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

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 optimise 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.

Keywords: biogas; circular economy; location-allocation; network analysis; wood terminal

1 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.

1.1 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 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].

1.2 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.

2 Materials and methods

2.1 Study area

The study area corresponded with the rural Kuudestaan region in South Ostrobothnia, Finland. 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.

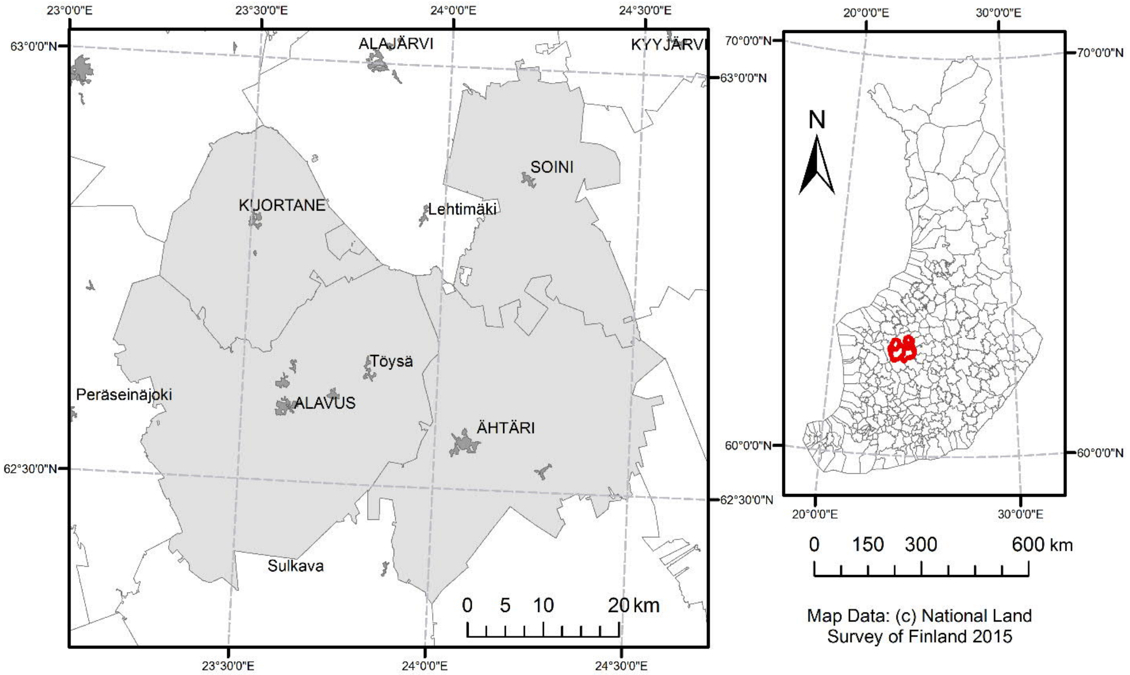

Figure 1. Location of the studied Kuudestaan region in Finland. Population centres (administrative borders) are indicated in dark grey. Municipality names are indicated by capital letters, and some major villages by lowercase letters.

2.2 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 more than 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.

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	Reference
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]

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.

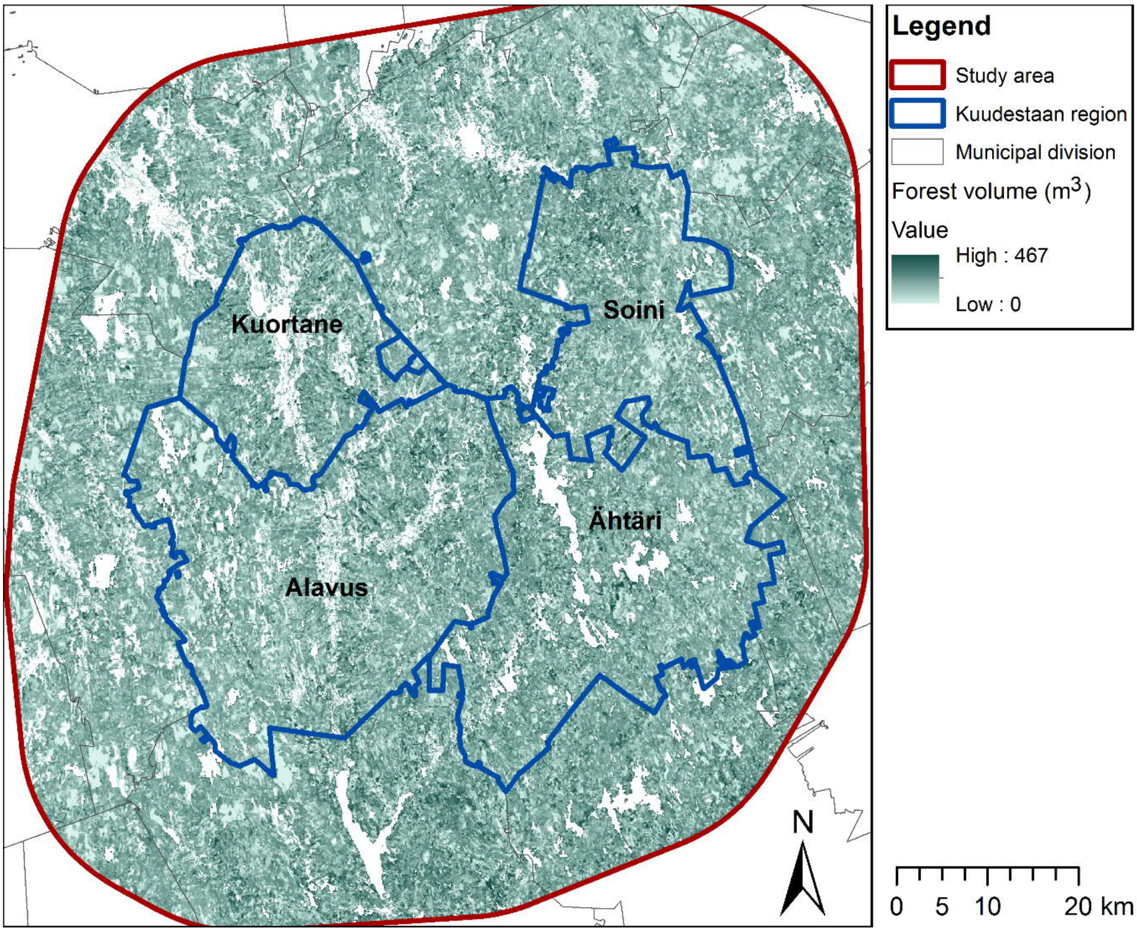

Figure 2. Forest inventory data in the study area (forest inventory data [37]; municipal

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.

2.3 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.

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.

(4) 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.

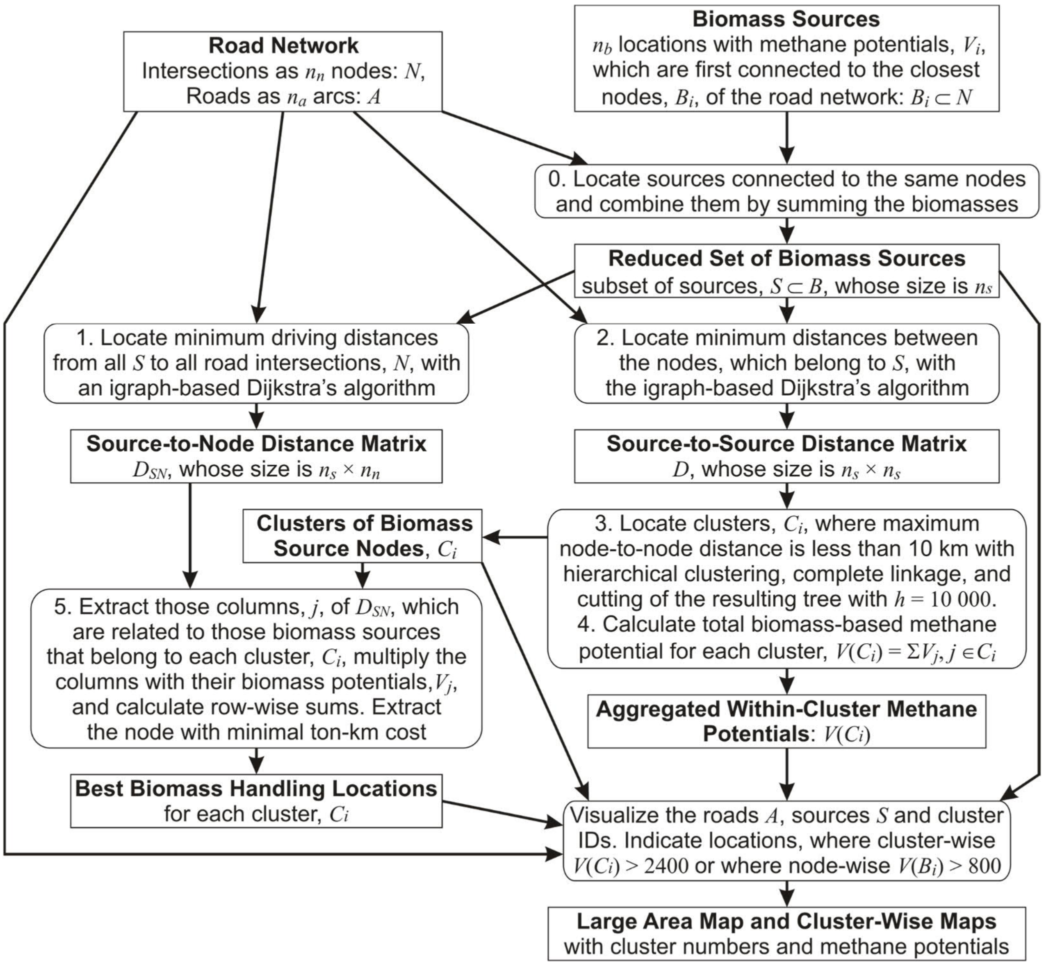

Figure 3. The flowchart used in this study for route optimization, hierarchical clustering and location optimization of biogas plants in the R program. Rectangles indicate source data sets and (intermediate or final) results, and the rounded rectangles data processing or calculation steps.

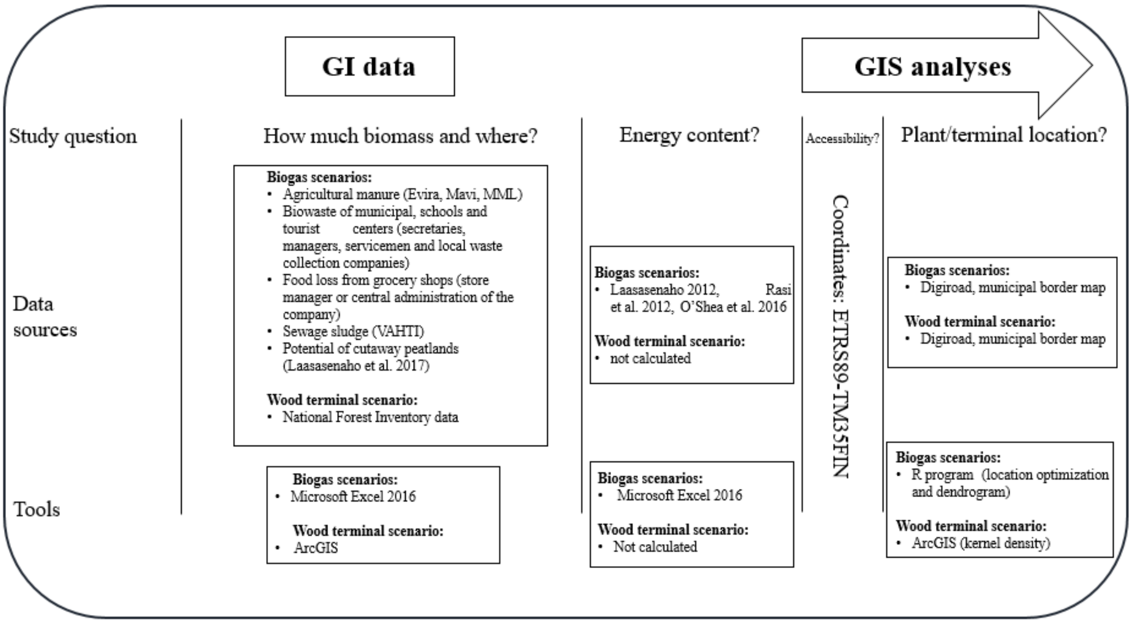

Figure 4. GIS process for determining the optimal locations of biogas plants and wood terminals in the study area. Four GIS-related questions are answered using biomass data and different GIS tools.

3 Results and discussion

3.1 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 (Fig. 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 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 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.

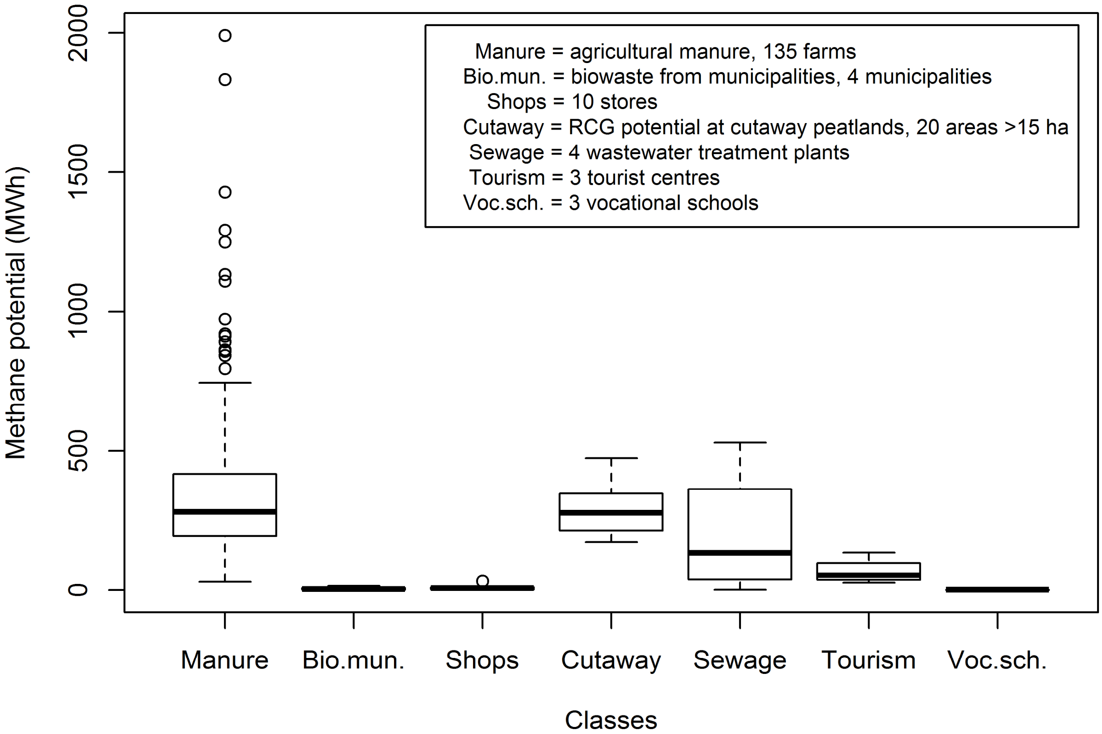

Figure 5. Studied feedstocks and their gross biogas potentials (MWh) in the study region as box-and-whiskers plots.

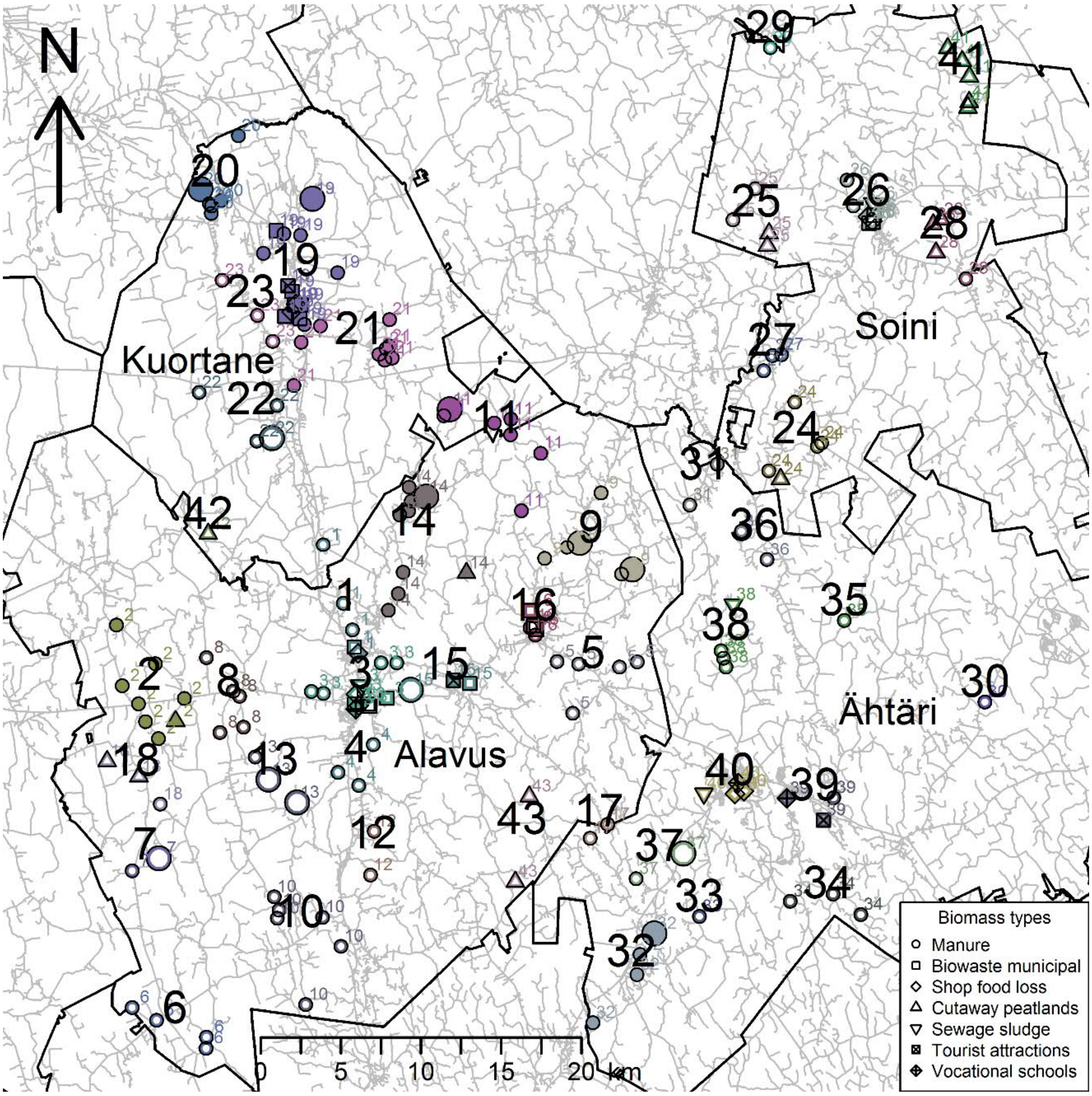

Figure 6. Feedstock production sites and their division into clusters (given as numbers) for the 13 potential farm biogas plants (larger circles) (>100 kW) and eight potential centralized biogas plant clusters (filled with colour) (>300 kW).

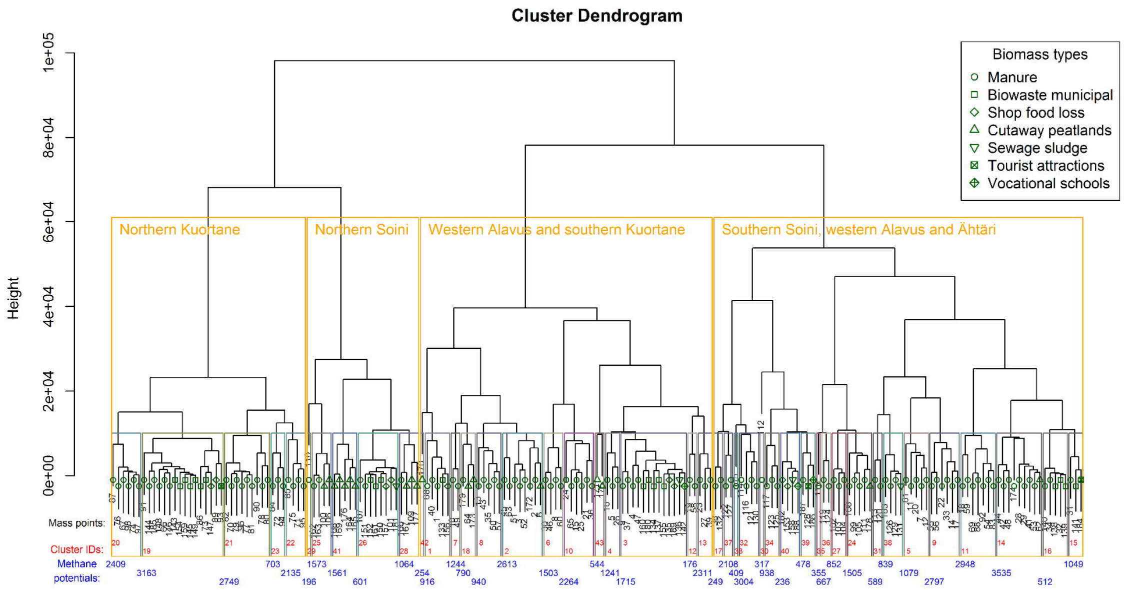

Figure 7. Dendrogram presenting centralized biogas plant clusters according to a transportation threshold of 10 km in the study region. Agglomerative clustering based on complete linkage was applied to combine biomass production sites as clusters when threshold distance was not exceeded. Rectangles are 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.

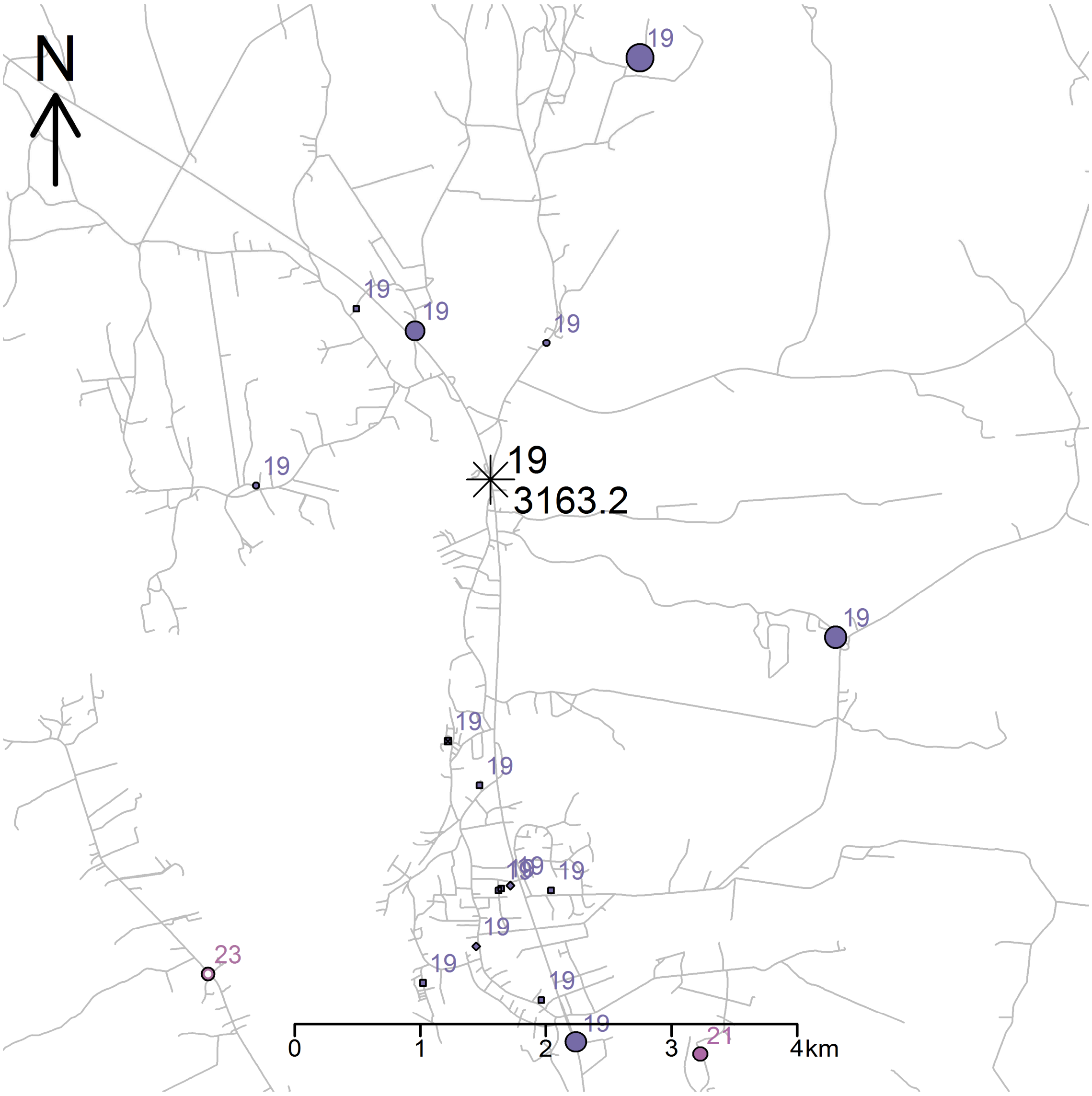

Figure 8. Example of the self-programmed optimization tool for identifying a suitable location for a power plant by minimizing transportation distance when biomasses are sparsely distributed in a potential biogas production area (cluster 19). The model minimizes the sum of total transportation needs. 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.

3.2 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.

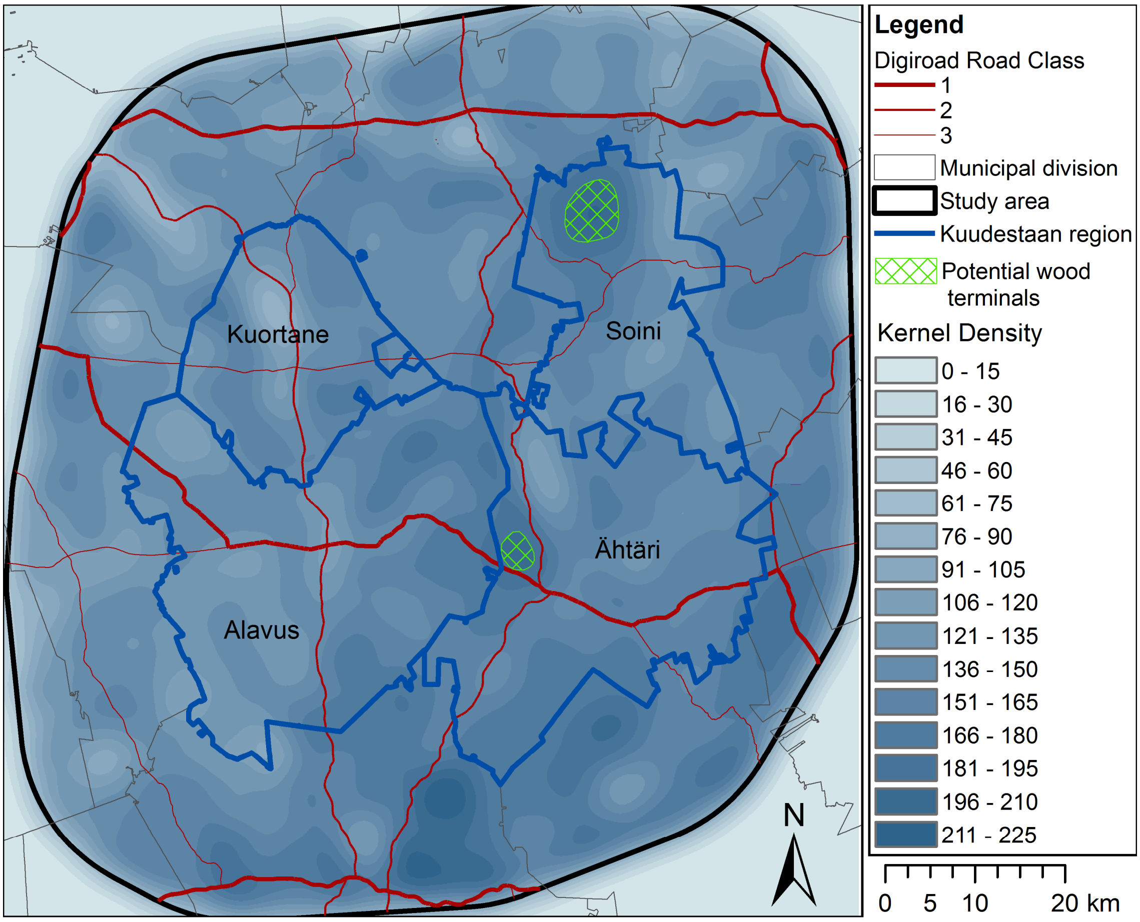

Figure 9. Kernel density map of wood resources (tree stand volume in m^3 ha^{-1}) in the study area. Darker colours indicate greater density of wood resources (forest inventory data [37]; roads [39]; municipal borders [38]). Potential wood terminal locations are located in areas with dense wood resources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

3.3 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.

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

GIS method	**The method can be used for**	**Reference**
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 complex including conceptual modelling, 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]

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 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.

5 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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