cultivation without having negative effect to food self-sufficiency. Several studies have analysed bioenergy potential in a region (Kukk et al., 2010; Voivontas et al., 2001). For example, Kukk et al. (2010) performed soil-suitability analysis to evaluate energy potential of selected energy crops on abandoned agricultural areas in Tartu County in Estonia.

Fibre hemp (*Cannabis sativa* L.) and energy sunflower (*Helianthus annuus* L.) produce high above ground biomass yield and are low-intensive crops to cultivate (Gill and Vear, 1980; Lauk et al., 2009; Zimdahl, 2004). They suppress weeds well and are so fast growing that they do not require any kind of herbicide treatment (Gill and Vear, 1980; Zimdahl, 2004). Hemp grows well under natural conditions and does not require excessive use of outgoings (Ranalli, 1999; Saxena et al., 1999). Fibrous hemp is a plant that easily adapts to new vegetation conditions and is characterized by a rich diversity of forms. It is a phytosanitary plant, which makes possible its introduction into a variety of crop rotations. Hemp generates about 10–15 t of biomass (dry matter) per hectare and it is estimated that 1 ha of hemp absorbs about 2.5 t CO_2, which results in a significant reduction of the greenhouse effect (Mankowski and Kolodziej, 2008).

Sunflower, being one of the major oil crops cultivated worldwide, is considered also as an energy crop. Sunflower expresses a higher photosynthesis rate than other C_3 plants and grows rapidly to achieve a high biomass yield, up to 19 t ha^{-1} in dry matter in wide range of environments, from the equator to 55 N latitude (Hu, 2008).

Several studies have estimated the suitability of sewage sludge as an organic fertiliser (Christodoulakis and Margaris, 1996; Richards et al., 1998). It is rich in organic matter, macroelements (N, P, K, Mg, S) and other microelements necessary for both plants and

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soil fauna (Kosobucki et al., 2000). However, the levels of heavy metals found in sewage sludge are considerably higher than in typical agricultural land (Delgado et al., 2002; Sloan et al., 1998). Some toxic metals trace elements from sewage sludge can be stored in plants and contaminate the food chain (Adriano, 2001; Juste and Mench, 1992; Rulkens, 2008; Wenzel et al., 1999). Aggelides and Londra (2000) confirmed that sludge application improved the physical, chemical and biological properties of the soil. However, it is not well known, how the application of sewage sludge affects the soil–crop interaction, fibre hemp and sunflower plants emergence, above ground biomass and the lignin content formation. The amount of lignin per kg of dry matter (DM) is very important in briquetting (Kers et al., 2010; Mankowski and Kolodziej, 2008).

Hemp and sunflower are considered to be phytoextracting plants (Angelova et al., 2004; Gang and Weixing, 1998; Teerakun and Reungsang, 2005; Van der Werf, 2004); they can absorb heavy metals and toxic elements from the soil. The heavy metal concentration in plants does not limit their use in briquette production as bioenergy resources. Additionally, heavy metals immobilized in the ash can be used later in Portland cement production (Rulkens, 2008).

El Saeidy (2004) indicates that hemp and sunflower are suitable for briquetting and using as a solid fuel as well as briquettes made from rape, meadow and wheat straw or, for example, poplar wood. Pressed fuels of herbaceous origin have many advantages over the unprocessed herbaceous mass. Dry fuel will not decompose biologically because of fungi and microorganisms and can therefore be preserved for a long time. Also the pressed herbaceous material is cheaper to transport and store because of low humidity and high calorific value. Equable moisture content and size of the piece allows regulating the burning regime in the heating appliance more precisely and ensures higher efficiency (Olt and Laur, 2009). Briquettes are made by compression of dry waste materials. No chemical additives are used in the production process. Shives get stuck together as a result of high pressure and temperature. The cellular structures within the material release lignin, which binds individual particles into a compact unit-briquette (Kers et al., 2010; Mankowski and Kolodziej, 2008).

The aims of this study were to investigate (i) the lignin content of fibre hemp and energy sunflower plants grown on different nitrogen (N) treatments and (ii) the quality of the briquettes made from different plant types of fibre hemp (i.e. monoecious and dioecious), energy sunflower and the combination of fibre hemp and energy sunflower. Specific attention is paid to the impact of different nitrogen resources on the emergence and density of plants.

2. Materials and methods

2.1. *The field trial and experimental details*

To investigate the suitability for bioenergy production of monoecious and dioecious fibre hemp cultivars (cv) and one energy sunflower cultivar, a long-term field trial was established in 2008 at the Institute of Agricultural and Environmental Sciences of Estonian University of Life Sciences, near Tartu (58° 23′N, 26° 44′E), Estonia, on Stagnic Luvisol (WRB 1998 classification) soil (sandy loam surface texture, Corg 1.12%, and N_{tot} 0.12%, pH_{KCl} 5.6). The plants were grown on different N treatments: N_0 (without N), N_{100} (mineral N fertiliser NH_4NO_3), municipal sewage sludge from Tartu, vetch (cv Carolina) and cattle slurry (slurry). The applied amount of N_{tot} for all treatments (with the exeption of N_0 treatment) was 100 kg N ha^{-1}. The sowing rate of hemp, sunflower and vetch cultivars was 200, 25 and 60 viable seeds m^{-2}, respectively. Vetch was sown at the same time as the hemp and sunflower seeds. Dioecious and monoecious

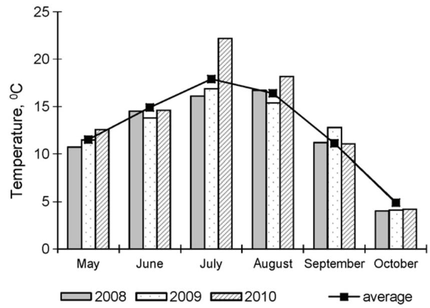

Fig. 1. Average temperature (°C) during vegetation period in 2008–2010.

hemp cultivars used in the field study were Chameleon, Finola and Santhica-27, USO-31, respectively. Sunflower cultivar in the trial was Wielkopolski. This paper presents data from 2008 to 2010. Cv Chameleon was used in 2008–2009, cv Finola in 2010, cv Santhica-27 in 2009 and cv USO-31 in 2008 and 2010, cv Wielkopolski in 2009 and 2010.

Seeds were sown with plot drill (Wintersteiger) on 20, 19 and 22 of May in 2008, 2009 and 2010, respectively, to a depth of 3–5 cm, with 15-cm between rows. The experiments were performed in a randomized complete block design with four replications; plot size was 13 m^2. Fertilisers were applied once: the sewage sludge and slurry were applied and incorporated into the soil prior to sowing, mineral N fertiliser (NH_4NO_3) was applied by hand after plant emergence (on 6 June 2008, 2 June 2009 and 9 June 2010). The sewage sludge was applied to the same plot in 2008 and in 2010, but, in 2009, the sludge was applied to an adjacent plot. According to earlier studies, the 60 viable seeds per m^2 of vetch were considered equivalent to application of 100 kg mineral N ha^{-1} (Lauk and Lauk, 2006; Lauk et al., 2007). During the vegetation period no pesticides were applied or mechanical or manual weeding done.

Meteorological data were collected from automatically working meteorological station approximately 2 km from trial site. The temperature and precipitation data of 2008 and 2009 were similar to the long-term average (Figs. 1 and 2).

In 2010 the temperature was higher than usual (in July the temperature was 5.1 °C higher than long-term average) but total precipitation in the growth period (May–August) was similar to the long-term average of being 277 mm, i.e. 10 mm lower than normal. Growing Degree Days (GDD) – base temperature 5 °C, from sowing date to the harvest time was as follows: 1130 GDD in 2008, 1228

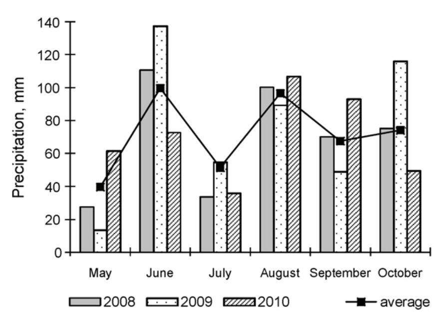

Fig. 2. Precipitation (mm) during vegetation period in 2008–2010.

Table 1
The chemical composition of sewage sludge and slurry in 2008–2010.

	Sludge			Slurry		
	2008	2009	2010	2008	2009	2010
DM[a] %	18.2	22.4	18.6	6.6	6.6	9.1
pH_{KCl}	6.8	5.8	6.4	6.3	7.2	6.8
N_{tot} %	5.2	4.2	4.9	4.5	3.8	2.8
P_{tot} %	1.9	1.2	1.6	0.9	0.8	0.7
K_{tot} %	0.4	0.6	0.7	3.2	1.3	2.6
C %	31.8	32.4	33.1	37.5	37.1	34.7

[a] DM – dry matter; N_{tot} – total nitrogen; P_{tot} – total phosphorus; K_{tot} – total potassium.

GDD in 2009 and 1239 GDD in 2010. Vegetative period (mean temperature below 5 °C for at least 3 day) ended at 5th November in 2008, 8th October in 2009 and 7th October in 2010. The vegetative period starts in Estonia usually in the last week of April or in the first week of May. The GDD of long term average for vegetative period in Estonia is 1259. The results of chemical analyses from the sewage sludge and slurry are presented in Table 1.

Plant emergence from 1.0 m^2 of each experimental plot with 4 replications was determined on 6, 8 and 9 June in 2008, 2009 and 2010, respectively. Above ground biomass was harvested by hand and measured on 11 and 18 September and 23 August 2008, 2009 and 2010, respectively. By harvest time the dioecious hemp cultivars were in matured stage and monoecious hemp cultivars in late waxy dough stage in all trial years. Sunflower cultivar Wielkopolski were in 2009 in matured stage and in 2010 in late waxy dough stage; plants grown on sewage sludge treatment were in matured stage. The weight and height of plants from these biomass samples were also determined. The dry matter (DM) content in energy crops was determined; the above ground biomass yield g m^{-2} was calculated. The soil bulk density was determined twice a year – before sewage sludge application and after harvesting. Samples for the briquetting were taken at the end of September in 2009 and 2010.

2.2. Chemical analyses and briquetting

Acid digestion by sulphuric acid solution (Methods of Soil, 1986) was used to determine P and K total content in sewage sludge and slurry. After the digestion, the content of total phosphorus (P_{tot}) was determined colorimetrically (spectrometer Jenway 6300; UK). Total potassium (K_{tot}) content was determined by flame photometry (Jenway PFP7; Bibby Scientific Ltd., UK). Total nitrogen (N_{tot}) content of oven-dried samples was determined by the dry combustion method on a varioMAX CNS elemental analyzer (ELEMENTAR, Germany). Crude fat in sunflower plant samples was determined with analyzer Soxtec 2043 (FOSS Tecator Technology). The percentage of lignin in the DM of different cultivar samples was determined in the Plant Biochemical Laboratory of The Estonian University of Life Sciences (Tecator ASN 3430; AOAC, 1990).

Briquettes were made from the above ground biomass of fibre hemp (i.e. monoecious and dioecious), energy sunflower and also the combination of dioecious fibre hemp and energy sunflower. The material for briquetting was taken from the above ground biomass (whole plant mass containing seeds) grown in 2009 and 2010 and was gathered in both years as a mean from the different N treatments, that is, we did not evaluate briquette quality separately on N_0, mineral nitrogen, slurry, sewage sludge or vetch treatments. Briquettes were made at the Institute of Technology of Estonian University of Life Sciences using screw type of briquetting machine.

The samples of hemp and sunflower were ground with Cutting Mill SM 100 comfort (Retsch GmbH) and pressed into briquette without sifting. For analyzing hemp and sunflower briquettes' ash fusibility behaviour, upper limit of calorific value of dry mass and lower limit of calorific value of material for consumption the Cutting Mill SM 100 comfort (Retsch GmbH) with screen and Cutting Mill ZM 200 (Retsch GmbH) was used.

Ground hemp and sunflower plants were pressed into briquettes. The following processes are involved in the briquetting/pressing:

1. Pressure is applied to the briquetting material.
2. Temperature rises because of friction between the particles of the briquetting materials and friction between the press and briquetting materials.
3. As a result of the high temperature and pressure during the process, the wooden plant cellular structure breaks.
4. Because of the heat the lignin contained in the material softens and glues the particles of the material together.

Biomasser BS06 briquetting device was used for the experiments. This device is a screw press meant for briquetting thatch and hay. The productivity of the device during the experiment was Q = 39.0–52.9 kg h^{-1}. The length of cooler-stabilizer was L = 3000 mm. The briquette produced by this device was of random length and diameter D = 70 mm. Analysis of the briquettes was done by the Fuel Analysis Laboratory and methods used for determination of different briquette characteristics were: moisture content (%) of the briquettes were determined by CEN/TS 14774, ash content in DM by CEN/TS 14775, volatiles (%) by CEN/TS 15148, sulphur in DM (%) by ISO 334, chlorine in DM by ISO 587, calorific value in DM and actual (MJ kg^{-1}) by CEN/TS 14918 and characterization of ash behaviour by CEN/TS 15370.

2.3. Statistical analyses

The trial data were processed using Pearson's correlation, variance analyses (ANOVA) and descriptive statistics. Normal distribution assumptions were checked using the Shapiro-Wilk normality test. Tukey test was used as a post hoc test of significance differences between means. The means are presented with their standard errors (±S.E.). Significance is presented with $P < 0.05$ if not indicated otherwise. Statistical analyses were carried out using the statistical software R version 2.6.1 (R Development Core Team, 2011).

3. Results

3.1. The emergence of fibre hemp and energy sunflower

The emergence of hemp plants in the field was generally low (Table 2); depending on N treatments and trial year that of cultivars Chameleon, Finola, Santhica-27 and USO-31 fluctuated between 49–96%, 14–34%, 22–46% and 21–72%, respectively.

The emergence of fibre hemp was significantly influenced by cultivar, N treatment, plant type and year with the proportion of variation 50%, 11%, 10% and 9%, respectively ($P < 0.001$ for all fac-

Table 2
Mean (±S.E.) emergence of hemp and sunflower (piece m^{-2}) over cultivars and trial years.

Treatment	Hemp		Sunflower
	Dioecious	Monoecious	
N0	102 ± 16 a[a]	90 ± 12 a	22 ± 4 a
N100	123 ± 17 a	92 ± 15 a	22 ± 2 a
Sludge	84 ± 17 a	39 ± 3 b	20 ± 4 a
Vetch	112 ± 22 a	77 ± 16 a	20 ± 2 a
Slurry	111 ± 18 a	70 ± 13 a	19 ± 4 a

[a] Different letters in the columns note significant differences between treatments.

tors). The emergence of dioecious hemp plants over trial years and N treatments was 16% higher than of monoecious hemp plants.

Sewage sludge treatment had the most deleterious effect on emergence of hemp plants resulting in the lowest plant density; emergence as an average of trial years and cultivars was 31%, whereas for the other treatments the same data fluctuated between 45 and 65%. Soil bulk density of the sewage sludge treatment was 1.68 ± 0.03 g cm^{-3} being 0.11–0.22 g cm^{-3} higher than the other N treatments. By contrast, emergence of energy sunflower plants was, in 2009, the best in sewage sludge treatment, significantly better than on vetch and slurry treatments. However, in 2010, the emergence of sunflower plants did not differ significantly between treatments.

3.2. The weight and height of fibre hemp and energy sunflower

Fibre hemp plant weight and plant density per unit of area were influenced by emergence ($r = -0.43$; $P < 0.001$; Table 3). Additionally, plant weight was significantly influenced by N treatment and plant type with the proportion of variation 42% and 12%, respectively ($P < 0.001$). Plants weight was lowest in the treatment where their seeds were sown with vetch seeds. This was expected, because the plant density in this treatment was the highest. Plant weight was significantly higher in sewage sludge treatment, because emergence and plant density were the lowest in this treatment. Plant weight of monoecious hemp was higher than dioecious hemp in all trial years. The mean plant weight of monoecious hemp over N treatments in 2008, 2009 and 2010 was 10.4 ± 1.23, 7.90 ± 1.55 and 5.60 ± 1.49 g DM $plant^{-1}$, respectively; the same data for dioecious hemp was 6.4 ± 0.73, 3.60 ± 0.58 and 3.10 ± 0.94 g DM $plant^{-1}$, respectively.

Height of hemp plants was greatest on N_{100}, followed by sewage sludge and slurry treatments, with means of trial years and cultivars of 1.42 ± 0.07, 1.35 ± 0.007 and 1.29 ± 0.11 m, respectively. The shortest hemp plants were grown on the N_0 treatment, with a mean of trial years and cultivars of 0.83 ± 0.09 m. Energy sunflower plant height did not differ significantly over N treatments and trial years.

Table 3
Mean (±S.E.) weight per plant (g DM $plant^{-1}$) of hemp and sunflower over cultivars and trial years.

Treatment	Hemp		Sunflower
	Dioecious	Monoecious	
N0	2.7 ± 0.74 b[a]	4.4 ± 1.52 b	28.4 ± 12.90 b
N100	4.1 ± 0.85 a	8.1 ± 1.29 a	35.7 ± 9.40 b
Sludge	8.4 ± 0.76 a	15.2 ± 1.20 a	62.3 ± 21.80 a
Vetch	1.9 ± 0.54 b	3.6 ± 0.63 b	27.6 ± 2.95 b
Slurry	4.7 ± 1.09 a	8.4 ± 1.93 a	38.0 ± 0.60 b

[a] Different letters in the columns note significant differences between treatments.

Table 4
Mean (±S.E.) above ground biomass (g DM m^{-2}) of hemp and sunflower over cultivars and trial years.

Treatment	Hemp		Sunflower
	Dioecious	Monoecious	
N0	292 ± 49 b[a]	270 ± 53 b	557 ± 214 b
N100	546 ± 101 a	663 ± 66 a	735 ± 83 b
Sludge	640 ± 64 a	681 ± 57 a	1353 ± 631 a
Vetch	229 ± 29 b	274 ± 45 b	681 ± 11 b
Slurry	385 ± 55 a	364 ± 41 a	781 ± 48 b

[a] Different letters in the columns note significant differences between treatments.

3.3. The above ground biomass yield of fibre hemp and energy sunflower

The above ground biomass of hemp and sunflower was positively correlated with plant weight ($r = 0.64$, $P < 0.01$ for hemp; $r = 0.87$, $P < 0.01$ for sunflower). The above ground biomass of fibre hemp was significantly influenced by treatment, cultivar and year with the proportion of variation 46%, 26% and 3%, respectively ($P < 0.001$ for all factors; Table 4).

The above ground biomass of hemp plant types did not differ significantly. The more favorable treatments for fibre hemp and energy sunflower cultivars above ground biomass formation were sewage sludge and N_{100} treatment, followed by slurry. The mean above ground biomass of monoecious and dioecious hemp and energy sunflower over trial years and N treatments were 450 ± 36, 418 ± 36 and 821 ± 136 g m^{-2} in DM, respectively. The mean above ground biomass of hemp over trial years and plant types grown on sewage sludge treatment was 661 ± 42 g m^{-2} in DM, which was statistically the same with treatment N_{100} and 1.8 times higher than the above ground biomass of slurry treatment. The mean above ground biomass of sunflower over trial years grown on the sewage sludge treatment was 1353 ± 631 g m^{-2} in DM, which differed significantly only from the vetch treatment.

3.4. The lignin content of fibre hemp and energy sunflower

The lignin content of fibre hemp was significantly influenced by year, treatment and plant type with the proportion of variation 36%, 30% and 16% (Table 5). The influence of cultivar was not significant. Correlation analyses showed that the lignin content of hemp was significantly influenced also by emergence, i.e. by the density of plants ($r = 0.45$; $P < 0.05$).

The lignin content of the dioecious and monoecious hemp cultivars as a mean of N treatments was in 2008 8.93 ± 0.39, 7.99 ± 0.60%, in 2009 10.96 ± 0.37, 9.59 ± 0.30% and in 2010 10.31 ± 0.44, 9.53 ± 0.53%, respectively (Table 6). The mean lignin content of monoecious hemp over N treatments and trial years was 1.03% smaller in comparison with dioecious hemp. The lignin content of hemp stems over trial years and cultivars grown on sewage sludge treatment was 8.51 ± 0.36%, which was lower than of other N treatments and significantly lower from the hemp plants grown on slurry and N_{100} treatments.

Table 5
ANOVA mean squares for influence of the year, N treatment, plant type and cultivar on lignin content of hemp plants.

Source of variability	Degrees of freedom	Mean square	P-value
Year	2	9.210	<0.001
Treatment	4	3.797	0.006
Plant type	1	8.019	0.003
Variety	2	0.237	0.611
Year × treatment	8	0.619	0.334
Treatment × plant type	4	0.164	0.829
Error	8	0.452	

Table 6
Mean (±S.E.) lignin content (% in DM) of hemp and sunflower over cultivars and trial years.

Treatment	Hemp		Sunflower
	Dioecious	Monoecious	
N0	9.74 ± 0.35 ab[a]	8.83 ± 0.23 a	8.01 ± 0.18 a
N100	11.05 ± 0.89 a	9.54 ± 0.11 a	9.18 ± 1.25 a
Sludge	9.10 ± 0.69 b	7.92 ± 1.07 a	9.55 ± 0.72 a
Vetch	9.73 ± 0.77 ab	8.79 ± 0.91 a	9.67 ± 0.80 a
Slurry	10.73 ± 0.40 a	10.09 ± 0.63 a	9.06 ± 0.22 a

[a] Different letters in the columns note significant differences between treatments.

The lignin content of different cultivars was dependent on their development stage also ($P<0.05$). The mean lignin content of dioecious and monoecious hemp plants over trial years and N treatments was 10.1 ± 0.32 and 9.0 ± 0.31%, respectively. Dioecious hemp plants were in matured stage and monoecious hemp plants in late waxy stage by harvest time in all trial years. For example, Chameleon flowered in 2009 in all N treatments from 22 July until 20 August, cultivar Santhica-27 started to flower on 3 August and ceased flowering in early September. Therefore, the cultivar Chameleon seeds were mature by harvest (on 18 September) and stem lignin content was higher than in cultivar Santhica-27, in which seeds were at this time still in the waxy stage. The development rate of plants is dependent on accumulation rate of GDD. In 2008 and 2009 GDD was similar to the long-term average. Because of higher accumulation rate of GDD in 2010 (1484 GDD by the end of vegetation period) the monoecious hemp matured in this year by the end of September.

The mean lignin content of sunflower over N treatments and trial years was 9.09 ± 0.32% which did not differ significantly from the same data of hemp plant types. The lignin content of energy sunflower cultivar over trial years grown on sewage sludge treatment was 9.55 ± 0.72%. The lignin content of sunflower was not influenced significantly by trial year and N treatment. N treatment influenced significantly the development rate of sunflower whereas the development rate of sunflower plants grown on sewage sludge treatment was higher compared with other N treatments. Sunflower started to flower in 2009 and 2010 in the sewage sludge treatment on 28 and 26 July, respectively, followed by slurry treatment (on 11 and 2 August, respectively). The last to flower were the sunflower plants in the N_0 treatment (on 17 and 9 August, respectively).

3.5. *The briquette quality of fibre hemp and energy sunflower*

The highest calorific value in dry matter was in the briquette samples from sunflower (17.07–17.37 MJ kg^{-1}); these also had the lowest moisture content of 5.9–6.2% (Table 7). The moisture content of other briquette samples fluctuated between 6.5 and 6.8%. Briquettes made from dioecious and monoecious type of hemp had slightly lower calorific values of 16.60–16.74 MJ kg^{-1} and 16.56–16.64 MJ kg^{-1}, respectively. Calorific values of briquettes pressed from different materials did not differ significantly and compared well with each other. Chlorine content of briquettes made from hemp was approximately tenfold higher in comparison with briquettes made from sunflower. All briquette samples had a sulphur content of less than 0.05%.

Regardless of higher ash content of monoecious hemp and energy sunflower the analysis of ash behaviour indicated that the ash of these briquettes did not flow even at the temperature 1350 °C. The ash of dioecious hemp and the combination of dioecious hemp and energy sunflower briquettes started to sinter at 1140 °C and 840 °C, respectively (Fig. 3). The lowest hemispheric point in the case of dioecious hemp was measured at 1310 °C.

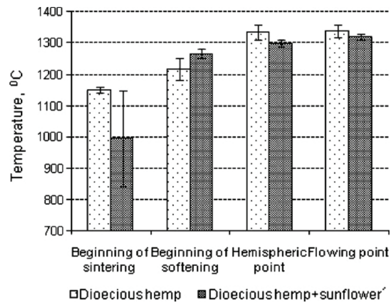

Fig. 3. Characterisation of ash behaviour of dioecious hemp and the combination of dioecious hemp and sunflower.

Briquettes made from the dioecious hemp had a correct shape and held together; no major fractures appeared. On the other hand, briquettes made from the monoecious hemp had large fractures on the surface, were very brittle and disintegrated readily. Briquettes pressed from sunflower were very hard and dense, had a correct shape and did not fracture. Crude fat content in herbaceous material may influence the briquette durability. In our trial the crude fat content in sunflower above-ground biomass as a mean of N treatments was 3.1 ± 0.56%. Briquettes made from a mixture of sunflower and dioecious hemp held together better than those from monoecious hemp, but were brittle and had many fractures.

4. Discussion

Energy crops suitability has been evaluated soil-specificly using large scale soil databases (Kukk et al., 2010); also overall regional level analysis have been performed (Voivontas et al., 2001). It has been suggested that some traditional crops (for example fibre hemp and sunflower) may be considered also as energy crops. Fibre hemp and sunflower have the potential to produce high above ground biomass (Hu, 2008; Mankowski and Kolodziej, 2008). In this trial the above ground biomass of fibre hemp and energy sunflower was not as high as declared in Southern areas (Hu, 2008; Mankowski and Kolodziej, 2008), but it was relatively high in Nordic conditions considering low production inputs. The more favourable treatments for fibre hemp and energy sunflower above ground biomass formation were N_{100} and sewage sludge treatments. The emergence and density of hemp plants grown on sewage sludge treatment was the lowest therefore the density stress within plants was smaller and nutrient supply per plant higher in comparison with other N treatments. Plant weight is influenced by density of plants per unit of area (Struik et al., 2000). In our study the plant weight on sewage sludge treatment was significantly higher in comparison with other N treatments. Several studies have declared that the plant weight of fibre hemp increases with increasing N supply (Piotrowska-Cyplik and Czarnecki, 2003; Struik et al., 2000). For example, Piotrowska-Cyplik and Czarnecki (2003) concluded that the addition of anaerobic sewage sludge in high doses to pot experiments with hemp increased plant height by one and half and plant weight two–sevenfold. Our investigation confirmed the significant positive correlation between plant weight and above ground biomass of hemp and sunflower. Struik et al. (2000) concluded that the effect of plant density on above ground biomass of fibre hemp was statistically not significant, which the results of our paper sup-

Table 7
Combustion testing parameters of briquettes from hemp and sunflower.

Determinable parameter	Ash in DM[a] (%)	Volatiles (%)	Sulphur in DM (%)	Chlorine in DM (%)	Calorific value in DM (MJ kg^{-1})	Calorific value, actual (MJ kg^{-1})
Dioecious hemp	5.3–6.3	77.0–79.0	<0.05	0.35–0.37	16.6–16.7	15.3–15.4
Monoecious hemp	6.1–7.6	76.6–78.1	<0.05	0.26–0.32	16.5–16.6	15.3–15.4
Sunflower	7.9–10.1	75.5–81.4	<0.05	0.03–0.04	17.1–17.4	15.8–15.9
Dioecious hemp and sunflower	6.5–7.7	77.0–80.1	<0.05	0.03–0.04	16.7–16.8	15.5–15.6

[a] DM – dry matter.

port. Regardless of different emergence and plant density the above ground biomass of hemp plant types did not differ significantly.

Since the current study was performed on Stagnic Luvisol soil, fibre hemp and sunflower biomass could differ by establishing plantation on soils with different characteristics than indicated in the current study. Struik et al. (2000) declared that the effect of N fertilisation to fibre hemp yield was insignificant on soil with a high soil N content.

Our study confirmed El Saeidy's (2004) results that fibre hemp and energy sunflower are suitable solid fuel for briquette production. The quality of briquetted fuel depends on ash quantity. The ash content of both monoecious and dioecious hemp in our study is comparable with the ash content of herbaceous grasses, e.g. reed canary grass (Burvall, 1997). In comparison, the ash content of sunflower was relatively high by the harvest time at the end of September. Many studies have confirmed that the ash content of herbaceous energy crops decreases with delayed harvest system (Heinsoo et al., 2011; Pahkala, 2007). The ash content of sunflower would probably decrease with delayed harvest also. Further studies should clarify the suitable harvest time for energy sunflower. Proper harvest time for briquette production from all cultivars of fibre hemp is probably in the first part of November in Estonian conditions, because by this time the dry matter content in hemp stems is high (82%), probably the lignin content as well and snow cover usually not so far (Lauk et al., 2009). Therefore, harvest time consideration in industrial hemp production for bioenergy purposes is not as important as quality hemp fibre production. Furthermore, Pasila (2004) has indicated the possibility of harvesting fibre hemp in spring although the preliminary observation in our study indicated fibre hemp lodging during winter.

Briquettes made from sunflower and hemp has good chemical composition compared to many other herbaceous materials (Burvall, 1997). In our study the sulphur and chlorine content was relatively low both in hemp as well as in sunflower samples, which is very important because the high content of sulphur and chlorine causes the corrosion during burning process in furnace.

Characterisation of ash behaviour is another important indicator to take into account. The lower are the temperatures when the ash begins to melt (sintering and softening point), the lower should be burning temperatures in furnace to avoid negative results caused by ash alterations. But even more important ash behaviour characteristics are the temperatures of hemispheric and flowing points, when the ash starts to stick to the grate. Our study inticated that monoecious hemp varities and energy sunflower cv Wielkopolski had notably good ash behaviour characteristics (the ash did not melt up to 1350 °C). Rice (2008) has concluded additionally that the average value of melting temperature for hemp is almost as high as for wood and higher than the values for almost any other nonwood biomass.

The briquette of high quality has to be with correct shape and durability. Many researchers have concluded that fat/oil in compressed material results in lower pellet/briguette durability (Briggs et al., 1999; Cavalcanti, 2004). This is because fat acts as a lubricant between the particles. Due to the hydrophobic nature of the fat, fat inhibits the binding properties of the water-soluble components in the compressed material such as starch, protein, and fibre (Thomas et al., 1998). Sometimes the (natural) fat in the cell wall may come out of the cell and act as a binding component between particles and make solid bridges, which may positively influence the pellet durability (Thomas et al., 1998). In our trial the latter may have happened with sunflower samples during the pressing process. Briquettes pressed from sunflower had a correct shape and did not fracture. The factors influencing the briquette compactness and durability are somewhat different for hemp and sunflower plants. In other words, the quality of briquette made from hemp plants was dependent on lignin quantity.

The quality and structural integrity of the briquette is affected by the size of particles, moisture, contents of lignin and cellulose, but also by the cellular structure of plant stems and leafs which affects the back stretch (Clauss, 2001). A higher lignin content with a small particle size and low moisture glues the briquette more strongly together. Our study showed that lignin content of hemp plants depends on plant type, its development rate, harvest time and N treatment. Dioecious hemp had slightly higher lignin content than monoecious hemp.

Briquettes made from the monoecious hemp had large fractures on the surface, were very brittle and disintegrated readily. In comparison, briquettes made from dioecious hemp plants had the correct shape and compactness. Nevertheless, briquettes made from a mixture of sunflower and dioecious hemp had many fractures.

Peiretti (2009) has indicated that the lignin content increases with increasing growth stage. In our trial the stems of dioecious hemp lignified by harvest time and therefore the lignin content as a mean of N treatments was higher in comparison of monoecious hemp. Energy sunflower Wielkoploski development rate on sewage sludge was higher in comparison of other N treatments and therefore the lignin content in plants grown on sludge treatment was 0.99–2.43% higher by the harvest time.

Additionally to plants biological singularity the development rate depends on GDD accumulation rate (Rodríguez et al., 2001). In 2010 the accumulation rate of GDD was much higher than usual. The long term average GDD for the vegetation period (May–September) in Estonia is 1259. The year 2010 was exceptional when GDD was 1484 by the end of September. By this time even monoecious hemp samples were in matured stage (data not shown). The dioecious hemp was in matured stage by harvest time in all trial years. The dioecious hemp needs lower GDD values for maturating and therefore this plant type is more suitable for briquetting in Estonian diverse climatic conditions.

The lignin content was influenced by emergence also, i.e. the higher the density of plants the higher the lignin content. The emergence of fibre hemp plants was in our trial generally low fluctuating between 14 and 96%. The lignin content of fibre hemp plants grown on the sewage sludge treatment was lower than the same data from the other N treatments. Fibre hemp quality in textile production is estimated through the bast fibres/wood fibres ratio (Ranalli, 1999). Ranalli (1999) confirmed that with lower plant density and wider stalks the bast fibres/wood fibres ratio decreases which is not preferred in quality fibre production. Overall lignin content analyses in the context of plant density are few. Therefore further experiments should clarify the physiological processes related with plant density and lignin content.

Aggelides and Londra (2000) said that sludge application improved the physical, chemical and biological properties of the soil. In our study sewage sludge treatment destroyed the physical texture of the soil allowing it to become caked. The soil lost its grainy structure and hemp seeds did not contact the soil fully resulting in significantly decreased seed germination and plant emergence. Probably the town Tartu sewage sludge mineralization period was too short. For example, the dry matter content of sludge is comparable with manure dry matter content (ca 20%), but the consistency of sludge used in this trial was gelatinous, gluey and sludge formed large particles with the soil. Struik et al. (2000) declared that hemp seed germination is very sensitive to poor soil structure, especially in the shortage or excess of water. In our trial the sewage sludge thickened the soil texture and the soil bulk density was significantly higher compared with the other N treatments. Additionally, poor hemp seed emergence in the current study could be explained also by the limited time between sewage sludge and seed application since delayed or reduced germination of some seeds have been declared on soils recently treated with sludge (Van Kleeck, 1954).

5. Conclusion

Fibre hemp and energy sunflower both have potential as raw material for biomass briquetting. Calorific values (16.6–17.4 MJ kg^{-1}) of briquettes pressed from different materials did not differ significantly and compared well with each other. Briquettes with the correct shape were made from sunflower and dioecious hemp. The factors influencing the briquette compactness and durability are somewhat different for hemp and sunflower plants. The compactness of hemp briquettes was dependent on lignin content. The average content of lignin in dioecious hemp was higher than of monoecoius hemp; the dioecious hemp was in matured stage by harvest time in all trial years. The dioecious hemp needs lower GDD values for maturating and therefore this plant type is more suitable for briquetting in Nordic climatic conditions. The comparison of different N treatments indicated that application of sewage sludge results in decreased emergence and density of fibre hemp plants and therefore also a decrease in lignin content. The emergence, plant weight and lignin content of energy sunflower cv Wielkopolski was not influenced by N treatment. Further studies are needed to evaluate also the economical and energetic values of briquetting the biomass of fibre hemp and energy sunflower.

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Teadusorganisatsiooniline ja – admistratiivne tegevus:

2009 - …	Eesti Mullateaduse Seltsi liige

Teadustöö põhisuunad:

Bioenergiakultuuride muld-taim süsteem ning väetamis- ja energiaefektiivsus

Osalemine uurimusprojektides:

2008 – 2013	Sihtfinantseeritav teema nr. SF0170052s08: „Agroökosüsteemide mitmekesisus, terviklikkus ja jätkusuutlikkus“

2012 – 2014	„Elurikkuse, mulla ja maapõue andmesüsteemide geoinformaatiline arendus“
2011 – 2012	„Mullastikukaartide- ja andmebaaside rakendused jätkusuutlikuks maakasutuseks ja põllumajandustootmiseks“
2010 – 2011	INTERREG IV A Programm 2007–2010 projekt „Energiapositiivne farm“
2010 – 2011	MTÜ Tartumaa Arendusseltsi tellitud uuring „Tartumaa maaressurss”
2008 – 2009	Mullafüüsika labori sisustamine
2007 – 2008	„Biomassi ja Bioenergia kasutamise edendamise arengukava 2007–2013“ alusel tellitud uuring „Maaressurss”

Erialane enesetäiendamine:

22.08-26.08. 2011	Tartu Ülikooli korraldatud kursus „Statistilised mudelid loodusteaduses“, 2 ECTS
28.02-17.03.2011	Tartu Ülikooli korraldatud kursus „Statistikatarkvara R“, 2 ECTS
22.03-25.03.2011	Eesti Maaülikooli ja programmi PRIMUS korraldatud kursus „Isotoopide kasutamine N aineringe uurimisel põllumajanduslikes ökosüsteemides“, 2 ECTS
17.01-21.01.2011	Eesti Maaülikooli ja PRIMUS programmi korraldatud kursus „Statistika: kogemused, praktika ja juhendamine põllumajandus- ja keskkonnateadustes“, 2 ECTS
01.03-04.03.2010	Eesti Maaülikooli ja PRIMUS programmi korraldatud kursus „Teaduslik kirjutamine“, 1 ECTS
20.01-21.01.2010	Helsingi Ülikooli korraldatud kursus „Energiaanalüüs põllumajanduses“ 5 ECTS
28.08-31.08.2009	Tallinna Tehnikaülikooli Tartu Kolledži korraldatud kursus „12. Põhjamaade mulla zooloogia sümpoosium ja PhD kursus“
8.06-14.06.2008	Eesti Maaülikooli korraldatud BOVA kursus „Procedures for writing a CC journal scientific article“

13.05-23.05.2008	Eesti Maaülikooli korraldatud kursus „Vee ja mulla seosed“, 6 ECTS

Ettekanded rahvusvahelistel konverentsidel:

14 – 16.06.2011	24. NJF kongress: Food, Feed, Fuel and Fun – Nordic Light on Future Land Use and Rural Development, SLU, Uppsala, Rootsi. Postriettekanne: Lämmastikväetise efektiivsus päideroo kasvatamisel sõltuvalt mullastik-klimaatilistest tingimustest
13–24.05.2010	Rahvusvaheleline konverents: Biosystems Engineering 2010, Eesti Maaülikool, Tartu. Suuline ettekanne: Päideroo energiakasutuse efektiivsus ja majanduslik tasuvus sõltuvalt lämmastikväetiste kasutamisest ja transpordikaugusest
09–10.09.2009	428. NJF konverents: Energy conversion from biomass production, Aarhusi Ülikool, Taani. Postriettekanne: Päideroo energiakasutuse ja maa kasutuse efektiivsus sõltuvalt lämmastikväetiste kasutamisest
10–12.03.2009	Rahvusvaheline konverents: Integrated Assessment of Agriculture and Sustainable Development (AgSAP), Holland. Suuline ettekanne: Asukohapõhine energiakultuuride planeerimine
25–26.09.2007	405. NJF seminar: Production and Utilisation of Crops for Energy, Vilnius, Leedu. Postriettekanne: Kasutamata maaressurss bioenergia tootmiseks

LIST OF PUBLICATIONS

1.1 – Articles indexed by Thomson Reuters Web of Science / teadusartiklid, mis on kajastatud Thomson ReutersWeb of Science andmebaasis

Kukk, L., Roostalu, H., Suuster, E., Rossner, H., Shanskiy, M., Astover, A. 2011. Reed canary grass biomass yield and energy use efficiency in Northern European pedoclimatic conditions. Biomass and Bioenergy 35(10):4407–4416.

Alaru, M., **Kukk, L.**, Olt, J., Menind, A., Lauk, R., Vollmer, E., Astover, A. 2011. Lignin content and briquette quality of different fibre hemp plant types and energy sunflower. Field Crops Research 124(3):332–339.

Kukk, L., Astover, A., Muiste, P., Noormets, M., Roostalu, H., Sepp, K., Suuster, E. 2010. Assessment of abandoned agricultural land resource for bio-energy production in Estonia. Acta Agriculturae Scandinavica: Section B, Soil and Plant Science 60(2):166–173.

1.2 – Peer-reviewed articles in other international research journals with an ISSN code and international editorial board, which are circulated internationally and open to international contributions / teadusartiklid teistes rahvusvahelistes teadusajakirjades

Alaru, M., Olt, J., **Kukk, L.**, Luna del Risco, M., Lauk, R., Noormets, M. 2011. Methane yield of different energy crops grown in Estonian conditions. Agronomy Research 9:13–22.

Kukk, L., Astover, A., Roostalu, H., Rossner, Helis., Tamm, I. 2010. The dependence of reed canary grass (*Phalaris arundinacea* L.) energy efficiency and profitability on nitrogen fertilization and transportation distance. Agronomy Research 8:123–133.

3.2 – Articles in books Publisher by the publishers not listed in Annex / artiklid lisas mitte loetletud kirjastuste välja antud kogumikes

Kukk, L., Astover, A., Roostalu, H., Noormets, M., Muiste, P. 2007. The abandoned agricultural land resource for bio-energy production: a case study of Estonia. NJF Report 3(4):115–118.

3.4 – Articles Publisher in conference proceedings not listed in Section 3.1 / artiklid, mis on avaldatud valdkonda 3.1 mittekuuluvates konverentsikogumikespublikatsioonid

Kukk, L., Suuster, E., Astover, A., Noormets, M., Roostalu, H. 2009. Soil optimized suitability analysis for allocation of energy grasses. Proceedings of the conference on Integrated Assessment of Agriculture and Sustainable Development: Setting the Agenda for Science and Policy (AgSap 2009). Egmond aan Zee, The Netherlands, March 10–12, 372–373.

Suuster, E., **Kukk, L.**, Astover, A., Noormets, M. 2009. Spatial assessment of abandoned agricultural land for bio-energy production. Proceedings of the conference on Integrated Assessment of Agriculture and Sustainable Development: Setting the Agenda for Science and Policy (AgSap 2009). Egmond aan Zee, The Netherlands, March 10–12, 386–387.

3.5. Articles and presentations published in local conference proceedings / artiklid ja ettekanded, mis on avaldatud kohalikes konverentsikogumikes

Tamm, I., Astover, A., **Kukk, L.**, Roostalu, H. 2009. Muutused Eesti põllumuldade toiteelementide bilanssides perioodil 1996–2006. Agronoomia 2009, Jõgeva, 2 –17.

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Kukk, L. 2007. Bioenergiakultuuride kasvatamise võimalused põllumajanduslikust kasutusest väljajäänud maal Ida-Viru, Järva ja Tartu maakondades. Noorteadlased taastuvenergiast: Noorteadlaste taastuvenergia teadustööde konverents, Tartu, 53–62.

5.2. – Conference abstracts that do not belong in section 5.1. / konverentsiteesid, mis ei kuulu valdkonda 5.1

Alaru, M., **Kukk, L.**, Lauk, R., Noormets, M. 2011. Heavy metals content in barley's grain influenced by waste water sludge after effect. Food, Feed, Fuel and Fun – Nordic Light on Future Land Use and Rural Development (24th NJF Congress), SLU, Uppsala, Sweden, June 14–16, 205.

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Kukk, L., Astover, A., Roostalu, H., Suuster, E., Noormets, M. 2009. Energy and land use efficiency of reed canary grass (*Phalaris arundinacea* L.) depending on nitrogen fertilisation. Energy conversion from biomass production – EU-AgroBiogas (NJF Seminar 428), Viborg, Denmark, September 9–10, NJF Report 3(3), 61–62.

6.3 – Popular science articles / populaarteaduslikud artiklid

Roostalu, H., Astover, A., **Kukk, L.**, Suuster, E. 2008. Bioenergia tootmise võimalustest põllumajanduses: III osa. Maamajandus, detsember 2008, 34–36.

Roostalu, H., Astover, A., **Kukk, L.**, Suuster, E. 2008. Bioenergia tootmise võimalustest põllumajanduses: II osa. Maamajandus, november 2008, 42–45.

Roostalu, H., Astover, A., **Kukk, L.**, Suuster, E. 2008. Bioenergia tootmise võimalustest põllumajanduses: I osa. Maamajandus, oktoober 2008, 32–35.

Astover, A., Roostalu, H., **Kukk, L.**, Muiste, P., Padari, A., Suuster, E., Ostroukhova, A. 2008. Potentsiaalne maaressurss bioenergia tootmiseks. Eesti Põllumees 38, 17.

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