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Preface

This report is a part of the Sustainable Bioenergy Solutions for Tomorrow (BEST) research program, which is joint research program by FIBIC Ltd, and CLEEN Ltd. BEST program is funded by the Finnish Funding Agency for Technology and Innovation, Tekes.

The report belongs to BEST research program's Working Package 2 (WP2) "Radical improvement of bioenergy supply chains", and it's Task 2.1 "Raw materials". This report is a LCA sustainability analysis of cultivation of novel high-yielding field bioenergy crops, with comparison with willow and reed canary grass.

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Name of the report: LCA analysis of novel high-yielding bioenergy crops compared with willow and reed canary grass

Key words: bioenergy, biomass, willow, Salix, reed canary grass, Phalaris arundinacea, Brown knapweed, Centaurea jacea, Late-flowering golden-rod, Solidago gigantea, Sunflower, Helianthus maximilianii, Sakhalin knotweed, Fallopia sachalinensis.

Summary

The aim of this study was to compare the climate change effects (greenhouse gas emissions or carbon footprint during life cycle) of the novel bioenergy crops brown knapweed (*Centaurea jacea*), late-flowering golden-rod, (*Solidago gigantea*), sunflower (perennial, *Helianthus maximilianii*) and Sakhalin knotweed (*Fallopia sachalinensis*) to more conventional bioenergy crops willow (*Salix* sp.) and reed canary grass (*Phalaris arundinacea*) and maize (*Zea mays*). All these crops except maize are perennials and all of them have high dry matter yields. The carbon footprints of these crops were also compared with those of firewood and fossil fuels. The biomasses were assumed to be utilized by combustion in a CHP-plant or (for brown knapweed and maize) in a biogas plant.

The models used to evaluate the carbon footprint included the three most important greenhouse gases (CO_2, CH_4, N_2O), which were converted to carbon equivalents (CO_2-eq) and summed through the whole production chain. The carbon footprints of investigated crops and production systems were located between 8 - 15 g CO_2-eq/MJ in combustion. Willow and reed canary grass had carbon footprints of 10 – 11 g CO_2-eq/MJ, which are not high values compared to novel crops. In transport biogas production, carbon footprints varied between 18 – 30 g CO_2-eq/MJ, when raw matter used was brown knapweed or maize. These values are substantially lower compared to fossil fuels.

The most important GHG emissions in bioenergy production chains were caused by nitrous oxide emissions of farmland, production of fertilizers and liming of the fields. Also assumed yield levels affected the carbon footprint significantly. Uncertainty in these values can have a significant effect on the final results. On the other hand, by improving these high-emission points in production chains, carbon footprint of field bioenergy could be reduced.

Contents

1 Introduction

Impact of fossil fuels on global warming has created the need to look for alternative means of energy production. The use of renewable energy is constantly increasing, with bio-energy one of the main sources of renewable energy. Accordingly, there is a constant demand for new economically and technically viable bio-energy production systems and biomass sources, in order to allow a significant alternative for fossil fuels in energy production. In accordance with this, economically viable production methods (e.g. burning or biogas fermentation) and high yielding biomass producers (annual or perennial plants, residues and other biomasses) are constantly looked for and their environmental, economical and social sustainability studied.

Before taking a new bio-energy source into use, it is essential to study the effects of its use on climate change, especially compared with conventional energy sources. For this reason, we studied not only the profitability or net energy production potential of the selected novel high-yielding bio-energy crops, but their carbon footprints as well. The modelling of the carbon footprint, according to the GHG emissions of the new crops throughout their life cycle, was the main driver for writing the present report.

2 Materials and definitions

2.1 The objective of the research and implementation.

The aim of this study was to find out, through life cycle assessment (LCA) modelling, what are the climatic impacts of production and usage for energy of the novel bioenergy crops brown knapweed (*Centaurea jacea*), late-flowering golden-rod, (*Solidago gigantea*), sunflower (perennial, *Helianthus maximilianii*) and Sakhalin knotweed (*Fallopia sachalinensis*), compared with more conventional field bio-energy crops willow (*Salix* sp.), reed canary grass (*Phalaris arundinacea*) and maize (*Zea mays*), when produced on surplus fields. The climate change mitigation potential of these crops was analyzed by comparing the climate impact of the life cycles of the studied crops with current sources of energy (fossil fuels or wood).

The research was conducted by ISO 14040 LCA standard. The study used available information about emissions of cultivation and other life cycle stages of the studied crops. Information was supplemented by literature data.

2.2 Defining study

The study of environmental impact was limited to the effects on climate change. The three most important greenhouse gases were considered in the calculation; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The results of the study are expressed as the carbon footprint of a product, which reflects the combined effect of different greenhouse gases, and is expressed as CO_2 equivalent (CO_2-eq). CO_2-eq characterization of the different greenhouse gases is a result of multiplying with coefficients that indicate the effect of a greenhouse gas on climatic warming as compared with the impact of CO_2.Characterization coefficients used in the study are assembled in Table 1.

Table 1. *Greenhouse gas emissions characterization coefficients*

Greenhouse gas	Characterization coefficient
Carbon dioxide	1
Methane	25
Nitrous dioxide	298

For a LCA it is necessary to determine the factors that are taken into account in the system analysis. In the present study, all the factors from the cultivation of the crops spanning till production of energy were taken into consideration (Table 2).

Table 2. *The phases of the life cycle considered in calculations.*

Cultivation	Agricultural N_2O emissions
Liming	Lime production and use
Fertilisation	The production and use of fertilizers
Field jobs	Fertilizer distribution, tilling, seeding, planting, spraying, harvesting, baling, liming
Transport of bales	Transportation of bales or biomass from the field to the plant
Energy production from crops	Combustion of biomasses or conversion into biogas

Seed production is not taken into account in this LCA. In addition, the infrastructure, including e.g. manufacture of various engines, tractors or other equipment, as well as buildings and roads, are ignored. Also distribution and further use of the energy products (heat, biogas, electricity) are not included in this LCA.

2.3 Data sources

The data used in this study are based on the information obtained from the cultivation of crop trials. The annual yields of the crops in the different cultivation scenarios used in this study are collected in Table 3.

Table 3. *The annual yields of the studied crops in different cultivation scenarios in the present trials.*

Cultivated plant	Yield, 1. & 2. year (t/ha/a)	Yield, 3. year(t/ha/a)	Yield, 4. -n. year (t/ha/a)
Brown knapweed *Centaurea jacea*, autumn harvest	0	15	15
Brown knapweed *Centaurea jacea*, spring harvest	0	10	6
Brown knapweed *Centaurea jacea*, without start up fertilization	0	10	6
Brown knapweed *Centaurea jacea*, recycling fertilization	0	10	6
Late-flowering golden-rod, *Solidago gigantea* German, autumn harvest	0	15	15
Late-flowering golden-rod, *Solidago gigantea* German, spring harvest	0	10	10
Late-flowering golden-rod, *Solidago gigantea* Polish, autumn harvest	0	15	15
Late-flowering golden-rod, *Solidago gigantea* Polish, spring harvest	0	10	10
Sunflower, perennial *Helianthus maximilianii*, spring harvest	0	8	8
Sakhalin knotweed *Fallopia sachalinensis*, spring harvest	0	15	15
Salix, harvest period 4 years	7,5	7,5	7,5
Reed canary grass, *Phalaris arundinacea*	0	6	6
Maize *Zea mays*	16 (only 1.st year)	0	0

Maize is an annual crop. Other crops are perennials and they could be grown for the duration of 10 years. Important issues in a LCA are nitrogen fertilisation and liming. The estimated volumes of these procedures have been collected in Table 4. Fertilisation is done each year, while liming is carried out every ten years.

The fuel consumption information is required for the calculation of the biomass road transports as well as in the farm jobs. The transport range of herbaceous biomass bales to a heat generation plant was assumed to be below 70 kilometres and that of woody biomasses (willow chips) 150 kilometres. In the case of biomass transport to a biogas plant, the estimated distance was 10 kilometres (autumn harvested brown knapweed or maize). The fuel consumption of farm jobs was extracted from Mikkola & Ahokas (2009).

The emission factors of different field operations and transport are based on literature sources listed in Table 5. The emission factor warranty value 3.6 kg CO_2-eq./kg N by Yara is used in the manufacture of fertilizer. The electricity used in biogas fermentation is expected to be standard electricity in Finland. Heat in the process is expected to be produced by burning woodchips. Heat emission factors are from an MTT (unpublished) assessments for food carbon footprint. Other information related to the production of biogas, such as the use of the energy is based on Tuomisto & Helenius (2008) and Pertl & al. (2010).

Table 4. *Used nitrogen fertilisation and liming of tested crops.*

Cultivated plant	Start up fertilisation (kg Nitrogen/ha/a)	Annual fertilisation (kg Nitrogen/ha/a)	Liming (t/ha/10a)
Brown knapweed *Centaurea jacea*, autumn harvest	24	90	5
Brown knapweed *Centaurea jacea*, spring harvest	24	70	5
Brown knapweed *Centaurea jacea*, without start up fertilization	0	70	5
Brown knapweed *Centaurea jacea*, recycling fertilization	0	144	5
Late-flowering golden-rod, *Solidago gigantea* German, autumn harvest	24	70	5
Late-flowering golden-rod, *Solidago gigantea* German, spring harvest	24	70	5
Late-flowering golden-rod, *Solidago gigantea* Polish, autumn harvest	24	70	5
Late-flowering golden-rod, *Solidago gigantea* Polish, spring harvest	24	70	5
Sunflower, perennial *Helianthus maximilianii*, spring harvest	24	70	5
Sakhalin knotweed *Fallopia sachalinensis*, spring harvest	24	200	5
Salix, harvest period 4 years	15	15	0
Reed canary grass, *Phalaris arundinacea*	40	70	3
Maize *Zea mays*	120	-	5

Table 5. *The literature sources of emission factors.*

The phase of life cycle	Literary source
Lime manufacturing	Grönroos & Voutilainen 2001
Usage of lime	IPCC 2006
Fertilizer manufacturing	Yara
Use of the arable land and fertilisation	IPCC 2006
Field work and transports	LIPASTO
The Heat (chips)	MTT

In the LCA of the crops used in direct combustion, the direct effects of burning on climate change were taken into account was as well. However, the CO_2 emissions of these renewable energy sources were not taken into account, as it can be assumed that crops have assimilated and will again if cultivated bind by photosynthesis the same amount of carbon dioxide as released by burning. However, emissions of methane and nitrous dioxide released from incineration are taken into account. However, the volume of these emissions varies a lot. Methane emissions are particularly affected by disturbances in the burning process, while combustion chamber type and firing temperatures affect N_2O emissions. It was assumed that different crops emitted relatively same (rather small) amounts of methane and N_2O. In this study, the emission factors used for renewable fuels are as estimated by Yrjänäinen (2011).

3 Results

3.1 The carbon footprints of crops in heat generation

The carbon footprints of crops used in heat generation are presented in Fig. 1. The carbon footprints vary between 8 - 15 g CO_2-eq/MJ. Most of the carbon footprint comes from liming, emissions of N_2O and fertilization. Field machinery (implements) exerts a very small impact on carbon footprint. The crop yields and cultivation technologies have a significant impact on results.

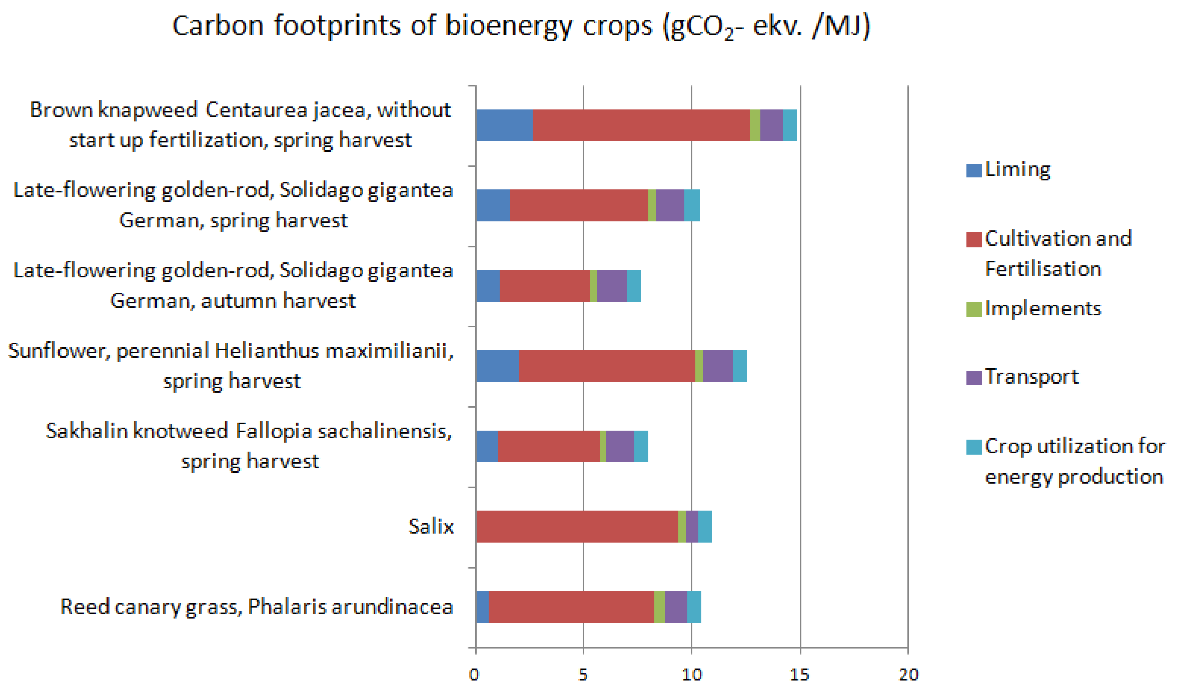

Figure1. The carbon footprints per energy content of energy crops produced for heat generation.

The study also assessed the impact of pellet and briquette making on carbon foot prints. By using pellet and briquette in the transport, fuel consumption can be reduced, as plant mass is then more compact than in bales, and the number of truck loads can be reduced. However, making pellets and briquettes consumes energy. For this reason, the making pellets or the briquettes is estimated to have little influence on the examined carbon footprint.

3.2 The carbon footprint of biogas

Carbon footprints of various components of the life cycle of autumn harvested brown knapweed and maize for biogas are shown in Fig. 2.

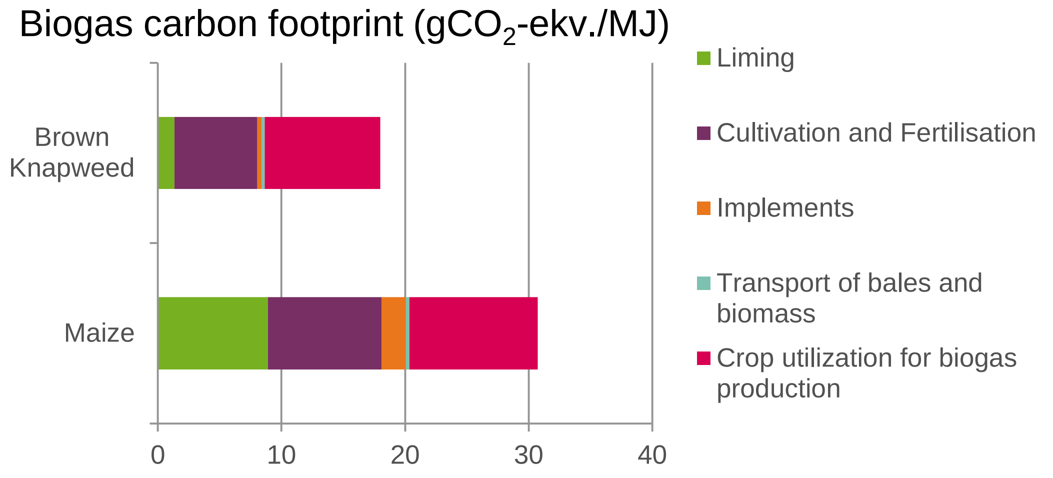

Figure 2. The carbon footprints per energy content of biogas produced from the studied energy crops maize and brown knapweed.

The main components of carbon footprint of energy crops produced for biogas are liming, fertilization, N_2O emissions, and the manufacturing processes of biogas. Also the use of machinery, particularly self-propelled maize silage cutter, must be taken into account in the carbon footprint. The use of machinery has little importance for biogas carbon footprint. Also the transport of bales or biomass will not give rise to any significant share of the total carbon footprint in hypothetical transportation distances.

4 Evaluation of results

The emissions reported in the previous chapter can be compared with other fuels used in energy production. Because the results are based to a large extent on estimates, the results contain large amounts of uncertainty, which is dealt with in this chapter.

4.1 Heat production

In Finland the most common fuels for heat production are coal, natural gas, peat, as well as firewood. In the following the carbon footprints of field crops calculated in Chapter 3 are compared with the footprints of conventional fuels. The comparisons are shown in Fig. 3.

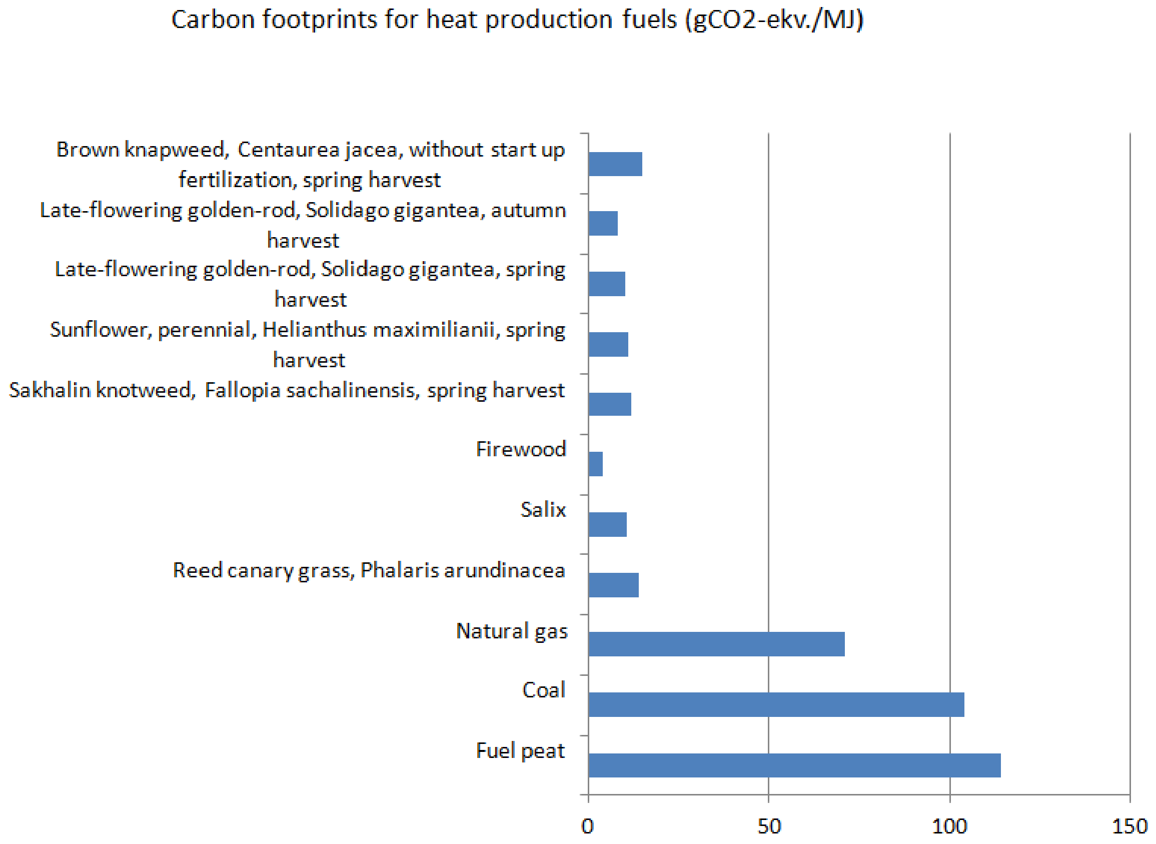

Figure. 3. The carbon footprints of heat production by field bio-energy crops compared with firewood, peat and fossil energy sources.

The fuel emissions in this comparison have been collected from several sources. The information for CO_2 emissions from combustion was obtained from the Statistics Centre of Finland. Other incineration emissions has been estimated by Yrjänäinen (2011). For the other stages of the life cycle, emissions are collected from the sources collected in Table 6.

Table 6. The literature sources of emissions of compared fuels.

Fuels	Literary source
Firewood	Cuperus 2003
Natural gas	Viebahn & Krewitt 2003
Coal	Sokka et. al 2005
Fuel peat	SYKE et. al 2010
Salix	Börjesson, P. 2006

The comparison shows that carbon footprints of the investigated field energy crops are considerably smaller than those of the traditionally used fossil fuels for heat generation in Finland. However carbon footprint of the most common renewable biomass in heat generation in Finland, firewood, is slightly lower than those of the field bio-energy crops. The difference between fossil fuels and renewable energy sources is due to the fact that the combustion of fossil fuels releases a significant amount of carbon dioxide, causing the majority of the carbon footprint of fossil fuels. Also the burning of renewable energy sources generates carbon dioxide emissions, but these are ignored in the calculation, as the same amount of carbon dioxide as released in burning is assimilated from the air by photosynthesis.

When comparing the emissions, one has to remember that the estimations contain large uncertainties, caused by variations in different phases of production (fertilization, liming, yield) and variation in combustion techniques. Also there may be differences in different sources of information and studies that were referred to here. Nevertheless, the carbon footprints of the studied field energy crops can, with good certainty, be concluded to be smaller than the footprints of fossil fuels.

4.2 The biogas

The suitability of biogas as fuel for transport is constantly being developed, and from this point of view, biogas was also examined in this study. Thus, the carbon footprint of biogas from energy crops can be compared with the fuels currently used in traffic, such as petrol and diesel. This comparison is presented in Fig. 4.

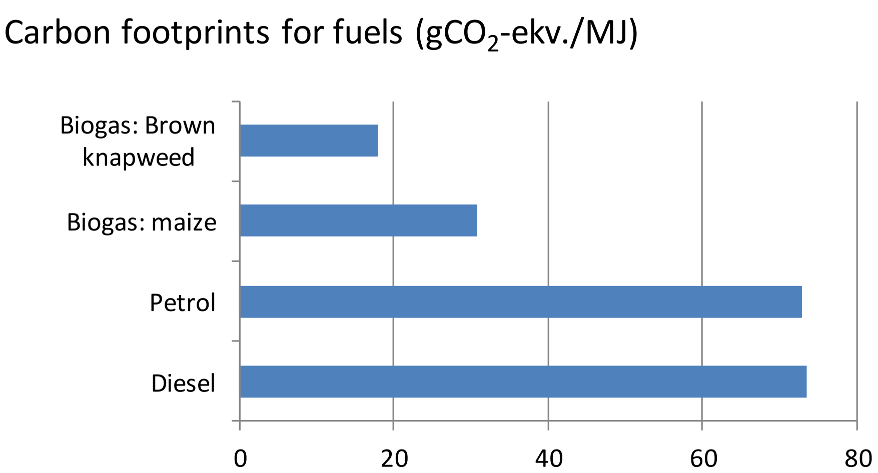

Figure 4. Carbon footprints for traffic fuels

Petrol and diesel carbon footprints have been calculated using the official Statistics of Finland for fuel classification (Tilastokeskus 2010), as well as Fortum's Ekotasetiedote (2002). Nitrous oxide and methane emissions of fuel burning were not taken into account in this comparison, but these can be expected to be relatively small. Carbon dioxide emissions of combustion, however, are taken into account, and they are the main part of the petrol and diesel carbon footprints.

As shown in Fig. 4, it can be noted that the carbon footprint of biogas produced by energy crops is significantly lower than those of the currently used fossil fuels. However, please note that the usability and logistics of biogas as a fuel for transport need to be substantially improved before its consumption can be significantly increased. Currently, only a couple of farm size fueling stations can be found in Finland. A comprehensive refueling network would require expensive pipeline networks or gas transports to the refueling stations, as now is the case with natural gas.

5 Conclusions

The carbon footprints of investigated bioenergy crops varied between 8-15 g CO_2-eq/MJ. The biogas carbon footprints were 18-30 g CO_2-eq/MJ. The liming, used in cultivation of all crops, caused considerable carbon dioxide emissions, together with N_2O and fertilization emissions of cultivation. An important component in emissions was also the manufacturing of biogas.

A very important factor from the point of view of the carbon footprint of bio-energy crops are yield levels. High biomass yields relative to inputs signify small effects on climate change. Also the possibility to use recycled fertilizers can improve the environmental performance of bioenergy crops. It should be noted that in practical farming the yields can be considerably lower than in trials. E.g. harvesting losses in practical farming can be considerably higher than in trials on experimental plots. Trials can be established in the most favourable field parts, while the growth conditions in farms can vary significantly.

Logistics is one of the bottlenecks in plant biomass production. Transportation of light, but large bales is not economically viable, at least for long distances. In some cases, longer transport distances might also be possible, but it should be noted that longer distances will increase the carbon footprint.

This study examined the effects of bio-energy crops on climate change only. The cultivation of crops has always also other effects on the environment, the most significant in Finnish environmental conditions being eutrophication of water systems. Nitrogen and phosphorus run-offs from the field as well as air emissions indirectly, also result in eutrophication. The eutrophication impact of perennial energy crops is not known very well. Acidification, in turn, is caused e.g. by ammonium emissions, particularly when using manure as fertilizer.

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