Tampere University

KARI LAASASENAHO

Biomass Resource Allocation for Bioenergy Production on Cutaway Peatlands with Geographical Information (GI) Analyses

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ACADEMIC DISSERTATION
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Dedication

This thesis is dedicated to my family

PREFACE

The PhD studies have been the most giving adventure for me. During these 5 years, I have learnt about life more than ever. In one point, I said to my wife that it could be possible to write a hilarious rustic comedy about our family life. When we moved from Jyväskylä city to our home municipality, called Soini, during my PhD's many things have happened: Broke of my research group at University of Jyväskylä and shift to Tampere University of Technology in 2015 (and finally Tampere University in 2019). I started as an organic farmer and forest owner in 2016, having wonderful kids and having full renovation of our detached house. I finished teacher education in biology and geography at University of Jyväskylä in 2016 and I had different projects at Seinäjoki University of Applied Sciences (related to bio- and circular economy and work as a higher education coordinator in the "Kuudestaan" region). I also held a position of responsibilities in Soini municipality and many other tasks, such as teaching tropical biogas applications to Ghanaian students and taking part of the competition organized by Sitra (Finnish Innovation Fund) and Valio (manure hackathon). There hasn't been calm moment in my life during these years. Hopefully, I can relax for now on.

I want to thank my supervisor prof. Jukka Rintala for understanding and caring attitude and especially for good advices. I am grateful for my co-supervisor, Dr. Anssi Lensu from University of Jyväskylä, because without his assistance and advice in GI analyses, I would have been in trouble! Thanks to prof. Jukka Konttinen, who gave me an opportunity to start as a PhD student at University of Jyväskylä, Department of Chemistry without being a chemist! Special thanks are acknowledged to adjunct professor, Risto Lauhanen, who became my thesis advisor and fellow worker. Also, I want to thank Dr. Prasad Kaparaju from Griffith University, Australia. He taught me a lot about laboratory analyses. All these great people had patience to guide me from the beginning. Additionally, adjunct prof. Jyrki Hytönen and prof. Kalev Sepp are acknowledged for the pre-examination of this thesis. Special thanks are also acknowledged to laboratory staff Mervi Koistinen and Leena Siitonen and fellow students Henri Karjalainen, Francesca Renzi, Mikko Hietanen, Tiina Karppinen, and Asseri Laitinen from University of Jyväskylä. I want to thank Dr. Antti Pasila, and Dr. Tapani Tasanen, Dr Terhi Junkkari, Ms Terhi Ojaniemi, Ms Kirsti Mustalahti, Ms Taru Mäki at Seinäjoki University of Applied Sciences, Mr Esa Vuorenmaa at University consortium of Seinäjoki, Mr Jorma Tukeva and other staff member at Sedu Tuomarniemi (Seinäjoki Joint Municipal Authority for Education). They created pleasant working environment and offered a room without charge as part of "research hotel" activity (Seinäjoki University Consortium) in the next to the Panda couple in Ähtäri.

The funding of this thesis or data collection was given by different projects: Drop in the Sea (data collection, project number, 12316), Supporting grant from Tekniikan edistämissäätiö and South Ostrobothnia Regional Fund, EU's rural development funding (Local action group Kuudestaan) and European regional development funding (data collection, project numbers 9062 and A72570 respectively). Finally, it was a miracle that I made my PhD's in a moderate time. It has been privilege that we have had so many important people supporting me and my family. Mom, Dad, my 5 sisters and their families, Merja-mummu i.e. mother-in-law. Without their help, this would have never happened. Hard working values, learned from my dad, Dr. Martti Laasasenaho, have been carrying me through uneasy times.

This thesis is dedicated to my family: Mirka, my wife, sons Pyry and Sisu and a daughter, Aava, who are my inspiration.

Soini 20.11.2019
Kari Laasasenaho

"*Mitä vannottiin, se pidetty on, yli päämme kun löi tulilaine*"
-Yrjö Jylhä, "Hyvästi Kirvesmäki", Kiirastuli collection of poems from 1941

ABSTRACT

In recent years, technical and economic challenges in combustion of spring harvested dry reed canary grass (RCG, *Phalaris arundinacea*) has led into a situation where a significant amount of cutaway peatlands were out of intensive RCG growing in Finland. At the same time, thousands of hectares of cutaway peatlands were released annually from peat extraction, which still would allow energy crop growing without competition with food production. The objective of this work was to assess alternative uses for the cutaway peatlands for fresh RCG growing for bioenergy production. It was studied where are the most favourable areas for such practices at national and regional level and finally location optimization of bioenergy plants was made in a local scale inside a Finnish study area. In this work, fresh harvested RCG was shown to be a feasible energy crop on the cutaway peatlands if the cultivation is optimized. Compared to the traditional RCG combustion, fresh harvested RCG can have higher biomass yields, lower lignin content and better digestibility in biogas process. Land suitability assessment showed that, theoretically, ca. 300 km^2 of future cutaway peatlands are suitable for biogas energy crop production by 2045 in Finland. It could be possible to grow energy crops, over 100 Gg total solids (TS) a year and having biogas potential of ca. 300 GWh. Especially, North and South Ostrobothnia regions are potential locations for this practice due to high peat extraction intensity in national level. Consequently, the precise local potential of cutaway peatlands was studied also with a questionnaire in a case study area in South Ostrobothnia. It was found that landowners of the cutaway peatlands are interested in bioenergy production, and they usually prefer forestry as an after-use method. In the final part of the thesis, bioenergy plant location optimization was done with multiple feedstocks including a biogas plant scenario and a wood terminal scenario. The R and ArcGIS software programs were used to identify potential locations for 13 farm-scale biogas plants (>100 kW) and 8 centralized biogas plants (>300 kW), and two potential wood terminals. These tools could be applied for different biomass resources and used in relevant decision makings to plan the locations of bioenergy plants in other countries as well.
Keywords: Circular economy, decentralized renewable energy production, bioenergy planning, geographic information systems, location allocation

TIIVISTELMÄ

Viime vuosina ruokohelven (*Phalaris arundinacea*) käyttö polttolaitoksissa on vähentynyt merkittävästi johtuen teknisistä ja taloudellisista haasteista. Tilanne johti siihen, että huomattava määrä myös turvetuotannosta vapautuvia suopohjia jäi pois intensiivisestä ruokohelven viljelystä. Tästä huolimatta suopohjia vapautuu edelleen tuhansia hehtaareja vuodessa, mikä tarjoaisi mahdollisuuden viljellä energiakasveja kestävästi ilman kilpailua ruoantuotannon kanssa. Työn tavoitteena oli arvioida vaihtoehtoista käyttöä suopohjille bioenergiantuotannon, eli tässä tapauksessa tuoreen ruokohelven kasvatuksen muodossa. Tutkimuksessa selvitettiin, mitkä olisivat tälle toiminnalle otollisimmat alueet kansallisella ja alueellisella tasolla, ja lopulta bioenergian tuotantolaitosten sijainninoptimointi tehtiin paikallisella tasolla suomalaisella tutkimusalueella. Tutkimuksessa selvisi, että tuoreena korjattu ruokohelpi voi olla kannattava energiakasvi suopohjilla, jos sen viljely on optimoitu. Perinteiseen polttoketjuun verrattuna tuorekorjattu ruokohelpi mahdollistaa suurempia biomassasaantoja, alemman ligniinipitoisuuden ja paremman sulavuuden biokaasuntuotannossa. Turvetuotantoalueiden soveltuvuutta arvioitaessa todettiin, että Suomessa vuoteen 2045 mennessä turvetuotannosta vapautuvasta suopohjasta teoreettisesti noin 300 km^2 soveltuisi energiakasvien tuotantoon biokaasuntuotantoa varten. Tältä alueelta olisi mahdollista saada energiakasveja yli 100 Gg (kuiva-aine) vuodessa, mikä olisi bruttoenergiana n. 300 GWh. Erityisesti Pohjois- ja Etelä-Pohjanmaa ovat potentiaalisia paikkoja, koska siellä on kansallisella tasolla paljon turvetuotantoalueita sekä mahdollisuuksia maatilakohtaisille biokaasulaitoksille. Niinpä jatkotutkimuksia tehtiin eteläpohjalaisella tutkimusalueella, jossa suopohjien omistajista hankittiin lisätietoja kyselylomakkeella ja havaittiin, että suopohjien maanomistajat ovat kiinnostuneita bioenergiaa kohtaan ja he suosivat metsänkasvatusta jälkikäyttömenetelmänä. Opinnäytetyön loppuosassa määritettiin usealle biomassavaihtoehdolle soveltuvien biokaasulaitosten ja puulle tarvittavien terminaalien sijainteja tutkimusalueella. R- ja ArcGIS-ohjelmistoilla löydettiin 13 maatilakohtaisen (> 100 kW) ja 8 keskitetyn biokaasulaitoksen (> 300 kW) sekä kahden potentiaalisen puuterminaalin optimaalinen sijainti. Näitä työkaluja voitaisiin soveltaa erilaisiin biomassoihin ja hyödyntää niitä bioenergialaitosten sijainnin suunnittelussa myös muissa maissa.

CONTENTS

1 Introduction 21

2 Background 24
- 2.1 Decentralized bioenergy production 24
- 2.2 Biomass production on cutaway peatlands 26
- 2.3 GIS as a tool for bioenergy planning 31
  - 2.3.1 The nature of spatial knowledge 31
  - 2.3.2 GIS applications in bioenergy planning 34

3 Research objectives and questions 39

4 Materials and methods 40
- 4.1 RCG sampling 41
- 4.2 Chemical analyses 42
- 4.3 Scenario studies for biogas production and combustion of fresh RCG 45
  - 4.3.1 Energy input and output on cutaway peatland 45
  - 4.3.2 Net energy yield and energy balance 49
  - 4.3.3 CO_2 emissions in cultivation 50
  - 4.3.4 Economic profitability 50
- 4.4 The study area 51
- 4.5 GIS studies 52
  - 4.5.1 Kernel density analyses for assessing potential cutaway peatlands for bioenergy production 52
  - 4.5.2 Mapping local landowners 55
  - 4.5.3 Optimizing the location of biogas plants 55
- 4.6 The interview and statistical analyses 57

5 Results and discussion 59
- 5.1 Feasibility of biogas production and combustion of fresh RCG grown on cutaway peatland 59
  - 5.1.1 The composition of fresh RCG 59
  - 5.1.2 Biogas production and combustion scenarios 62
- 5.2 National energy crop potential of cutaway peatlands 65
- 5.3 Landowners' perspective to use cutaway peatlands for energy crops 70
  - 5.3.1 Assessing the potential future cutaway peatlands for bioenergy 70
  - 5.3.2 Landowners views on peatlands after-use and bioenergy 72

5.3.3 Correlations between variables ... 76
5.4 Bioenergy plant location optimization with GIS tools ... 78
5.4.1 Biogas plant location optimization ... 78
5.4.2 Wood terminal location optimization ... 83
5.5 General discussion ... 85

6 Conclusions ... 88

7 Future outlook ... 90

8 References ... 91

List of Figures

Figure 1. Decentralized energy production by using renewable energy (modified from Vezzoli et al. 2018). Large centralized power plants are replaced by smaller interconnected production units.

Figure 2. Peat extraction dynamics from pristine mire to after use phase (modified from Salo & Savolainen 2008).

Figure 3. The most common after-use alternatives for cutaway peatlands based on drainage conditions during peat extraction (modified from Vapo 2017).

Figure 4. Bioenergy production alternatives for cutaway peatlands considered in this study.

Figure 5. An example related to integration of different map layers in GIS (modified from Foote & Lynch 1995)

Figure 6. The role of data model in GIS (adapted from Longley et al. 2011).

Figure 7. Different stages in GIS data collection (adapted from Longley et al. 2011).

Figure 8. Progress in renewable energy mapping (modified from Calvert et al. 2013).

Figure 9. The Kuudestaan area – a map of the study area (left). Its location in Finland is denoted with the red square (right) (paper III).

Figure 10. GIS methodology used in this study to identify national potential of near future cutaway peatlands for bioenergy (paper II).

Figure 11. Energy inputs in both studied bioenergy production chain when fully biomass yield, 6 Mg ha^{-1}, can be achieve (paper I).

Figure 12. Peat extraction areas by municipalities in 2014 in Finland (© NLS 2014, paper II).

Figure 13. Kernel density estimation results of Finnish peat extraction areas. The search radius was 50 km. The colour illustrates the relative density only, not specific units (© NLS 2014, paper II).

Figure 14. Logistically the potential peat extraction areas and remote peat extraction areas in the case study area were determined by using Buffer tool in the ArcGIS program (paper III).

Figure 15. Kernel density map of the most potential areas to grow energy crops on cutaway peatlands by the year 2035 according to the respondents. The colour illustrates the relative density only, not specific units (© NLS 2014, paper III).

Figure 16. The area released from peat extraction per year which could be utilized in energy crop cultivation based on the landowner's willingness to do so in the case study area. Only over 15 ha units are considered (paper III).

Figure 17. Feedstock production sites and their division into clusters in the study area (given as numbers). Marks filled with colour indicate potential centralized biogas plant clusters based on a maximum transportation distance of 10 km for the different feedstocks (> 300 kW; >2400 MWh/a). Larger circles indicate potential farm biogas plants using a single farm's manure as feedstock (>100 kW; >800 MWh/a) (paper IV).

Figure 18. Dendrogram presenting centralized biogas plant clusters according to a transportation threshold of 10 km in the study region. Agglomerative clustering based on complete linkage was used to combine feedstock production sites as clusters when threshold distance was not exceeded. Clusters with a biogas potential exceeding 2,400 MWh/a are considered as clusters for potential centralized biogas plants (generating over 300 kW) These clusters can help to identify biomasses that can be integrated for bioenergy production. Green rectangles are used to indicate clusters, and symbols indicate type of feedstock. Biomass points (n = 189) and cluster IDs (total 43) are indicated in the bottom part of the figure. Biogas potentials are presented in blue and larger regions within the study area with yellow rectangles and region names (paper IV).

Figure 19. Example of the self-programmed optimization tool for identifying a suitable location for a centralized biogas plant by minimizing transportation distance when biomasses are sparsely distributed in a potential biogas production area (cluster 32 in Ähtäri municipality). The

model minimizes the sum of total transportation needs. The potential plant location is presented as an asterisk (gross biogas potential indicated below the asterisk in MWh). The biomass sources are manure from large farms. The size of the points are indicating the relative mass of the feedstock source. This cluster was not including cutaway peatlands.

Figure 20. Kernel density map of wood resources in the study area (tree stand volume in m^3 ha^{-1}. Darker blue colours indicate greater density of wood resources (forest inventory data: NFI 2013; roads: Digiroad 3/2017; municipal borders: NLS 2017). Potential wood terminal locations are located in areas with dense wood resources near the highest road classes. Color represents relative densities and not specific units (paper IV).

Figure 21. The process of using GI tools in bioenergy production planning. The original papers supporting the process are mentioned in brackets. The process is a circle where dialog between phases occurs.

List of Tables

Table 1. Selected GIS-based decision support models studied for different bioenergy applications (paper IV).

Table 2. Objectives, materials and analyses used in this thesis.

Table 3. List of analyses, methods and equipment used in the laboratory studies (paper I).

Table 4. Average diesel fuel consumed by tractor and the time for each harvesting operation of RCG on 1 ha of field and a biomass yield of 4 Mg (TS). These values were applied to the scenario calculations (paper I).

Table 5. Data used for transportation of biomass and other general assumptions used for the scenarios (paper I)

Table 6. Energy and emissions factors used for calculating energy inputs during the handling of fresh RCG at biogas and combustion plants (paper I)

Table 7. Subsidies which are available for farms and renewable energy producers in Finland (paper I).

Table 8. The composition of freshly harvested RCG (two cuts) for biogas production and combustion (paper I).

Table 9. Energy balance of fresh RCG grown on cutaway peatland for biogas production and combustion (paper I).

Table 10. Net income per hectare of cutaway peatland per year if RCG is fully utilized in a CHP plant on cattle-based farms (the cost of manpower is excluded) (paper I).

Table 11. Energy crop and biogas potential for future cutaway peatlands in Finland (paper II).

Table 12. Background information of the respondents and environmental values in the survey conducted in this study (n = 25, if less, then there were missing values) (paper III).

Table 13. Different after-use methods evaluated by the landowner of the peat extraction areas (paper III).

Table 14. The three most realistic bioenergy after-use alternatives from the landowner's perspective in every biomass type (paper III).

Table 15. Spearman's correlation coefficient (2-tailed, $p < 0.05$) between the significant variable pairs in the survey (paper III).

ABBREVIATIONS

AHP	The analytical hierarchical process
BMP	Biological Methane Potential
CHN	Carbon, Hydrogen, and Nitrogen analysis
CHP	Combined Heat and Power
DES	Decentralized Energy System
ELY	Centre for Economic Development, Transport and the Environment
GAF	GIS – Analytical Hierarchy Process – Fuzzy Weighted Overlap Dominance
GHG	Greenhouse Gas
GI	Geographic Information
GIS	Geographic Information Systems
GPS	Global Positioning System
HHV	Higher Heating Value
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change)
LHV	Lower Heating Value
MCE	Multi-Criteria Evaluations
NEY	Net Energy Yield
NLS	National Land Survey of Finland
PV	Photovoltaic panels
RCG	Reed canary grass
$R_{O/I}$	Energy input-to-output ratio
SDSS	Spatial decision support systems
T-F	Timothy-fescue grass mixture
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids

ORIGINAL PUBLICATIONS

Publication I Laasasenaho K, Renzi F, Karjalainen H, Kaparaju P, Konttinen J, Rintala J. 2019. Feasibility of cultivating fresh reed canary grass on cutaway peatland as feedstock for biogas production and combustion. Submitted manuscript to Mires and Peat Journal.

Publication II Laasasenaho K, Lensu A, Rintala J. 2016. Planning land use for biogas energy crop production: The potential of cutaway peat production lands. Biomass and Bioenergy 85:355–362.

Publication III Laasasenaho K, Lensu A, Rintala J, Lauhanen R. 2017. Landowner's willingness to promote bioenergy production on wasteland –future impact on land use of cutaway peatlands. Land Use Policy 69:167–175.

Publication IV Laasasenaho K, Lensu A, Lauhanen R, Rintala J. 2019. GIS-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas. Sustainable Energy Technologies and Assessments 32:47-57.

Author's contribution

I. Kari Laasasenaho wrote the first draft of the manuscript and participated in the laboratory experiment as the corresponding author. Henri Karjalainen and Francesca Renzi made partially the laboratory experiments and took part in commenting the manuscript. Prasad Kaparaju instructed the laboratory experiment and attended in writing the manuscript as well. Jukka Konttinen took part in writing and commenting the manuscript. Jukka Rintala gave valuable comments for the final manuscript and finalized the manuscript together with Laasasenaho.

II. Kari Laasasenaho wrote the first draft of the manuscript and made the ArcGIS analysis in the guidance with Anssi Lensu. Laasasenaho is also the corresponding author. Anssi Lensu and Jukka Rintala partially wrote and gave comments into the manuscript. The article was finalized with all co-authors.

III. As a corresponding author, Kari Laasasenaho wrote the first draft of the manuscript and carried out the survey and GIS analysis with ArcGIS program. Laasasenaho attended also data analysis. Anssi Lensu instructed the data analysis and partially planned the survey. He was also participated in writing process with Jukka Rintala and Risto Lauhanen. Risto Lauhanen commented the survey and took part of the data analysis. The article was finalized with all co-authors.

IV. Kari Laasasenaho wrote the first draft of the manuscript and collected the GI data. Laasasenaho is the corresponding author together with Anssi Lensu who attended in writing the article, made the data analyses with the R and ArcGIS programs, and gave comments to the data collection. Jukka Rintala and Risto Lauhanen wrote also parts of the manuscript and commented the calculations and the method. The article was finalized with all co-authors.

1 INTRODUCTION

Production of renewable energy from biomass is one method to replace fossil fuels and to mitigate the associated greenhouse gases. The use of biomass for bioenergy production is increasing, because of the shifting trend toward circular economy that replaces traditional fossil resources and mitigates climate change. Globally, currently the biggest portion of renewable energy is still produced from biomass by combustion but at the same time the sustainability of bioenergy production has been under discussion (Popp et al. 2014, Tomei & Helliwell 2016, Landolina & Maltsoglou 2017, International Energy Agency 2018).

The availability of biomass is important when bioenergy systems are developed. It is important to know where, how much, and when the biomass can be harvested. The shift from centralized, fossil fuel based, energy production to decentralized bioenergy production is always including geospatial questions, such as: Where is it sustainable and reasonable to produce energy? How can biomass supply be secured when the biomass production fluctuates, and where is the least costly location for the power plant when also transportation costs and GHG emissions of the mass are taken into account? Where are the consumers for the final energy? To answer these kinds of questions, geographic information (GI), which can be simplified as being location tied information, is needed. Geographic Information Systems (GISs) and spatial analysis methods can help to solve e.g. biomass resource allocation and energy plant location allocation types of problems (Long et al. 2013).

Recently, decentralized energy system and the production of renewable energy have been under development in many countries. The decentralized renewable energy production has been considered to be an environmentally friendly option for centralized, fossil fuel based, power plants. The main idea in distributed energy production is to decentralize the whole energy system so that the energy is produced in many smaller units instead of using large centralized plants. The most important advantage in the distributed energy production is the improvement of energy security and the possibility to produce energy from multiple resources (Sipilä et al. 2015). However, e.g. the bioenergy production has faced challenges, such as poor economic profitability and sufficient land availability (Landolina & Maltsoglou 2017).

Consequently, it is important to optimize the use of biomass in the current situation. One crucial step for establishing bioenergy plants is finding viable locations. GIS-based methods have been used for bioenergy potential estimations

(Long et al. 2013). However, further optimization is needed especially in rural areas for combining several biomass resources that are large enough and for solving logistical challenges due to long transportation distances. Spatial distribution of biomass resources and the most effective production location for energy can be investigated by combining location optimization methods and GIS. GIS-based methods have been used, for example, to estimate regional biogas potentials (Batzias et al. 2005, Ma et al. 2005, Vänttinen 2010, Höhn et al. 2014) or to find optimal locations for bioenergy plants (Xie et al. 2010, Sliz-Szkliniarz, & Vogt 2012, Silva et al. 2014, Bojesen et al. 2015, Franco et al. 2015, Mayerle & Figueiredo 2016, Villamar et al. 2016 etc.). Optimization methods have also been used, for example, to calculate the best supply chains of biofuels (Huang at al. 2010). When GIS and location optimization methods are combined, many advantages can be reached like better visualization of candidates in problem solution (Murray 2010). Consequently, accurate knowledge about spatial distribution of biomasses is needed. The bioenergy potential maps can be used as one tool for implementing national circular economy strategies in practice (e.g. Lehtonen et al. 2014). Also other renewable energy potential maps, such as solar radiation and wind potential maps, have been made earlier in countries, such as USA and Canada (Zhu 2011).

GIS methods can be used to assess potential land use for energy crop production. Traditionally, agrobiomass has been grown on agricultural lands. However, the sustainability of the energy production is uncertain as first generation energy plants are competing with food production (Landolina & Maltsoglou 2017). One solution for such unsustainable practice is to grow energy plants on non-agriculture areas such as cutaway peatlands. In Finland, approximately 70,000 hectares of peatland is under peat extraction (ELY 2014). These areas are offering a potential wasteland to promote bioenergy production. Each year, thousands of hectares of these lands are getting out of production as the productivity of these lands lasts usually only for a few decades (Salo & Savolainen 2008). Currently, there are over 20,000 hectares of cutaway peat production lands in Finland and it is estimated that about 44,000 hectares of peatlands will be out of production by year 2020 (Flyktman 2007). However, landowners are always making the decision about the after-use methods (Salo & Savolainen 2008). About 26–42 % of cutaway peat production lands are suitable for agriculture or energy crop growing depending on boulder-poor tills (Picken 2006). For instance, reed canary grass (*Phalaris arundinacea*) can be grown successfully on cutaway peatlands (Pahkala 1998, Parviainen 2007). Actually, in Finland, thousands of hectares of cutaway peatlands were brought under RCG cultivation since the 1990s (Pahkala et al. 2008). However, in practice RCG has appeared to be a challenging feedstock for combustion due to its characteristics e.g. lightness, slagging, and the need of an ideal co-firing ratio with the primary fuel

(Kautto 2014). This has resulted in a rapid decrease in cultivation area to as low as 6,000 ha by the end of 2015 (Farm business register 2015) and consequently led to a situation where significant amount of cutaway peatlands were out of intensive RCG growing due to technical and economic challenges. However, there has been a common interest to screen different after-use methods for cutaway peatlands and in that situation we wanted to study fresh RCG as feedstock for biogas production. The cultivation of fresh RCG makes bioenergy utilization different from spring harvested dry RCG and as a perennial plant, fresh RCG can be harvested twice a year in the same way as traditional Finnish fodder plants.

RCG is not the only alternative on cutaway peatlands as many Finnish domestic grasses like timothy grass (*Phleum pratense*) have been successfully tested in cutaway areas since the 1990's. However, according to plant experiments, reed canary grass is the most high-yielding grass species in peat lands (Puuronen et al. 1997). The yield per hectare can vary from 5 to over 12 Mg TS (total solids) on cutaway peatland when fertilization and liming are optimal (Puuronen et al. 1997, Lamminen et al. 2005, Parviainen 2007). According to Järveoja et al. (2013) reed canary grass is the best after-use alternative if GHG emissions are taken into consideration. Also, different willow species (*Salix* spp.) and wood species (such as birch, *Betula* spp.) have been grown and tested on cutaway peatlands (Paappanen et al. 2011, Jylhä et al. 2015). In general, wood and willow species have been analysed for instance in the sense of combustion and gasification (Hytönen 1996, Storalski et al. 2013), having biomass yield from 3 to 6 Mg ha^{-1} a^{-1} on cutaway peatlands (Hytönen 1996, Hytönen et al. 2016). For instance, vehicle fuel production could be a potential alternative, because Finnish government has made a decision to have at least 50,000 gas-powered vehicles on the roads by 2030. As a comparison, there were only 6,665 at least partly gas-powered vehicle in Finland in 2018 (Trafi 2019, Huttunen 2017).

More knowledge is needed on combining bioenergy production with sustainable land use forms on cutaway peatlands in the current situation. Previously, it has been challenging to assess the total potential of cutaway peatlands for bioenergy production as there has been a limited number of studies where the total bioenergy potential in different geographical scales is calculated and optimized. Consequently, the objective of this work was to detect potential cutaway peatlands for growing energy crops in national, regional and local scales with GIS-based analyses. The work is consisting also laboratory analyses and a questionnaire-based survey for landowners to assess the best technology for producing bioenergy on cutaway peatlands. At the beginning of the thesis, a state of art on decentralized bioenergy production, cutaway peatlands, and GIS is provided, following materials and methods, results and discussion of the data analysis. Recommendations for further research are given in the final chapter.

2 BACKGROUND

2.1 Decentralized bioenergy production

Decentralized energy systems (DESs) are studied worldwide (e.g. Kaundinya et al. 2009, Orehounig et al. 2015, Adil & Ko 2016, Bogdanov & Breyer 2016, Scheubel et al. 2017). DES means a system, in which energy is produced close to the final consumers, rather than at large and remote plants elsewhere (Sipilä et al. 2015). DES has been an interesting alternative for centralized energy system due to the potential of reducing transmission losses, supporting power supply in off-grid locations and decreasing carbon emissions (UN 2018, Vezzoli et al. 2018). Because DES is using multiple ways to produce energy, it allows the development of a competitive energy market for customers. It may also offer a sustainable and technically smarter choice to produce energy. The technical solutions, such as information technology and solid-state-electronics, have made it possible to control the power flow and grid stability. Consequently, renewable energy technologies, such as photovoltaic panels (PV), wind turbines or biomass based CHP plants (Combined Heat and Power) can be integrated into the same grid (Fig. 1) (IPCC 2007).

There are social advantages to use a DES. DES supports local business opportunities and enables local employment. E.g. local waste can be used in power plants, which might reduce the cost of local waste management. In a wider context, it can improve energy security and increase self-sufficiency in energy (Sipilä et al. 2014). Currently, there are many research trends, which are occurring in DES studies, such as distributed generation, micro-grids, and smart micro-grids (Adil & Ko 2016). Also, grid-connected and stand-alone systems have been studied (Kaundinya et al. 2009). There has also been a stronger research focus in storage systems and demand responses technology (IPCC 2007). DES is e.g. enabling the end-users becoming energy producers but also as active participants in network balancing operations (Altmann et al. 2010). On the other hand, the security control of the grids plays a more important role in the future and a smart grid control is needed (Sakumara & Miura 2017).

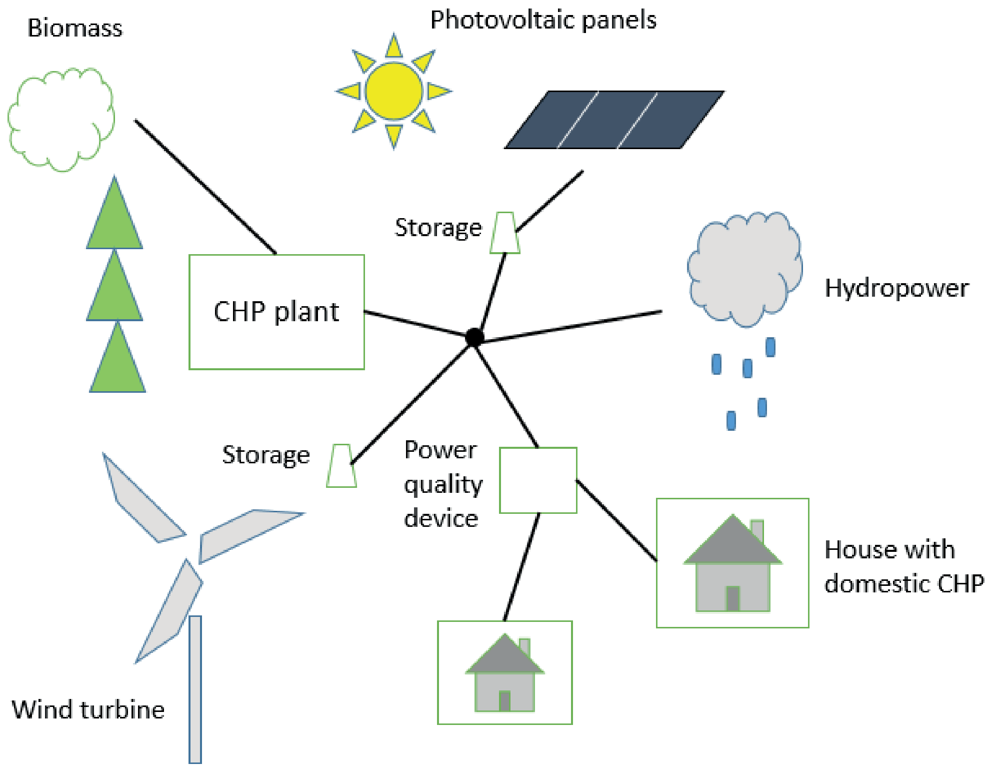

Figure 1. Decentralized energy production by using renewable energy (modified from Vezzoli et al. 2018). Large centralized power plants are replaced by smaller interconnected production units.

Despite many useful factors, decentralized energy production has also faced challenges and slowdowns. DES has suffered a wide range of technical, economic, socio-cultural, institutional, and environmental barriers (Yaqoot et al. 2016). For example, in Germany renewable energy production has been delayed by decision-making of the government and, for example, the decentralized energy system in Great Britain has faced social and governmental issues (Chmutina & Goodier 2014, Koistinen et al. 2014). In addition, the availability of biomass resources has been recognized as one of the notable barriers in bioenergy production (Nalan et al. 2009, Long et al. 2013, Yaqoot et al. 2016). Stakeholders play an important role throughout the various phases from the bioenergy plant planning to project implementation. By integrating the different stakeholders, it is possible to identify conditions that are applicable for bioenergy (Lloyd 2015). According to Yaqoot et al. (2016), availability has been seen as a barrier because the biomass growth is irregular and hence its use as energy source is intermittent. Also, Long et al. (2013) have noted that the spatial knowledge about biomass resources is imperfect and not all the resource types are in discussion. This is the reason why biomass resource allocation should be taken under further consideration.

Availability of biomass resources can be investigated by biomass resource allocation studies. Because smaller biomass based CHP units are needed in renewable DES, it is essential to know where it is reasonable and economically feasible to make bioenergy. Bioenergy has different limitations compared to e.g. solar and wind energy, because the biomass collection and transportation makes its assessment with GIS-based methods more complicated. That's why biomass needs e.g. logistic optimization (Zhang 2015). Also, sustainable production of biomass needs to be secured, which means e.g. land availability, intermediate biomass storage, and harmony with other land use such as food production (Landolina & Maltsoglou 2017).

2.2 Biomass production on cutaway peatlands

Peatlands are areas that have a peat layer naturally accumulated at the surface soil or sometimes in the edge of water bodies. Peatland ecosystem is including different types of organic soil wetlands or mires, such as bogs and fens, which are common especially in Nordic countries. Peat itself is partially decomposed organic material, originating mostly from plants, such as *Sphagnum* mosses, which has accumulated under anoxic, waterlogging, acidic, and poor nutrient conditions. Globally, there are almost 4,000,000 km^2 of peatlands and most of the peatlands are pristine. Anyhow, ca. 500,000 km^2 of peatlands are under agriculture, forestry, or peat extraction. Peat is important fuel and it was used 17.3 Mt as energy worldwide in 2008. Peat extraction is common especially in Finland as well as in Sweden, Ireland and the Baltic countries. (WEC 2013)

Finland is the biggest peat producer globally and it is the most densely mired country in the world. The total peatland is ca. 90,000 km^2 in Finland, and about 0.8 % (700 km^2) of the total peatland area is under active peat extraction (WEC 2013, ELY 2014). There are many applications for the extracted peat, such as horticulture, bedding material, and compost ingredient, alongside fuel use. Anyhow, the largest use is as energy in combustion plants (Savolainen & Silpola 2008, WEC 2013). About 4 % of the total energy consumption (1.35 EJ) was produced by peat in Finland in 2016 (Statistics Finland 2017), but there has been active debate going on in Finland to stop the use of peat as energy because of its impact on climate change.

In peat production the first phase, preparation, includes e.g. permission process, ditch digging and drainage, which could last from 11 to 15 years in Finland. Peat extraction itself can last usually from 15 to 30 years, depending on the weather and the thickness of the peat layer (Fig. 2). The extraction technology is usually divided between two different techniques: milled peat, which is based on turning and drying process, and sod peat, which is based on pressing the peat into cylindrical sods (Alakangas et al. 2011). The peat layer is on average 2 m thick, but the thickness depends on the topography. Usually, there are 40–50 peat extraction days annually in Finland (Salo & Savolainen 2008), which means that ca. 10 cm thick layer of peat is removed every year.

Environmental impacts, such as global warming effect (slowly renewable energy source) and loss of natural habitat, and impacts on water cycle and quality occurs during the peat extraction phase. The extraction is regulated by several laws in Finland (WEC 2013, Ministry of Environment 2015). Globally, GHG emissions caused by peat mineralization in drained peatlands have been under investigation (IPCC 2013). Soil-originated GHG emissions can be significant in drained peatlands, if there is a thick layer of peat and if oxygen can penetrate deep into the soil due to low water-table (e.g. cultivated peatlands in Grønlund et al. 2008, Shurpali et al. 2008, Kandel et al. 2013, Karki et al. 2014). As solutions, RCG growing and afforestation have been suggested to be suitable after-use methods on cutaway peatlands due to their positive affect on carbon cycle in peatlands (e.g. Mäkiranta et al. 2007, Shurpali et al. 2008, Shurpali et al. 2009, Gong 2013, Järveoja et al. 2013). However, ecosystem respiration and CO_2 balance of RCG cultivation on cutaway peatlands is especially dependent on soil moisture content and during wet years, the RCG cultivation can be as a sink for atmospheric C (Shurpali et al. 2009). On the other hand, there usually is a thin peat layer on cutaway peatlands because the peat is extracted from the peatlands by peat extraction activities (Salo & Savolainen 2008) and eventually this may cause less soil-originated GHG emissions during the after-use phase.

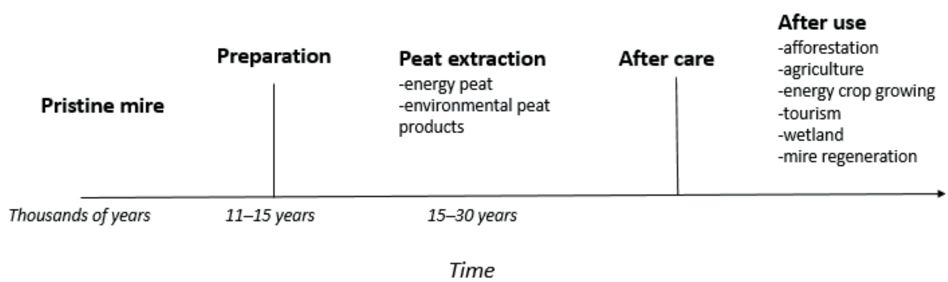

Figure 2. Peat extraction dynamics from pristine mire to after use phase (modified from Salo & Savolainen 2008).

Annually, 2,000–5,000 ha of peatlands are released from extraction in Finland (Salo & Savolainen 2008, Salo 2015). It has been estimated that totally 44,000 ha of peatland will be reclaimed by 2020 (Flyktman 2007). Cutaway peatlands can be defined as wastelands after the peat extraction. Wasteland is one form of marginal land and in this study wasteland is considered as a patch of land having no appreciable vegetative cover and degraded by natural as well as anthropogenic activities (Oxford Dictionary 2016). These soils could be considered to increase bioenergy production without causing a competition with food production. However, there are several after-use alternatives for cutaway peatlands, such as forestry, agriculture, nature conservation, wetland, and tourism, and the final after-use method is decided by the landowners (Leupold 2004, Salo & Savolainen 2008) (Fig. 3).

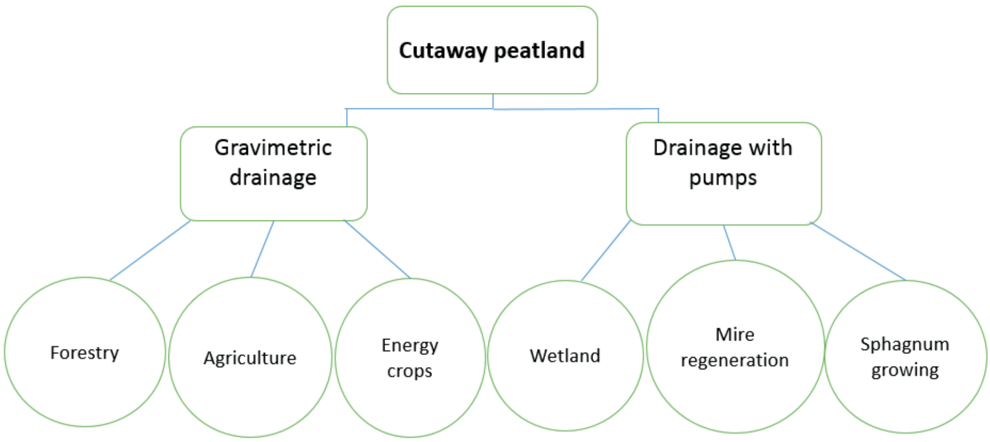

Figure 3. The most common after-use alternatives for cutaway peatlands based on drainage conditions during peat extraction (modified from Vapo 2017).

Currently, afforestation is the most common after-use method for cutaway peatlands in Finland. Another popular choice for cutaway peatlands is agriculture, especially in farm intensive regions, such as South-Ostrobothnia. However, several factors affect the choice: e.g., soil type, drainage conditions, landowners' interests, and possible transportation distance between the cutaway peatland and population centres. It is also important to realize that different sections of the peat extraction areas are not released from production at the same time, which can limit the after-use method (Salo & Savolainen 2008, Salo 2015). Furthermore, nature conditions, such as acid sulfate soils, topography and groundwater levels are crucial factors to take into account. E.g. acid sulfate soils can cause acidification if the anoxic soil is oxidized by e.g. lowering the ground water level. Oxidization can lead to the formation of sulfuric acid, which is then released to nearby water system. However, this can be avoided by using lime and land use planning (Nuotio et al. 2009). Currently, any after-use methods are not limited by law in general (Salo 2015, personal communication by Finnish Regional State Administrative Agencies 2019). If biomass growing is planned, the minimum analysis suggested for mineral subsoils are pH, sulfur content, and fine material (<0.06 mm) percentage (Picken 2006).

There is a long tradition to use cutaway peatlands for growing biomass. In Northern Europe, biomass, such as: willow, reed canary grass (RCG), and forest energy have been studied (Leupold 2004, Pahkala et al. 2005, Picken 2006, Parviainen 2007, Salo & Savolainen 2008, Järveoja et al. 2013, Jylhä et al. 2015). About 26–42 % of these areas are suitable for energy crop growing and 57 % for afforestation, based on the mineral sub-soil characteristics. Rest of the cutaway peatlands are usually too wet for biomass growth (Picken 2006). However, especially the poor nutrition is often a challenge. Phosphorus and potassium are the limiting nutrients on cutaway peatlands. A recommendation is that 10–20 cm thick layer of peat is left on the surface soil to improve soil fertility, if cutaway peatlands are used for agriculture or forestry (Pahkala et al. 2005, Salo & Savolainen 2008). Soil preparation, fertilization, and mixing of the bottom peat with the underlying mineral soil can improve plant growth conditions (Leupold 2004, Huotari et al. 2006, Salo & Savolainen 2008, Huotari et al. 2009). E.g. the RCG biomass yield is 6 Mg TS ha^{-1} a^{-1} in optimal growing conditions on cutaway peatlands (Parviainen 2007). For woody biomass, such as birch (*Betula* spp.) and willow (*Salix* spp.) the biomass yield is ranging from 3 to 6 Mg TS ha^{-1} a^{-1} having calorific values of 19.30 and 18.54 MJ kg^{-1} TS respectively (Hytönen 1996, Hytönen & Reinikainen 2013, Hurskainen et al. 2013, Hytönen et al. 2016, Alakangas et al. 2016).

Location of the cutaway peatland is an essential property in bioenergy planning, because the transportation distance of biomass to a biomass utilization plant has a notable effect on the net energy yield. Variety of factors are affecting to the feasible transportation distance, such as trailer capacity, plant species, and bioenergy conversion technology. E.g. in the case of RCG, the highest economically feasible transportation distance to a combustion plant is roughly 70–80 km with spring harvested biomass (Lötjönen & Knuuttila 2009).

In 2006, the total area under RCG cultivation was predicted to be around 100,000 ha in Finland by 2015 (Laitinen et al. 2006). However, dry harvested RCG appeared to be a problematic plant for combustion due to e.g. lightness, slagging, and the need of an ideal co-firing ratio with the primary fuel (Kautto 2014). As a result, large investments became necessary for the power plants (e.g. separate feeding line for RCG feedstock). Despite the known potential of RCG, these challenges led to a situation where the demand for RCG decreased and the cultivation area dropped to as low as 6,000 ha by the end of 2015 (personal communication with Vapo, Farm business register 2015). Nowadays, RCG has a minor role in energy business and it is usually sold as an agriculture bedding material (Kautto 2014).

Most of the studies related to cutaway peatlands are considering combustion of the produced biomass (e.g. Pahkala et al. 2005, Picken 2006, Parviainen 2007, Salo & Savolainen 2008, Järveoja et al. 2013, Jylhä et al. 2015). However, there is a limited amount of studies handling other possible energy conversion technologies. Different plant species, also suitable for cutaway peatland, have been studied in the sense of biogas, biodiesel, bioethanol, and gasification, but not applied directly on cutaway peatlands. Conversion technologies, other than combustion, can offer, in some circumstances, more sustainable production chain. E.g. biogas is one possible alternative as nitrogen rich digestate can be recycled on the cutaway areas. As a comparison, nitrogen is lacking from combustion ash, which increases the use of inorganic fertilizers (Lötjönen & Knuuttila 2009). This is the reason why RCG and other plants on cutaway peatlands should still be studied, even if some of the earlier experiments have been problematic. Biogas is a gas mixture, consisting mainly of methane (60 %), carbon dioxide (40 %), and other minor components. Biogas is formed in anaerobic conditions by microbes and the process is usually mesophilic (ca. 35 °C) or thermophilic (ca. 55 °C) in industrial scale. Microbes can produce biogas from organic wastes and biomasses, such as energy crops. Biogas production technology has been proved to be mature and well developed (Mao et al. 2015). Previous studies have shown that the BMP (biological methane potential) of RCG ranged from 246 to 430 dm^3 kg^{-1} volatile solids (VS) under mesophilic conditions (Lehtomäki et al. 2008, Metener 2009, Kandel 2013, Nekrošius et al. 2014, Butkute et al. 2014), which makes it a notable energy crop on cutaway peatlands. In Figure 4, biogas production and gasification have been described as potential energy conversion alternatives on cutaway peatlands.

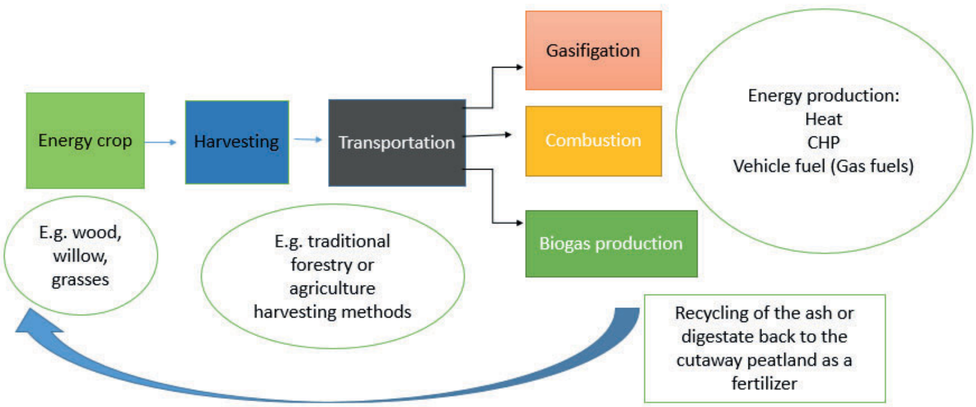

Figure 4. Bioenergy production alternatives for cutaway peatlands considered in this study.

It is essential to notice the spatial distribution of cutaway peatlands in bioenergy studies, because the cutaway areas are very fragmented, and the dynamics of the cutaway process is often complicated. If biomass for bioenergy is produced in the cutaway peatlands, mass production and allocation need very careful planning and synchronization. The releasing times are weather dependent, the ownership may cause challenges, and the biogas production may also need other than cutaway area originated biomasses. These facts make the use of cutaway peatlands a challenging and interesting research objective.

2.3 GIS as a tool for bioenergy planning

2.3.1 The nature of spatial knowledge

Geographic Information System (GIS) is "an information system which allows the user to analyse, display, and manipulate spatial data, such as from surveying and remote sensing, typically in the production of maps" according to the Oxford English Dictionary (2017). Sometimes, the same abbreviation refers to Geographic Information Science, which is an academic discipline, studying geographic information systems. However, the abbreviation of pure GI (Geographic Information) means, when simplified, information tied to a known location on the surface of the Earth (Longley et al. 2011). One of the first GIS was developed for the Canadian Government in the mid-1960's. The purpose was to build a computerized map-measuring system to identify the nation's land resources and their potential uses. Also, remote sensing, in which data is collected by an airplane or later with satellites, has been a major reason for GIS development since 1950's. First computer created maps were produced in 1960's and 70's but it was not until 1995 when UK was the first country in the world having complete digital map of its area in a database. Actually, many current GIS applications, such as GPS (Global Positioning System), were originally meant for military purposes and e.g. the Cold War, was a major technical driver in GIS development (Longley et al. 2011).

The nature of spatial knowledge is relatively diverse. GI can be handled with GIS applications, which are tools, usually computer-based systems that allow users to analyse spatial data, edit the GI, and present the results. There are multiple opportunities to utilize GIS, because usually it is rare that things would happen without any kind of connection to some known location. Especially, field studies need location-specific spatial information. The physical location can be described by using geographic coordinates, such as longitudes and latitudes (λ,φ), and it can include also elevation (*h*) and time (e.g. date). Then, spatial information can be handled for processing and storing in GISs. Practically, different digital map layers can be uploaded into a GIS application, and then e.g. connections or overlaps between different map layers can be calculated (Figure 5).

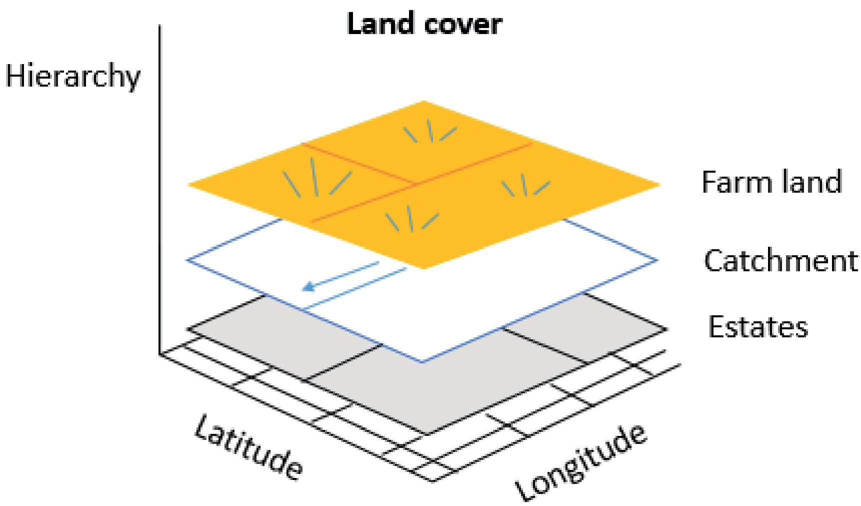

Figure 5. An example related to integration of different map layers in GIS (modified from Foote & Lynch 1995).

The data can be illustrated in GIS applications either as discrete (real objects such as agricultural fields, lakes, etc.) or as continuous fields (such as temperature). Traditionally, both of these abstractions can be stored as vector objects or as raster images. The location attribute references are points, lines, polygons, and sometimes even point clouds. GIS applications include many tools for data management and analyses, such as data analyses, geocoding, map layer overlay studies, slope and aspect estimation, hydrological and cartographic modelling, topological modelling, geometric network analyses, geostatistical interpolation, and Multi Criteria Decision Analysis tools (Longley et al. 2011, Kresse & Danko 2012).

The process where GIS is used as one of the decision support tools, is called, a spatial decision support system (SDSS), which have been under development since 1980's (Armstrong et al. 1986). Spatial decision making means a process where many decision alternatives, whose outcomes are location-tied, can be evaluated and ranked. Typical example of spatial decision making is location allocation problems, such as arranging of daily, or emergency services. SDSS are usually complex to develop and manage because there is a great number of variables, such as multiple objectives, multiple evaluation criteria, many interrelated causative forces, space-time-related factors, and a large amount of technical information included. SDSS is a sosio-technical process, which has a supporting role in decision making, and therefore decision makers themselves should never be ignored (Eldrandaly 2011, Zhu 2011). Consequently, limitations of SDSS have to be noticed and recently, guide books have been published concerning the use of GIS in commercial and non-commercial activity (e.g. Tomlinson 2013).

Nevertheless, even if GIS has a useful role in the integration of data, GI is still just a simplification of the real world (Figure 6). Accuracy of GI data depends on the scale of vector data and the resolution (or pixel size) of raster data. Large scale maps contain much more object detail compared to small scale maps. Even if there are maps with the same scale, the detail level is not always as high. Naturally, this may have a negative effect on the accuracy of the results. The most common limitations and challenges are related to data collection phase, simplified coordinate systems, measurement errors, imperfect models, and wrong judgments (Zhu 2011).

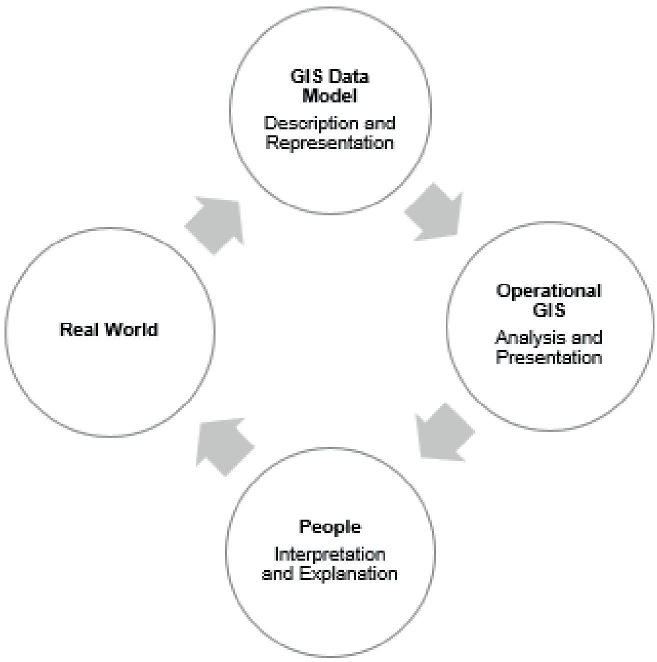

Figure 6. The role of data model in GIS (adapted from Longley et al. 2011).

2.3.2 GIS applications in bioenergy planning

Currently, GIS is widely utilized in scientific, governmental, business, and industrial use. Despite the fact that the roots of GIS are originally in geography, it can be used in disciplines such as biology (e.g. Maksimov et al. 2017), environmental science (e.g. Zhang et al. 2017), archaeology (e.g. Ruiz et al. 2017), climatology (e.g. Geletič et al. 2016), or even architecture (e.g. Wei et al. 2017).

Allocation of natural resources is one concrete example of using GIS. There can be found several studies globally, where biomass resources are mapped for bioenergy (Long et al. 2013). Many of them are related to biogas plant location optimization (such as Ma et al. 2005, Thompson et al. 2013, Höhn et al. 2014, Comber et al. 2015, Silva et al. 2017), combustion (Voivontas et al. 2001, Zhang 2015, Paredes-Sánchez et al. 2016), or to bioethanol (Hermann et al. 2014, Zhang et al. 2017) or biodiesel production (Beccali et al. 2009, Hermann et al. 2014, Niblick & Landis 2016). Many other studies are directly related to general biomass potential assessment for bioenergy (e.g. Lovett el al. 2009, Schreurs et al. 2011, Esteves et al. 2012, Haase et al. 2016, Vukašinovic´ & Gordic´ 2016). In general, studies can be divided into two GIS-based approaches, suitability analyses and optimality analyses. In suitability analyses, or sometimes called Multi-Criteria Evaluations (MCEs), buffers and spatial overlay analyses are usually used to assess land suitability for bioenergy. As a comparison, optimality analyses are used for location-allocation problems to match bioenergy supply and demand (Comber et al. 2015). Some studies concerning GIS methods and their applications for bioenergy are described in Table 1.

Table 1. Selected GIS-based decision support models studied for different bioenergy applications (paper IV).

GIS method	The method can be used for	Reference
Markov chain model	Forecasting the spatial distribution of Danish livestock intensity and future biogas plants	Bojesen et al. 2015
Mixed integer linear programming model	Biorefining plant location optimization by remote sensing and road network	Xie 2009
GIS – Analytical Hierarchy Process – Fuzzy Weighted Overlap Dominance (GAF) model	Decision support on suitable locations for biogas plants	Franco et al. 2015
Kernel density and p-median problem	Pinpointing areas with high biomethane concentration (Kernel density). Whereas p-median problem is applied by choosing facilities such that the total sum of weighted distances allocated to a facility is minimized	Höhn et al. 2014
Modified p-median problem	Evaluating biomass supply catchments (an extension to the p-median model)	Comber et al. 2015
Modified Dijkstra algorithm	A systemic approach to optimizing animal manure supply from multiple small scale farms to a bioenergy generation complex including conceptual modelling, mathematical formulation, and analytical solution.	Mayerle & Figueiredo 2016
A Multi-criteria Spatial Decision Support System integrated with GIS/ELECTRE TRI methodology	Addressing real-world problems and factual information (e.g. soil type, slope, infrastructures) in biogas plants site selection.	Silva et al. 2014
The analytical hierarchical process (AHP)	Decision support process, which captures qualitative and quantitative aspects of information (such as environment and economy) into GIS environment for the siting of anaerobic co-digestion plants	Villamar et al. 2016

There are a few important steps to follow when the GI data is collected. GIS is usually a network of five different elements: data, data producers, hardware, software and people. All these five elements need co-operation and maintenance (Longley et al. 2011). The bioenergy planning starts with preparation and material collection. If the data is not already in digital form, it has to be digitized and edited. Further improvements and evaluation, such as choosing the right coordination system, are crucial steps as well. When data is analyzed with GIS, it is usually a constantly evolving process including interaction between different steps (Fig. 7).

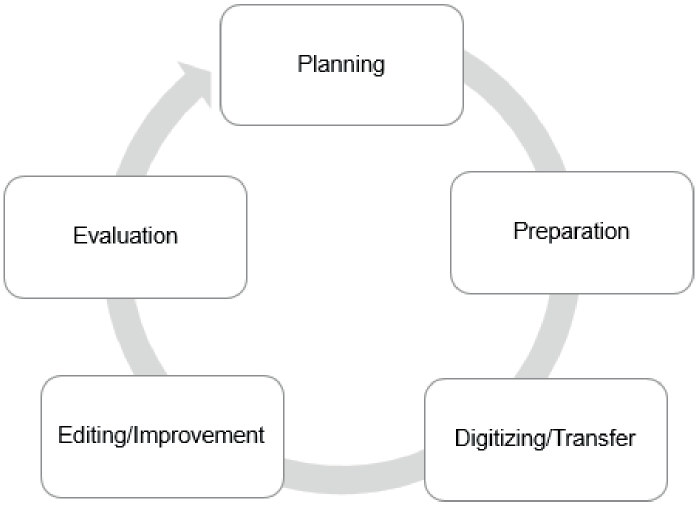

Figure 7. Different stages in GIS data collection (adapted from Longley et al. 2011).

According to Calvert et al. (2013), GIS can offer several advantages in renewable energy production planning. The production planning is a process where several key stakeholders are involved. E.g., interdisciplinary co-operation is done to share inputs and outputs. In governmental stage, GIS is producing information about resource inventories and spatial planning. Further on, GIS can be a powerful site searching and assessment tool for industrial purposes. The utilizing of GIS in renewable energy planning includes three stages, which are improving the accuracy of the analysis (Fig. 8). In the first stage (resource inventories) GIS is used to identify the theoretical potential of renewable energy resources. At the second phase (resource accessibility), e.g. economic circumstances can be analysed with different limiting factors, such as overlay and map algebra techniques. In the final stage, local knowledge can be added e.g. by using a questionnaire.

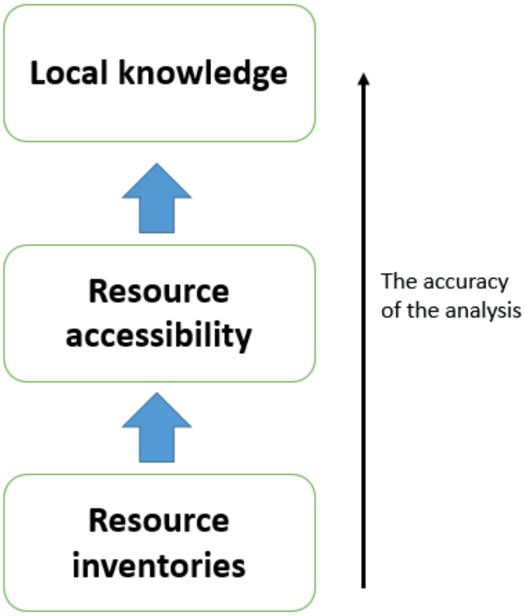

Figure 8. Progress in renewable energy mapping (modified from Calvert et al. 2013).

There is a long tradition to use GIS especially in forestry. GIS has had a great influence in forestry, where the spatial variability of forest biomass can be recognized more precisely, especially using remote sensing. It is possible e.g. to calculate the amount of forest biomass per hectare and assess forest sales revenues. There can be versatile ways to get the spatial data about the forest, and GIS is helping to both store and handle the often quite large amounts of data. The utilization of GIS is developing all the time e.g. by using laser scanning by airplane or drones. The same techniques, as the ones that are used in remote sensing, have become more popular also in agriculture. GI helps to plan roads for forest industry, but also to identify protected nature areas and vulnerable environments (Räsänen 2014, Holopainen et al. 2015). Altogether, it has been recognized that GIS has an emerging role in sustainable bioenergy planning (Hiloidhari et al. 2017).

Currently, the capacities of data storage and handling have increased significantly. This has made it possible to perform more complex tasks and to solve more complex problems. E.g. new algorithms are being developed all the time (Miller et al. 2016). According to Maliene et al. (2011), the future professional GIS applications, together with artificial intelligence could be powerful problem solving tools in near future in the world. GIS has also proved to be capable to work as an operational planning tool. The operational planning tool allows the user to combine real time data such as energy market prices in hourly basis. This makes GIS a powerful tool to handle information e.g. in the case of combining GI data and Internet of Things (IoT). GIS can play significant role in energy business development, since it brings effectiveness and savings also into bioenergy planning (Resch et al. 2014).

3 RESEARCH OBJECTIVES AND QUESTIONS

The objective of this work was to assess the potential of cutaway peatlands for growing energy crops in national, regional and local scales in Finland. The objective was to assess this potential with laboratory and scenario studies, questionnaire, and GIS-based analyses. It was studied whether fresh harvested RCG from cutaway peatland could be used for bioenergy production (paper I) and where are the most favorable areas for such practices at national and regional level (paper II). The spatial configuration and local bioenergy potential of cutaway peatlands were investigated in the individual studies (papers II-IV).

The first objective (paper I) was to calculate the energy yield (biogas and combustion) and chemical composition of fresh RCG grown on cutaway peatland. Based on the laboratory studies, the economic feasibility and cultivation originated CO_2 emissions were evaluated.

The second objective (paper II) was to identify the location of future cutaway peatland in Finland and to apply GIS methods to calculate national and regional potential to produce biogas from RCG and T-F (timothy-fescue mixture). The aim was to identify the best locations to support farm-scale biogas plants.

The third objective (paper III) was to study landowners' after use choices on cutaway peatlands. The aim was to integrate the willingness to grow bioenergy crops based on the survey and GI tools to identify the best places for bioenergy production in local scale.

At the end, the objective (paper IV) was to use location allocation methods to identify optimal locations for biogas plants and wood terminals in a case study area consisting of four municipalities. The data from the above mentioned studies was combined with data about other available organic wastes on the study area. The main aim was especially to support decision making in the field of bioenergy and use interdisciplinary methods in bioenergy planning.

4 MATERIALS AND METHODS

An overview of the objectives and methods conducted in this thesis is presented in Table 2. Bioenergy potential of fresh RCG grown on cutaway peatland was assessed in laboratory studies (paper I). GIS-based methods were used to assess national and regional cutaway peatland potential (papers II, IV). Additionally, a survey was used in studying landowners' perspective on after use of cutaway peatland related questions (paper III).

Table 2. Objectives, materials and analyses used in this thesis.

Objective	Materials/Programs	Analyses/Methods	Paper
To assess the suitability of fresh RCG for bioenergy production on cutaway peatland	RCG field studies, laboratory studies, previous biomass studies / Microsoft Excel	BMP assays, bomb calorimeter, TS,VS and ash, Klason lignin, TKN, VFA's, CHN, NEY, Ro/i, previous studies (CO_2 calculations and energy yield)	I
Identify the location of future **cutaway peatland in Finland** and develop GIS method for planning regional energy crop growing	Topographic database, Acid sulphate soils (GTK), previous biomass studies / ArcGIS v. 10.2, Microsoft Excel	ArcGIS tools: Selection, Merge, Intersection, Spatial Statistics (Calculate area), Summarize, Spatial Analysis (kernel density)	II
To assess **landowners' perspective** for using cutaway peatlands for bioenergy in the case area.	Paikkatietoikkuna web service, Evira, NLS (the estates and farm locations) / Wepropol 2.0 program (the questionnaire), SPSS ver. 22.0., ArcGIS ver. 10.3, Microsoft Excel,	Spearman correlation coefficent, Paikkatietoikkuna web service: Measure an area on the map, ArcGIS: Selection, Merge, Intersection, Buffer, Spatial Analysis (kernel density)	III
To use location allocation methods to **identify optimal location for bioenergy** plants in the case study area.	Local waste stream information, previous studies, raster data on forest wood volume, Luke, NLS, Evira, Digiroad, municipal border map / Microsoft Excel, R v. 3.4.3, ArcGIS v. 10.5.1	ArcGIS tools: Kernel density, raster-to-point tool R and its add-on packages: shp2graph v. 0.3 and igraph v. 1.1.2; hierarchical clustering, dendrogram, self-programmed logistic optimization tool	IV

GTK = Geological Survey of Finland
Evira = Finnish Food Safety Authority
NEY = Net Energy yield
Ro/i = Energy input-to-output ratio
VFA = Volatile Fatty Acids
CHN = Carbon, Hydrogen, and Nitrogen analysis
Luke = Natural Resources Institute Finland
NLS = National Land Survey of Finland
TKN = Total Kjeldahl Nitrogen

4.1 RCG sampling

Bioenergy potential of freshly harvested RCG for bioenergy on cutaway peatland was assessed with several chemical analyses and literature concerning farming practices (paper I). RCG, growing at two cutaway peatlands located in Ilomantsi (N 62° 54.36', E 31° 18.22') and Alajärvi (N 62° 59.41', E 24° 18.05') were sampled for this study. Both locations were left out of intensive RCG growing due to technical and economical failures in RCG combustion in Finland. The average temperature and precipitation in 2014, were 4.5 °C and 565 mm, at the nearest weather station Möksy (N 63.09°, E 24.26°, Alajärvi) and 4.1 °C and 560 mm at Mekrijärvi (N 62.77°, E 30.98°, Ilomantsi) respectively (Finnish Meteorological Institute 2016). The RCG variety palaton was planted in the year 2002 in Ilomantsi and in 2004 in Alajärvi and both locations were fertilized (60 N kg ha^{-1}, 50 P kg ha^{-1}, 30 K kg ha^{-1}) in 2011.

Four sampling areas were selected from adequately growing locations (10–50 hectares of extensively cultivated RCG fields) by using a collection frame (0.25 m^2) and the minimum distance between each sampling spot was at least 10 m. The samples were harvested by cutting the plants at the height of 3 cm from ground level. The first harvesting time was on the 16th of June 2014 at Alajärvi (10 years after planting) and on the 18th of June 2014 at Ilomantsi (12 year after planting). The second harvest was done on the 5th of August (Alajärvi) and on the 7th of August (Ilomantsi) in 2014. The samples were stored in cooled rubber bags and plastic buckets, which were flushed with nitrogen gas (99 % pure). In the laboratory, the storage was carried out in 4 °C. Fresh RCG samples were cut with scissors and milled to 2 cm particle size for the biochemical methane potential (BMP) assays, whereas the rest of the samples were dried and preserved in room temperature until used for other analyses.

4.2 Chemical analyses

All chemical analyses, methods and equipment used in this study are listed in Table 3 (paper I). Short descriptions of the arrangements and equations are described in this chapter.

Heating value of RCG was measured by using a bomb calorimeter (gross calorific heating value). A method, where paraffin and cotton wire were used to prevent the loss of milled RCG, was carried out (University of Jyväskylä 2014). The heating value of -45.1 kJ g^{-1} for paraffin, -5.9 kJ g^{-1} for iron wire, and -17.5 kJ g^{-1} for the cotton string were used. The energy released from iron wire, paraffin and cotton wire were taken into account by subtracting the values from the final results using Eq. 1 (Alakangas et al. 2016).

$$HHV = \frac{C\Delta T - Q_h}{m_{sample}} \quad (1)$$

where C is the heat capacity of the calorimeter (8773.4 ± 9.5 J K^{-1}), ΔT is the temperature difference (K) reading on the thermometer which has an error of ± 0.002 K, m_{sample} is the mass of the dry sample (g) with weighing error of ±0.001 g and Q_h is the energy released from the combustion of the paraffin layer, the iron wire, and the cotton string (J).

The BMP was determined in three parallel batch assays. Inoculum, used in laboratory experiment, was originated from a farm-scale biogas plant (Metener Oy biogas plant Laukaa, Finland). The biogas plant (mesophilic process) was treating cattle manure, fodder and industrial based sewages. Glass bottles with 0.75 dm^3 working volume was used in the assays. For the 1st harvest, inoculum of 9.27 ml RCG of 9.92 g for Alajärvi samples and 9.81 g for Ilomantsi samples were added to reach inoculum to substrate VS ratio of 1. The corresponding values for the 2nd harvest were 9.01 mL of inoculum, 4.84 g for Alajärvi samples and 4.80 g for Ilomantsi samples, respectively. These values were chosen in the 2nd harvest to reach an inoculum to substrate ratio of 2. 2.25 g of $NaHCO_3$ was added to adjust the nearly neutral pH. Anoxic conditions were created into the bottles by flushing the headspaces with N_2 (99 % purity) for 3 min. The bottles were then sealed by rubber stoppers and preserved statically in 35±1˚C. The formed biogas was collected into aluminum bags. The BMP experiment was carried out for 63 to 68 days in both harvests.

In addition, ash, TS, and VS content, pH, CHN (Carbon, Hydrogen, and Nitrogen analysis), Klason-lignin, TKN (Total Kjeldahl Nitrogen), VFAs (Volatile Fatty Acids, including acetic acid, iso-butyric and butyric acid, propionic acid, iso-pentanoic (iso-valeric) and pentanoic (valeric) acid and hexanoic (caproic) acid) and the composition of hydrocarbons were measured (Table 3).

Table 3. List of analyses, methods and equipment used in the laboratory studies (paper I).

Analyses	Method and equipment
Heating value	Bomb calorimeter (IKA-Kalorimeter C400 Adiabatisch) equipped with a thermostat (Julabo F20 HC, 17.2 °C) and a thermometer (IKA-TRON DKT400) were used. Air dried RCG was milled to 2 mm size particles. The sample was then further dried to 100 °C for less than 30 min on a hot plate. When pressurizing the bomb, the dried sample was covered with paraffin to prevent the loss of fuel. Cotton string was attached to the iron wire to ensure the ignition of paraffin (applied method, University of Jyväskylä 2014).
Methane content	Gas chromatograph fitted with flame ionization detector (STP, T = 293 K, p = 1 bar, Perkin-Elmer Clarus 500, Perkin Elmer Elite Alumina 30 m x 0.53 mm) was used (Lehtomäki 2006). Operation conditions were as follows: oven 100 ºC, detector 225 ºC and injection port 250 ºC, and argon was used as a carrier gas (Bayr 2014).
Biogas volume	Water displacement column with 0.05 dm^3 accuracy was used.
Ash, TS, VS	(APHA 1998) standard was used
pH	pH meter (Phenomenal VWR) was used
C, H, N content	(Vario EL III 2005)
Klason-lignin	Two-step strong acid hydrolysis was used (Sluiter et al. 2008). Dried samples (0.3 g) were placed in a 100 mL bottle and sulfuric acid were added (3 mL with concentration of 72 %), then having water bath for 1 h at 30 °C. The second stage was carried out as follows: 84 mL of deionized water was added to dilute sulfuric acid concentration to 4 %. Then, after autoclave for 1 h (1.4 bar, 121°C), the samples were vacuum filtered (glass filtering funnel crucibles). The residues (acid insoluble lignin) were dried in an oven at 105 °C for 16 h. The final Klason-lignin content was determined after subtracting the ash content after incinerating (determined at 550 °C for 3 h).
TKN	Performed according to Tecator application note (ANALYTICAL, Perstorp; 1995) and Kjeltec system (Tecator Kjeltec System 1002 distilling unit) was used.
VFAs	Gas chromatograph (GC-2010 PLUS Shimadzu) fitted with FID and Perkin Elmer Elite FFAP column (30 m, 0.32 mm, 0.25 µm) (Bayr 2014) were used. The analysis included the following acids: acetic acid, iso-butyric and butyric acid, propionic acid, iso-pentanoic (iso-valeric) and pentanoic (valeric) acid and hexanoic (caproic) acid.
Hydrocarbons	The samples were dried at 40 °C for 1–2 days and homogenized to <1 mm particle size. Dry matter (DM) content was analyzed using a Sartorius MA 30 moisture analyser at 105 °C. High-performance liquid chromatography (HPLC) system equipped with a Shimadzu RI-detector was used to determine monosaccharides (d-glucose, d-xylose and l-arabinose) on a Dionex Summit (Sluiter et al. 2008).

4.3 Scenario studies for biogas production and combustion of fresh RCG

In this study, two scenario studies were used to assess the use of fresh harvested RCG for biogas production and combustion (paper I). The scenario studies included energy needs from cultivation of fresh RCG (with two cuts annually), CO_2 emissions from machineries, economic incomes and costs of cultivation and energy production. The scenario calculations are presented per 1 ha of cutaway peatland with multiple background parameters, assuming that the RCG was grown on a larger area of 15 ha (personal communication with Vapo). The average transportation distance to the energy plant was assumed to be 5 km (Tables 4–6).

As RCG is a perennial plant, the planting cycle was assumed to be 5 years. Consequently, energy input and output per each year were calculated separately. In the land preparation phase, the RCG seed rate of 10 kg ha^{-1} was assumed, whereas in the harvesting phase the biomass was utilized from the second cultivation year onwards (with 4 TS Mg ha^{-1}, Pahkala et al. 2005). The biomass from the subsequent three years were 6 TS Mg ha^{-1} (Ahokas 2013). The RCGs was assumed to be ensilaged for biogas production while for combustion drying and baling was included (moisture content target of 15 %). The total N fertilizer need of 60 + 60 N kg ha^{-1} was assumed before and after the early 1st cut (40 N kg ha^{-1} during the plantation year, Pahkala et al. 2005). In the biogas scenario, the cultivation was assumed to be annually fertilized partly with the digestate after the second year, while in the combustion scenario fertilization was assumed to be done totally with inorganic fertilizer.

4.3.1 Energy input and output on cutaway peatland

Energy input and output were calculated to assess cultivation of fresh RCG. Literature was applied for agronomic practices and average fossil fuel consumption of RCG cultivation in both scenarios (Pahkala et al. 2005, Ahokas 2013). The energy content for diesel fuel was assumed to be 10.5 kWh dm^{-3}. In both scenarios, the direct energy inputs included machinery used for:

1. Land preparation and planting (ploughing, 2x harrowing, flattening and seeding, fertilization)
2. Harvesting and transportation (based on Finnish agronomic practices, Ahokas 2013)
3. Processing and handling of the biomass at the energy plant

In the biogas scenario, the harvesting was assumed to include cutting, windrowing, chipping and ensiling, transportation, and fertilization. In the combustion scenario, the harvesting was assumed to include cutting, fluffing (3x), windrowing, baling, transportation of bales, and fertilization.

In the biogas and combustion plants, energy requirements for processing and handling was assumed to include the feeding of the biomass with a front load tractor (biogas) and energy required for conveying bales to mechanical crushing (combustion). The indirect energy required for manufacture of mineral fertilizer was assumed to be 2 kg of fossil oil per 1 kg of inorganic N fertilizer (Wood & Cowie 2004). However, the handling of biogas digestate or combustion ash in energy plants were not included in the scenarios (Tables 4–6).

Energy output was calculated as an average BMP (methane energy yield of 10 kWh) and higher heating value (HHV) of the experimental results and annual biomass yield from 4 to 6 Mg TS ha^{-1}. The power plant (CHP) operating efficiency (η) was assumed to be 0.87 with 32 % of electricity and 55 % of heat for both biogas and combustion plants (Winquist et al. 2015). All power plant integrated equipment (e.g. conveyors) and wet biomass heating were assumed to be part of the plant's efficiency factor.

Table 4. Average diesel fuel consumed by tractor and the time for each harvesting operation of RCG on 1 ha of field and a biomass yield of 4 Mg (TS). These values were applied to the scenario calculations (paper I).

Farm operation	Diesel fuel consumption (dm^3)	Reference	Time (h)	Reference
Land preparation and planting				
Ploughing	30	Ahokas 2013	1.1	Pahkala et al. 2005
Harrowing (2x, S harrow)	10	Ahokas 2013	1.15	Pahkala et al. 2005
Planting and fertilization	6	Ahokas 2013	0.61	Pahkala et al. 2005
Flattening (pesticide addition, excluded*)	6	Target*	0.53	Pahkala et al. 2005
Fertilization (2x during the harvesting years)	12	Target*	–	–
Liming	6	Target*	–	–
Loose harvesting for biogas				
Mowing	5	Ahokas 2013	0.50	Pahkala et al. 2005
Windrowing	2	Ahokas 2013	–	
Crushing and collection with target chipper	9	Ahokas 2013	0.60	Pahkala et al. 2005
Transportation & ensilation	0.6 (dm^3 km^{-1})	Ahokas 2013	0.11	Pahkala et al. 2005
Baling for combustion (moisture 15–20 %)				
Mowing	5	Ahokas 2013	0.50	Pahkala et al. 2005
Fluffing (3x)	6	Ahokas 2013	–	
Windrowing	2	Ahokas 2013	–	
Baling	8	Ahokas 2013	0.72	Pahkala et al. 2005
Transportation (including bale lifting and transport with a trailer)	0.6 (dm^3 km^{-1})	Ahokas 2013	0.36	Pahkala et al. 2005

* The value was used as a target value for scenario calculations

Table 5. Data used for transportation of biomass and other general assumptions used for the scenarios (paper I).

Transportation	Unit	Parameter	Reference
Bales for combustion			
1 bale	m^3	1.47	Laurila 2006
Volume needed in the trailer	m^3	1.88	This study
Trailer volume	m^3	30	Assumption
Density of bale	Mg m^{-3}	0.35	Taminco 2016
TS content	%	80	Target*
Loose harvesting for biogas			
Density of grass	Mg m^{-3}	0.3	Taminco 2016
TS content	%	27	This study
Trailer capacity	Mg	9	Höhn et al. 2014
General			
Transportation distance	km	5	Target*
Biomas yield	TS Mg ha^{-1}	6	Target*
Cutaway peatland needed for power plant	ha	50	Target*
Total N conversion factor		0.55	Prade et al. 2012
Power plant overall efficiency	η	0.87	Target*

* The value was used as a target value for scenario calculations

Table 6. Energy and emissions factors used for calculating energy inputs during the handling of fresh RCG at biogas and combustion plants (paper I).

Handling in a farm-scale power plant	Unit	Parameter	Reference
Front loader capacity	m^3	1	Target*
Tractor front bale lifter	Bale	1	Target*
Distance between storage and feeding line	m	50	Assumption
Diesel consumption	$L\ h^{-1}$	5	Ahokas 2013
Time consumption per bale/front loader	min	4	Estimation
Bale mass	kg	350	Taminco 2016
Density of loose harvested RCG	$kg\ m^{-3}$	300	Taminco 2016
TS content of loose harvested RCG	%	0.27	This study
TS content of baled dry grass	%	0.8	Target*
Weima WL bale crusher in combustion plant	kW	55	Laurila 2006
Power	kW	55	Laurila 2006
Width	mm	1.5	Laurila 2006
Diameter	mm	368	Laurila 2006
Consumption of electricity	kWh	30	Laurila 2006
Productivity	bale h^{-1}	0.86	Laurila 2006
Average electricity emission factor in Finland	$gCO_2\ kWh^{-1}$	220	Motiva 2016

* The value was used as a target value for scenario calculations

4.3.2 Net energy yield and energy balance

Net energy yields (NEYs) of the biogas and combustion scenarios were calculated by subtracting the sum of direct (E_{Idir}) and indirect (E_{Iind}) energy inputs from energy output (EO) with Eq. 2 (Prade et al. 2012).

$$NEY = EO - (\sum EI_{dir} + \sum EI_{ind}) \quad (2)$$

In the combustion scenario, the heating value of the RCG as received (energy output in 15 % moisture) was calculated by using Eq. 3 (Alakangas et al. 2016).

$$Q_{net,ar} = Q_{net,d} \times \frac{100 - M_{ar}}{100} - 0.02441 \times M_{ar} \quad (3)$$

where $Q_{net,ar}$ is the heating value of RCG as received (MJ kg^{-1}), $Q_{net,d}$ is the lower heating value (LHV) of the fuel in TS (MJ kg^{-1}) and M_{ar} is moisture content of RCG as received (15 %). The value 0.02441 (MJ kg^{-1}) is the energy needed to vaporize the moisture out from RCG. LHV was calculated by using Eq. 4 (Alakangas et al. 2016).

$$Q_{p,\,net,\,d} = Q_{v,\,gr,\,d} - 212.2 \times w(H)d - 0.8 \times [w(O)d + w(N)d] \qquad (4)$$

where $Q_{p,net,d}$ is the LHV (kJ kg^{-1}), $Q_{v,gr,d}$ is the experimental HHV (kJ kg^{-1}), and w(H)d, w(O)d and w(N)d correspond to the amount of each element (mass fraction) in dry fuel.

In the both scenarios, the energy output-to-input ratio ($R_{O/I}$) was calculated by dividing the energy output by the energy input with Eq. 5 (Prade et al. 2012).

$$R_{O/I} = EO/(\sum EI_{dir} + \sum EI_{ind}) \qquad (5)$$

4.3.3 CO_2 emissions in cultivation

The produced CO_2 emissions in biogas and combustion scenarios were calculated based on the diesel consumption of machinery on RCG cultivation. The emission factor for diesel was 265 g CO_2 kWh^{-1} (Alakangas et al. 2016, Hippinen & Suomi 2012). Also, the saved CO_2 emissions from the use of renewable energy utilization (NEYs) were compared to the emissions produced using fossil fuel with diesel engine efficiency of 0.85 (ZREU 2001). The soil-originated emission caused by peat mineralization was not considered in the scenarios.

4.3.4 Economic profitability

The economic viability of biogas and combustion scenarios were assessed by calculating the incomes and costs of RCG cultivation. The incomes included income from selling the produced renewable electricity (32 %) and heat (55 %) and the EU agriculture subsidies in Finland (C2 area) (Winquist et al. 2015, ELY 2015). Also, tariffs concerning renewable energy selling were included (Table 7).

The costs of RCG cultivation included the following: diesel (0.80 € dm^{-3}), RCG seeds (5.5 € kg^{-1}), N fertilizer (1.2 € kg^{-1}), fodder preservative (1.23 € dm^{-3}), electricity (0.1 € kWh^{-1}) and bale wire (11.43 € ha^{-1}) (Pahkala et al. 2005, Winquist et al. 2015, Hankkija 2016, Kivijärvi 2016). Even though liming was not included into the energy input calculations due to irregular need of pH adjustment on cutaway peatlands, it was calculated on to the economic profitability with 334 € ha^{-1} (Salo & Savolainen 2008, Peltotuhka 2016). The cost of manpower was not included in the scenarios.

Table 7. Subsidies which are available for farms and renewable energy producers in Finland (paper I).

Energy or farm subsidy	Unit	Price	Reference
District heating (without subsidy)	€ MWh^{-1}	60.93	Winquist et al. 2015
Microelectricity producer (without tariff)	€ MWh^{-1}	57.9	Winquist et al. 2015
Tariff (over 100 kVA only microelectricity)	€ MWh^{-1}	83.5	Winquist et al. 2015
Tariff (over 100 kVA and with heat premium)	€ MWh^{-1}	133.5	Winquist et al. 2015
Plant-based farm*	€ ha^{-1}	477	ELY 2015
Cattle-based farm*	€ ha^{-1}	537	ELY 2015

* Including compensatory allowance, basic subsidies (Cap's) and environmental allowance and cattle raise in cattle based farm

4.4 The study area

A suitable case study area was selected, based on where the future cutaway peatlands are being released in Finland (paper II). The case study area, called "Kuudestaan" region in Ostrobothnia, Finland, was selected to investigate landowners' perspectives towards bioenergy production and also for logistical optimization of bioenergy plants (Fig. 9, paper III and IV). "Kuudestaan" region is one of the European Union's (EU) Rural Development Action Group. The region has strong forestry and agriculture, and also peat extraction intensity. The Rural Development Action Group has highlighted the energy crop production as an after-use alternative for the cutaway peatlands in its strategy. The municipalities in the region are Alavus, Kuortane, Soini, and Ähtäri, and the total population size is ca. 25,000 and the total area 3,119 km^2 (Erkkilä & Ahonpää 2014, NLS 2017a).

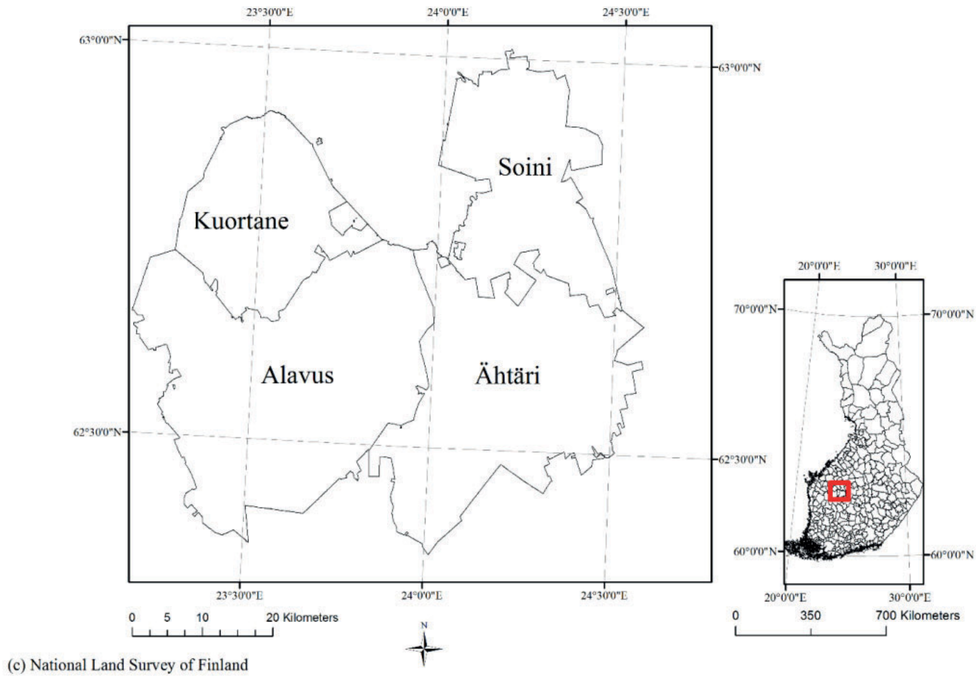

Figure 9. The Kuudestaan area – a map of the study area (left). Its location in Finland is denoted with the red square (right) (paper **III**).

4.5 GIS studies

4.5.1 Kernel density analyses for assessing potential cutaway peatlands for bioenergy production

Kernel density analyses were used in papers II–III to assess local, regional and national potential in using cutaway peatlands for bioenergy production. The national potential analyses were performed with ArcGIS v. 10.2 (ESRI Inc., Redlands, CA) ArcMap program and the current peat extraction sites were identified with the MapSite service (produced by National Land Survey of Finland, NLS) in paper II. Then, Topographic database (© NLS, 2014 supplied as 12 x 12 km map tiles) was used in the ArcMap program to extract the soil class 32,113 (organic soil mining polygons), and the map tiles from whole country were combined with Merge tool.

The map layer, which contained all peat extraction areas in Finland was divided by municipalities and counties (© NLS, 2014) with Intersection tool. Calculate Areas (in the Spatial Statistics tools) and Summarize tools were then used to calculate the regional total of peat extraction area. All area calculations were made with Field calculator in the attribute table.

Acid sulfate soils were taken into account by using a map produced by Geological Survey of Finland (GTK). The soils under high and even low risk of acidification were noted and Intersection, Calculate area, and Summarize tools were used by regions.

The most intensive peat extraction sites in Finland were identified by using Kernel Density (in the Spatial Analysis tools) in ArcGIS. For this study, the peat extraction areas (originally presented as polygons) were converted into points with Feature to Point tool. The raster size used was 1 km and search radius was 50 km. Each kernel was weighted by the size of peat extraction area. The methodology in paper II is summarised in Fig. 10.

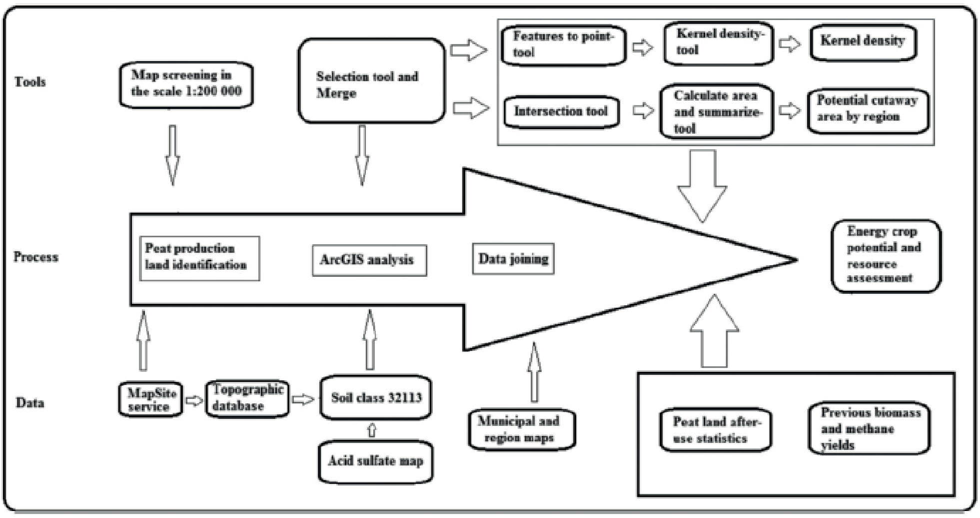

Figure 10. GIS methodology used to identify national potential of near future cutaway peatlands for bioenergy (paper II).

The energy crop potential was calculated based on an assumption that 30 % of the cutaway peatlands are suitable for growing energy crops (Picken 2006, Vapo 2014). The assumption was that every peat extraction site, currently under production, would be linearly removing into after use phase in 30 years.

Because of intensive ditch drainage of the peat extraction area, ditch loss was taken into account (ditch width of 2.5 m, including 0.5 m ditch bank on both sides, Alakangas et al. 2011). The potential methane production gross energy yield on cutaway peatlands were then calculated based on dry biomass yields of 5 Mg ha^{-1} and 4 Mg ha^{-1}, and methane yields of 214 and 311 m^3 Mg^{-1} for dry timothy-fescue (T-F) grass mix and RCG, respectively. Methane potential of RCG was estimated in our own studies (paper I). In the case of T-F, unpublished data was used, but the laboratory experiments were similar to RCG described in chapter 4.2. Equations used in this study are as follows:

Area for energy crops by region:

TAE = Area *by region* (ha) × 30 (%) (6)

Ditch loss per hectare (%):

DL = 500 (m) × 2.5 (m) / (10000 (m^2) × 100 (%)) (7)

Biomass yield, (Mg TS):

BY = *Plant dependent dry biomass yield* (Mg ha^{-1} a^{-1}) × TAE × (100 % – DL) (8)

Biogas gross energy yield:

Plant dependent methane yield (m^3 Mg^{-1}) × BY × (10 kWh m^{-3}) (9)

The kernel density estimation was used also in the next phase, when the suitable landowners were identified from the interview in a local level (paper III). The landowners who were interested in bioenergy after-use methods on future cutaway peatlands were located with the ArcGIS program (v. 10.3.1) by using ETRS89 TM35FIN coordinates. The peat extraction sites were determined by using soil class 32,113 from the Finnish topographic database (paper II). The coordinates were defined to be the center of the owned peat extraction area in Microsoft Excel 2016, and that table was added into the ArcGIS program. Kernel density estimation was made with the Kernel Density tool by emphasizing the points according to the area size (a cell size of 200 m and a search radius of 5 km were used).

In the paper IV, the second scenario aimed to locate wood terminals in the study area and kernel density was also utilized in it. In that scenario, the density of forest biomass was based on the raster values in the national forest inventory data (Finnish National Forest Inventory, NFI 2013). Total forest biomass (m^3 ha^{-1}) with a raster pixel size of 1.0 ha was taken into account in the study area. The raster data on forest wood volume were processed with the ArcGIS software, v. 10.5.1 (ESRI Inc., Redlands, CA). In the first phase, raster data were converted to points using the raster-to-point tool. The raster size in the output file of the kernel density analysis was chosen as 1 km, and the search radius was 5 km (each kernel was weighted by the wood or forest stand volume). Finally, the kernel density results were interpreted contemplating the municipal border map (NLS, 2017) and closeness of roads based on Digiroad data (Finnish Transport Agency 2018: Digiroad 3/2017).

4.5.2 Mapping local landowners

In paper III, local landowners were identified in the study area so that their perspective on different forms of after-use on cutaway peatlands could be investigated. This was examined by choosing those landowners who had at least 15 ha of current peat extraction area in their lands. The checking was made by using Paikkatietoikkuna web service, which contains maps from the National Land Survey of Finland (NLS) (Paikkatietoikkuna 2016). The area size was calculated with Finnish Topographic database (map layer) and the "Measure an area on the map" tool. The area limitation (15 ha) was based on the opinion of after-use experts from a national bioenergy company Vapo (personal communication by Ari Laukkanen, Kimmo Aho and Juha Kinnunen on the 12th of January 2016). The map data was from the year 2014.

Because of the remote locations of the peat extraction areas, only the peat extraction areas and landowners within a 10 km radius (by Euclidean distance, personal communication by Ari Laukkanen, Kimmo Aho and Juha Kinnunen on the 12th of January 2016) from the local middle or large scale farms or center of the municipality was chosen. The farm size limitations were based on farms having more than a 50-head of cattle, 500 poultry, 30 horses, or 500 pigs. The farm size and location (address) were found out with data collected by Finnish Food Safety Authority, Evira. The data was supplemented partially by previous studies (Laasasenaho 2012). The identification of potential future cutaway peatlands was made with ArcGIS v 10.3.1 (ESRI Inc., Redlands, CA, USA) by using Buffer tool. Finally, the contact information for sending the survey questionnaires, related to the estate codes (inside the buffer zone), were requested from NLS.

4.5.3 Optimizing the location of biogas plants

In this part of the thesis, two biomass use scenarios were studied in the case study area (paper IV, Figure 9). The biogas scenario aimed to find locations for biogas plants (with capacities of either 100 or 300 kW) by using GIS-data based route optimization, hierarchical clustering, and location optimization. In the scenario, potential feedstocks included different farm-originating manures; sludge from wastewater treatment plants; and source-separated biowaste from vocational schools, municipal waste management, grocery stores, and tourist centers. Also, the use of reed canary grass (RCG; *Phalaris arundinaces*), which can be potentially grown on cutaway peatlands in landowners' perspective, was considered (paper III).

Manures from large farms were included in the study (with more than 50 heads of cattle, 500 pigs, 30 horses, or 500 heads of poultry in 2016). Their coordinates (addresses) were obtained from the databases of the Finnish Food Safety Authority (Evira), the Agency for Rural Affairs (Mavi), and the National Land Survey of Finland (NLS). The amount of manure produced per animal and finally per farm was calculated based on animal age and species (Rasi et al. 2012). The amount of human bio waste was obtained from the municipalities and operators of these services. The amount (TS) of sewage sludge was obtained from waste water treatment plants located in Alavus, Soini and Ähtäri (VAHTI; Finnish Environment Institute 2017). The biogas yield of different feedstocks was assumed to be 107 m^3 CH_4 Mg^{-1} fresh matter (FM) and 162 m^3 CH_4 Mg^{-1} TS for biowaste and sewage sludge, respectively (Laasasenaho 2012). The values of agriculture manures were 19, 10, 48, 39, and 81 m^3 CH_4 Mg^{-1} FM for cattle, pig, horse, sheep and goat, and poultry manure, respectively (Laasasenaho 2012, Rasi et al. 2012, O'Shea et al. 2016).

Coordinates of the locations of various feedstocks were verified using the MapSite online map (NLS 2017b, coordinate system: ETRS89 TM35FIN). If e.g., two animal owners/farmers housed their animals in the same shelter (situated next to one another) these biomass points were merged together into the same point.

In the scenario, a 100-kW farm biogas plant (for the manure from only one farm) and a 300-kW centralized biogas plant (manure from several farms and organic waste from several sources) that could annually produce 800 MWh and 2,400 MWh gross biogas energy, respectively, were considered in location optimization (8,000 annual energy production hours).

The location optimization of the biogas plants was calculated taking into account the road network (Digiroad 3/2017). The road network was prepared with shp2graph v. 0.3 and the actual route optimization was performed using the igraph v. 1.1.2 (Csardi & Nepusz 2006) add-on packages in the R software, v. 3.4.3 (R Core Team 2017). Farm-scale biogas plants were considered when the potential gross biogas energy yield of the farm exceeded 800 MWh annually. A self-programmed location optimization tool based on a threshold transport distance of 10 km was used to logistically determine reasonable biomass feedstock clusters for potential centralized biogas plants (Dagnall et al. 2000). Clusters were a group of individual biomass points located close to one another with a potential gross energy yield exceeding 2,400 MWh/year within 10 km. These clusters were identified based on hierarchical clustering using complete linkage (maximum distance between cluster representatives) as the agglomeration method and further analyzed with the dendrogram tool.

Finally, the optimal biogas plant location inside of the potential clusters was calculated by multiplying gross biogas potential (MWh) by the distance between different feedstock collection points (m). Then, the potential biogas plant was placed onto the point where the sum of transportation needs for all feedstocks was the smallest.

4.6 The interview and statistical analyses

The interview about different after-use methods and bioenergy production on cutaway peatlands was sent to 75 landowners in total, (including 69 private persons, 5 companies, and 1 foundation, paper III). The answers were presented anonymous and confidential. About one third of the landowners (33 %) did answer the survey. 24 % of the respondents were women and 76 % were men. The respondents had median of upper secondary education (in ordinal scale from comprehensive to university degree) and median age class of 41–50 years old. The survey included background information, such as sex, age, education, home town, the location of owned property under peat extraction, the size of the peat extraction area on the property, the year peat extraction ends/ending of the rental contract, and the planned after-use method. After the background section, the respondents were asked to evaluate different after-use and bioenergy production alternatives, and also environmental values. The answers were asked to be given on an ordinal scale (from 1 to 7 = from does not matter to matters a lot) in the latter questions.

The evaluated bioenergy choices were combustion, biogas, and gasification from agriculture energy plants, wood, or energy willow.

Environmental values were including questions related to general attitude towards nature, global warming and greenhouse gases, water pollution and nature well-being. In addition, the same scale was used to evaluate different barriers to the utilization of cutaway lands for bioenergy production. The questions concerned challenges, such as: problematic water economy, low fertile soils, stones and bedrock, logistics, frost damage, etc. Separate questions also handled the willingness to produce bioenergy on cutaway (yes, probably, no).

The survey was asked to be filled in on the Internet where the answers were collected using the Wepropol 2.0 program. A voluntary guidance event was organized in Tuomarniemi Forest School and it was also possible to answer the survey in paper form. The respondents were also contacted by phone to remind them about the survey. In addition, one interview was carried out by using mobile phone.

The answers from the survey were analyzed with the SPSS program v. 22.0 (IBM Inc., Armonk, NY). Spearman's correlation coefficient values were determined for background variables and environmental attitudes and for bioenergy production alternatives (2-tailed). The statistical significance level of $p = 0.05$ (Analyze → Correlate → Bivariate) was used and missing values were omitted pairwise. Combined values for environmental values and different forms of bioenergy (combustion, biogas production and gasification of agriculture or forest based plants and energy willow) were calculated by using the Compute Variable tool.

5 RESULTS AND DISCUSSION

In this chapter, the results are presented and discussed as follows: At first, the feasibility of reed canary grass growth for biogas and combustion is assessed on the cutaway peatlands (Chapter 5.1). After that, the locations and amounts of potential cutaway peatlands are detected for growing energy crops in Finland (Chapter 5.2). Then, the landowners' perspective on the different bioenergy production options on cutaway peatlands (Chapter 5.3) and a method to location optimization of bioenergy plants are presented when data collected from cutaway peatlands are combined with other local biomasses in the study area (Chapter 5.4.). Finally, general discussion is given in Chapter 5.5.

5.1 Feasibility of biogas production and combustion of fresh RCG grown on cutaway peatland

5.1.1 The composition of fresh RCG

The feasibility of using freshly harvested RCG grown on cutaway peatlands in combustion and biogas production was studied (paper I). The results suggests that the use of fresh RCG with two cuts per growing season can be a successful after-use method for cutaway peatlands to produce biomass for biogas production or for combustion. This could produce an alternative for the dry spring harvested RCG, which has not been technically and economically successful. However, the RCG biomass yields in both studied case areas appeared to be relatively low (RCG of 2.7 and 4.2 Mg ha^{-1} a^{-1} in Alajärvi and Ilomantsi, respectively) compared to RCG cultivated (1st and 2nd harvest) in two fertilized (N, P, K) Finnish test fields (total annual yield of 6.8 and 8.1 Mg TS ha^{-1}, (Seppälä et al. 2009)). The study locations were extensively cultivated (insufficient fertilization after 2011), which was leading to low biomass production. Consequently, RCG cultivation on cutaway peatlands must be optimized with sufficient fertilization and possibly liming to achieve higher biomass yields.

The results are concluded in Table 8. The harvest time had a profound influence on the biomass composition. This makes bioenergy utilization different from spring harvested dry RCG. In the both places, the TS, VS, ash, Klason lignin, glucan content, and HHV were increasing in the 2nd cut, whereas biomass yield, nitrogen content, xylan and arabinan contents and BMP were higher in the 1st cut. The carbohydrate content in RCG was in accordance to the literature values for general non-wood feedstock, which are for cellulose 30–45 %, hemicellulose 20–35 %, and lignin 10–25 % respectively (Alén 2011). Previously, in a three harvest study, a decrease in lignin content without any increase in cellulose was reported in RCG after the second harvest and an increase in lignin and cellulose was noticed only after the third harvest (Tilvikiene et al. 2016). This was attributed to the fertilization of crop between the harvests. Also, harvesting a crop before flowering may result in low lignin content, and may improve the biodigestibility of the crop (Kandel et al. 2013b). The ash content (from 1.5 to 2.1 % of wet weight (w/w) or from 5.5 to 6.9 %, changed in TS, Table 8) of the freshly harvested RCG samples in the present study is similar to spring or late autumn harvested RCG (e.g. 5.5 to 6.5 % of TS, Alakangas et al. 2016). The traditional spring harvest of RCG has proved to be the most optimal way in combustion purposes according to many studies (e.g. Burvall 1997, Pahkala et al. 2005). Combustion of fresh harvested RCG is meaningful only if the mixing ratio in the main fuel is maintained to avoid technical issues, such as slagging and corrosion (Raiko et al. 2002).

Table 8. The composition of freshly harvested RCG (two cuts) for biogas production and combustion (paper I). Standard deviation is not marked if it is less than 10% of the mean of the result.

Parameter	**Unit**	**Alajärvi**		**Ilomantsi**	
		First harvest	Second harvest	First harvest	Second harvest
Biomass yield	Mg TS ha^{-1}	1.9	0.77	3.5	1.7
TS	% (w/w)	23.6	28.5	21.8	33.5
VS	% (w/w)	22	26.5	20.6	31.4
Ash	% (w/w)	1.5	2	1.2±0.1	2.1
Experimental HHV	MJ kg TS^{-1}	15.8	16.3	14.8	16.0±1.7
Methane yield	dm^3 kg VS_{added}^{-1}	338.3	276.9±46.2	347.8±35	324.2±53.1
Methane yield HHV	MJ kg TS^{-1}	11.5	9.4	12	11.1
Total N	mg g TS^{-1}	14.9	15.0	17.8	14.3
C	% TS	45.5	45.0	45.5	45.2
H	% TS	6.3	6.1	6.2	6.2
N	% TS	1.6	1.4	1.5	1.3
Klason Lignin	% TS	15.1±1.6	16.7	14.7	17.8
Glucan	% TS	35.9	39.6±4.0	36.7	38.9±4.2
Xylan	% TS	17.5	10.8±2.5	17.8	15.3
Arabinan	% TS	13.4±2.7	4.0±0.8	13.1±2.2	9.3±4.5

The fresh RCG has a high moisture content, which can lower the energy value of the grass as received in a combustion plant (vs. spring harvested dry RCG), whereas in biogas production, the high moisture content is decreasing the BMP per fresh matter but it is not affecting the energy value of the produced biogas. The BMP values were lower than the values of 368 and 323 dm^3 kg VS_{added}^{-1} (Kandel et al. 2013b) and 390 and 367 dm^3 kg VS_{added}^{-1} (Nekrošius et al. 2014) for RCG after 1st and 2nd harvests respectively. However, even higher BMP values have been measured in long term (over 100 days) batch experiments (Lehtomäki et al. 2008). Whereas, the HHV values were close to the values of 15.2–16.1 MJ kg TS^{-1} reported for freshly harvested RCG in Poland (Kołodziej et al. 2016). These results indicate that lignin content increases in the 2nd cut and thereby increases the HHV of the RCG. However, the HHV of the 2nd harvested RCG is still lower than the traditional spring harvested RCG (17.6–17.9 MJ kg TS^{-1}, Alakangas et al. 2016).

5.1.2 Biogas production and combustion scenarios

Net energy yield, energy output-to-input ratio, economic profitability, and CO_2 emissions were then calculated for biogas production combustion scenarios based on experimental BMP and HHV of the study and previous studies.

The both scenarios resulted in a similar NEY of 9.3 MWh ha^{-1} a^{-1} (Table 9), while the biogas scenario had $R_{0/I}$ of 5.1 compared to 3.8 for combustion scenario. Consequently, freshly harvested RCG cultivated on cutaway peatlands can be considered as an energetically potential crop for biogas technology or combustion. However, RCG cultivation should follow the traditional agronomic practices, sufficient fertilization and proper water table adjustment, in order to improve biomass and energy yields on cutaway peatlands. Compared to traditional spring harvested RCG, fresh RCG may result in higher biomass yields with several cuts, lower lignin content, and better digestibility for biogas production. Anyhow, there are several after-use alternatives for cutaway peatlands, which are competing with RCG cultivation in practice (Salo & Savolainen 2008). Currently, the afforestation is seen as the best after-use method amongst the landowners (paper III).

Table 9. Energy balance of fresh RCG grown on cutaway peatland for biogas production and combustion (paper I).

Scenarios	NEY (MWh ha^{-1} a^{-1})	Energy Ratio ($R_{O/I}$)	CO_2 emissions (Mg CO_2 ha^{-1} a^{-1})	CO_2 savings (Mg CO_2 ha^{-1} a^{-1})
Scenario: Biogas	9.3	5.1	0.6	2.8
Scenario: Combustion	9.3	3.8	0.6	2.8

NEY values are similar between biogas and combustion, but higher inorganic fertilization needs (lack of N in combustion ash compared to biogas digestate), feedstock drying (high moisture content of fresh RCG) and handling are increasing energy inputs in the combustion scenario (Figure 11). Consequently, the biogas scenario had lower energy inputs and higher $R_{O/I}$ per year (Table 9). If the moisture is evaporated, the NEY of the combustion scenario could increase significantly. However, any kind of feedstock handling may result changes in $R_{0/I}$ values in both scenarios, which makes comparison challenging. In a Swedish study, the $R_{0/I}$ for hemp cultivation (spring harvested dry hemp in combustion and autumn harvested in biogas production) were calculated to be 2.7 in CHP-based biogas and 6.8 in combustion scenarios (Prade et al. 2012). Bioenergy production parameters and cultivation steps are similar in this study. However, hemp is harvested as a dry plant in spring for combustion and it is a much more lignified and fibre rich crop than fresh harvested RCG (Prade et al. 2012). Also, general parameters such as transportation distance (4 km vs. 5 km in this study) are different in the Swedish study and these may lead to different $R_{0/I}$ values compared to this study.

The CO_2 emissions were calculated for energy inputs in both scenarios. The energy input related CO_2 emissions were 0.6 Mg CO_2 ha^{-1} for both scenarios. The similar values were caused by the smaller emission factor of bale crushing machine, which was assumed to be working with electricity, and also due to the reason that bales had higher energy content per m^3 than loose harvested RCG when transporting the feedstock from cutaway peatlands to the power plant. Despite the small difference, the biogas scenario had lower energy input related CO_2 emissions per hectare (3.1 Mg) compared to the combustion scenario (3.0 Mg) during 5 years (Table 9). This study suggests that fertilization is one of the factors that affects the overall energy inputs and CO_2 emissions. For instance, avoiding the use of inorganic N fertilizer in the biogas scenario is beneficial for recycling nutrients and decreasing GHG emissions. Bioenergy production was also considered in the emission calculations when bioenergy was replacing fossil diesel engine in power plant (the last column in Table 9). Overall, both scenarios were replacing the same amount of fossil diesel due to similar NEY values.

The economic profitability in the both scenarios is dependent on energy input costs, energy selling circumstances, and subsidies (economic feasibility varies from 42 to 2,542 € ha^{-1} a^{-1}, Table 10). Naturally, the net incomes are the lowest in the first two years when the biomass yields are the lowest. The best net incomes of 8,822 (biogas) and 9,474 € ha^{-1} (combustion) are achieved when the produced heat and electricity can be utilized fully with tariffs. The combustion resulted higher energy selling incomes even though the biogas scenario had the lowest net costs per hectare. The total net incomes can be from 4,705 to 5,135 € lower per hectare, if there are no tariffs available. In this study, the biogas and the combustion scenarios had the overall costs of 315 and 325 € ha^{-1} a^{-1}, respectively. Consequently, the cultivation costs of fresh RCG are higher compared to the traditional combustion of spring harvested dry RCG (252 € ha^{-1} a^{-1}, Pahkala et al. 2005). The costs in Pahkala et al. (2005) consisted of normal agricultural field work including preparing, fertilization, and harvesting costs (without manpower).

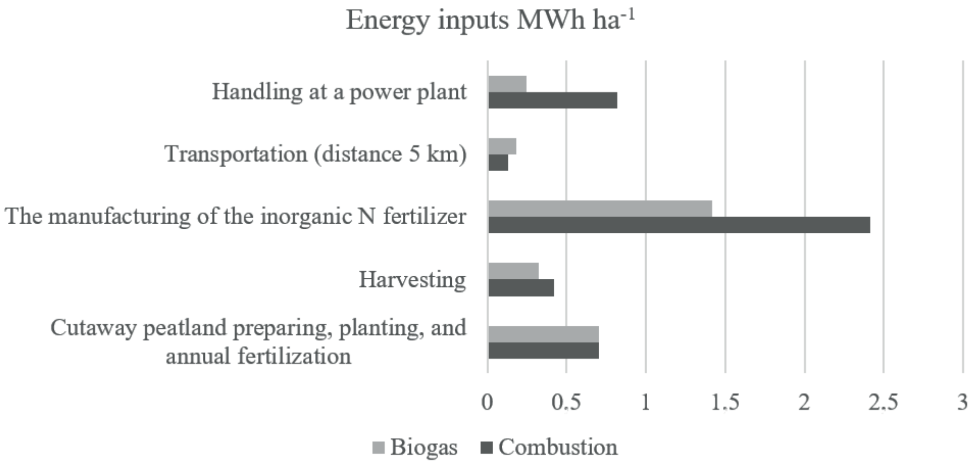

Figure 11. Energy inputs in both studied bioenergy production chains when full biomass yield, 6 Mg ha^{-1}, can be achieved (paper I).

Table 10. Net income per hectare of cutaway peatland per year if RCG is fully utilized in a CHP plant on cattle-based farms (the cost of manpower is excluded) (paper I).

Year	Cost of cultivation (€ ha^{-1} a^{-1})	Income without tariff (€ ha^{-1} a^{-1})	Net income without tariff (€ ha^{-1} a^{-1})	Income with micro el. prod. tariff and without heat tariff (€ ha^{-1} a^{-1})	Net income with micro el. prod. tariff and without heat tariff (€ ha^{-1} a^{-1})	Income with full tariffs (Over 100 kVA, € ha^{-1} a^{-1})	Net income with full tariffs (Over 100 kVA, € ha^{-1} a^{-1})
				Scenario: Biogas			
1st	495	537	42	537	42	537	42
2nd	370	1,083	714	1,170	800	1,939	1,569
3rd	236	1,357	1,120	1,486	1,250	2,640	2,404
4th	236	1,357	1,120	1,486	1,250	2,640	2,404
5th	236	1,357	1,120	1,486	1,250	2,640	2,404
Total	1,573	5,691	4,117	6,164	4,590	10,396	8,822
				Scenario: Combustion			
1st	495	537	42	537	42	537	42
2nd	261	1,133	873	1,227	966	2,067	1,806
3rd	290	1,432	1,141	1,573	1,282	2,832	2,542
4th	290	1,432	1,141	1,573	1,282	2,832	2,542
5th	290	1,432	1,141	1,573	1,282	2,832	2,542
Total	1,627	5,966	4,339	6,482	4,855	11,101	9,474

The present scenario analysis used simplified assumptions and there were notable limitations. For instance, biomass yield and cultivation practices were based on literature values on standard crop management on agriculture fields and not on cutaway peatlands. Harsh environmental conditions may lead to a high consumption of diesel fuel, which in turn, results in negative economic and climatic impact on cutaway peatlands. Also, some of the background parameters may have notable effect on economic profitability (excluded costs of manpower, machinery type, site conditions, changes in subsidies and tariffs over time, etc.). Furthermore, other indirect economic gains, such as environmental benefits, or hazards, were not included in the scenario calculations.

5.2 National energy crop potential of cutaway peatlands

The location and the area of the current peat extraction areas in Finland was studied to identify future cutaway peatlands with a kernel density analysis and Finnish Topographic database in ArcGIS (paper II). There were nearly 2,900 geographically separate areas under soil class 32,113 (organic soil mining). Total covered area was 985.24 km^2. The average size of one unit was 34 ha, having median size of 17 ha. The densest area of peat extraction is situated in Western part of Finland (Figure 12), and almost half (ca. 45 %) of the total national peat extraction area is located in South and North Ostrobothnia.

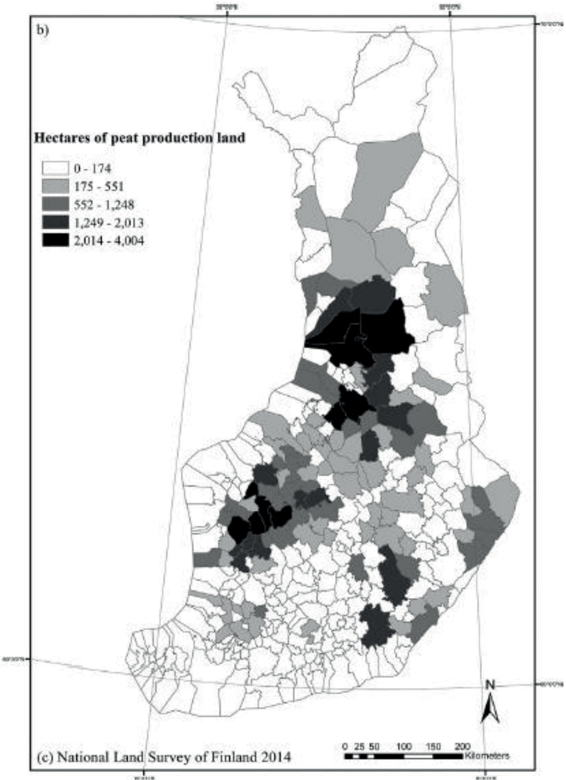

Figure 12. Peat extraction areas by municipalities in 2014 in Finland (© NLS, 2014, paper II).

Kernel density analysis was then used to identify the densest peat extraction regions. These regions were as follows: North Satakunta and southwestern parts of South Ostrobothnia, East Ostrobothnia and the northwestern parts of Central Finland, the western part of North Ostrobothnia, and the northwestern part of North Ostrobothnia and the southwestern part of Lapland (Fig 13).

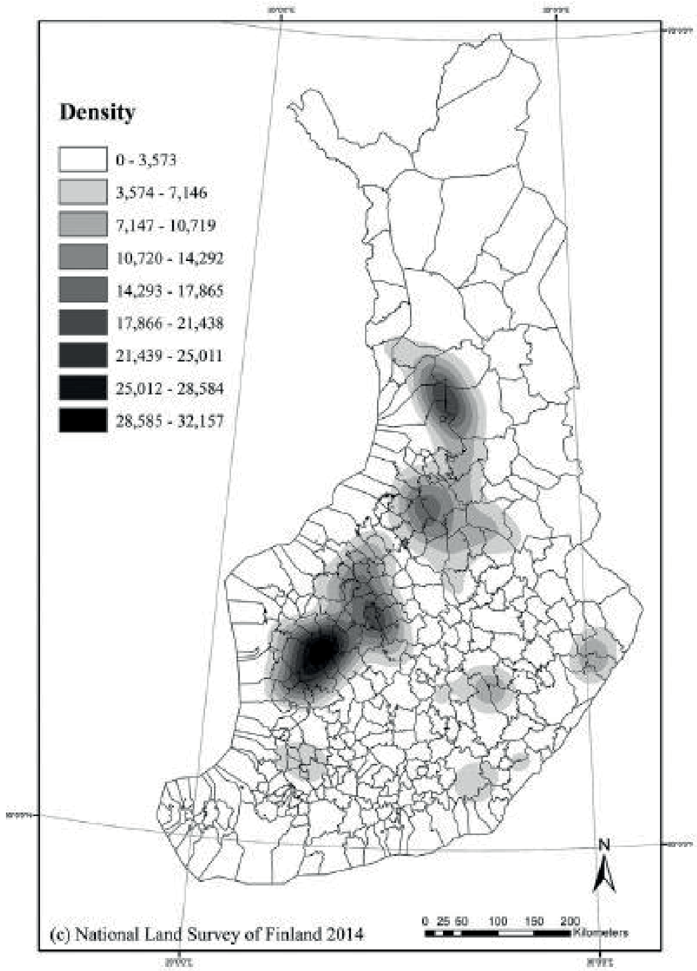

Figure 13. Kernel density estimation results of Finnish peat extraction areas. The search radius was 50 km. The colour illustrates the relative density only, not specific units (© NLS, 2014, paper II).

Nationally nearly, 30,000 ha or 300 km² of future cutaway peatlands could be theoretically used for energy crops by 2044 when a 30 % share of the whole peat extraction land is assumed to be used for energy crops (Table 11). The most intensive peat extraction areas have also the highest potential for energy crops in the future. This means ca. 10,000 ha and 20,000 ha in 2024 and 2034 respectively, when the peat extraction areas are cumulatively released for after use in the near future. Both, South and North Ostrobothnia, have over 6,000 ha of land area for this purpose by 2044. Other notable counties, having ca. 2,000 ha potential, are Central Finland, Satakunta and Lapland. If the national potential would be fully utilized, the biomass yield of fresh RCG or T-F from these areas could be about 100 Gg (TS) annually with two cuts. This means about 300 GWh annual gross energy yield as methane.

Table 11. Energy crop and biogas potential for future cutaway peatlands in Finland (paper II).

Region	Suitable for energy crops, ha	CH4 potential (2 cuts a^{-1})			
		RCG, Mg a^{-1}	RCG, GWh a^{-1}	T-F, Mg a^{-1}	T-F, GWh a^{-1}
Uusimaa	84	295	1	369	1
Varsinais-Suomi	307	1,075	3	1,344	3
Kantahäme	257	901	3	1,126	2
Päijäthäme	74	258	1	323	1
Kymeenlaakso	569	1,993	6	2,491	5
Satakunta	2,256	7,895	25	9,869	21
Central Finland	2,244	7,853	24	9,817	21
Etelä-Savo	1,006	3,521	11	4,401	9
North Karelia	1,287	4,503	14	5,629	12
Pirkanmaa	1,336	4,675	15	5,844	13
South Karelia	613	2,147	7	2,683	6
Ostrobothnia	206	722	2	902	2
Pohjois-Savo	1,624	5,685	18	7,106	15
South Ostrobothnia	6,541	22,892	71	28,615	61
Central Ostrobothnia	1,049	3,672	11	4,590	10
North Ostrobothnia	6,677	23,368	73	29,210	63
Kainuu	1,505	5,267	16	6,583	14
Lapland	1,923	6,729	21	8,412	18
Åland	0	0	0	0	0
Totally	29,557	103,451	322	129,313	277

Acid sulfate soil was not considered when suitability for energy crops was calculated.
RCG = Reed canary grass, dry biomass yield assumption 4 Mg a^{-1} (two harvests)
T-F = Timothy-Fescue grass, dry biomass yield assumption 5 Mg a^{-1} (two harvests)

The peat extraction areas under acid sulfate soils were then determined with Topographic database and acid sulfate soil maps produced by the Geological Survey of Finland. Acid sulfate soils are under risk of acidification, and thus are not feasible for crop production even though their use for crop production is not legally limited (personal communication by Finnish Regional State Administrative Agencies 2019). There are totally 9,791 ha of peat extraction areas, which are under acid sulfate soils near the coastline of the Baltic Sea in Western Finland.

The kernel density and Topographic database applied in this study were found to be useful in defining the potential regions for energy crops. The kernel density method indicated that the intensity of peat extraction is the highest in Western Finland. This could help to identify biomass potential for e.g. farm biogas plants (paper IV) because there are important agricultural businesses especially in South Ostrobothnia (Niemi & Väre 2018) but farm biogas plants are rare according to

Finnish biogas register (Huttunen & Kuittinen 2015). These GIS methods give a good starting point for bioenergy planning because cutaway peatlands for energy crop growing can be determined in national and regional scale, and this can further support distributed bioenergy production. These methods identify national hotspots and show, which part of Finland has the largest potential to use cutaway peatlands for this practice. In Southern Finland, the peatland intensity is low. There are large peatlands in Northern Finland, but e.g. low population and energy demand, and cold climate limit the peat extraction there (Virtanen 2008). However, the spatial distribution of peat extraction by region is similar compared to previous studies conducted by Leinonen (2010). Similar kernel density analyses have been made earlier, e.g. Höhn et al. (2014), but not applied to cutaway peatlands.

This study may have practical limitations as in the GIS analysis the local hydrology and topography are not considered, even though in practice these are crucial for the after-use (Picken 2006). However, Topographic databases gives, at least spatially, more accurate results compared to official land use statistics. E.g. in the official peat extraction statistics, the amount of peat extraction area is approximately 700 km^2 in Finland (ELY 2014), while in the soil class 32,113, the area was more than 985 km^2. Consequently, there is over 200 km^2 of land in the class, which is possibly out of production. This extra area may also include support areas, such as roads, storage, buildings, etc., which will decrease the actual extraction area, but it has to include also areas already in after use process. This made it challenging to assess the technical and practical potential, and it can even lead to wrong interpretation of the result. Therefore, different methods, such as hydrological measurements and soil analyses have to be done in smaller geographic scales.

The cutaway peatlands are notable land resources in Northern Europe. For example, Swedish and Estonian cutaway peatlands were assumed to be 5,000 ha and 18,000 ha in Sweden and Estonia, respectively, in 2010 (Vasander et al. 2003). The after use alternatives of cutaway peatlands are current questions especially in Finland, where ca. 44,000 ha of peat extraction areas are to be transferred to after use phase by 2020 (Flyktman 2007). Despite the unsuccessful development of the bioenergy concept (combustion) for spring harvested RCG (Farm business registration 2015), RCG growing on cutaway peatlands could have environmental advantages, such as reduction of soil originated greenhouse gases and erosion control (Kirkinen et al. 2007, Shurpali et al. 2009, Gong 2013, Järveoja et al. 2013). However, if a thick layer of peat is left on the cutaway peatlands, mineralization of peat can lead to significant net GHG emissions from the soil and accelerate global warming (e.g. Kandel et al. 2013, Karki et al. 2013, Kekkonen et al. 2019). Consequently, RCG growing can be a potential after-use method if the plants are growing on mineral sub-soil and there is only a thin peat layer left on the ground. RCG have been tested for biogas production in previous studies (e.g. Lehtomäki et al. 2008, Seppälä et al. 2009, Kandel 2013), but other energy conversion technologies, other than combustion, are studied only little on cutaway peatlands.

5.3 Landowners' perspective to use cutaway peatlands for energy crops

5.3.1 Assessing the potential future cutaway peatlands for bioenergy

The bioenergy production alternatives on cutaway peatlands were assessed with a questionnaire for the landowners and GIS-based methods to make further bioenergy plant planning in "Kuudestaan" study area (paper III). At first, remote cutaway areas were cut out by using buffer zones with 10 km Euclidean distance from municipal centres and large farms. There were totally 4,742 ha of peat extraction areas within the buffer zone and it covered 79 % of the whole peat extraction area. The buffer zone analysis showed that most of the peat extraction areas in the case study area are close to municipal centers and large scale farms. However, Soini municipality was an exception. There large peat extraction areas were not covered by the buffer zone because the areas were situated in sparsely inhabited locations (Fig. 14).

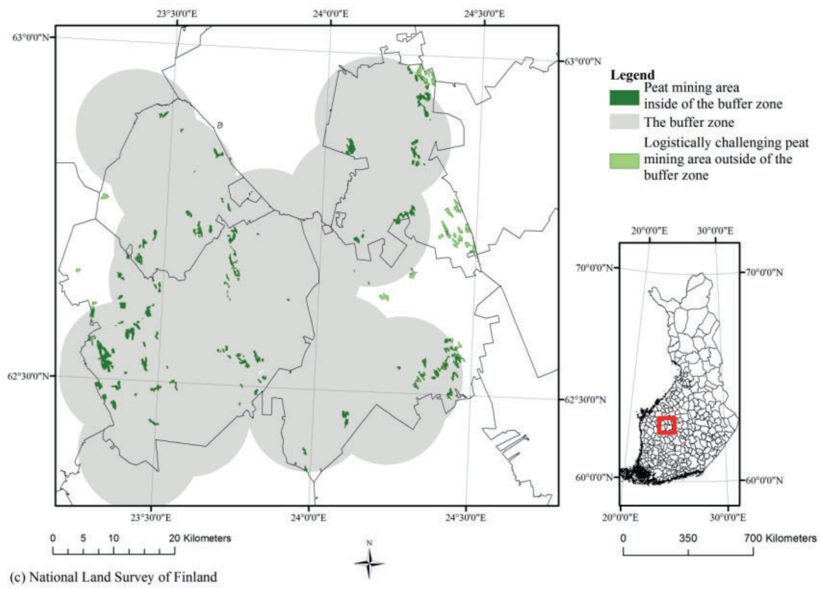

Figure 14. Logistically the potential peat extraction areas and remote peat extraction areas in the case study area were determined by using Buffer tool in the ArcGIS program (paper III).

The accuracy of the buffer analysis could be improved by calculating the easily accessible zone by using the road network, instead of Euclidean distance. This could have been implemented with the Network Analyst toolset in ArcGIS. However, the major concern was the low amount of farms, which were taken into account in the buffer zone. Most of the farmers do not share their background information, so the spatial information about all available middle and large-scale farms was inadequate in the GI data collection when the buffer zone was created. A larger buffer zone could have improved the analysis results especially in the case of Soini municipality, as well as if the farms and population centers in neighbor municipalities would have been considered.

The reason why significant areas are left outside of the buffer zone is caused by the smaller population and the amount of agriculture. E.g. Soini is mostly sparsely inhabited, having a total population of only 2,284 inhabitants (Statistics Finland 2013). As a comparison, in the city of Alavus, the population size at the same time was 12,228 (Statistics Finland 2013). Consequently, this can be seen as a more comprehensive buffer zone in Alavus.

5.3.2 Landowners views on peatlands after-use and bioenergy

A questionnaire was sent to landowners to investigate landowners' perspective on the different after-use methods. When the survey data was collected, it was found out that the respondents lived a little bit over 20 km away from the owned peat extraction area on average. They also had a positive attitude towards nature. Most of the respondents owned peat extraction area either in Soini or in Alavus (84 %) and the mean owned area sizes in these municipalities were 27 and 22 ha respectively (Table 12).

The highest ranked after-use method was afforestation amongst all of the respondents (on average 5.6 out of 7; from 1 to 7 = not important … very important, Table 13). 80 % of the landowners were interested in growing biomass for energy production as an after-use method. When the interest to grow biomass for bioenergy production was asked, the highest potential was in Alavus and Soini municipalities (Fig. 15). There were significantly lower potentials in Kuortane and Ähtäri municipalities, and actually, none of the landowners were interested in energy crops in Ähtäri. Anyhow, it has to be taken into account that the energy crop potential is not in use immediately because there are long renting contracts and many years of peat extraction going on. Nonetheless, the cumulative amount of land available for energy crops is ca. 500 ha by year 2035 (Fig. 16). Notable areas are released for after-use phase by mid-2020's.

56 % of the respondents were farmers and most of them (86 %) were also interested to use their agricultural fields for growing energy crops as well (320 ha in total). The best bioenergy production chain amongst the respondents was forest energy for heat production. In general, wood was considered as the best biomass type while the agro biomass was the second most favourable option. Energy willow seems to be the least attractive choice of all bioenergy alternatives (Table 14).

Table 12. Background information of the respondents and environmental values in the survey conducted in this study (*n* = 25, if less, then there were missing values) (paper III).

Background	Parameter	Std. Deviation	*N*
Mean distance between home and the owned peat extraction area	20.3 km	33.2	24
Median size of the peat extraction area	over 30.1 ha		24
Mean ending year of the peat extraction	year 2023	7.1	21
The most common after-use method in the peat extraction plan	Undefined		23
Interested in producing biomass for bioenergy production as an after-use method	Yes		20
	No		5
Farmers	Yes		14
Integrated environmental value*	5.3	1.6	Min. 24

*evaluation from 1 to 7 = not significant … very significant

Table 13. Different after-use methods evaluated by the landowner of the peat extraction areas (paper III).

After-use method*	Mean value	Std. Deviation	*N*
Afforestation	5.6	1.5	25
Energy crop plantation	5.0	1.7	24
Agriculture	4.8	1.8	24
Special plant cultivation	4.3	1.6	25
Wetland	3.9	1.7	25
Pasture	3.4	2.0	19
Mire regeneration	3.4	2.1	24
Nature tourism	2.9	1.5	24

*evaluation from 1 to 7 = not important … very important

Table 14. The three most realistic bioenergy after-use alternatives from the landowner's perspective in every biomass type (paper III).

Bioenergy production chain*	Value	Std. Deviation	*N*
Forest biomass for heat production	5.00	1.44	25
Forest biomass for CHP	4.92	1.41	25
Forest biomass for syngas based heat production and CHP	4.56	1.58	25
Agrobiomass for heat production	4.40	1.8	25
Agrobiomass for CHP	4.40	1.87	25
Agrobiomass for biogas based CHP	4.40	1.85	25
Energy willow for heat production	4.20	1.89	25
Energy willow for CHP	4.16	1.86	25
Energy willow for syngas based vehicle fuel production	3.84	1.8	25

*evaluation from 1 to 7 = not a meaningful method … a very meaningful method

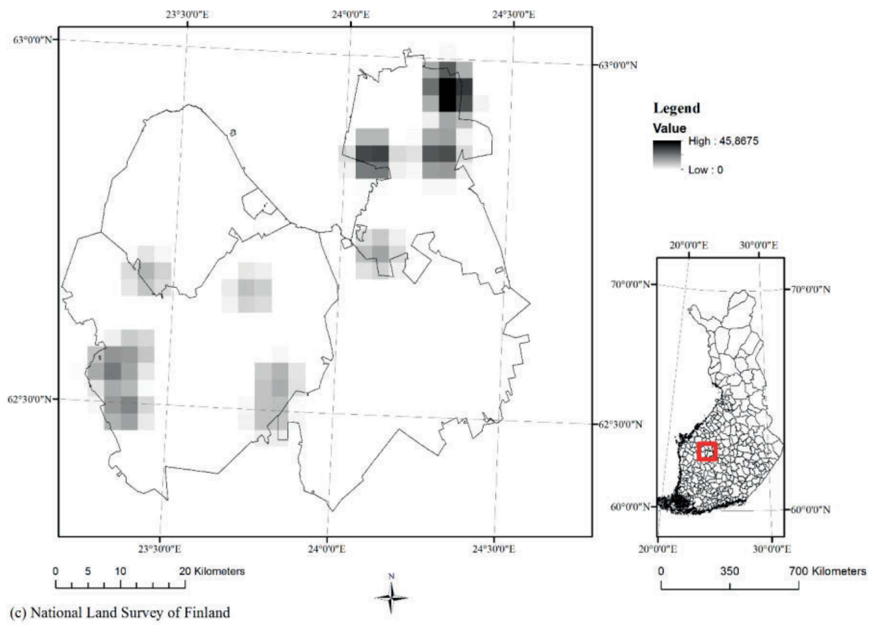

Figure 15. Kernel density map of the most potential areas to grow energy crops on cutaway peatlands by the year 2035 according to the respondents. The colour illustrates the relative density only, not specific units (© NLS, 2014, paper III).

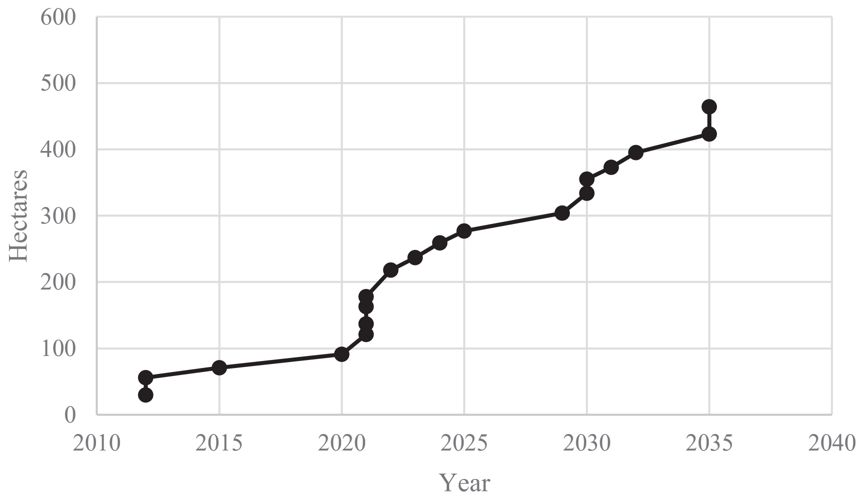

Figure 16. The area released from peat extraction per year which could be utilized in energy crop cultivation based on the landowner's willingness to do so in the case study area. Only over 15 ha units are considered (paper III).

Afforestation can be seen as a natural and neutral choice because 86 % of the land is anyhow covered by forest in Finland (Natural Resource Institute Finland 2015). For instance, many respondents had a negative impression about RCG because of the cultivation for combustion plants failed in the last 10 years (fall in RCG cultivation, Farm business register 2015, Kautto 2014). Interesting was that in this study area the landowners clearly prefer economically profitable after-use methods. E.g. wetland is not such an interesting alternative, which was one of the most preferred after-use methods according to local inhabitants in North Ostrobothnia (Kittamaa & Tolvanen 2013).

The popularity of afforestation can also be seen in previous studies (Selin 1999, Kittamaa & Tolvanen 2013, Karjala 2014). In general, the respondents of this survey were quite similar to average forest owners in Finland. A typical forest owner is a 60-year-old man and approximately 25 % of forest owners are women in Finland (Hänninen et al. 2011). This can be seen e.g. as a similar proportion of women in this study (24 %). However, the lack of knowledge about the bioenergy technology may cause even systematic bias into the results. Different energy conversion technologies, such as gasification and biogas production, can be unfamiliar to many Finnish people. Because these technologies are not in wider use, the economical income levels are most likely partially unknown.

The results also show that GIS-based methods are promising ways to investigate potential land resources for bioenergy. Spatial data can be collected from a survey, which can overall help power plant planning. Anyhow, there are many factors affecting to the final decision making. If more societal support is addressed to energy crop growing, more cutaway peatlands will be taken into bioenergy production.

5.3.3 Correlations between variables

The correlations of different background values and measured variables were then studied with Spearman's correlation analysis (Table 15). The goal was to observe specifically future land use related questions. The strongest positive correlation was noted between the willingness to promote energy crop cultivation and the willingness to promote special plant growing. A significant correlation was also detected between the distance between the owner's home and the owned area, and the ending time of the contract/peat extraction. Moreover, the size of the owned area was positively correlated with the willingness to promote future forest energy.

Furthermore, a significant negative correlation coefficient was obtained between the size of the area and the distance between home and the area. It means that people who are living close to the owned area usually own the biggest peat extraction areas. Significant negative correlation was also measured between the willingness to promote energy crop cultivation and the willingness to promote mire regeneration. However, the highest negative correlation was calculated between the willingness for mire regeneration and the size of the owned area.

Table 15. Spearman's correlation coefficient (2-tailed, p < 0.05) between the significant variable pairs in the survey (paper III).

Variable pairs	Correlation coefficient	p-value (2-tailed)	*N*
Positively correlating variables			
The willingness for energy crop cultivation//The willingness for special plant growing	0.672	< 0.000	24
The ending time of production//The distance between home and the area	0.515	0.02	20
The willingness to promote future forest biomass usage in bioenergy production//The size of the owned area	0.46	0.024	24
The willingness for afforestation//The willingness for wetland	0.44	0.028	25
Negatively correlating variables			
The willingness for mire regeneration// The size of the owned area	–0.637	0.001	23
The willingness for energy crop cultivation//The willingness for mire regeneration	–0.562	0.004	24
The distance between home and the area//The size of the owned area	–0.447	0.028	24
Nature matters to you//The distance between home and the area	–0.408	0.048	24

This study suggests that afforestation will supposedly be the most common after-use method in Finland. A new finding in this study was that if bioenergy is wanted to be promoted, especially the biggest cutaway peatlands will most probably be converted to forest energy. Moreover, also the distributed bioenergy can be enhanced because the local people usually own the biggest cutaway peatlands. As a suggestive result, the distance between home and the owned area was not seen as a barrier to bioenergy production (correlation coefficient ρ = –0.386, p = 0.063, n =

24). This can be interpreted as a clearly positive effect towards the promotion of distributed bioenergy.

In addition, there were interesting negative correlations between the willingness to promote regeneration of peatlands and energy crop cultivation. This could be seen as a disagreement between the regeneration of mires and the cultivation of energy crops. There might be disagreement between nature conservation values and bioenergy. But, as a contradiction, a suggestive result was also that the people with high environmental values are the most willing to promote agro biomass usage in bioenergy production in cutaway peatlands (correlation coefficient between the future willingness to promote agro biomass usage in bioenergy production and environmental integrate $\rho = 0.360$, $p = 0.084$, $n = 24$).

5.4 Bioenergy plant location optimization with GIS tools

5.4.1 Biogas plant location optimization

Potential feedstocks, their energy potentials, and logistically potential cutaway peatlands were determined in the study area for biogas plant location optimization (paper IV). The locations for farm-scale biogas plants and centralized biogas plants were then determined. There was biomass available for 13 farm-scale biogas plants (with a 100-kW energy production potential or higher) in the study area. The median gross energy potential of all farms was about 300 MWh/a. The highest gross biogas potential for one farm was 1,990 MWh/a. The overall gross biogas potential in these 13 potential farms was 15.5 GWh annually. This means 27.1 % of the total gross biogas potential in the area. Seven of these farms are in rural villages in Alavus municipality, four in Kuortane municipality, and two in Ähtäri municipality (Figure 17).

Furthermore, there were eight potential clusters for centralized biogas plants in the study area (with a 300-kW energy production potential or higher). The results overlap partially in both scenarios because these centralized biogas plants also include large individual farms. In practice, seven of the potential farm biogas plants also belong to the potential centralized biogas clusters. In the scenario of centralized biogas plants, it was logistically optimal to combine agricultural manures and other organic biomasses such as potential RCG from cutaway peatlands. For example, cutaway peatlands could be combined with manure from large scale farms to achieve higher biogas yields. The agglomeration method identified three large domains or groups: Northern Kuortane and northern Soini belong to the first group; western

Alavus and southern Kuortane to the second group; and southern Soini, eastern Alavus, and Ähtäri to the third group (Figure 18). Gross biogas potentials ranged from 2,409 MWh to 3,535 MWh annually in these potential clusters, when the total gross biogas potential of the eight clusters was 23.2 GWh (representing 40.6 % of the total gross biogas potential of the study area).

Optimal locations for the biogas plants were then computed inside each cluster by using self-programmed R code. The code identified the best locations that minimize transportation needs based on the Digiroad data. As an example, the cluster number 32 is illustrated in Fig. 19, where the optimal biogas plant location was defined based on manure from large scale farms.

The biggest source of biogas is the cattle manure and large-scale farms have an important role in future biogas production in the study area. However, in some cases, biogas yield can be increased through combining manure with other organic waste and potential RCG cultivation in cutaway peatlands. The largest biogas potential was found in western part of the region, whereas no potential locations for biogas installations were identified in northeastern part of the area. However, extra grass/energy crops from agriculture fields could improve the profitability of biogas plants in this situation. For example, in Denmark, the largest farms have been identified as relevant and vital for future biogas production. The average farm size in that country has increased from 131 heads of cattle to 238 heads per farm from 1999 to 2009 (Bojesen et al. 2015). Overall, agricultural residues, such as grass and slurries, have also been found to be important biomass sources in other rural GIS-based biogas analyses, representing from 50 % to over 90 % of total biogas potential (Höhn et al. 2014, Villamar et al. 2016).

Notably, the cultivation of energy crops on prior cutaway peatlands was confirmed as a potential feedstock source for a biogas plant in this study. In Alavus, two clusters were including cutaway peatlands under 10 km transportation distance from potential centralized biogas plant (cluster numbers 2 and 14, Figure 17). However, the most of the cutaway peatlands are usually over 10 km away from large farms, which can make the transportation distances long and the feasibility of the centralized biogas plants may decrease (as cluster numbers 25, 28, 41, 42, and 43, Figure 17). Also, it has to be taken into account that there are certain limitations addressed on cutaway peatland cultivation, such as high ground water levels, boulders and extreme temperatures. This is partially leading the landowners to choose forestry as an after-use alternative instead of energy crop production (paper III).

In this study, the data quality is affected by the feedstock variability. All of the feedstock types have annual variations that are affected by several factors, such as human dietary habits, and population size (e.g. number of tourists). Also, weekly amount and contents of organic waste from grocery stores and schools differ. Seasonal variations are significant, such as the effect of pasturing to manure collection, school summer vacations, etc. Consequently, it is important that a continuous cost effective biomass supply for bioenergy is available throughout the year (Calvert & Mabee 2014). One of the stable feedstock for biogas plant is e.g. manure from large-scale farms because the pasturing time is shorter in larger animal units in Finland.

An additional complication is that wastewater treatment plants and biowaste sources are usually located more than 10 km transportation distance away from large farms in this study area. However, there was one cluster in western part of the study area where it was reasonable to combine organic waste from a tourist center, grocery stores, municipal collection facilities, and large-scale farms (near the town center of Kuortane). GIS tools were especially useful in identifying spatial relations between different feedstocks and finally determining the actual biogas plant location (as in Figure 18). Anyhow, too long transportation distances might be a challenge in rural areas in Finland if agriculture based feedstocks and human based organic waste are attempted to be combined for biogas production.

The route optimization, hierarchical clustering, and location optimization methods could be improved in the future. For example, location optimization can be improved by selecting the best candidate locations after clustering based on a number of criteria, such as evaluating different land use forms. Multi-criteria evaluation could be one option, as done by Mayerle & Figueiredo (2016). Also, adjusting the transportation threshold limit (10 km) lower or higher could provide different perspectives or logistical solutions for biogas plant location. For example, by setting the threshold limit to 12 and 15 km, the number of potential clusters increases to 9 and 11, respectively. However, since biogas plants are often placed near the spatial mean of feedstock sources, transportation distances would still be less than 10 km from the sources to the biogas plant in many cases. Still, it is possible to balance biomasses between clusters and make even a more even distribution of locations considering biogas potential among all clusters. This means also that a larger amount of cutaway peatlands could be included into the potential clusters. However, it might be beneficial to start planning biogas plants from clusters with fewer large actors, such as cluster 32, to avoid complex situations with many participants (Figure 19).

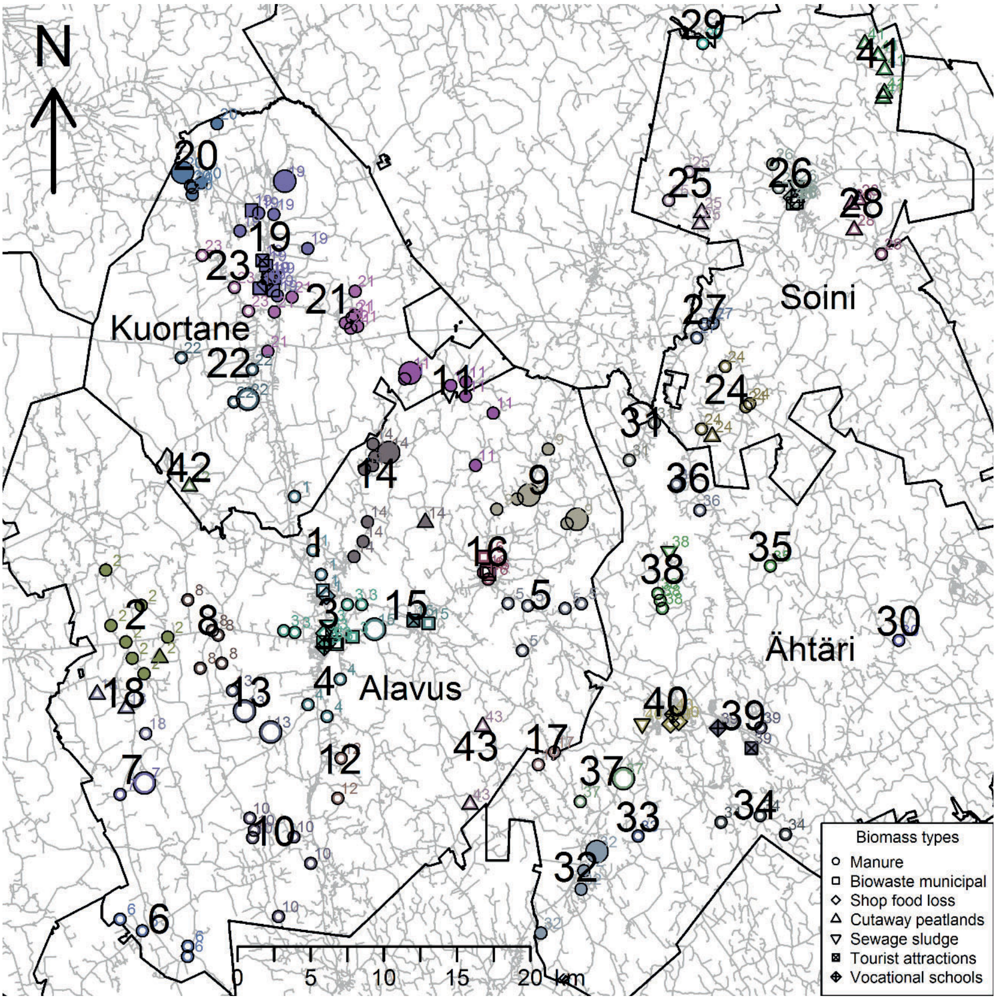

Figure 17. Feedstock production sites and their division into clusters in the study area (given as numbers). Marks filled with colour indicate potential centralized biogas plant clusters based on a maximum transportation distance of 10 km for the different feedstocks (> 300 kW; >2400 MWh/a). Larger circles indicate potential farm biogas plants using a single farm's manure as feedstock (>100 kW; >800 MWh/a) (paper IV).

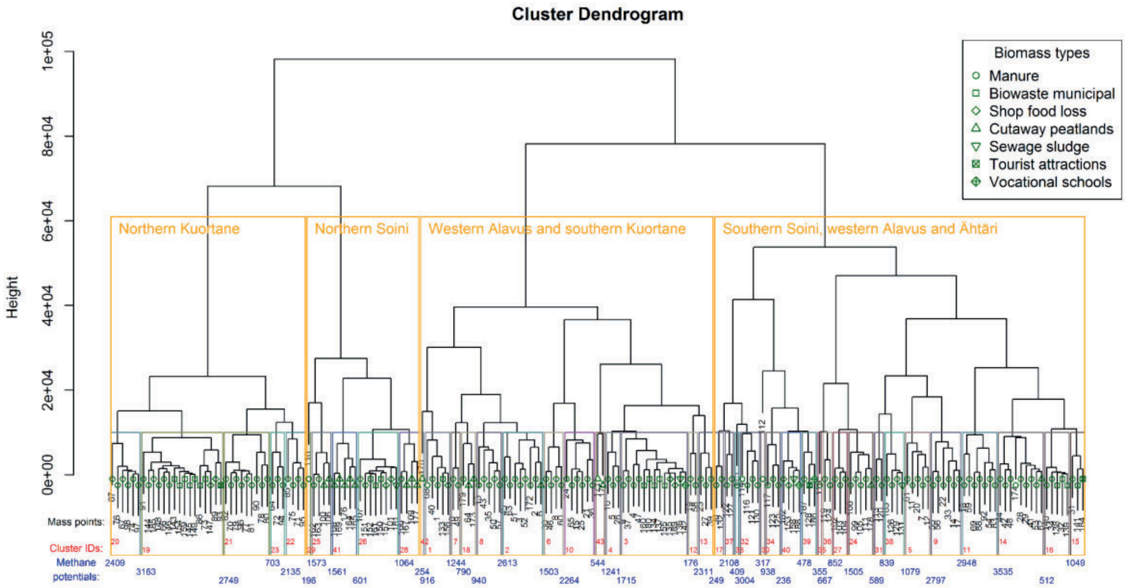

Figure 18. Dendrogram presenting centralized biogas plant clusters according to a transportation threshold of 10 km in the study region. Agglomerative clustering based on complete linkage was used to combine feedstock production sites as clusters when threshold distance was not exceeded. Clusters with a biogas potential exceeding 2,400 MWh/a are considered as clusters for potential centralized biogas plants (generating over 300 kW) These clusters can help to identify biomasses that can be integrated for bioenergy production. Green rectangles are used to indicate clusters, and symbols indicate type of feedstock. Biomass points (n = 189) and cluster IDs (total 43) are indicated in the bottom part of the figure. Biogas potentials are presented in blue and larger regions within the study area with yellow rectangles and region names (paper IV).

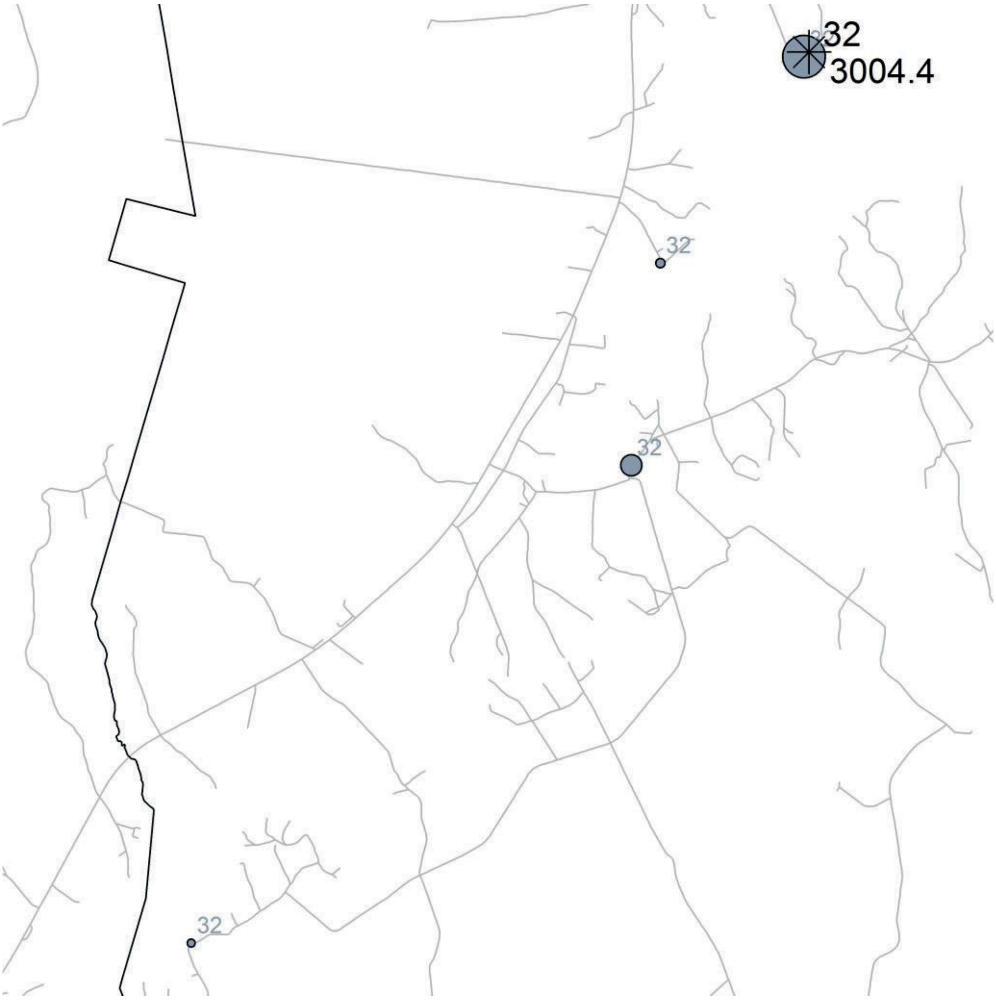

Figure 19. Example of the self-programmed optimization tool for identifying a suitable location for a centralized biogas plant by minimizing transportation distance when biomasses are sparsely distributed in a potential biogas production area (cluster 32 in Ähtäri municipality). The model minimizes the sum of total transportation needs. The potential plant location is presented as an asterisk (gross biogas potential indicated below the asterisk in MWh). The biomass sources are manure from large farms. The size of the points are indicating the relative mass of the feedstock source. This cluster did not include cutaway peatlands.

5.4.2 Wood terminal location optimization

Kernel density analyses and road network data were applied to determine the optimal locations of wood terminals in the study area (paper IV). It was found that the densest wood resources are located on the border of the Alavus and Ähtäri municipalities and in northern parts of the Soini municipality (Fig. 20). The road network covers the first area quite well, especially considering that a highway (class

#1 road) crosses the area. In the case of the latter area, the densest wood resources are located close to a lower quality road network. Anyhow, the roads are appropriate for truck transportation. If wood processing at terminals becomes popular, these prior areas could be considered in the future. This would increase wood storage capacity and enhance the balance of the wood supply (e.g., BioHub project 2018). However, if afforestation will be the most common after-use method for cutaway peatlands, it would eventually increase the local wood resources and affect the results of this kind of analyses.

Previously, a similar kind of GIS analysis has been done in the same area concerning wood terminals (Pajoslahti 2014). In the previous study, suitable wood terminal locations were determined based on land use – not forest density data. Also, the existing wood terminal locations in Alavus, at the Ähtäri Myllymäki railway station, and in the center of Soini were not congruent with real wood availability. Furthermore, existing terminals have been established near of railways and high-class roads without considering forest resources.

GIS can offer useful applications for forestry (e.g. Calvert & Mabee 2014). In early summertime, there is no need for terminals because fast-track transportation routes are used to directly transport wood from forest roadsides to mills. However, terminals are necessary buffer storages for fresh-felled saw logs in springtime. Currently, road network and environmental limitations are considered with GIS by different wood procurement organizations (Uusitalo 2003, Lauhanen et al. 2014). Anyhow, soil quality and constantly evolving phenomena, such as weather conditions, are challenges for GIS analyses (Xie et al. 2010, Franco et al. 2015). Actually, the utilized forest inventory data included nature conservation areas and small-sized local forests or protected aquatic ecosystems (NFI 2013) where logging cannot be done. Their possible effect on practical location optimization solutions should be considered (e.g., Kangas et al. 1996). In the future, expert knowledge and consensus solutions can be used in decision making to achieve better results (e.g., Kangas et al. 1996). In fact, the amount of forest biomass based on data from the Finnish NFI (2013) is freely available online, making these data easy to access and utilize. Also, remote sensing can provide especially more up-to-date information on forest resources.

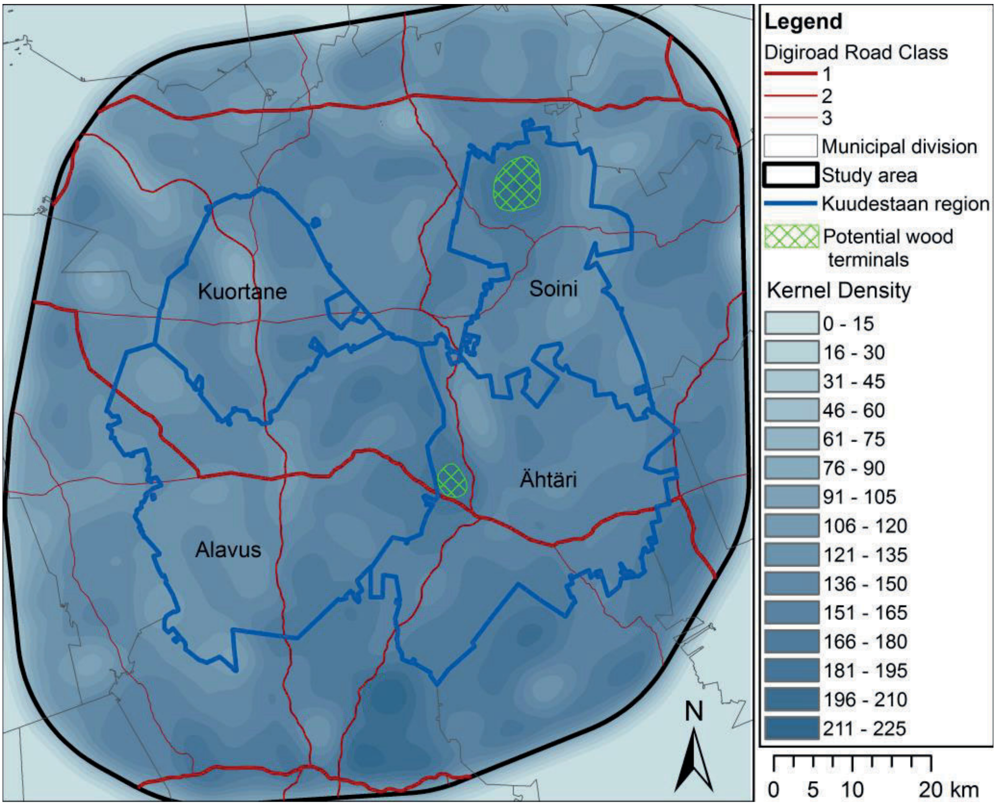

Figure 20. Kernel density map of wood resources in the study area (tree stand volume in m^3 ha^{-1}. Darker blue colours indicate greater density of wood resources (forest inventory data: NFI 2013; roads: Digiroad 3/2017; municipal borders: NLS, 2017). Potential wood terminal locations are located in areas with dense wood resources near the highest road classes. Color represents relative densities and not specific units (paper IV).

5.5 General discussion

If cutaway peatlands are wanted to be used for decentralized bioenergy production in practice, it will require clear cooperation between bioenergy producers, landowners, experts, and other stakeholders so that the failures are avoided. On a large scale, it is important to take into account the role and potential of cutaway peatlands for supporting bioenergy production and mitigating climate change because the biomass production provides an opportunity to increase carbon sequestration. However, there is a risk of peat soil CO_2 emissions, which should be avoided. Also, it is important that these areas are individually studied, because the landowners always decide the after-use method. Growing energy crops for biogas production can be profitable if logistically the best cutaway peatlands can be reserved. However, in cutaway peatlands, growing conditions can be challenging and the economic profitability must be calculated on a case-by-case basis. In addition, land ownership can be complicated, which makes it challenging to grow energy crops. The best situation is, if there exists a landowner who has several tens of hectares of cutaway peatland and if his/her large farm is located nearby. In this case, construction of farm-scale biogas plants may be more feasible, but in this kind of situations, there exists a risk that the cutaway peatland may be used for traditional field cultivation without a clear target for energy crop cultivation (large farms may need extra area for manure spreading to avoid harmful environmental effects, such as eutrophication of waters). According to paper IV, many operators may be needed to achieve sufficient power efficiency in biogas plants. Also, the levels of EU subsidies will probably decrease, which will affect the economic profitability (recent debate concerning EU politics). According to this work, it seems that afforestation will continue to be the most important after-use method for most of the cutaway peatlands (e.g. Hytönen et al. 2016). Afforestation is a good form of after-use, for example in remote areas and in a situation where agriculture is not feasible.

The use of GIS should be included in the design of bioenergy plants in order to achieve savings. GIS offers the opportunity to find the most advantageous bioenergy plant locations locally. It is clear that bioenergy production is not profitable in every location, so mapping the bioenergy potential can save resources and time of the bioenergy plant designer. Consequently, development activities can be directed to the locations where a sufficient amount of biomasses are found and where we avoid the issue that the same bioenergy plant design is offered to everyone. At the same time, transportation related greenhouse gases can be avoided even in the bioenergy planning phase when the plant is set up in an optimal location.

The best way to apply these methods could be that energy crops suitable for local environment are first evaluated and then an assessment of land use and energy potential is carried out. Thereafter, optimization of transportation routes along the road network and minimization of transportation needs can be made (Figure 21). However, GIS analyses may include simplification of the data and may include problems with data quality, which should be considered when applying them for decision-making. In general, GI analysis is always a complex process, which needs proper management. It is crucial to keep up the proper knowledge about the GIS tools and set clear goals. It has to be clear that GIS is always just one of the decision support tools, and it can never replace the decision maker itself. The future sustainable bioenergy production needs effective land use planning, where GIS-based methods can be one of the practical decision making tools in this process.

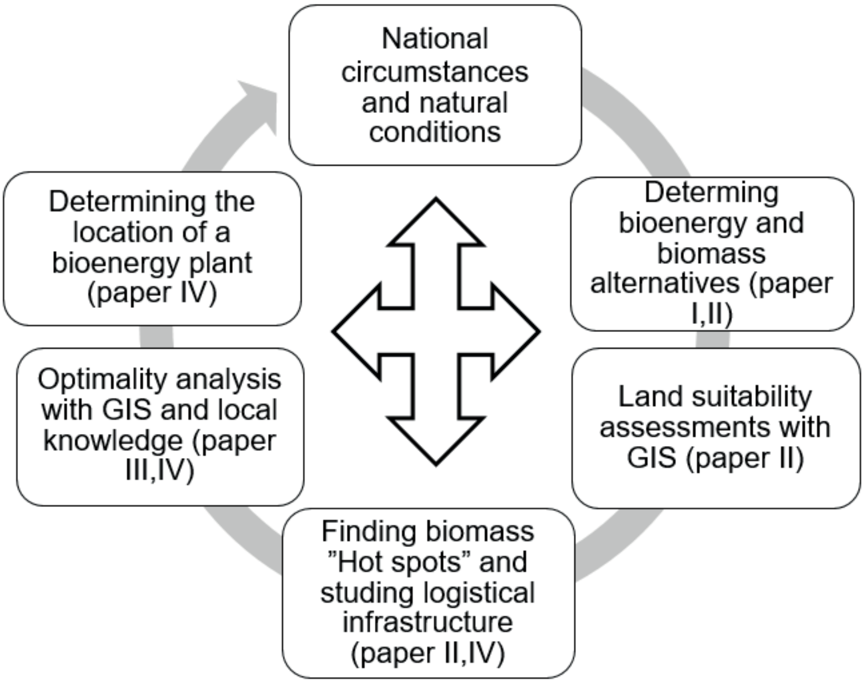

Figure 21. The process of using GI tools in bioenergy production planning. The original papers supporting the process are mentioned in brackets. The process is a circle where dialog between phases occurs.

6 CONCLUSIONS

As the combustion of spring harvested RCG grown on cutaway peatlands has been decreasing, the aim of this work was to assess feasibility of producing biogas from fresh RCG grown on cutaway peatlands by applying laboratory and scenario studies, by conducting a questionnaire-based survey, and by performing GI analyses. GIS methods were used to assess the location of cutaway peatlands and also to optimize biomass transportation for possible decentralized bioenergy production plants based on spatial distribution of cutaway peatlands. The work consists of four studies, where GIS tools provide as cross-sectional analytical method. The purpose was to utilize spatial information at national level and ultimately to provide more detailed spatial information for local and regional bioenergy planning.

Results of this study indicate that the use of fresh RCG could be a feasible energy crop for biogas production and combustion in decentralized bioenergy plants compared to traditional spring harvested dry RCG if cultivation is optimized. A net energy yield of 9.5 MWh ha^{-1}, an energy ratio of 3.9 and overall CO_2 savings of 2.9 Mg CO_2 ha^{-1} (in 20 % moisture) were obtained for the combustion scenario and the equal values for the biogas production scenario were 9.3 MWh ha^{-1}, 5.1 and 2.8 Mg CO_2 ha^{-1}, respectively. Moisture content as received, biomass handling at the power plant and the inorganic N fertilizer requirement were the most important factors affecting the energy ratios. However, the harsh environmental conditions, fragmented and remote locations, typical of peatlands, could limit the cultivation of cutaway peatlands.

In national level, there were almost 1,000 km^2 of peat extraction lands in 2014 in Finland. Theoretically almost 300 km^2 of cutaway peatlands could be used for energy crops until year 2045 (RCG, T-F) having biomass yield and methane potential of 100 Gg a^{-1} and 300 GWh a^{-1} respectively. Approximately 45 % of these areas are located in South and North Ostrobothnia, and there the future potential for using cutaway areas for energy crops is the biggest. The densest peat extraction by region is in South Ostrobothnia. This future resource could support decentralized farm scale biogas plants in the region.

Landowners of cutaway peatlands were interested in bioenergy production as an after-use method on the chosen study area. The most popular after-use method for cutaway peatlands in the near future is afforestation. Significant correlation was noted between the future willingness to promote forest biomass usage in bioenergy production and the size of the owned area. This means that usually the greater the owned land area, the better alternative forest energy is. The study pointed out that almost 500 ha or 8.2 % of the current peat extraction areas could be used for energy crop cultivation by 2035 in the study region. In general, agriculture and agro biomass for energy are both popular methods, but societal support has to be stronger in the future. According to the landowners, the most wanted bioenergy chain is heat production from forest biomass. Less attractive alternatives are agro biomass production and energy willow. Gasification of biomasses seems to be less attractive technique having even negative impressions; especially in the case of energy willow.

Finally, 13 farm-scale biogas plants (100 kW or higher) and eight centralized biogas plants (300 kW or higher) considering a threshold distance of 10 km were identified by using route optimization, hierarchical clustering, and location optimization tools in the study area. In addition, two wood terminals were identified using kernel density estimation, forest inventory database, and road networks in the study area. The results suggest that the co-digestion of bio wastes and potential fresh RCG from cutaway peatlands could be logistically reasonable in some circumstances.

Altogether, the land use of cutaway peatlands will be influenced by the needs of future circular economy. Cutaway peatlands can have a supplementary role as a place to grow more biomasses on marginal lands. GIS methods are especially useful for scenarios where biomass resources are allocated to bioenergy and where the biomasses are distributed across rural areas. These developed tools can help relevant business developers and decision makers to plan the locations of bioenergy plants. This helps also to plan effective and sustainable decentralized bioenergy production.

7 FUTURE OUTLOOK

Currently, circular economy strategies will increase the demand of biomass in the future, and the bioenergy production is not necessarily the major utilization method for biomass. Especially in Finland, it could be reasonable to launch national strategy for cutaway peatlands and to support e.g. afforestation. Recently, there have been many biorefinery plant projects going on in Finland and afforested cutaway peatlands could increase the national climate targets and self-sufficient of wood especially in South and North Ostrobothnia regions. However, greenhouse gas impacts should be considered and more sustainable solutions preferred. From the landowner's perspective, it would also be important to know, which after use method is the most feasible. Some kind of governmental strategy and stronger guidance could help landowners in decision making and improve the speed of the after-care process. This would also bring positive environmental effects, such as faster carbon fixation and better ability to avoid soil erosion when the surface of the cutaway peatlands would be covered by plants more quickly.

In the field of GIS, great advantages are achieved more in the future when data analysis capacity of computers is increasing and when the Internet is enabling real time, online, and automatized data analysis and automatized big data analysis. These services can offer more complex calculations with the computers and allows development of new more complex algorithms. It would be important to perform studies related to biomass allocation. This could include new technical solutions, such as real time monitoring of the biomass even including its growing stages on the fields. In the next step, location optimization methods could be used in real-case bioenergy plant planning with the potential farmers and making more detailed logistical optimizations based on actual biomasses and conservation areas. Also, suitable locations for biogas plants and wood terminals should be developed based on multi-criteria evaluations, such as evaluating criteria for economic feasibility and taking existing infrastructure into account.

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Feasibility of cultivating fresh reed canary grass on cutaway peatland as feedstock for biogas production and combustion.

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Planning land use for biogas energy crop production: The potential of cutaway peat production lands

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ABSTRACT

Each year, thousands of hectares of peatland that had been harvested are being released in Finland, which can offer an opportunity to increase energy crops and attain the bioenergy targets for non-agriculture lands. In this study, the Geographic Information System (GIS) method was used to improve the assessment of decentralized renewable energy resources. The amount of peat production lands and future cutaway areas for energy crop production was calculated as a case study by using ArcGIS and the Finnish Topographic database. There are almost 1000 km^2 of peat production lands in Finland, and theoretically, approximately 300 km^2 of cutaway peatlands could be used for energy crops after 30 years. The dry biomass yield of reed canary grass (*Phalaris arundinacea*) or timothy-fescue grass (mix of *Phleum pratense* and *Festuca pratensis*) could be higher than 100 Gg a^{-1} in these lands indicating methane potential of approximately 300 GWh. The exhausted peat production areas in the western region of Finland have significant potential for use for energy crops; North and South Ostrobothnia account for almost 45% of the total peat production land. A future goal could be to use the cutaway peat production lands more efficiently for bioenergy to mitigate climate change. Since the use of wastelands (including peatlands) are being considered in Europe as a way to avoid competition with food production, the GIS method used in the study to identify suitable peat lands could be applicable to biomass resource studies being conducted in many countries.

1. Introduction

Many agro biomass plants, traditionally grown on agricultural land, are suitable for producing bioenergy, through combustion, gasification, pyrolysis [1], and biogas technology [2]. However, the first-generation energy plants are competing with food production [3]. One solution for avoiding the competition is to grow energy plants on non-agriculture areas such as cutaway peat production lands. Versatile wastelands have been studied in India to promote *Jatropha curcas* for biodiesel [4]. Additionally, in Sweden, energy willow has been studied in landfill areas, and in Latvia, abandoned farmland has been estimated for bioenergy production [5,6].

1.1. Peatland utilization and cutaway dynamics

Peatlands are areas that have a naturally accumulated peat layer at the surface soil. Peat consists of partially decomposed organic material, originating mostly from plants, which has accumulated under oxygen deficiency, waterlogging, acidity, and nutrient deficiency conditions. Worldwide, peatlands cover almost 4,000,000 km^2 and most of peatlands are in pristine condition. Approximately 500,000 km^2 of peatland have been used in agriculture, forestry, and peat extraction. In 2008, the total amount of peat consumed as fuel worldwide was 17.3 Mt [7]. Finland is the most densely mired country and the biggest peat producer in the world. The total peatland is about 90,000 km^2, and about 0.8% (700 km^2) of the total peatland is under production in Finland [7–9]. Peat is used for energy generation or environmental peat products (e.g., horticulture, bedding material, and compost ingredient). Most is used as energy in combustion plants [7,10]. In 2013, peat energy accounted for about 4% of the total energy consumption in Finland when the total energy consumption was 1.34 EJ [11].

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The preparation phase, including permission and water drying, lasts from 11 to 15 years in Finland, while the peat production phase itself can last from 15 to 30 years (Fig. 1). The most popular peat form, milled peat, is based on a process in which the surface layer to a depth of 10–40 mm is collected with tractors after the turning and drying process. Another form, sod peat, is produced by pressing the peat into cylindrical sods. The peat in peat production areas is on average 2 m thick, but the thickness depends on the topography. There are usually 40 to 50 peat harvesting days annually in Finland [12] during which an approximate 10 cm thick layer is removed every year (with 20–30 production years). Peat production has negative environmental impacts, such as positive global warming effect (slowly renewable energy source) and loss of nature habitat and water quality. Production is regulated by several laws and is implemented as environmentally friendly as possible in Finland [7,12].

Each year, 2000–5000 ha are released from production since the production phase usually lasts for only a few decades [12,13]. It is estimated that about 44,000 ha of peatland will be reclaimed by 2020 [14]. After-use of peat production lands may include forestry, agriculture, nature conservation, wetland, and tourism (Fig. 1). The most common after-use method in Finland is forestation. Another choice for cutaway peatlands is growing energy crops and producing energy. However, several factors affect the choice of after-use methods, e.g., the need to pump water, soil type, land owners' interests, and possible transportation distance between the cutaway land and the final use of the biomass.

Different sections of the peat production area are not released from production at the same time, which should be taken under further consideration before any decision is made about their after-use [12]. Furthermore, acid sulfate soils as well as topography and groundwater levels are essential factors to consider. Acid sulfate soils can cause acidification if land use methods such as ditch digging oxidize otherwise anoxic soil. When sulfide is oxidized, it can start a reaction that leads to the formation of sulfuric acid. Acidification can be prevented by liming the soil and carefully planning land use [15]. After-use forms of cutaway lands are not limited by law [12,13]. The minimum analysis suggested for mineral subsoils are pH, sulfur content, and fine material (<0.06 mm) percentage [16]. According to Salo and Savolainen [12], especially during the 1990s much of the peat production area moved to the after-use phase when the oldest peat production lands were exhausted in Finland.

1.2. Energy crops and increased bioenergy production on cutaway peatlands

Cutaway peat production areas can be used to grow energy crops if the natural water level can be kept low enough with gravity drainage. If the water level has been adjusted with pumps, the hydrological conditions are usually too wet for agriculture. In that case, a suitable after-use method is wetland or mire regeneration [12]. About 26–42% of cutaway peat production lands are suitable

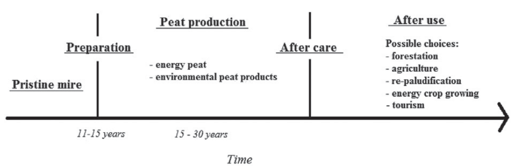

Fig. 1. Peat production land dynamics from pristine mire to the after-use phase in Finland (modified from Salo and Savolainen [12]).

for agriculture or energy crop production depending on the boulder-poor areas [16]. The biggest peat producer in Finland, Vapo, used approximately 30% of the cutaway lands in practice for agriculture or energy crops in 2010 [17]. Nevertheless, the use of fertilizer is necessary in many cases to ensure the normal growth of the plants, biomass production, and proper soil fertility [12].

If agricultural use will be possible, reed canary grass (RCG, *Phalaris arundinacea*) can be grown on cutaway peatlands [18,19] as well as timothy grass (*Phleum pretense*). RCG is the most high-yielding grass species in peatlands [20] with dry biomass yields of 5 to ca 12 Mg ha^{-1} a^{-1} when fertilization and liming are optimal [20,21]. However, in practice, the dry biomass yield is usually closer to 5 Mg ha^{-1} a^{-1} because of e.g. frost damage and temporary flooding [22]. In addition, the need of ditches decreases the biomass yield because of the intensive drainage process. There are usually 500 m of ditches per hectare of peat production land [23]. According to Järveoja et al. [24], reed canary grass is the best after-use alternative if GHG (greenhouse gas) emissions, related to soil use and biomass combustion, are considered. Similar results were calculated by Kirkinen et al. [25].

In 2009, there were about 20,000 ha of RCG cultivation on cutaway lands and agricultural fields in Finland. RCG was a promising plant species when renewable energy was the focus; however, because technical difficulties (the need to separate the feeding line into the combustion chamber) appeared in combustion plants, RCG farming has decreased significantly since 2010 [26]. Instead of combustion, RCG have methane potential ranging from 246 to 430 dm^3 kg^{-1} volatile solids (VS), and can be used in biogas plants [3,27,28]. Cutaway peat production areas could offer opportunities for neighboring farmers to make farm-scale biogas plant investments more profitable when local available feedstock resources increase. Peat production areas are usually large units (from tens to even hundreds of hectares) and logistically easily accessible [12]. In addition, farmers have harvesting equipment for energy crops. Co-digestion of crops with cow manure can stabilize the process and increase the amount of biogas and even decrease farming-associated greenhouse gases [29]. For instance, 50 ha of cutaway peatland for energy crops would theoretically offer an 815 MWh gross energy yield for a farm-scale biogas plant (dry biomass yield of 5 Mg ha^{-1} a^{-1} with a methane yield of 326 dm^3 kg^{-1} total solids (TS) [28]). Consequently, it is essential to recognize cutaway peat production lands as part of potential wasteland for energy crop production to increase decentralized renewable energy production.

The energy crop resources of cutaway peatlands can be estimated by using Geographic Information Systems (GISs). GIS-based methods have been used to calculate regional biogas potential [6,30–34]. Spatial distribution of biomass resources and the most effective utilization location for energy production can be investigated by combining location optimization methods and GIS. Optimization methods have been used to calculate the best supply chains of biofuels [35]. When GIS and location optimization methods are combined, there are many advantages such as better visualization in solving problems [36].

The objective of this study was to apply GIS-based methods to calculate the area of peat production land in Finland. Based on the area, the future after-use potential of cutaway peatlands for energy crop production can be assumed by using previous studies and knowledge of biomass yields in peatlands. This type of research has not been conducted in such wide context before, and the results of this study can offer knowledge for policymakers and energy businesses stakeholders to develop bioenergy-based commercial activity in rural areas. The GIS method used in the study can be applied in other countries, if biomass resources must be allocated. This study did not include greenhouse gases or energy inputs related to energy crop production (harvesting, transportation, etc.).

2. Materials and methods

2.1. Spatial analysis of peat production in ArcGIS

The GIS-based analysis of peat production in Finland was performed with the ArcGIS v. 10.2 ArcMap program. The peat production sites in Finland were observed with the MapSite service (produced by National Land Survey of Finland, NLS) on a scale of 1:200,000 (human-made objects were updated in 2013). The maps used in this study were made by NLS and are in the Topographic database (© NLS, 2014 supplied as 12 km × 12 km map tiles). The map layer containing all types of nature was added to a map project in the ArcGIS program for further analyses. The polygons representing areas under organic soil mining (class value 32,113 in topographic database) were extracted with the ArcGIS Selection tool into new map layers. All map tiles containing organic soil mining polygons were then combined together using the Merge tool.

The resulting map layer contained all peat production areas in Finland, and they were then defined by commonalities with the Intersection tool using Finnish municipality and region maps (© NLS, 2014, the names and the locations of the regions are presented in Fig. 2). Then the surface area of the regional peat production lands was calculated by using the Calculate Areas (in the Spatial Statistics tools) and Summarize tools. All calculations based on the areas were made with the Field calculator in the attribute table and Microsoft Excel v. 2010.

We visualized the risk of acidification on the cutaway lands by using maps produced by the Geological Survey of Finland (GTK). The maps visualize the various probabilities (from low risk to high risk) of acid sulfate soils; in this study, even low-risk areas were included. The same tools (Intersection, Calculate Areas, and Summarize) were used to calculate peat production land in sulfur-rich areas by region. Differences in local hydrology or boulder-rich areas were not included.

Finally, Kernel Density (in the Spatial Analysis tools) was analyzed with ArcMap to identify the most intensive peat production areas in Finland. First, separate peat production areas were converted into points with the Feature to Point tool. The raster size in the Kernel Density analysis was 1 km, and the search radius was 50 km. Each kernel was weighted by the peat production area size. The methodology is illustrated in Fig. 3.

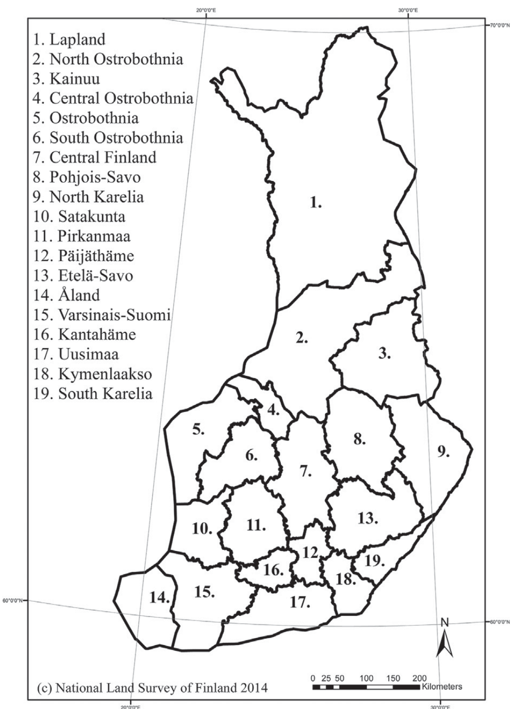

Fig. 2. Finnish regions used in the spatial classification of current peat production areas (© NLS, 2014).

2.2. Energy crop biomass estimation

The suitability of peat production areas for growing energy crops was estimated based on previous studies on cutaway land suitability for agricultural purposes. The value used in this analysis was 30% (Eq. (1)); in practice, approximately 30% of the cutaway areas were used for energy crops and agriculture in 2010 [17]. A previous study presented theoretical values, based on mineral subsoils, in the same scale (26–42%) [16]. This study relies on the near-future scenario in which every current peat production area will be in the after-use phase after 30 years. The linear percentage of current peat production land exhausted by year can be justified because according to Flyktman [14], the need for new peat production areas is close to linear in Finland. Consequently, it can be assumed that cutaway areas are released from production in direct proportion. The future peat production area (size not yet established) was not assessed in this study.

Ditch loss was calculated based on 2.5 m ditch width (including 0.5 m ditch bank on both sides), because ditches are not visible in soil class 32,113 (Eq. (2)). Biomass yield and methane potential were calculated based on Eqs. (3) and (4). The plant-dependent biomass yield and the methane potential were calculated based on dry biomass yields of 5 Mg ha^{-1} and 4 Mg ha^{-1} and methane yields of 214 and 311 m^3 Mg^{-1} for dry timothy-fescue grass mix and RCG, respectively. All yields are unpublished field data that sit well within the range of empirical studies in the literature [3,22,27,28].

Equations used in this study:

Area for energy crops by region, *TAE*:

$$Area\ by\ region\ (ha) \times 30\ (\%) \tag{1}$$

Ditch loss per hectare, DL (%):

$$500\ (\mathrm{m}) \times 2.5\ (\mathrm{m}) \Big/ 10000\ \left(\mathrm{m}^2\right) \times 100\ (\%) \tag{2}$$

Biomass yield, BY (TS):

$$Plant - dependent\ dry\ biomass\ yield\left(Mg\ ha^{-1}\ a^{-}\right)^{1} \times TAE \times (100\% - DL) \tag{3}$$

Biogas gross energy yield, BP:

$$Plant - dependent\ methane\ yield\ \left(m^3\ Mg^{-1}\right) \times BY \times 10\ (kWh) \tag{4}$$

3. Results

The spatial density of the current peat production in Finland and the area suitable for growing energy crops was studied using the

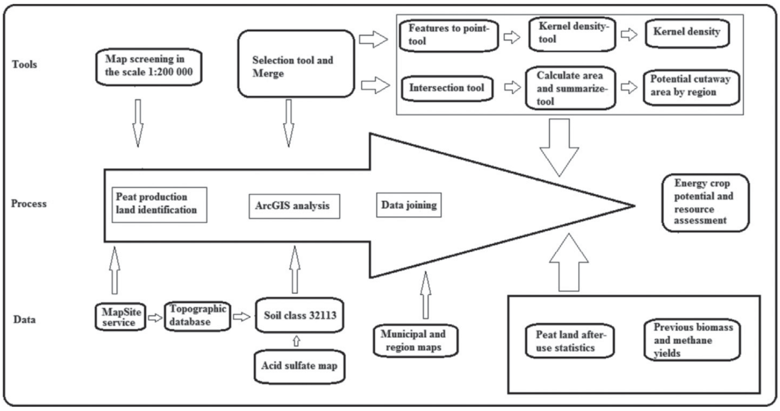

Fig. 3. Description of the GIS methodology used to plan land use for biogas energy crop production in the case study.

ArcGIS program, previous studies on methane and biomass yields, and after-use statistics. There are nearly 1000 km^2 of peat production land in Finland, and almost 2900 geographically separate peat production units (or soil class 32,113) were found in this study, with an average size of 34 ha. The biggest area was almost 700 ha and the smallest just a few square meters. The median size was 17 ha. The most intensive areas for producing peat are the central and western regions of Finland, and the South Ostrobothnia and North Ostrobothnia regions account for almost 45% of the total peat production area (Fig. 4).

Kernel density was estimated to identify peat production density (Fig. 5). The densest peat production is in South Ostrobothnia, and the intensity is clearly emphasized in the western region of the country. Four areas are under especially intensive peat production: North Satakunta and southwestern parts of South Ostrobothnia, East Ostrobothnia and the northwestern parts of Central Finland,

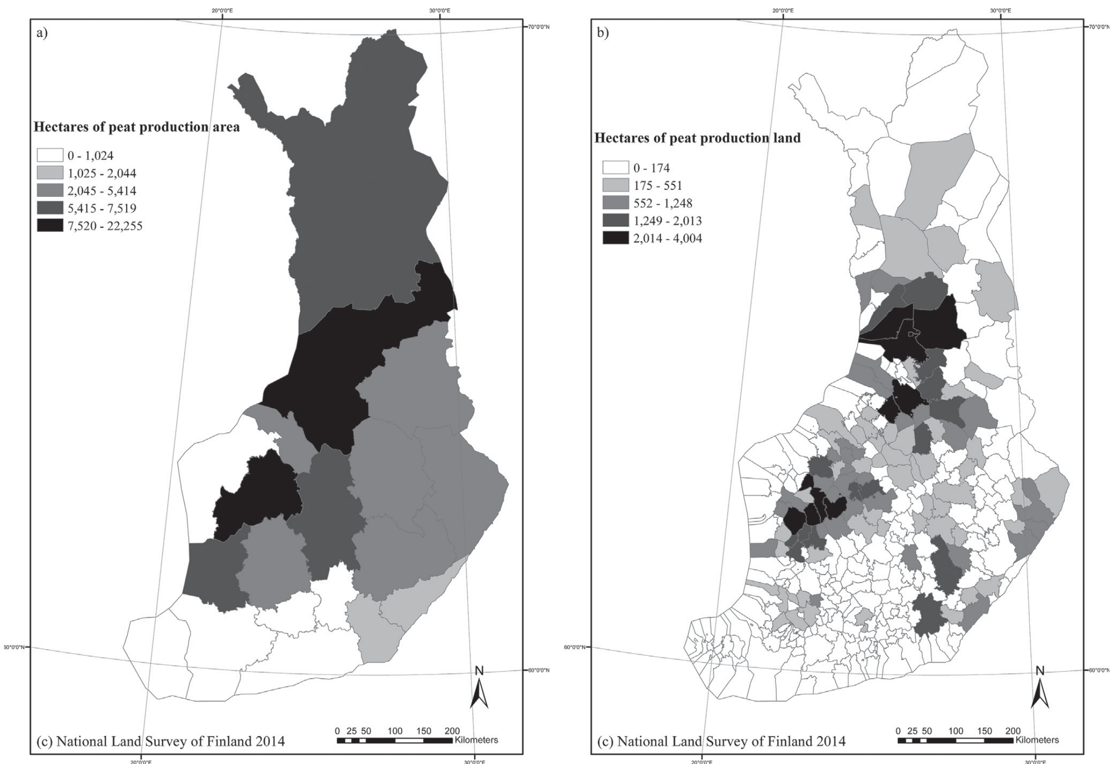

Fig. 4. Current peat production in Finland by region (a) and municipality (b). The darker the color, the denser the peat production area (© NLS, 2014).

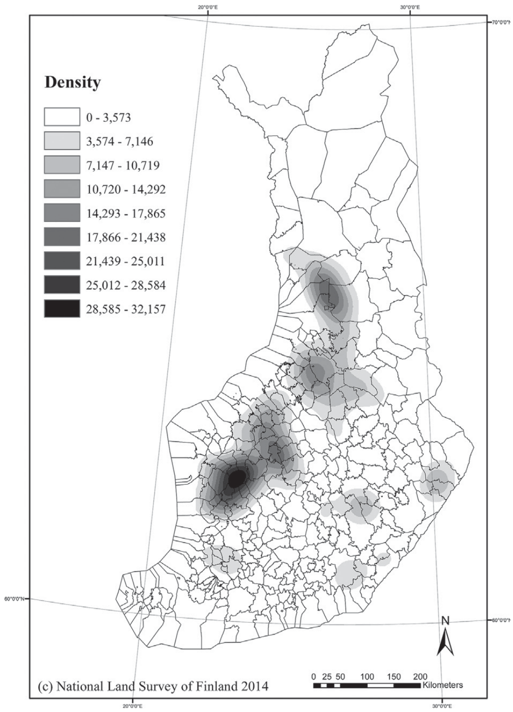

Fig. 5. Kernel density estimation for peat production in Finland was weighted by area size. The search radius was 50 km. The color illustrates the relative density only, not specific units (© NLS, 2014).

the western part of North Ostrobothnia, and the northwestern part of North Ostrobothnia and the southwestern part of Lapland.

The area suitable for future energy crops was then identified by using geographic information and after-use statistics. Nearly 30,000 ha of peatland theoretically could be used to grow biomass for bioenergy by 2044 (Table 1). South and North Ostrobothnia will have 6500 and 6700 ha, respectively, by 2044, and about 2000 ha areas can also be found in the Central Finland, Satakunta, and Lapland regions. If the area is used for grass, either RCG or timothy-fescue, annually about 100 *Gg* dry biomass yield could be produced with both plant species assuming two harvests per year, respectively, in Finland. This means the gross methane potential is approximately 300 GWh per year.

The peat production areas in acid sulfate soils were identified by using GIS-based data (Fig. 6). Most of the acid sulfate peat production soils are located in the western region and especially near the coastline of the Baltic Sea. Many of the areas under intensive peat production are at risk of soil-related acidification. For instance, there are thousands of hectares of such land in South and North Ostrobothnia (Table 2).

Because peat production land is released from production section by section, a future scenario for energy crop was created. For the next 10–20 years, only 10,000–20,000 ha of the total area (30,000 ha) could be usable for energy crops (Fig. 7).

4. Discussion

The GIS method had several limitations: data availability and resolution. The same types of limitations were observed in other GIS-based bioenergy studies by Stork et al. [35] and Abolina et al. [6]. Consequently, this method is suitable only for assessing large-scale resources. The result is a coarse estimate of the after-use potential of the peat production areas for agriculture purposes in the near future, because differences in local hydrology or boulder-rich areas were not included. The most significant factor in the after-use of cutaway land is hydrology, because agriculture is not possible in wet fields. In addition, boulders and pool-forming sites, including hard silt, can be found in many mires, and every peat production site has unique geography [16]. This will affect the accuracy of the analysis. Therefore, this method targets the locations with the most potential, but we must conduct future studies on a smaller geographic scale. In this study, limitations were related to the calculations and simplifications that made assessing the technical and practical feasibility for all of Finland difficult. For example, the release or exhausted time of the peat production sites is not constant because it depends on weather conditions, the demand for the peat, and the value of other energy resources [14]. Nonetheless, peatland exhausted time points can be included in the GIS-based method.

The results of this study can be used to inform landowners and local farmers to support regional energy crops and to develop energy entrepreneurship. According to Salo and Savolainen [12], the landowner is always the final decision-maker regarding the after-use method. The choice is often related to location. If the cutaway land is near farms, the biggest possible amount of cutaway land is most likely chosen for agricultural use [26]. Different after-use methods compete with each other, and the most popular method, forestation, might be an attractive choice for many landowners because the annual management costs can be lower in forest management than in agriculture. Instead of forestation, the energy crop resource found in cutaway areas could play a significant role in the biogas production plans for some rural areas. In some areas, energy crops in cutaway areas have a significant effect on the regional bioenergy potential.

According to Peura and Hyttinen [37], the biogas potential of South Ostrobothnia is 609 GWh annually if manure and RCG from fallow land are included. According to this study, an additional 71 GWh can be achieved in South Ostrobothnia if cutaway peatlands are used to grow RCG and the biomass used in biogas production in the near future. South Ostrobothnia has been a traditional peat production area because of the large peat reservoirs and peat demand of nearby cities [10]. There are still uncertainties in the total methane potential because the variability shown in previous studies is large; for example, the methane potential of RCG varies from 246 to 430 $dm^3\ kg^{-1}$ VS [2,27,28]. Consequently, the methane potential of RCG in Finland could vary from 234 to 408 GWh annually even if the biomass yield is the same. As a comparison, the potential for Finnish biogas only in agriculture fields is assumed to be 13.5 TWh a^{-1} if 5000 km^2 are used to grow grass [38]. In addition, the biomass yield per hectare itself is a very sensitive aspect of biogas potential and yield.

The potential of energy crops on cutaway lands is emphasized in the western region of Finland. In southern Finland, the lack of peat production is a result of naturally low peatland intensity. However, climatic and economic circumstances (e.g., cool climate, low population density, and large transportation distances) limit peat production and energy crops in northern Finland, even though the peatland intensity is high [8]. These factors can have negative effects on energy crop production. Spatial circumstances were not analyzed in this study (except acid sulfate areas), and the estimate was based on after-use statistics. The statistics apply to all geographic locations.

This study supports a previous study conducted by Leinonen [39] on the spatial distribution of peat production by region. The

Table 1
Peat production area in 2014 (© NLS, 2014), future cutaway lands suitable for energy crops, and annual dry biomass and methane yields after 30 years in Finland.

Region	Peat production, ha	Suitable for energy crops, ha	% Of all of the energy crop area	CH_4 potential (2 cuts a^{-1})			
				RCG, Mg a^{-1}	RCG, GWh a^{-1}	T-F, Mg a^{-1}	T-F, GWh a^{-1}
Uusimaa	281	84	0.3	295	1	369	1
Varsinais-Suomi	1024	307	1.0	1075	3	1344	3
Kantahäme	858	257	0.9	901	3	1126	2
Päijäthäme	246	74	0.2	258	1	323	1
Kymeenlaakso	1898	569	1.9	1993	6	2491	5
Satakunta	7519	2256	7.6	7895	25	9869	21
Central Finland	7479	2244	7.6	7853	24	9817	21
Etelä-Savo	3353	1006	3.4	3521	11	4401	9
North Karelia	4289	1287	4.4	4503	14	5629	12
Pirkanmaa	4452	1336	4.5	4675	15	5844	13
South Karelia	2044	613	2.1	2147	7	2683	6
Ostrobothnia	687	206	0.7	722	2	902	2
Pohjois-Savo	5414	1624	5.5	5685	18	7106	15
South Ostrobothnia	21,802	6541	22.1	22,892	71	28,615	61
Central Ostrobothnia	3497	1049	3.5	3672	11	4590	10
North Ostrobothnia	22,255	6677	22.6	23,368	73	29,210	63
Kainuu	5016	1505	5.1	5267	16	6583	14
Lapland	6409	1923	6.5	6729	21	8412	18
Åland	0	0	0.0	0	0	0	0
Totally	98,524	29,557	100.0	103,451	322	129,313	277

Acid sulfate soil was not considered when suitability for energy crops was calculated.
RCG = Reed canary grass, dry biomass yield assumption 4 Mg a^{-1} (two harvests).
T–F = Timothy–Fescue grass, dry biomass yield assumption 5 Mg a^{-1} (two harvests).

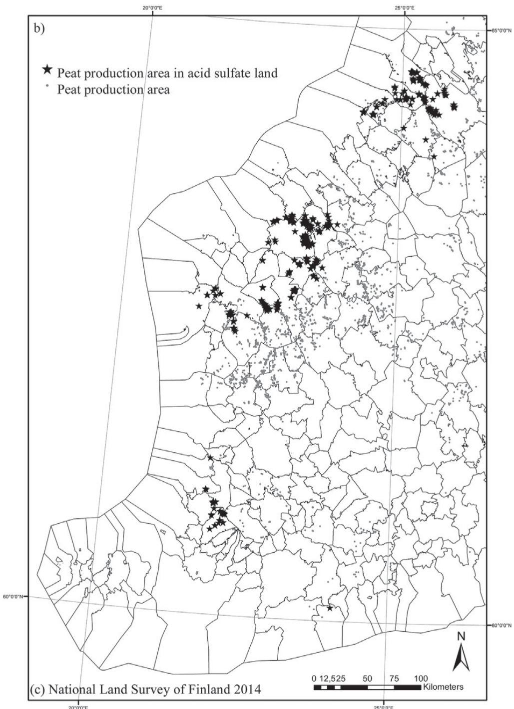

Fig. 6. Current peat production areas in acid sulfate soil in Finland (© NLS, 2014).

Table 2
Current peat production area under acid sulfate soils by region in Finland.

Region	Peat production area under acidsulfate soils, ha
Uusimaa	31
Varsinais-Suomi	300
Satakunta	171
Ostrobothnia	486
South Ostrobothnia	4994
Central Ostrobothnia	2
North Ostrobothnia	3806
Totally	9791

amount of peatland under peat production is much higher in this study compared to the official peat production statistics when the area is calculated by using soil class 32,113. The area, with class number 32,113, is more than 985 km^2, and officially, the area currently used for peat production is approximately 700 km^2 in Finland [9]. The difference between these values is caused by the fact that many cutaway areas are still waiting for after-use or they are support areas (out of production, roads, storage, buildings, etc., within the peat production areas), which will decrease the production area. In this study, it was not possible to identify unique after-use or why different areas were still under soil class 32,113. In Finland, soil class 32,113 includes other organic mining activities, such as organic soil mining for domestic use, but the area is meaningless compared to peat production. More than 300 areas total less than 1 ha each (which are most likely organic mining activities other than peat production), but the total area was only 100 ha. However, only 650 units of peat production areas larger than 50 ha were observed; the total area was 660 km^2, which is 67% of the total peat production area in Finland. In that sense, the Kernel density estimation, which was weighted by area size, gives a starting point for assessing the biomass potential for future farm-scale biogas plants. The peat production unit size is essential when profitability is assessed, because the bigger the area, the smaller the logistics costs [12].

The question of after-use methods for cutaway peatlands is important in Finland since the amount of peat production by country is the highest in the world. For example, in 2010 cutaway areas were assumed to be 5000 ha and 18,000 ha in Sweden and Estonia, respectively, but the area under peat production was much smaller than in Finland [40]. These countries share somewhat similar climatic conditions, peat production dynamics, peat

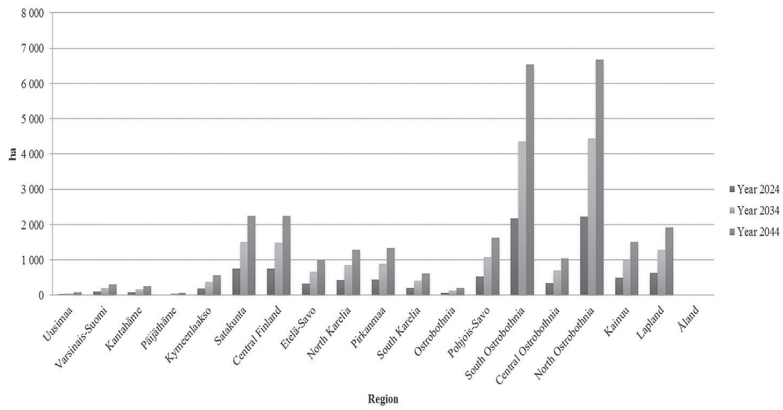

Fig. 7. The estimated cutaway area released for energy crop production by region in Finland in the next 30 year.

harvesting techniques, and after-use choices, but the biggest amount of cutaway area is located in Finland [41]. The challenge is to improve awareness of growing energy crops on cutaway areas for biogas because large-scale cultivation and use of RCG in combustion plants have decreased rapidly in Finland. Many things support the overall sustainability of energy crops in cutaway areas, such as reduction of greenhouse gas emissions [24,25] and rapidly decreased erosion of peat from the surface of the mire [41].

Consequently, more research is needed to study landowners' willingness to choose agriculture as an after-use method. Many peat production areas are situated in remote locations, which affect cost-effectiveness. More research is also needed to improve the assessments on a local scale, for instance, with case studies based on one or a few known peat production areas. The accuracy of this type of study could be improved by using soil analysis methods and groundwater levels.

5. Conclusions

GIS-based methods were used in this study to promote the use of wastelands for decentralized bioenergy production. Cutaway peat production land was used as a case study. The method was useful for allocating wastelands for bioenergy production but has data resolution and simplification limitations. The GIS-based method showed that almost 1000 km^2 of peat production land existed in 2014 in Finland. If 30% of the current peat production land is suitable for energy crops after 30 years, almost 30,000 ha theoretically could be used for energy crops. Approximately 45% of the peat production lands are located in South and North Ostrobothnia, and there the future potential for using cutaway areas for farming is the biggest. The densest peat production by region is in South Ostrobothnia, which could have a significant potential to use cutaway peat production lands for bioenergy production in farm-scale biogas plants. However, almost 5000 ha of peat production lands in the region are under acid sulfate soils, which must be considered, even though the after-use method is not regulated by law.

Previous studies and field experience have shown that the dry biomass yields of RCG and timothy-fescue-grass could be more than 100 Gg a^{-1} on cutaway lands in Finland by 2044 for both plant species. This means about a 300 GWh gross energy yield with biogas technology. Cutaway peatlands can have a significant effect on creating new biogas plants and supporting decentralized energy system development in rural areas in Finland. There are still challenges, such as landowners' interests and logistical arrangements, to overcome before cutaway peat production lands can be used for biogas production in practice.

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Landowner's willingness to promote bioenergy production on wasteland – future impact on land use of cutaway peatlands.

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Landowners' willingness to promote bioenergy production on wasteland – future impact on land use of cutaway peatlands

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ABSTRACT

Landowners are the key players in bioenergy production on wasteland; such as cutaway peatlands. In this study, the landowner's interest to use cutaway peatlands for bioenergy production was investigated using a survey and GIS (Geographic Information Systems) methods in an area in South Ostrobothnia, Finland. The focus was to identify which different bioenergy production chains are preferred by the respondents: combustion, gasification or biogas production from agriculture, energy-willow short-rotation forestry or forestry based energy crops. Also, the influence of personal environmental values on the selection was measured and the future impacts and barriers for the land use were assessed.

Afforestation was the most popular after-use method among the landowners. The next most favorable method was energy crop cultivation but it was highly dependent on economic profitability and subsidies. Currently, approximately 8.2% or 500 ha of the total peat extraction area could be used for bioenergy production in the region by 2035. Based on the survey, forest based biomass is the best option if bioenergy is to be produced. The next choice was agro biomass and the least favored plant was willow. This study suggests that the biggest cutaway peatlands will be converted to forest energy in the future. Suggestive results were that the owners with high environmental values are especially interested in agro biomass growing and the landowner having a distant home place does not have a negative influence on bioenergy production. Altogether, land use and biomass production of cutaway peatlands is connected with the demands of the Finnish bio-economy.

1. Introduction

In literature there has been a debate concerning land use planning and bioenergy production targets (Gamborg et al., 2012; Scarlat et al., 2013). The fundamental concern has been the effect of energy crops on land use and food prices; because the growing of energy plants for 1st generation biofuels has taken space from food production and increased food prices. In developing countries especially, this has been considered to have a negative socio-economic impact (Edrisi and Abhilash, 2016). Consequently, bioenergy production is increasingly conducted on marginal lands globally, to avoid competition with food production and to increase the sustainability aspect of bioenergy production (e.g. Xue et al., 2016; Stoof et al., 2015; Abolina et al., 2015).

The term "marginal land" has multiple definitions: the land can be economically barely profitable for agriculture purposes or it is not in commercial use. Marginal land can also be considered as "idle, under-utilized, barren, inaccessible, degraded, excess or abandoned lands, lands occupied by politically and economically marginalized populations or land with characteristics that make a particular use unsustainable or inappropriate" as defined in Dale et al. (2010). Wasteland is one form of marginal land. The definition of wasteland is also contradictory and environment dependent, but in this study wasteland is considered as a patch of land having no appreciable vegetative cover and degraded by natural as well as anthropogenic activities (as presented in Edrisi and Abhilash 2016; Oxford Dictionary, 2016).

Peat extraction lands, common in Finland as well as in Sweden, Ireland and the Baltic countries, can be specified as wasteland after peat extraction. Peat is a commonly used fuel especially in Finland and Ireland, where about 5–7% of primary energy consumption relies on peat. Peat is used as agricultural and horticultural purposes as well (World Energy Council, 2013). At the beginning of the peat extraction, the pristine mire is dried with ditches and the surface layer (vegetation and partially decomposed organic matter) is removed. After ca. 20–30 years of peat extraction, the area is left bare without vegetation. E.g. in Finland, about 2500 ha of peat extraction areas is shifting to cutaway phase annually (Leupold 2004; Salo and Savolainen 2008). Cutaway

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peatlands suit well the definition of wasteland because the pristine mire is modified and left barren by anthropogenic action. Even though the area can be considered as wasteland, the surface is usually barren or untapped only for a relatively short time (max. a few years), because it is recommended that a profitable after-use method is applied as soon as possible. However, the transition from barren surface to vegetative cover can vary greatly, depending on soil properties (Leupold 2004). Natural vegetation succession is a very slow process on cutaway peatlands (Huopalainen et al. 1998; Silvan and Hytönen 2016).

In Northern Europe, the cutaway peatlands have been identified as a potential wasteland to grow energy crops, such as: willow, reed canary grass (RCG), and forest energy (Leupold 2004; Pahkala et al., 2005; Picken 2006; Parviainen 2007; Salo and Savolainen 2008; Järveoja et al., 2013; Jylhä et al., 2015). However, a relatively small amount of cutaway peatland is suitable for energy crop production because there are challenges related to water level, remote locations, site nutrition, the size of the released area, landowner's interests and ignorance which can have a negative impact concerning bioenergy production. According to Picken (2006) about 26–42% of these areas are suitable for agricultural use and 57% for afforestation, based on the mineral subsoil characteristics. However, the poor nutrition is often a challenge on cutaway peatlands. Especially, phosphorus and potassium are limited nutrients. The nutrition can be improved by soil preparation, fertilization, and mixing of the bottom peat with the underlying mineral soil (Leupold 2004; Huotari et al., 2006; Salo and Savolainen 2008; Huotari et al., 2009).Nowadays, the most popular form of after-use is afforestation, but there are several other after-use methods available, such as: agriculture, tourism, restoration, and bird sanctuary (Leupold 2004; Salo and Savolainen 2008). If the bioenergy after-use method is chosen, then special attention must be paid to the location, since the transportation distance of biomass to a biomass utilization plant has a significant effect on the net energy yield. The cost-effective transportation distance is dependent on a variety of factors, such as: plant species, type of transportation method and bioenergy conversion technology. E.g. in the case of reed canary grass (RCG, *Phalaris arundinacea*) which is harvested in spring time for combustion, the highest economically transportation distance to a combustion plant is roughly 70–80 km (Lötjönen and Knuuttila 2009). If the distance is higher, the transportation costs are usually too high to achieve a feasible production chain.

Currently, peat extraction covers almost 1000 km^2 area in Finland and the most intensive extraction area is situated in the western parts of Finland (Laasasenaho et al., 2016). The status of peat as a natural resource is contradictory, because it has many environmental impacts. Peat extraction usually causes: deterioration of peatland habitats and biodiversity, hydrological problems, emissions into waterways, and increased greenhouse gas emissions (e.g. Mäkiranta et al., 2007). However, the extraction is regulated by Finnish Environmental regulation (Ministry of Environment, 2015). On the other hand, peat extraction can be a significant employer in rural areas. The conflict between economy and conservation of nature in peatland utilization has been studied (e.g. Chapman et al., 2003; Tolvanen et al., 2013). There are always trade-offs involved between services the ecosystem provides (clean air and water, flood protection etc.) and economical goals in peatland and people's opinions are highly dependent on a person's background, such as: home location (city or countryside) and education (Tolvanen et al., 2013). An inquiry, clarifying the attitude of local inhabitants towards different after-use methods (North Ostrobothnia region, Finland; Kittamaa and Tolvanen, 2013) indicates that the most favored after-use method is forestry or a bird sanctuary/wetland and the second favorable choice is agriculture or energy crop cultivation, whereas the least wanted after-use form is pasture or special plant tillage. The remarkable thing is that 52% of the local people highlighted recreational after-use choices in the study. Similar results about the popularity of afforestation and agriculture have been collected amongst the landowners of the peat extraction areas in Alavus, South Ostrobothnia, Finland (Karjala 2014). Consequently, because of a lack of studies concerning the landowners' background and their environmental opinions as well as their personal motivation versus their chosen after-use method, more studies were needed concerning landowners' interests.

Landowners' opinions towards bioenergy production on abandoned farm land has been investigated, e.g., in Latvia (concerning the growth of short rotation woody crops; Abolina and Luzadis, 2015). There, one of the biggest barriers for the utilization of abandoned farm land is the fact that the landowners do not live near the areas. In another study conducted in Michigan, USA, energy crop growing on marginal lands is limited by trade-offs between farmland availability and marginal land and only one third of the landowners were willing to rent their marginal lands at the rental rates offered (Hayden, 2014). In Finland, as well as in Sweden and in Canada, the peat extraction area is usually located on private or public land (Leupold, 2004). The peat producing company can own the peatland or it can rent the mires. When the peat is exhausted, the area is passed to the after-use phase and the landowner can decide the after-use method. Therefore, the landowner is the key player when the after-use methods are planned. Consequently, the objective of this study was to make a survey of the landowners of peat extraction areas and combine the data collected with geographical information systems (GIS) to recognize the spatial distribution of the potential bioenergy production areas. The main goal was also to improve the knowledge of landowner derived bioenergy after-use methods on cutaway peatlands and future impacts on land use within them.

2. Material and methods

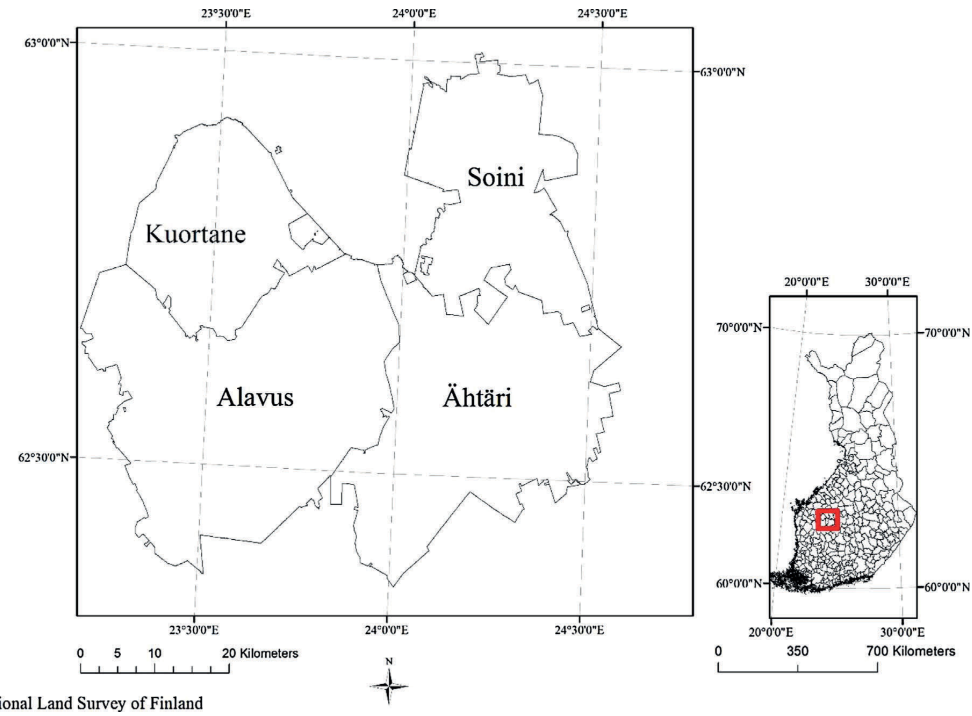
2.1. The study area

The study was conducted in the "Kuudestaan" region, Finland (Fig. 1). The region is one of the European Union's (EU) Rural Development Action Groups located in Western Finland (Erkkilä and Ahonpää, 2014) and the area was chosen because there is intensive peat extraction nationally (Laasasenaho et al., 2016). The municipalities in the area are Alavus, Kuortane, Soini and Ähtäri. There are in total approximately 25,000 inhabitants in the area whose size is 3119 km^2. Economic life is strongly based on forestry and agriculture (Erkkilä and Ahonpää, 2014) and thousands of hectares of peat extraction areas will become wastelands in the area in the near future. Mires and peat extraction intensity in the area is presented in Table 1.

2.2. Search for potential peat extraction areas and landowners

In this study, GIS based methods were used to recognize landowners and potential cutaway peatlands in the "Kuudestaan" region. At first, all the peat extraction areas in the "Kuudestaan" region and all the property or estate codes located within the area were checked using Paikkatietoikkuna web service which contains maps from the National Land Survey of Finland (NLS) (Paikkatietoikkuna, 2016). The estate code was accepted if there were at least 15 ha of peat extraction land within the landowner's property. The area limitation was based on an assumption of reasonable bioenergy production size by after-use experts from a national bioenergy company (personal communication by Ari Laukkanen, Kimmo Aho and Juha Kinnunen on the 12th of January 2016). The size of the areas was calculated by using the Finnish Topographic database and using the "Measure an area on the map" tool. The data on the map was from the year 2014.

Because peat extraction areas are usually situated in remote locations (Salo and Savolainen, 2008), only the most potential areas were then chosen. This meant that the peat extraction areas and landowners within a 10 km radius (by Euclidean distance, personal communication by Ari Laukkanen, Kimmo Aho and Juha Kinnunen on the 12th of January 2016) from the center of the municipality or local farms (from middle sized to big farms having more than a 50-head of cattle, 500 poultry, 30 horses or 500 pigs) were identified. The farm size and



(c) National Land Survey of Finland

Fig. 1. The Kuudestaan area– a map of the studied area (left). Its location in Finland is denoted with the red square (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mires, peat extraction and the area of protected mires in the "Kuudestaan" area. Total land area is 3119 km^2 (GTK, 2016).

Municipality	Mires, ha	Under peat extraction, %	Protected, %
Alavus	20400	12	7
Kuortane	9200	7	< 1
Soini	15900	11	9
Ähtäri	17800	6	2

location were obtained from the Finnish animal production regulation organization, Evira (Finnish Food Safety Authority). The information was supplemented, partially, based on a previous study in Soini (Laasasenaho, 2012). The identification was made with a buffer tool in ArcGIS v 10.3.1 (ESRI Inc, Redlands, CA, USA). After locating the suitable areas on the map, the landowners' contact information related to the estate codes were requested from NLS. The areas already removed to after-use were not included or analyzed in this study, because there is a lack of statistics concerning peat extraction areas' after-use.

2.3. The survey

The survey (see appendix) about different after-use methods was sent to 75 landowners in total, including 69 private persons, 5 companies, and 1 foundation. The answers were anonymous and confidential. The response rate of the survey was 33%. 76% of the respondents were men and 24% were women. The educational level was set in an ordinal scale and the respondents had a median of upper secondary education (from comprehensive school to university degree) and the median of age class was 41–50 years old (Table 2). The survey included: some background information (sex, age, education, home town, the location of owned property under peat extraction, the size of

Table 2
Background information of the respondents (n = 25, if less then there are missing values).

Background	Parameter	N
Sex	Women	6
	Men	19
Home municipality	Alavus	9
	Kuortane	1
	Soini	12
	Ähtäri	3
Median age class (a)	41–50	25
Median education class	Upper secondary education and training	24

the peat extraction area on the property, the year peat extraction ends/ending of the rental contract and the planned after-use method), evaluation of different after-use and bioenergy production choices, as well as questions related to environmental values. In the latter questions, the answers were asked to be given on an ordinal scale (from 1 to 7 = does not matter to matters a lot). The bioenergy choices were combustion, biogas production and gasification from agriculture energy plants, energy willow, or wood. Environmental values were measuring the general attitude towards nature, global warming and greenhouse gases, nature well-being, and water pollution. Also, different barriers to the utilization of cutaway lands for bioenergy production were evaluated with the same scale. The questions concerned general challenges in cutaway peatlands, such as: problematic water economy, stones and bedrock, low fertile soils, frost damage, logistics, etc. Separate questions also handled the willingness to produce bioenergy on cutaway peatlands as an after-use alternative (yes, probably, no). The survey was not sent to the largest Finnish peat producing company, despite the fact that it has a significant amount of land in the area. This was because it is usually selling the cutaway peatlands after peat extraction and the company does not usually operate after-use businesses.

The cover letter was sent via regular mail, but the survey was asked to be filled in on the Internet where the answers were collected using the Wepropol 2.0 program. A voluntary guidance event was held in Tuomarniemi Forest School where it was possible to answer the survey also in paper form. Because there was a lack of responses, the respondents were also contacted by phone to remind them about the survey during April and May 2016. Both the paper and electronic forms were used. In addition, one interview was carried out by phone.

2.4. Analyses

2.4.1. GIS analyses

The location of potential cutaway peatlands and after-use choice data from the survey were modified to GIS data. The landowners who were interested in bioenergy after-use methods on peat extraction areas were located with the ArcGIS program. Coordinates (ETRS-TM35FIN) were defined to the center of the owned peat extraction area and they were added to the ArcGIS program from the Microsoft Excel 2016 based table. Kernel density estimation was carried out with a Kernel Density tool by emphasizing the points according to the peat extraction area size. The cell size for the results was set to 200 m and the search radius to 5000 m. The most potential peat extraction areas were located by using soil class 32113 (the mining of organic soil, usually peat) from the Finnish topographic database by using methods from previous studies (Laasasenaho et al., 2016).

2.4.2. Statistical analyses

The survey was analyzed with the SPSS program v. 22.0 (IBM Inc., Armonk, NY). Spearman's correlation coefficient values were determined for background variables and environmental attitudes and for bioenergy production alternatives (2-tailed) with the statistical significance level of $p = 0.05$ (Analyze → Correlate → Bivariate). Missing values were omitted pairwise. The Compute Variable tool was used to calculate integrated values for environmental values and different forms of bioenergy (combustion, biogas production and gasification of agriculture or forest based plants and energy willow).

3. Results

3.1. Potential peat extraction areas

At first, logistically the most potential future cutaway peatland areas for bioenergy production were identified. Most of the peat extraction areas in the Kuudestaan region are inside the 10 km buffer zone defined from municipal centers and large scale farms. However, a large proportion of the peat extraction areas in the Soini municipality were located outside this buffer area, making them logistically challenging (Fig. 2). The total area under peat extraction is 6035 ha in the "Kuudestaan" region and 4742 ha are located inside the buffer zone (79% of the total peat extraction area).

3.2. The results of the survey

3.2.1. Evaluation of different after-use methods

The respondents lived a little bit over 20 km away from the owned peat extraction area on average, and they had a positive attitude towards nature. 84% of the respondents lived in Soini and Alavus, and the mean owned area sizes in these municipalities were 27 and 22 ha respectively (Table 3).

According to the survey, the highest ranked after-use method was afforestation amongst all of the respondents (on average 5.6 out of 7; Table 4). Anyhow, the interest to grow biomass for bioenergy production was the highest in both Alavus and Soini municipalities (Fig. 3). There was lack of responses from Kuortane and Ähtäri and none of the landowners were interested in bioenergy production in Ähtäri. However, in Alavus and Soini the cutaway peatlands in the potential locations are not immediately available, because there are long renting contracts and usually many years of peat extraction going on in the areas. The cumulative amount of released peat extraction areas for bioenergy production was close to 500 ha by the year 2035 (Fig. 4). However, a significant proportion of the peat extraction areas will be in the cutaway phase until the mid-2020′s.

Most of the landowners (80%) were interested in growing biomass for energy production as an after-use method. Over half of the respondents (56%) were farmers and 86% of them were also interested to use their agriculture fields in growing biomass for bioenergy production as well. This agricultural field area was 320 ha in total. The best bioenergy production chain was forest energy for heat production. Overall, the forest energy was considered as the best biomass type while the agro biomass was the second most favorable option. Willow seems to be the least attractive choice of all bioenergy conversion technologies (Table 5).

3.2.2. Correlations between variables

Different background values and measured variables were then analyzed with Spearman's correlation analysis to observe specifically future land use related questions. The statistical significance was measured between the variables presented in Table 6. The strongest positive correlation was noted between the willingness to promote energy crop cultivation and the willingness to promote special plant growing. Strong correlation was also seen between the distance between the home and the owned area and the ending time of the contract/peat extraction. Moreover, the size of the owned area was positively correlated with the willingness to promote future forest energy on the cutaway peatlands. Negative correlation was obtained between the size of the area and the distance between the home and the area, which means that local people usually own the biggest peat extraction areas. There was negative correlation also between the willingness to promote energy crop cultivation and the willingness to promote mire regeneration, but the highest negative correlation was calculated between the willingness for mire regeneration and the size of the owned area.

4. Discussion

The role of the cutaway peatland, as a potential wasteland to be promoted to grow energy crops, is notable. This study clarifies the future land use of peat extraction areas and suggests that afforestation will supposedly be the most common after-use method in Finland. In Finland, afforestation can be seen as a natural choice because most of the land (86%) is anyhow covered by forest (Natural Resource Institute Finland, 2015). Previous studies support this study about the popularity of afforestation (Selin 1999; Kittamaa and Tolvanen 2013; Karjala 2014). Anyhow, a new finding in this study was that forest energy will be the best bioenergy option on cutaway peatlands and that especially the biggest cutaway peatlands will most probably be converted to forest energy if bioenergy is promoted. The results also show that GIS based methods are promising ways to investigate potential peat extraction areas, as well as other wasteland types, in assuming biomass potential when it is used together with spatial data collected from a survey. The methods helped to recognize spatial distribution and gave data for, e.g., further bioenergy plant planning (Fig. 5).

However, the accuracy of the analysis could be improved by taking into account the road network and by optimizing plant locations and transport distances with the Network Analyst toolset in ArcGIS. The bigger concern was the scarcity in the location of large scale farms. Most of the farmers do not share their background information (when asked by Evira), so it was not possible to get spatial information about all available middle and large scale farms. This had a very significant effect on the searching of the most potential bioenergy production areas. In some cases, a larger buffer zone could have improved the

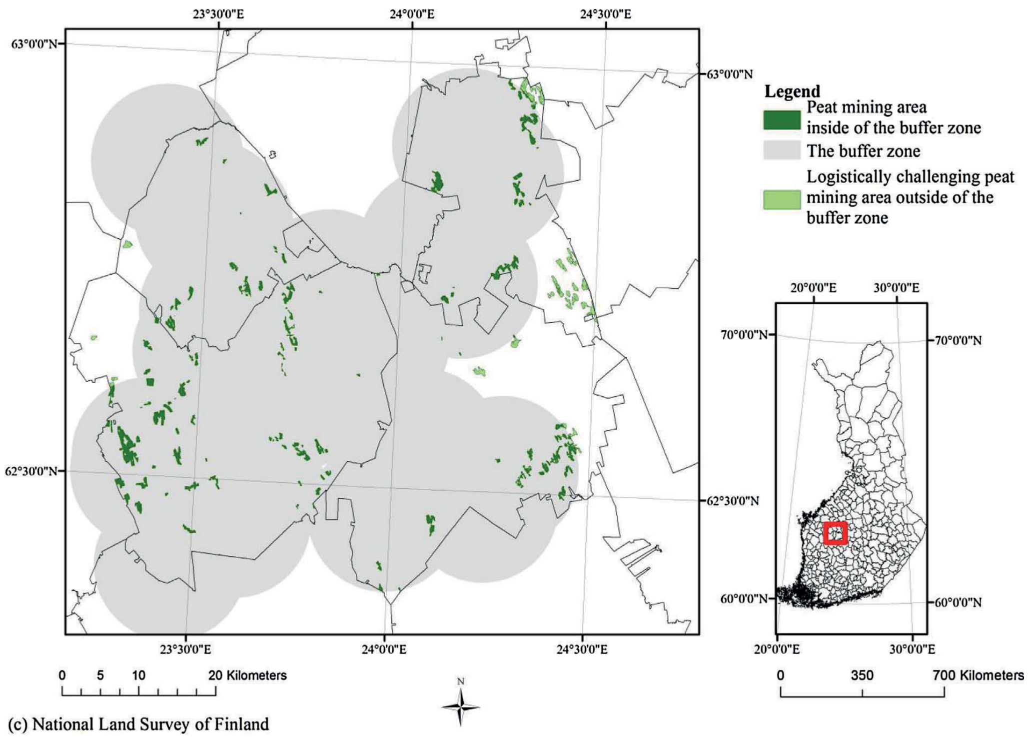


Fig. 2. Logistically the most promising peat extraction areas and remote peat extraction areas in the "Kuudestaan" region were determined using the ArcGIS program.

Table 3
Background information of the respondents and environmental values (n = 25, if less then there are missing values).

Background	Parameter	Std. Deviation	N
Mean distance between home and the owned peat extraction area	20.3 km	33.2	24
Median size of the peat extraction area	over 30.1 ha		24
Mean ending year of the peat extraction	year 2023	7.1	21
The most common after-use method in the peat extraction plan	Undefined		23
Interested in producing biomass for bioenergy production as an after-use method	Yes		20
	No		5
Farmers	Yes		14
Integrated environmental value*	5.3	1.6	Min. 24
*evaluation from 1 to 7 = not significant … very significant			

Table 4
Different after-use methods evaluated by the landowner of the peat extraction areas.

After-use method*	Mean value	Std. Deviation	N
Afforestation	5.6	1.5	25
Energy crop plantation	5.0	1.7	24
Agriculture	4.8	1.8	24
Special plant cultivation	4.3	1.6	25
Wetland	3.9	1.7	25
Pasture	3.4	2.0	19
Mire regeneration	3.4	2.1	24
Nature tourism	2.9	1.5	24
*evaluation from 1 to 7 = not important… very important			

analysis as well as if the farms and population centers in neighbor municipalities would have been taken into account.

However, the reason why significant areas of peat extraction areas are left outside of the buffer zone (10 km radius from large scale farms and municipality centrals) in Soini municipality is caused by the smaller population and amount of agriculture. The municipality is mostly sparsely inhabited in the countryside, having a total population of only 2284 inhabitants (Statistics Finland, 2013). This fact supports the assumption that peat extraction areas are usually located in remote locations (Salo and Savolainen 2008). Afforestation can be the best after-use method in these areas, because they are mostly already under traditional forestry. However, there are more people living in the city of Alavus, having a population size of 12,228 (Statistics Finland, 2013) which can be seen as a bigger and a more comprehensive buffer zone. The reason why there is overall bigger potential in Soini municipality is caused partially by the fact that the owned land areas are bigger compared to Alavus, where the division of land between the landowners is more fragmented. In other words, there are usually more landowners in one peat extraction area in Alavus than in Soini.

The respondents to the survey were quite similar to average forest owners in Finland. A typical forest owner in Finland is a 60-year-old man. Generally, only approximately 25% of forest owners are women (Hänninen et al., 2011) which can be seen as a similar proportion of women in this study (24%). The educational level of the respondents was relatively low, and even though there was a short information page about different bioenergy chains attached to the survey, the lack of knowledge can cause errors in the results. It was not possible to measure the level of background knowledge separately in the survey. Respondents could have a lack of knowledge specifically concerning different energy conversion technologies, such as gasification and biogas production, but also concerning economical income levels. The ignorance about economical income and rental rates could be studied e.g. by

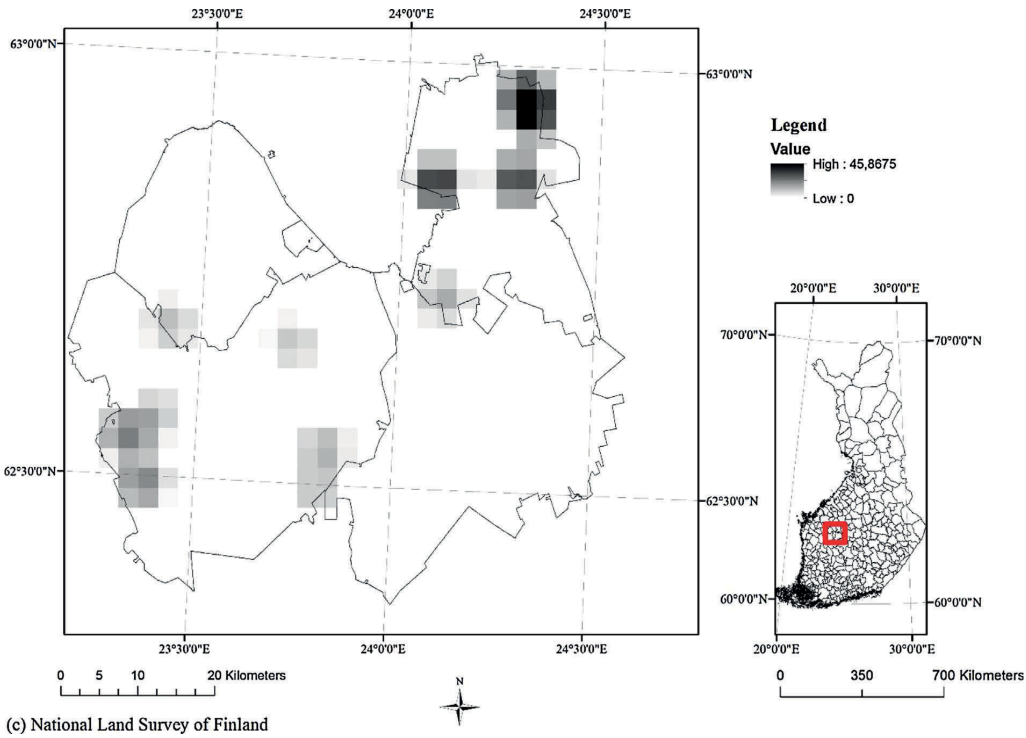


Fig. 3. Kernel density map of the most potential areas to grow energy crops on cutaway peatlands by the year 2035. The color illustrates the relative density only, not specific units (© NLS, 2014).

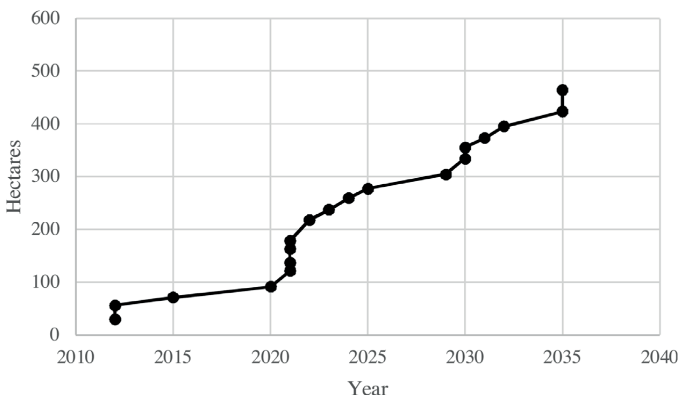


Fig. 4. The area released from peat extraction (over 15 ha units) per year which could be utilized in energy crop cultivation based on the landowner's willingness to do so in the "Kuudestaan" region.

using a contingent valuation survey (Hayden 2014). For instance, many landowners had a negative impression about RCG because the cultivation for combustion plants failed in the last 10 years (fall in RCG cultivation, Farm business register, 2015; Kautto 2014) which could have an effect on investments. This was seen during the guidance event held in Tuomarniemi Forest School and in the interview which was carried out by phone. Also, there was a lack of responses from Ähtäri and Kuortane municipalities. However, this could probably be interpreted as a signal of a slightly negative attitude towards biomass growing for energy production, but it is also caused by the smaller intensity of peat extraction.

It was notable that the landowners in the "Kuudestaan" region were not very interested in wetlands, which was one of the best after-use methods according to local inhabitants in North Ostrobothnia (Kittamaa and Tolvanen, 2013). Also, special plant tillage was evaluated much higher in this study. It is no surprise that landowners prefer economically profitable after-use methods.

According to the landowners, in some cases, if economic and environmental circumstances meet, energy crop growing and agriculture can be better options compared to afforestation. Depending on governmental decisions, such as energy crop subsidies, energy crop cultivation can become a more and more common way to utilize cutaway peatlands in the future. The fact that local people usually own the biggest cutaway peatlands has a positive effect if distributed bioenergy production is promoted. This study suggests that the biggest cutaway peatlands will fall into forest based bioenergy production more

Table 5
The three most realistic bioenergy after-use methods from the landowner's perspective in every biomass type (CHP = Combined Heat and Power).

Bioenergy production chain*	Value	Std. Deviation	N
Forest biomass for heat production	5.00	1.44	25
Forest biomass for CHP	4.92	1.41	25
Forest biomass for syngas based heat production and CHP	4.56	1.58	25
Agrobiomass for heat production	4.40	1.8	25
Agrobiomass for CHP	4.40	1.87	25
Agrobiomass for biogas based CHP	4.40	1.85	25
Energy willow for heat production	4.20	1.89	25
Energy willow for CHP	4.16	1.86	25
Energy willow for syngas based vehicle fuel production	3.84	1.8	25

*evaluation from 1 to 7 = not a meaningful method … a very meaningful method

commonly in the future. The interesting thing, as a suggestive result, is that the distance between home and the owned area was not seen as barrier to bioenergy production (correlation coefficient −0.386, p-value 0.063, n = 24) which can have a clearly positive effect towards the promotion of distributed bioenergy. There were interesting negative correlations between the willingness to promote regeneration of peatlands and energy crop cultivation. This could be seen as a disagreement between the regeneration of mires and the cultivation of energy crops; if more of the cutaway peatlands are used for bioenergy production. As a contradiction, a suggestive result was also that the people with high environmental values are the most willing to promote agro biomass usage in bioenergy production in cutaway peatlands (correlation coefficient between the future willingness to promote agro biomass usage in bioenergy production and environmental integrate 0.360, p-value 0.084, n = 24).

If local opportunities in the field of bioenergy are available, energy crop growing as an after-use alternative could attract many landowners. The choice to grow energy crops is anyhow highly dependent on future policies and subsidies. Consequently, if more societal support is addressed to energy crop growing, more cutaway peatlands will be taken into biomass cultivation. According to Bryngelsson and Lindgren (2013) large-scale bioenergy production on marginal lands is economically unfeasible because the soil is unproductive in many cases. The same kind of assumptions were observed amongst the landowners when most of them highlighted poor economic profitability, big investments and a lack of governmental support as being practical barriers. Anyhow, the feasibility is plant species dependent. According to Jylhä et al. (2015), there are possibilities for profitably bioenergy production with downy birch even in the climatic conditions in Northern Finland without any governmental incentive schemes or support. It was interesting that the distance between home and the location of the owned area, area size, frost damage or disagreements between the landowners were seen as

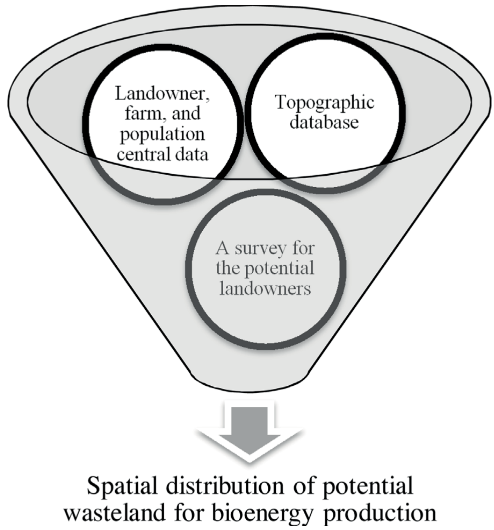


Fig. 5. Generic model of bioenergy planning on wasteland based on GIS data.

smaller barriers. As a contradiction, a remote home place of landowners was seen as a significant barrier to energy crop cultivation on abandoned agriculture land in Latvia (Abolina and Luzadis, 2015).

There is high interest in using cutaway peatlands as well as agricultural fields for bioenergy production. If the cutaway peatland of 494 ha is combined with the reported agricultural field area of 320 ha, the total potential area for bioenergy could be 814 ha. Theoretically, it would be possible to achieve 13–25 GWh of bioenergy in these areas every year. E.g. gross energy yield of combustion of birch (*Betula pubescens*), RCG by biogas production and willow by combustion could be 13.1, 15.6 and 25.2 GWh a^{-1} respectively (Table 7)

Therefore, the cutaway peatlands can have a supporting role in distributed renewable energy production. In the future more studies are needed, especially about bioenergy production, in which the potential cutaway peatlands are integrated into the same system with other biomass streams. In addition, the expansion of the Finnish forest industry and the need for pulp wood and saw logs is growing in conventional forest land areas.

5. Conclusions

This study investigated cutaway peat extraction lands' after-use for bioenergy production from the landowners' perspective. The results suggest that the most popular after-use method for cutaway peatlands in the near future is afforestation in Finland and combining GIS based methods and a survey can help effectively in the planning of bioenergy

Table 6
Spearman's correlation coefficient (2-tailed, $p < 0.05$) between the significant variable pairs in the survey.

Variable pairs	Correlation coefficient	p-value (2-tailed)	N
Positively correlating variables			
The willingness for energy crop cultivation//The willingness for special plant growing	0.672	< 0.000	24
The ending time of production//The distance between home and the area	0.515	0.02	20
The willingness to promote future forest biomass usage in bioenergy production//The size of the owned area	0.46	0.024	24
The willingness for afforestation//The willingness for wetland	0.44	0.028	25
Negatively correlating variables			
The willingness for mire regeneration//The size of the owned area	−0.637	0.001	23
The willingness for energy crop cultivation//The willingness for mire regeneration	−0.562	0.004	24
The distance between home and the area//The size of the owned area	−0.447	0.028	24
Nature matters to you//The distance between home and the area	−0.408	0.048	24

Table 7
Energy and biomass yields of birch (combustion), RCG (biogas) and willow (combustion) grown on cutaway peatlands.

Plant	Yield total solids (TS) Mg ha^{-1} a^{-1}	Ref.	Calorific value (TS) MJ kg^{-1}	Ref.	Energy yield MWh ha^{-1}a^{-1}
Birch (*Betula pubescens*)	3	Hytönen and Reinikainen (2013) and Hytönen et al. (2016)	19.30	Alakangas (2000)	16.1
RCG (*Phalaris arundinacea*)	6	Parviainen (2007)	11.52	Unpublished result	19.2
Willow (*Salix subsp.*)	6	Hytönen (1996)	18.54	Hurskainen et al. (2013)	30.9

production. Finland has large forest resources, so afforestation could be seen as a neutral and familiar choice for the cutaway peatlands. However, agriculture and energy crop growing are both popular methods, but specifically energy crop production needs better subsidies and other support from the society. The most promising and logistically approachable areas for bioenergy production in the “Kuudestaan” region are located in Alavus and Soini municipalities. The survey pointed out that almost 500 ha or 8.2% of the current peat extraction areas could be used for energy crop cultivation by 2035 in the “Kuudestaan” region. Most of the landowners who own over 15 ha of peat extraction land are interested in growing biomass for energy production as an after-use alternative. The best bioenergy chain is heat production from forest biomass. Less attractive are agro biomass production and energy willow. Overall, gasification of biomasses seems to be less attractive amongst the energy conversion techniques having even negative impressions; especially in the case of willow.

When background information and different variables were compared, significant correlation was measured between the future willingness to promote forest biomass usage in bioenergy production and the size of the owned area. It means that usually the greater the owned land area, the better alternative forest energy is; according to the landowner. There is negative correlation between regeneration of peatlands and energy crop production and it might cause conflicts between nature conservation and bioenergy production in the future. On the other hand, the people who are interested on afforestation are also interested to establish wetlands. But, as a suggestive result, the distance between the landowner’s home place and the peat extraction area is not considered a problem.

The future bio economy will have an influence on the land use of cutaway peatlands. Currently, cutaway peatlands have a supplementary role as a place to grow more biomasses on wastelands. This study suggests, also, that GIS based methods can be useful as decision-making tools in bioenergy production planning and the selection of power plant locations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2017.09.010.

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PUBLICATION
IV

GIS-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas.

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GIS-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas

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ABSTRACT

Currently, geographic information system (GIS) models are popular for studying location-allocation-related questions concerning bioenergy plants. The aim of this study was to develop a model to investigate optimal locations for two different types of bioenergy plants, for farm and centralized biogas plants, and for wood terminals in rural areas based on minimizing transportation distances. The optimal locations of biogas plants were determined using location optimization tools in R software, and the optimal locations of wood terminals were determined using kernel density tools in ArcGIS.

The present case study showed that the utilized GIS tools are useful for bioenergy-related decision-making to identify potential bioenergy areas and to optimize biomass transportation, and help to plan power plant sizing when candidate bioenergy plant locations have not been defined in advance.

In the study area, it was possible to find logistically viable locations for 13 farm biogas plants (> 100 kW) and for 8 centralized biogas plants (> 300 kW) using a 10-km threshold for feedstock supply. In the case of wood terminals, the results identified the most intensive wood reserves near the highest road classes, and two potential locations were determined.

Introduction

Currently, biomass is the most used renewable energy source in the world [1]. Biomass from plants, organic waste, and animal excreta is frequently utilized in bioenergy production. In rural areas, several types of biomass are available for bioenergy production depending on local factors, such as presence of agricultural residues (e.g., straw and manure) and availability of forest biomass. Bioenergy and biofuels can be created from biomass through several techniques, including mechanical, chemical, or biological treatments such as pelletizing, gasification, pyrolysis, or biological processes [2]. In fact, the use of biomass for bioenergy production appears to be increasing, and the different applications of biomass are expanding because of the shifting trend toward bio and circular economies that replace traditional fossil resources [2–4]. In different rural areas of Europe, investment in biogas plants using manure as fuel are increasingly considered while the use of wood biomass as such or as pellets in bioenergy plants is promoted as well. In this context, the availability of biomass for bioenergy production must also be guaranteed in the future.

Planning of bioenergy production

Stakeholders play an important role throughout the various phases of bioenergy development projects from the bioenergy plant planning to project implementation. By integrating the different stakeholders, it is possible to identify conditions that are applicable for bioenergy [5]. Planning locations for bioenergy plants is usually a demanding task because precise knowledge about biomass availability, yield, and chemical characteristics are required. Besides the location of the actual bioenergy plant, the need to introduce wood terminals has become especially urgent in Northern countries to balance the location of wood supplies and of conventional combined heat and power (CHP) bioenergy plants. This is as traditional wintertime harvesting of wood is becoming difficult due to warming winters, leading to a lack of hardening frost on roads with low bearing capacity [6].

The founding of a new bioenergy plant is always a geospatial

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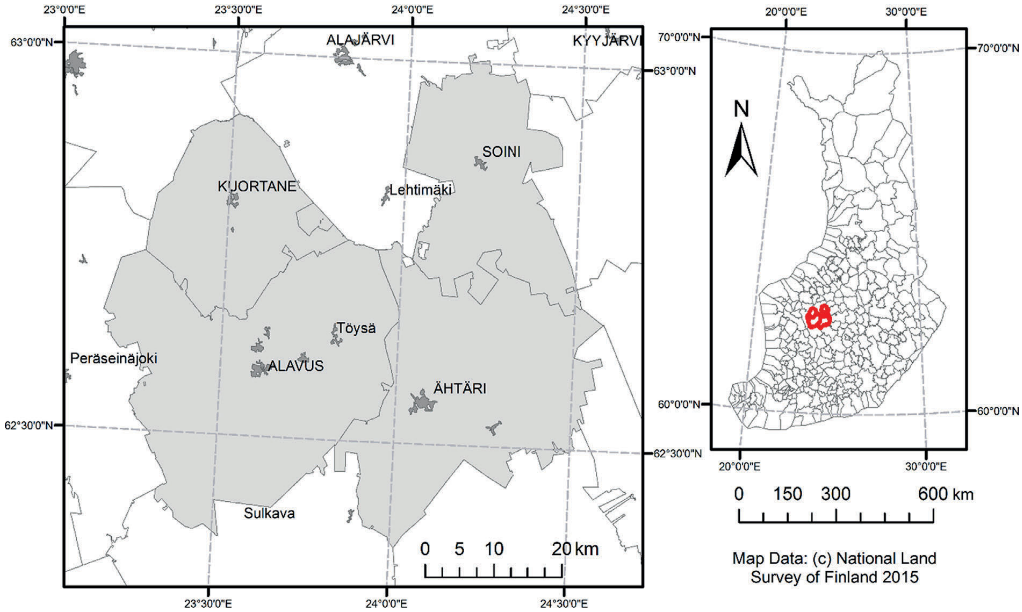

Fig. 1. Location of the studied Kuudestaan region in Finland. Population centres (administrative borders) are indicated in dark grey. Municipality names are indicated by capital letters, and some major villages by lowercase letters.

question. Biomass resources are usually sparsely distributed, making every case unique [7]. Different biomasses have different yields, yearly schedules, and characteristics and, accordingly, have distinct economic values, which influence, for example, the economic feasibility of the required transportation distances. Thereby, one crucial step for establishing bioenergy plants is finding viable locations for them. Methods based on geographic information systems (GISs) have been used in many disciplines as decision-making tools because they can solve location-allocation-related problems through, for example, minimizing transportation distances [8,9].

Feasibility of GIS tools for allocating biomass resources to bioenergy

Globally, several studies have mapped biomass resources for bioenergy production. In general, studies can be divided into two GIS-based approaches: suitability analyses and optimality analyses. In suitability analyses, which are sometimes called multi-criteria evaluations (MCEs), buffer and spatial overlay analyses are usually used to assess the location of potential biomass production plants, whereas optimality analyses are used for location-allocation issues to match biomass supply and the energy demands of society [9]. Suitability analyses have been previously based on the integration of different models or analytical techniques into a GIS environment, including Markov chains [10], multi-criteria models [11,12], analytic hierarchy process and map algebra [13], and kernel density analysis [14]. Meanwhile, optimality analyses for bioenergy plants have been based on Dijkstra's route optimization algorithm [15], remote sensing data and GIS-based mixed integer linear modeling [16], and the modified p-median problem [9]. Many other studies using GIS have directly examined or assessed general biomass potential for bioenergy production e.g., [17–22]. Also, some studies are handling analytical methodologies and development of heuristics in bioenergy supply chain [23]. GIS methods are especially useful in assessing land availability for energy crops [11–13,17]. In addition, sustainability of bioenergy projects could be improved by combining Life Cycle Assessments and GIS tools [24].

Feasible biomass transportation distance is feedstock dependent and is affected by several factors. The economics of biomass transportation distances are dependent, for example, on biomass composition, energy value (e.g., biogas potential), moisture, specific weight [25], and trailer capacity. In addition, local regulations affect waste-based management procedures and transportation practices, and therefore have a notable role in bioenergy planning [26]. GI Systems provide several tools for solving optimal logistic solutions and minimizing biomass transportation costs, but most of the tools require that the user specifies both source and destination locations for the transports. When planning a location for a new facility, this would require providing several possible plant locations (destination candidates), and then we could choose the best candidate. If such candidates do not exist or if we do not want to limit the search for best location to such set of candidates, the route optimization methodology needs to be altered to optimize routes from the source points to all other locations in the road network, as we have done in this study. Taking both transportation distances and biomass supply into account, the optimal size and location of plants can be determined.

The aim of the present study was to develop and assess the feasibility of a GIS-based solution for selecting the optimal location of biogas plants and wood terminals in a rural area based on minimizing the transportation needs of different biomasses. The optimal locations for biogas plants and wood terminals were therefore determined in the study area considering sparsely distributed biomasses. The aim was to create a model that can help local stakeholders to optimize bioenergy plant locations and to develop bioenergy and bio-refining-based business activities in rural areas.

Materials and methods

Study area

The study area corresponded with the rural Kuudestaan region in South Ostrobothnia, Finland (see Fig. 1). The total area of the region is 3,121 km^2, and the region contains 23,646 inhabitants [27,28] that mostly live in two major towns (Ähtäri and Alavus with 5,968 and

11,746 inhabitants, respectively). One hundred and thirty-five large farms (described in more detail later) are present in the region, and the economy of the region has been traditionally based on forestry activities. Currently, the potential feedstocks for bioenergy production are wood, agricultural residues (e.g., straw and manure), and municipal organic wastes. Wood is commonly used as fuel for heat production in district heating plants (12 plants) and in private houses, including farmhouses. There are three major wood terminals (1–2 ha in size, Metsä Group) where wood is temporarily stored and then transported to a pulp mill and biorefinery located in Äänekoski, Central Finland (average distance of 100 to 150 km). However, so far, no biogas plants are present in the study area (Fig. 1).

Scenarios and data of biomass resources

In this study, two biomass use scenarios were studied. The first one aimed to find locations for biogas plants with capacities from 100 to over 300 kW. The capacities were based on economically feasible farm biogas plant and centralized biogas plant sizing in Finland according to Natural Resource Institute Finland [29]. The other scenario aimed to locate wood terminals in the study area (Fig. 4).

In the biogas scenario, feedstocks included different manures from farms, separated biowastes from municipalities, vocational schools, grocery stores, and tourist centres (which is biowaste from catering services, but also includes biowaste and animal manure from Ähtäri Zoo); and sludge from wastewater treatment plants (Table 1). Furthermore, the use of reed canary grass (RCG; *Phalaris arundinacea*), which can be potentially grown on cutaway peatlands, was considered [30]. Intensive peat extraction regions are present in the study area, and hundreds of hectares of these sites will enter into the after-use phase in the near future and thus represent potential growing sites for energy crops.

Manures (total 264,273 t) from large farms with > 50 heads of cattle, 500 pigs, 30 horses, or 500 heads of poultry in 2016 were included in the study. Their locations (addresses) were obtained from the databases of the Finnish Food Safety Authority (Evira), the Agency for Rural Affairs (Mavi), and the National Land Survey of Finland (NLS). The amount of manure produced per farm was calculated based on animal age and species, and the mean amounts of manure produced per animal [31]. The amount (fresh matter; FM) of biowastes was obtained from the municipalities and operators of municipal waste collecting services. The amounts (total solids; TS) of sewage sludge (municipalities of Alavus, Ähtäri, and Soini) were obtained from the Environmental Protection database [32]. The methane potential of different biomasses are presented in Table 2.

Coordinates (ETRS89 TM35FIN) of the locations of various biomasses were verified using the MapSite [35] online map service. All biomass points situated next to one another were merged together into the same point (e.g., two animal owners/farmers housed their animals in the same shelter).

In the wood terminal scenario, the density of forest biomass was based on data generated by the Finnish National Forest Inventory [36] in the form of a raster layer. Total forest biomass (m^3/ha) was taken into account and was studied and considered relevant at a raster pixel size of 1 ha. The data is illustrated in Fig. 2.

Table 1
Annual amounts of manure and biowaste (Mg FM) and sewage sludge (Mg TS) generated in the study area.

Organic waste	Amount
Agricultural manure	264,273
Biowaste	
- municipal	127
- shops	103
- tourist centres	306
- vocational schools	4
Sewage sludge	494

Table 2
The methane potential of different biomasses used in this study.

Biomass	CH_4 potential	Unit	References
Biowaste	107	m^3 CH_4/Mg FM	[33]
Sewage sludge	163	m^3 CH_4/Mg TS	[33]
Cattle manure	19	m^3 CH_4/Mg FM	[33]
Pig manure	10	m^3 CH_4/Mg FM	[31]
Horse manure	48	m^3 CH_4/Mg FM	[31]
Sheep manure	39	m^3 CH_4/Mg FM	[34]
Poultry manure	81	m^3 CH_4/Mg FM	[31]

Data analysis

In the biogas plant scenario, > 100-kW farm biogas plants (only manure from one farm and > 300-kW centralized biogas plants (manure from several farms and biowaste from different sources) that could annually produce 800 MWh and 2,400 MWh gross biogas energy, respectively (8,000 annual working hours), were considered.

The locations of the biogas plants and allocation of biomasses to them were calculated taking into account the road network [38]. The analysis was computed in the R software, v. 3.4.3 [39], using the shp2graph v. 0.3 and igraph v. 1.1.2 [40] add-on packages. First, the road map data were extracted from the Digiroad 2017 database. Then, the road network was converted into a graph and the biomass source points were attached to the closest nodes of the graph with package shp2graph in R. A self-programmed location optimization tool then used the following approach (Fig. 3):

(1) It determined minimum driving distances from the biomass source points to all other nodes of the road network as a matrix, D_{SN}.
(2) It then determined minimum road distances between all biomass source points, into matrix D.
(3) It then used hierarchical clustering with complete linkage (a.k.a. maximum within cluster distance) for D to locate such clusters, where all distances were less than the chosen maximum transportation distance of 10 km.
(4) Based on the clustering results the biomass potentials were summed up, and those clusters were chosen, where the sum of potentials exceeded 2,400 MWh/a (> 300 kW centralized biogas plants). At the same step, also those biomass sources were detected and pointed out, whose potential exceeded the biomass need for a > 100 kW farm biogas plants, 800 MWh/a.
(5) At the last step, it picked those columns from the full distance matrix D_{SN}, which were related to the biomass sources in the chosen clusters, multiplied the picked columns with expected biomass weights for each source node, and calculated the node-wise sum of these weight (kg) × distance (m) results. Then, the cost-minimizing nodes were selected as the optimal locations for the centralized biogas plants for the chosen clusters.

In the wood terminal scenario, raster data on forest wood volume were fed into the ArcGIS software, v. 10.5.1 (ESRI Inc., Redlands, CA). First, raster data were converted to points using the raster-to-point tool. The raster size in the kernel density analysis was chosen as 1 km, and the search radius was 5 km. Each kernel was weighted by the wood or forest stand volume present in that location. The kernel density results were then interpreted taking into account roads [38] and the municipal border map [37]. The used GIS analyses are illustrated in Fig. 4.

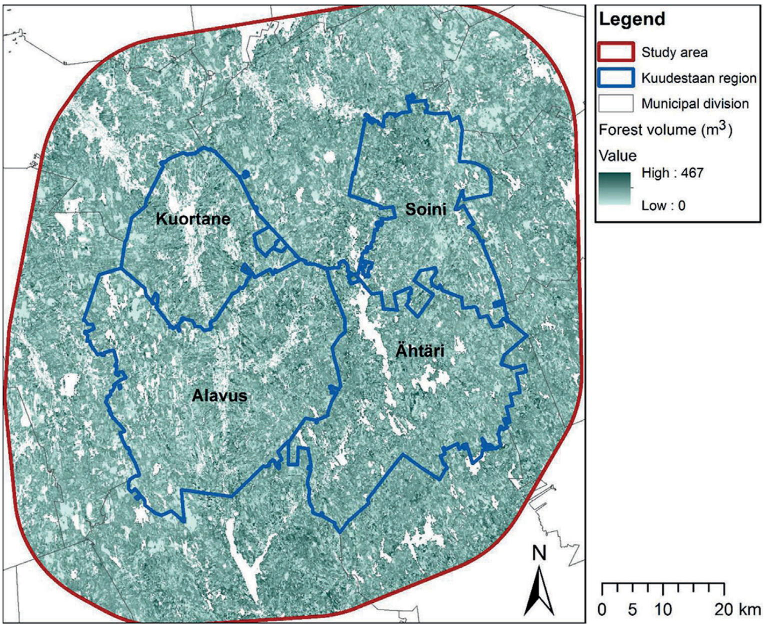

Fig. 2. Forest inventory data in the study area (forest inventory data [37]; municipal borders [38]). Darker shades of green indicate higher forest density. Numerous lakes (in white) decrease available wood resources, especially in the southeastern part of the area. Fields (in white or light green) decrease the available wood resources in the western part of the area.

Results and discussion

Biogas plant scenario

Potential locations for farm biogas plants (> 100 kW) and centralized biogas plants (> 300 kW) were determined in the study area using GIS-based optimization tools. Total gross methane potential in the area was 57.1 GWh per year (Fig. 5). Of the different feedstocks, the largest gross methane potential in the area came from livestock manure, ranging from 30 MWh to 1,991 MWh per farm annually.

In the scenario of farm-scale biogas plants, sufficient biomass was available for 13 farm biogas plants (with a > 100-kW energy production potential) in the study area (Fig. 6). The highest gross methane potential for one farm was 1,991 MWh/a (Fig. 5). The median value was about 300 MWh/a/farm. The total gross methane potential in these 13 potential farms was 15.5 GWh/a, representing 27.1% of the total gross methane potential in the area. The largest gross methane potential is found from farms located in rural villages, as indicated in Fig. 6. Seven of these are located in Alavus municipality, four in Kuortane municipality, and two in Ähtäri municipality.

In the scenario of centralized biogas plants, eight potential clusters (with a > 300-kW energy production potential) were identified in the study area (Figs. 6 and 7). These centralized biogas plants also include large individual farms, so the results partly overlap with those of the scenario considering farm biogas plants. In particular, seven of the potential farm biogas plants also belong to the potential centralized biogas clusters. In the centralized biogas plant scenario, it was logistically optimal to use agricultural manure as well as other biomasses. For example, in two cases in Alavus, biomass from cutaway peatlands could be combined with the manure from local farms to achieve higher methane yields (Fig. 6).

The study area can be divided into four large domains or groups based on accessibility by road network: northern Kuortane belongs to the first group; northern Soini to the second group; western Alavus and southern Kuortane to the third group; and southern Soini, western Alavus, and Ähtäri to the fourth group (Fig. 7). The eight clusters with the highest methane energy production potential for centralized biogas plants were clusters 2, 9, 11, 14, 19, 20, 21, and 32 (Fig. 6). Specifically, their gross methane potentials ranged from 2,409 MWh/a, which is equal to a nominal power of 301 kW (cluster 20 in Kuortane), to 3,535 MWh/a, which is equal to a nominal power of 442 kW (cluster 14 in Alavus). The total gross methane potential of the eight clusters was 23.2 GWh, representing 40.6% of the total gross methane potential of the area. The clusters included from 4 to 9 large farms.

Optimal locations for the biogas plants were then computed inside each cluster based on the road network. As an example, the localization of cluster number 19 is illustrated in Fig. 8, where the optimal biogas plant location was defined based on 6 farms, organic waste from 7 municipal sources, 1 tourism centre, and 2 grocery stores.

Livestock manure was the largest source of biomass to the potential biogas plants. However, in Alavus and Kuortane, a significant increase of methane potential was achieved through combining manure with biowaste and potential RCG cultivation in cutaway peatlands. The largest methane energy production potential is in the western part of the region, whereas no potential locations for biogas installations were identified in the Soini municipality (Fig. 6). In particular, large-scale farms (over 50 heads of cattle) have an important role in future biogas production in the study area. Only about 20% of the dairy farms have over 50 heads of cattle in Finland and the number of small farms is constantly decreasing [41]. For example, in Denmark, the largest farms were also identified, in most cases, as relevant and vital for future biogas production; average farm size in Denmark has increased from 131 heads of cattle to 238 heads per farm in ten years (from 1999 to 2009 [10]). Agricultural residues, including slurries and crops produced for energy, have also been found to be important biomass sources in other regional GIS-based biogas analyses, representing from 50% to over 90% of total biogas potential [13,14] in studied rural areas.

Notably, the cultivation of RCG on prior cutaway peatlands was confirmed as a potential feedstock source for a biogas plant in an area of intensive peat extraction. In Alavus, there were two areas where cultivation of RCG on prior cutaway peatlands could increase local biomass resources (Fig. 6). However, the cutaway peatlands are usually located over 10 km away from farms, which can make the logistic arrangements difficult (Fig. 7). Also, certain limitations of cutaway

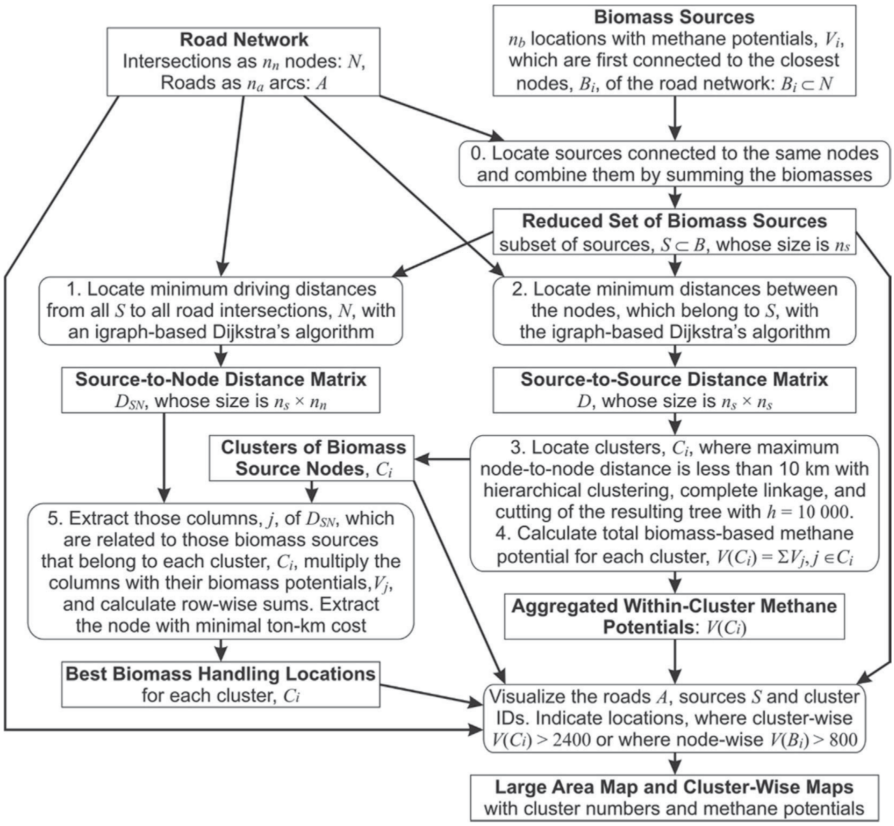

Fig. 3. The flowchart used in this study for route optimization, hierarchical clustering and location optimization of biogas plants in the R program. Rectangles indicate source data sets and (intermediate or final) results, and the rounded rectangles data processing or calculation steps.

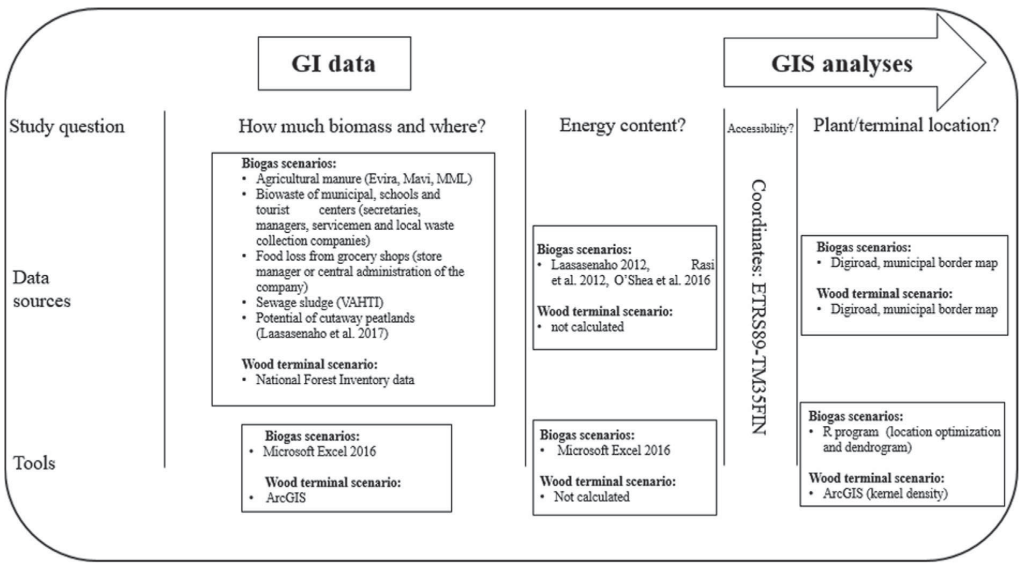

Fig. 4. GIS process for determining the optimal locations of biogas plants and wood terminals in the study area. Four GIS-related questions are answered using biomass data and different GIS tools.

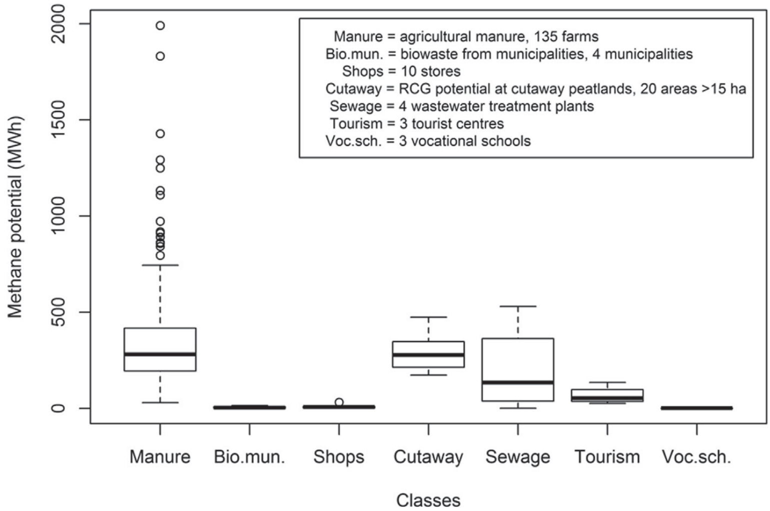

Fig. 5. Studied feedstocks and their gross biogas potentials (MWh) in the study region as box-and-whiskers plots.

peatlands must be addressed, such as the difficulty of cultivating agricultural crops in these areas because of typical high water levels [42]. Alternatively, forest biomass could be considered on remote cutaway peatlands, and in fact landowners generally prefer forestry as an after-use alternative instead of energy crop production [30].

The fact that sludge generated in wastewater treatment plants and biowaste generated in municipalities and tourist centres are often located far away from large-scale farms complicates the location of the biogas plant. However, in Kuortane, the increase of energy potential is achieved from combining the joint methane potential of biowaste (from

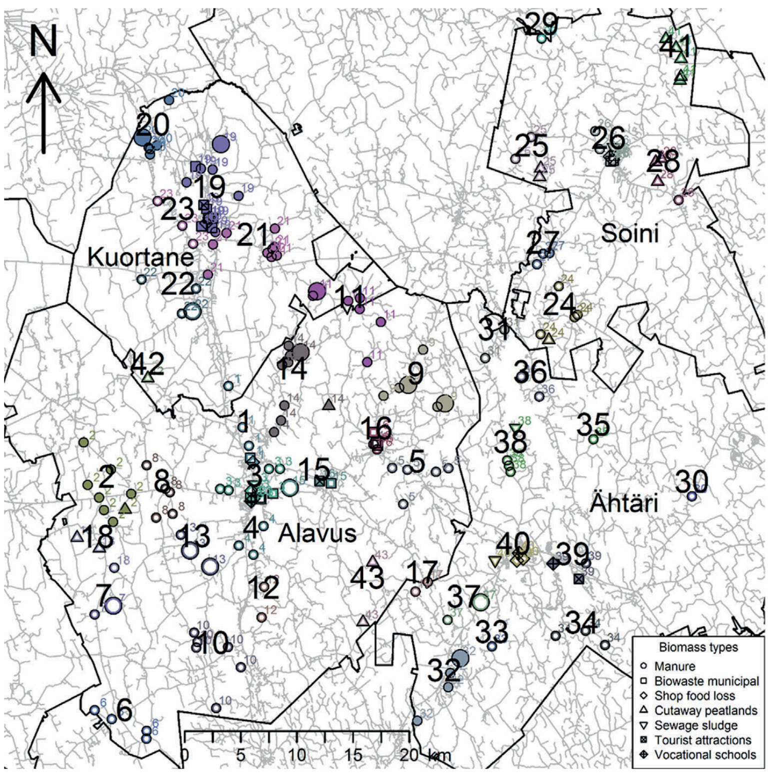

Fig. 6. Feedstock production sites and their division into clusters (given as numbers) for the 13 potential farm biogas plants (larger circles) (> 100 kW) and eight potential centralized biogas plant clusters (filled with colour) (> 300 kW).

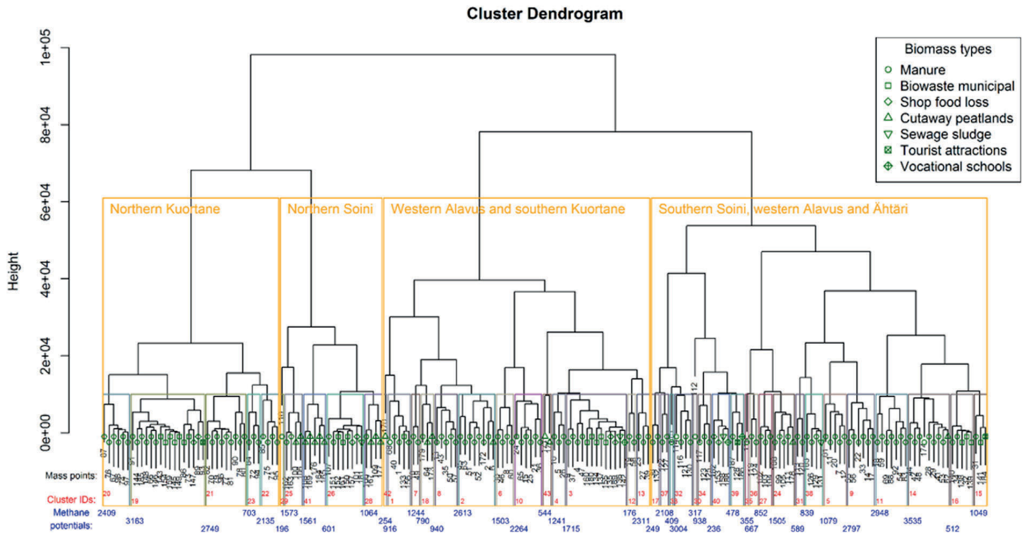

Fig. 7. Dendrogram presenting centralized biogas plant clusters according to a transportation threshold of 10 km in the study region. Agglomerative clustering based on complete linkage was applied to combine biomass production sites as clusters when threshold distance was not exceeded. Rectangles are used to indicate clusters, and symbols indicate type of biomass. Biomass points (n = 189) and cluster IDs (total 43) are indicated in the bottom left corner. Methane potentials are given in blue.

one tourist centre, grocery stores, and municipal collection facilities) and large-scale farms near the town centre (Fig. 8). Finally, the GIS tools used in the present study allocated biomasses according to reasonable transportation distances (10 km) and helped to plan biogas plants sizing.

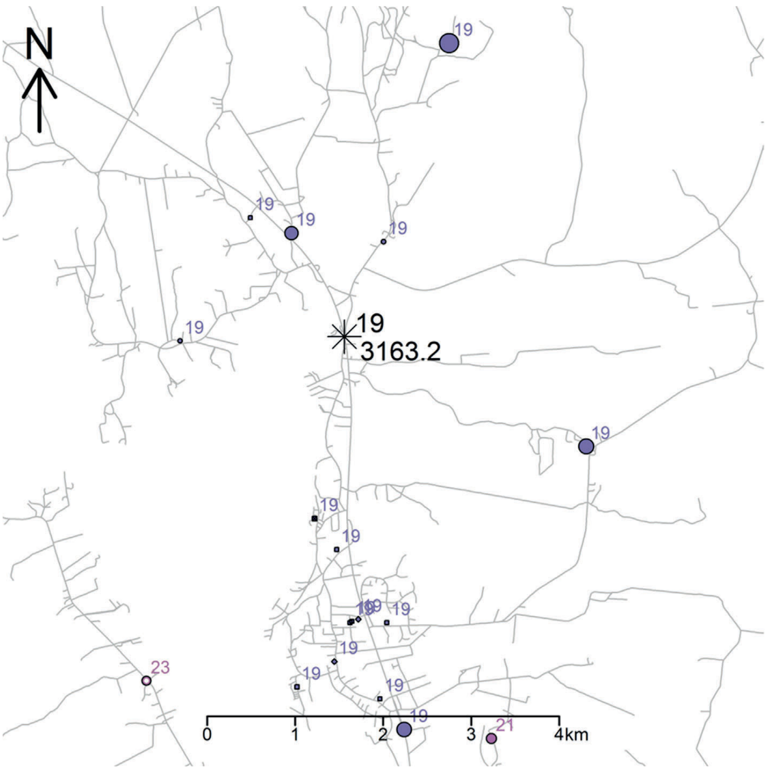

Fig. 8. Example of the self-programmed optimization tool for identifying a suitable location for a power plant by minimizing transportation distance when biomasses are sparsely distributed in a potential biogas production area (cluster 19). The model minimizes the sum of total transportation needs. The potential plant location is illustrated as an asterisk (energy potential indicated below the asterisk in MWh/a). The biomass sources are denoted with symbols explained in the legend of Fig. 7. The sizes of the symbols indicate feedstock quantities, or methane potentials, available at the sites.

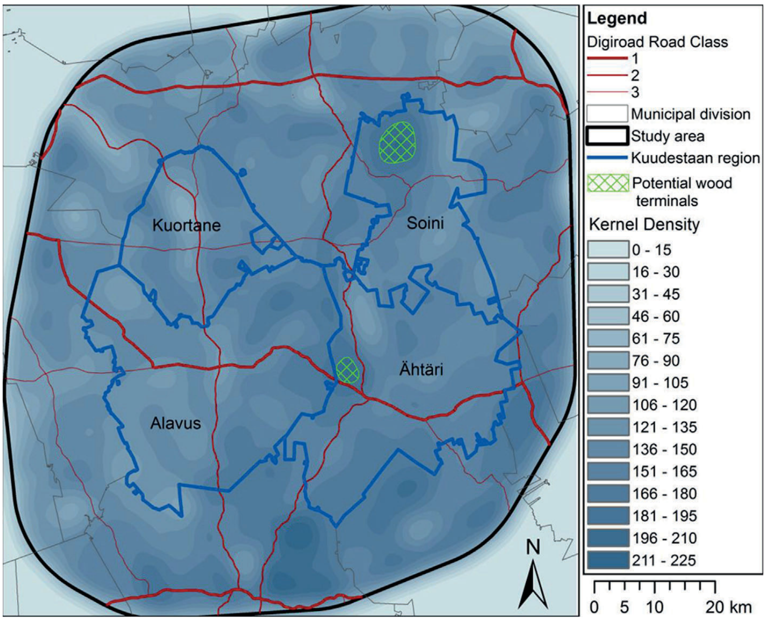

Fig. 9. Kernel density map of wood resources (tree stand volume in m^3 ha^{-1}) in the study area. Darker colours indicate greater density of wood resources (forest inventory data [37]; roads [39]; municipal borders [38]). Potential wood terminal locations are located in areas with dense wood resources near the highest road classes (in darker blue). Colour represents relative density and not specific units.

Wood terminal scenario

The optimal locations of wood terminals in the study area were determined based on kernel density analyses along with road network data (Fig. 9). The densest wood resources are located in northern parts of the Soini municipality and on the border of the Ähtäri and Alavus municipalities (Fig. 9). The road network covers the latter area quite well, especially considering that a class 1 road (i.e., a highway) crosses the area (Fig. 9). In the case of Soini, the wood resources are located near a road network of lower quality class. However, all the roads in the study area are still suitable for truck transportation of wood biomass.

Wood terminals in these prior areas (Fig. 9) could be considered if wood processing at intermediate terminals becomes popular, which would improve the balance of the wood supply and increase the need for wood storage capacity. The calculated wood terminal locations, however, were not equal to real existing terminals (Fig. 9). The terminal locations in Alavus, at the Ähtäri (Myllymäki) railway station, and in the centre of Soini municipality were not congruent with real wood availability. Furthermore, existing terminals locate in good logistical sites (near railways and trucks) to promote large-scale wood utilization without considering forest resources. Even so, it may be rational to establish small-scale terminals to serve more local bioenergy plants in the spots found in the present study (e.g., [43]).

Further, in reality, different wood procurement organizations do consider the well-being of the road network and environmental limitations [45–46], which the applied methods in this study do not automatically consider. When linking limited model calculations and real wood procurement together, expert knowledge and consensus solutions can be used in decision-making (e.g., [46]). For example, in late springtime, there can be weight limitations on local roads, and the drive-through of timber trucks is forbidden.

Feasibility of the methods for defining the locations of bioenergy plants

The present study developed and assessed methods consisting of route optimization, hierarchical clustering, location optimization, and kernel density estimation for identifying biomass processing or storing locations in cases of multiple feedstock such that transportation distances are minimized. The methods optimize biomass transportation from the collection point to non-predefined power plant location, which shows the progress together with previous studies using different GIS on bioenergy plant planning as summarized in Table 3. The goal was to achieve the highest potential bioenergy production and plant size with short transportation distances from collection points to all other locations in the road network. The results show that these methods are suitable for allocating biomass for bioenergy in rural areas and the methods can be considered as decision-making tools to help plan power plant size.

The optimization methods applied in this study promote the use of GIS tools in bioenergy planning. The same kind of R analyses have not previously been used in biogas plant planning while e.g. kernel density analyses were used in location biogas plants in Southern Finland (e.g., [14]).

In rural areas, it is important to include in the model the road network and not only Euclidean distance because geographic obstacles such as lakes and mountains can affect the structure of the road network in many cases. For example, in the present study, the road network considered the lakes, which forms approximately 7% of the total study area, and only a few of them can be crossed by using bridges [35]. Consequently, the structure of a road network has an essential role in transportation costs.

The method described in the present paper can be useful for municipal-level business developers and for promoting business activity in rural areas. The method helps to recognize energy potentials by clustering the feedstocks and by finding hotspots with kernel density analysis. In particular, the biogas plant optimization scenario was useful for identifying potential areas for bioenergy production given multiple potential feedstocks. Further, the self-programmed tool can help to optimize biogas plant locations by minimizing transportation costs, especially in situations when candidate biogas plant locations have not been defined in advance. Many GIS tools, such as e.g. Closest Facility and Location-Allocation in ArcGIS, require such candidate points. One clear advantage of this method is also that the configuration of biomass sources can be easily changed and the analysis can be re-run if some

Table 3
Selected GIS based decision support models studied for different bioenergy applications.

GIS method	The method can be used for	References
Markov chain model	Forecasting the **spatial distribution** of Danish livestock intensity and future biogas plants	[10]
Mixed integer linear programming model	Biorefining plant **location optimization** by remote sensing and road network	[16]
GIS – Analytical Hierarchy Process – Fuzzy Weighted Overlap Dominance (GAF) model	Decision support on **suitable locations** for biogas plants	[12]
Kernel density and p-median problem	Pinpointing **areas with high biomethane concentration** (Kernel density). Whereas p-median problem is applied by choosing facilities such that the total sum of weighted distances allocated to a facility is minimized	[14]
Modified p-median problem	Evaluating **biomass supply catchments** (an extension to the p-median model)	[9]
Modified Dijkstra algorithm	A systemic approach to **optimizing animal manure supply** from multiple small scale farms to a bioenergy generation complexincluding conceptual modeling, mathematical formulation, and analytical solution.	[15]
A Multicriteria Spatial Decision Support System integrated with GIS/ELECTRE TRI methodology	Addressing real-world problems and factual information (e.g. soil type, slope, infrastructures) **in biogas plants site selection**.	[11]
The analytical hierarchical process (AHP)	Decision support process, which captures qualitative and quantitative aspects of information (such as environment and economy) into GIS environment for the **siting of anaerobic co-digestion plants**	[13]

farms decide to leave out from proposed cooperatives.

The assessed optimization model can make location determination easy when centralized biogas plants are planned. Different network analyses and adjusting the transportation threshold limit (10 km) lower or higher could provide different allocations or logistical solutions for biogas plant location. For example, by adjusting the threshold limit to 12 and 15 km, the number of potential clusters increases to 9 and 11, respectively. The biogas plants are often placed near the spatial mean of biomass sources, because in many cases there are several rather large biomass sources. In these cases, the transportation distances would still be less than 10 km, because the distances from biomass sources to the centrally located plant are usually smaller than the maximum distance between the biomass sources. Also, it is possible to balance biomasses between clusters afterwards to reach an even more even distribution of locations considering biogas potential among all clusters.

According to the applied biogas plant location optimization method, the simplest transportation situation is in those large farms (at least 4,500 Mg of cow manure per year) which are considering the construction of farm biogas plant ($>$ 100 kW of gross power capacity). In practice, this means approximately 200 dairy cows or about 300 bulls a farm. In these cases, it may be easy to bring additional feedstock from smaller farms, because the manure quantities in them are smaller and thereby transport needs along the roads are minimized. According to the optimization model, the biogas plant localisation situation is particularly demanding if there are 2–3 equal size farms within the potential cluster, and the farm's own production of manure is not high enough for a farm biogas plant. In these cases, a large amount of manure has to be moved along roads from point to point, which increases the cost of transportation and emissions.

It was found that in three cases, the optimal centralized biogas plant location would locate the immediate presence of farms. In five cases out of eight, land-use conflicts could be encountered, because two of them were located in agricultural fields, two in the immediate presence of residential buildings, and one in timberland. Consequently, the optimization model is useful when there are a few of farms interested in building a biogas plant within a reasonably small distance from each other. Then, it can be found out, which farm is closest to the most optimal location and this farm can be suggested as the location of the biogas plant. This will minimize transportation costs and associated emissions of the biogas plant.

The accuracy of GIS analyses varies greatly depending on spatial and temporal resolution and data simplification. Early and seasonal variation in biomass quantities, because of weather conditions and soil quality, are demanding for GIS analyses [12,16]. In this study, all of the organic waste types have yearly variations that are affected by several factors, such as population size and animal grazing. It is important that a continuous, cost effective, feedstock for bioenergy is available throughout the year [47]. However, agricultural manure, for example, is a relatively stable potential biomass source for biogas plants, or at least the manure from large-scale farms.

In the case of wood terminals, the utilized forest inventory data included large forest conservation areas and small-sized local forests or protected aquatic ecosystems [36] where logging cannot be performed. These areas should be considered, and their possible effect on practical optimization solutions should be taken into account [45–46]. Also, peatland forests are usually only suitable for logging operations when the terrain is frozen with snow cover [44].

In general, the use of accurate and real case data enables GIS methods to provide useful results. In the present study, the location optimization performed in the R Statistics software computed the results based on annual average biomass quantities. However, certain uncertainties existed with respect to these data, e.g., the coordinates of large-scale farms were not precise because addresses generally point to the homes of farmers and not necessarily the locations of animal shelters. In addition, the optimal location of biogas plants is always situated at one of the nodes of the road network. In addition, in the chosen approach, biomass points were attached to the nodes of the road network and not, e.g., at the half-way point of a road vector. Consequently, the present GIS analyses may have small inaccuracies that should be taken into consideration during further decision making. The other choice is to improve the accuracy of locations and distances when choosing the participants of cooperatives related to centralized biogas plants. This has to be done in any case, if the suggested location of the centralized biogas plant is not suitable.

In practice, the existence and availability of required data may be limited because of legislation. In Finland, information on farms is given only for scientific purposes. In any case, these types of studies can be carried out with the involvement of research organizations and with farms that are willing to share information. The next step could involve finding potential farmers to participate in cooperative ventures and in making more detailed logistical optimizations based on actual biomasses. In the case of wood, the amount of forest biomass based on data from the Finnish [36] is freely available online, making these data easy to access and utilize. With respect to cooperative-based centralized biogas plants, several co-actors would be necessary to ensure that local biogas yields are high enough. It might be beneficial for business developers to begin from the clusters with fewer large actors, such as cluster 32 (Fig. 6), to avoid complex situations with many small participants. Finally, more detailed analyses of the economic profitability of bioenergy plants should be performed to assess if such plans are realistic: considering e.g. transportation mode (truck and train) and location of energy users.

Conclusions

In the present study, location optimization and kernel density tools were used to identify bioenergy production sites and to further optimize biogas plant or wood terminal locations in the R and ArcGIS software in a Finnish rural study area.

The results indicate that road-network-based route optimization, hierarchical clustering, location optimization and kernel density estimation are suitable tools for planning the locations of bioenergy plants because of their capacity to minimize transportation distances. These methods are especially useful for scenarios where biomass resources are allocated to bioenergy, the biomasses are distributed across rural areas, and candidate power plant locations and sizing have not been defined in advance. The location optimization tool in R software logistically identified viable clusters of farms and other biomass source sites for future biogas production, and the kernel density tool in the ArcGIS software identified the densest forest biomasses near road networks for future wood terminals. These tools can help relevant decision-makers and business developers to plan the locations of bioenergy plants, and this kind of approach could be applied in other parts of Finland or in other countries as well. However, GIS analyses may suffer from the simplification of the data, which should be taken into account when using this type of analysis for decision-making.

In the studied rural area, 13 farm biogas plants (> 100 kW) and eight centralized biogas plants (> 300 kW) considering a threshold distance of 10 km were identified. The results suggest that the co-digestion of biowastes and potential RCG from cutaway peatlands could be logistically reasonable in three centralized biogas plants. The kernel method also suggests that two wood terminals could be located in the study area to provide a constant wood supply for bioenergy production.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2019.01.006.

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