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

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

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

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

27 In the study area, it was possible to find logistically viable locations for 13 farm  
28 biogas plants (>100 kW) and for 8 centralized biogas plants (>300 kW) using a  
29 10-km threshold for feedstock supply. In the case of wood terminals, the results  
30 identified the most intensive wood reserves near the highest road classes, and two  
31 potential locations were determined.

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

34 **1 Introduction**

35 Currently, biomass is the most used renewable energy source in the world [1]. Biomass  
36 from plants, organic waste, and animal excreta is frequently utilized in bioenergy  
37 production. In rural areas, several types of biomass are available for bioenergy  
38 production depending on local factors, such as presence of agricultural residues (e.g.,  
39 straw and manure) and availability of forest biomass. Bioenergy and biofuels can be

40 created from biomass through several techniques, including mechanical, chemical, or  
41 biological treatments such as pelletizing, gasification, pyrolysis, or biological processes  
42 [2]. In fact, the use of biomass for bioenergy production appears to be increasing, and  
43 the different applications of biomass are expanding because of the shifting trend toward  
44 bio and circular economies that replace traditional fossil resources [2-4]. In different  
45 rural areas of Europe, investment in biogas plants using manure as fuel are increasingly  
46 considered while the use of wood biomass as such or as pellets in bioenergy plants is  
47 promoted as well. In this context, the availability of biomass for bioenergy production  
48 must also be guaranteed in the future.

### 49 ***1.1 Planning of bioenergy production***

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

61 The founding of a new bioenergy plant is always a geospatial question. Biomass  
62 resources are usually sparsely distributed, making every case unique [7]. Different  
63 biomasses have different yields, yearly schedules, and characteristics and, accordingly,  
64 have distinct economic values, which influence, for example, the economic feasibility

65 of the required transportation distances. Thereby, one crucial step for establishing  
66 bioenergy plants is finding viable locations for them. Methods based on geographic  
67 information systems (GISs) have been used in many disciplines as decision-making  
68 tools because they can solve location-allocation-related problems through, for example,  
69 minimizing transportation distances [8-9].

## 70 ***1.2 Feasibility of GIS tools for allocating biomass resources to bioenergy***

71 Globally, several studies have mapped biomass resources for bioenergy production. In  
72 general, studies can be divided into two GIS-based approaches: suitability analyses and  
73 optimality analyses. In suitability analyses, which are sometimes called multi-criteria  
74 evaluations (MCEs), buffer and spatial overlay analyses are usually used to assess the  
75 location of potential biomass production plants, whereas optimality analyses are used  
76 for location-allocation issues to match biomass supply and the energy demands of  
77 society [9]. Suitability analyses have been previously based on the integration of  
78 different models or analytical techniques into a GIS environment, including Markov  
79 chains [10], multi-criteria models [11-12], analytic hierarchy process and map algebra  
80 [13], and kernel density analysis [14]. Meanwhile, optimality analyses for bioenergy  
81 plants have been based on Dijkstra's route optimization algorithm [15], remote sensing  
82 data and GIS-based mixed integer linear modeling [16], and the modified p-median  
83 problem [9]. Many other studies using GIS have directly examined or assessed general  
84 biomass potential for bioenergy production [e.g., 17-22]. Also, some studies are  
85 handling analytical methodologies and development of heuristics in bioenergy supply  
86 chain [23]. GIS methods are especially useful in assessing land availability for energy  
87 crops [11-13, 17]. In addition, sustainability of bioenergy projects could be improved by  
88 combining Life Cycle Assessments and GIS tools [24].

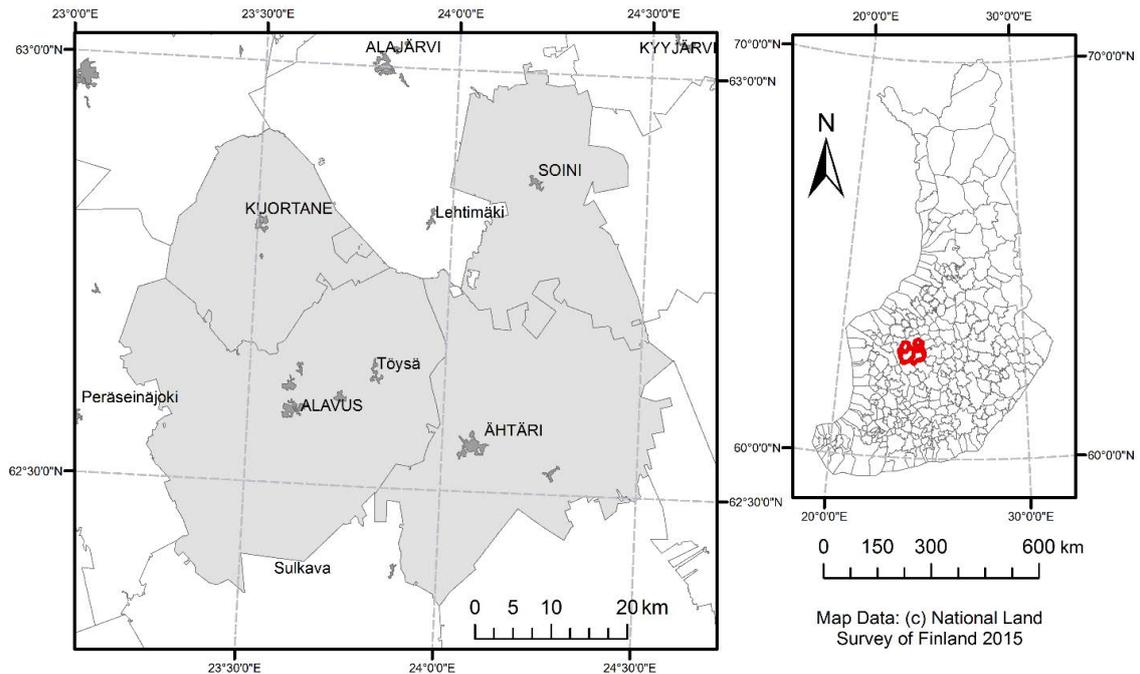
89 Feasible biomass transportation distance is feedstock dependent and is affected  
90 by several factors. The economics of biomass transportation distances are dependent,  
91 for example, on biomass composition, energy value (e.g., biogas potential), moisture,  
92 specific weight [25], and trailer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

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

111 **2 Materials and methods**

112 **2.1 Study area**

113 The study area corresponded with the rural Kuudestaaan region in South Ostrobothnia,  
114 Finland. The total area of the region is 3,121 km<sup>2</sup>, and the region contains 23,646  
115 inhabitants [27-28] that mostly live in two major towns (Ähtäri and Alavus with 5,968  
116 and 11,746 inhabitants, respectively). One hundred and thirty-five large farms  
117 (described in more detail later) are present in the region, and the economy of the region  
118 has been traditionally based on forestry activities. Currently, the potential feedstocks for  
119 bioenergy production are wood, agricultural residues (e.g., straw and manure), and  
120 municipal organic wastes. Wood is commonly used as fuel for heat production in  
121 district heating plants (12 plants) and in private houses, including farmhouses. There are  
122 three major wood terminals (1–2 ha in size, Metsä Group) where wood is temporarily  
123 stored and then transported to a pulp mill and biorefinery located in Äänekoski, Central  
124 Finland (average distance of 100 to 150 km). However, so far, no biogas plants are  
125 present in the study area.



126

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

## 130 **2.2 Scenarios and data of biomass resources**

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

136 In the biogas scenario, feedstocks included different manures from farms,  
 137 separated biowastes from municipalities, vocational schools, grocery stores, and tourist  
 138 centres (which is biowaste from catering services, but also includes biowaste and animal  
 139 manure from Ähtäri Zoo); and sludge from wastewater treatment plants (Table 1).  
 140 Furthermore, the use of reed canary grass (RCG; *Phalaris arundinacea*), which can be  
 141 potentially grown on cutaway peatlands, was considered [30]. Intensive peat extraction

142 regions are present in the study area, and hundreds of hectares of these sites will enter  
 143 into the after-use phase in the near future and thus represent potential growing sites for  
 144 energy crops.

145 Manures (total 264,273 t) from large farms with more than 50 heads of cattle,  
 146 500 pigs, 30 horses, or 500 heads of poultry in 2016 were included in the study. Their  
 147 locations (addresses) were obtained from the databases of the Finnish Food Safety  
 148 Authority (Evira), the Agency for Rural Affairs (Mavi), and the National Land Survey  
 149 of Finland (NLS). The amount of manure produced per farm was calculated based on  
 150 animal age and species, and the mean amounts of manure produced per animal [31].  
 151 The amount (fresh matter; FM) of biowastes was obtained from the municipalities and  
 152 operators of municipal waste collecting services. The amounts (total solids; TS) of  
 153 sewage sludge (municipalities of Alavus, Ähtäri, and Soini) were obtained from the  
 154 Environmental Protection database [32]. The methane potential of different biomasses  
 155 are presented in Table 2.

156 Table 1. Annual amounts of manure and biowaste (Mg FM) and sewage sludge (Mg TS)  
 157 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

158

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

Biomass	CH <sub>4</sub> potential	Unit	Reference
Biowaste	107	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[33]
Sewage sludge	163	m <sup>3</sup> CH <sub>4</sub> /Mg TS	[33]
Cattle manure	19	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[33]
Pig manure	10	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[31]

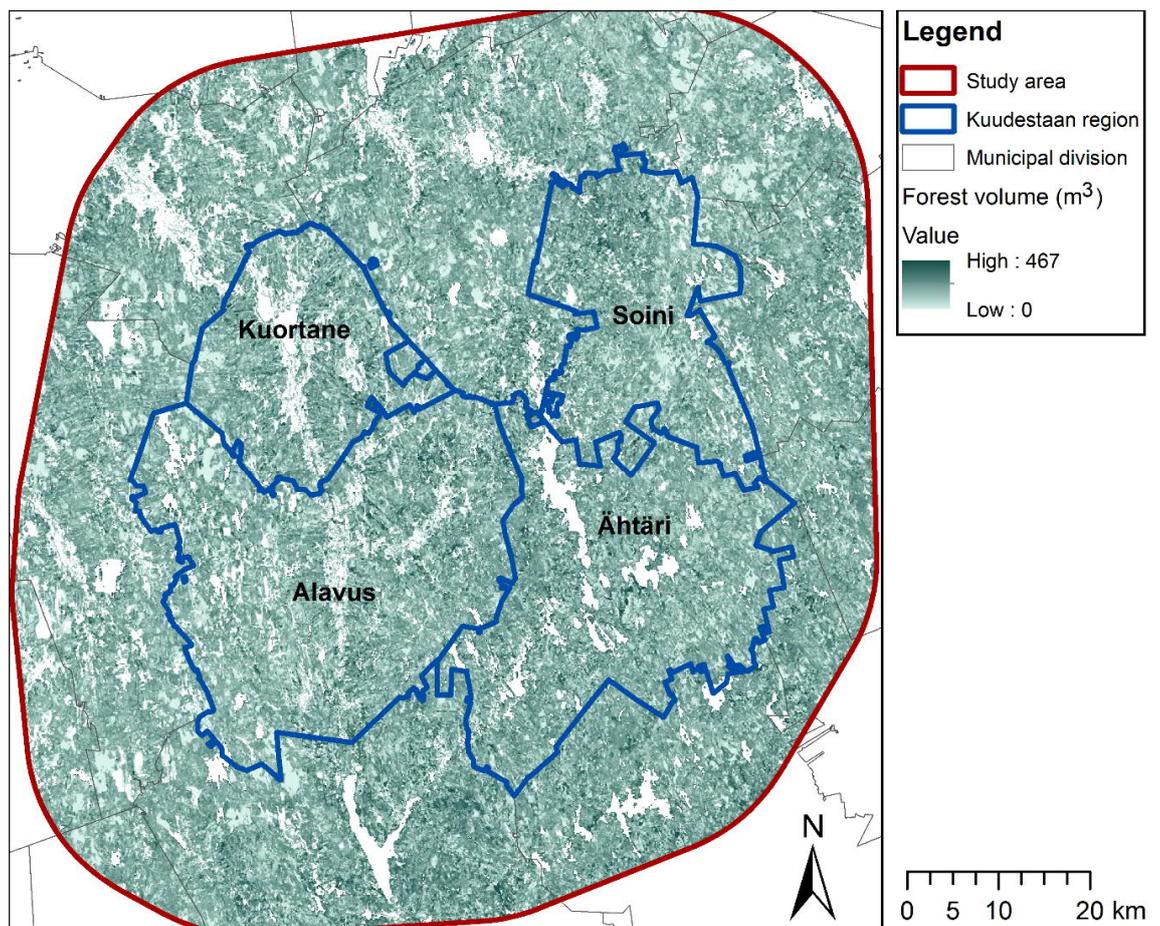
Horse manure	48	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[31]
Sheep manure	39	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[34]
Poultry manure	81	m <sup>3</sup> CH <sub>4</sub> /Mg FM	[31]

160

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

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

169



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

171 borders [38]). Darker shades of green indicate higher forest density. Numerous lakes (in  
172 white) decrease available wood resources, especially in the southeastern part of the area.  
173 Fields (in white or light green) decrease the available wood resources in the western  
174 part of the area.

### 175 **2.3 Data analysis**

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

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

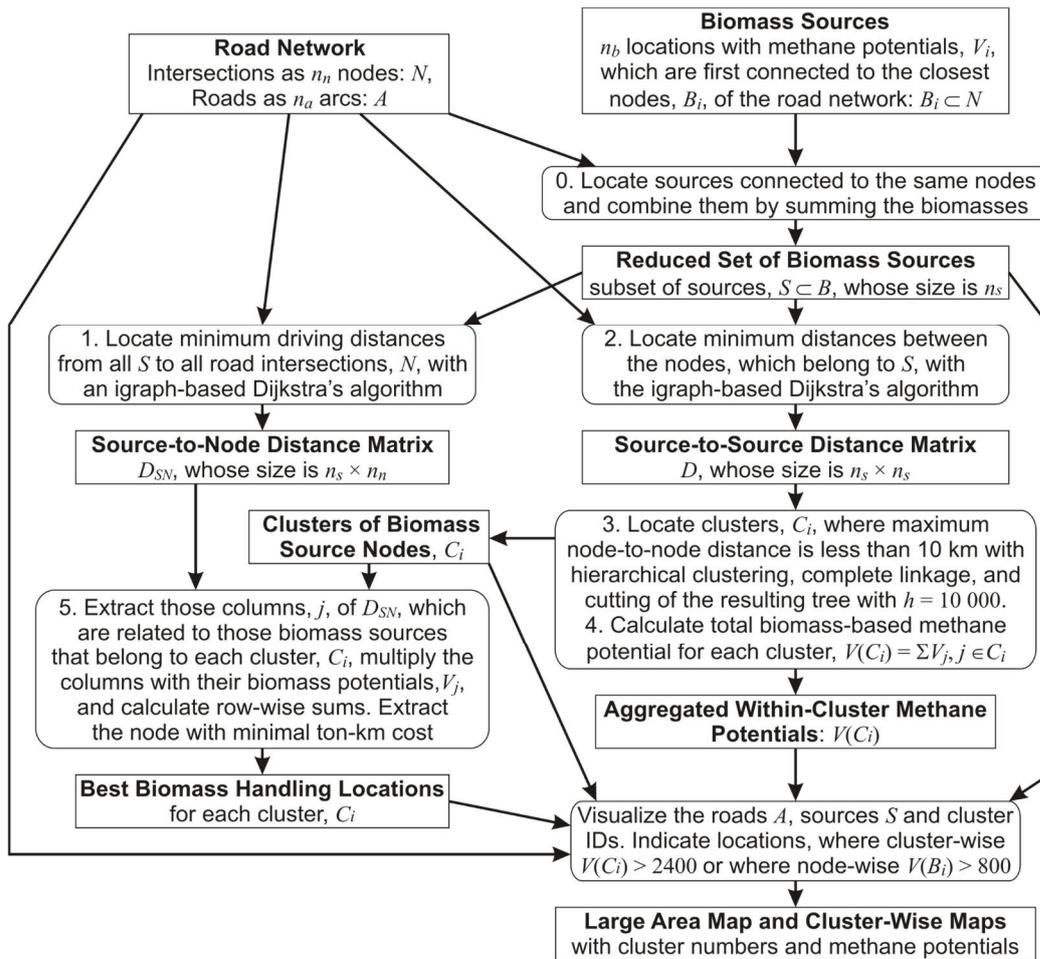
- 187 (1) It determined minimum driving distances from the biomass source points to all  
188 other nodes of the road network as a matrix,  $D_{SN}$ .
- 189 (2) It then determined minimum road distances between all biomass source points,  
190 into matrix  $D$ .
- 191 (3) It then used hierarchical clustering with complete linkage (a.k.a. maximum  
192 within cluster distance) for  $D$  to locate such clusters, where all distances were  
193 less than the chosen maximum transportation distance of 10 km.

194 Based on the clustering results the biomass potentials were summed up, and  
195 those clusters were chosen, where the sum of potentials exceeded 2,400 MWh/a  
196 (>300 kW centralized biogas plants). At the same step, also those biomass  
197 sources were detected and pointed out, whose potential exceeded the biomass  
198 need for a >100 kW farm biogas plants, 800 MWh/a.

199 (4) At the last step, it picked those columns from the full distance matrix  $D_{SN}$ , which  
200 were related to the biomass sources in the chosen clusters, multiplied the picked  
201 columns with expected biomass weights for each source node, and calculated the  
202 node-wise sum of these weight (kg)  $\times$  distance (m) results. Then, the cost-  
203 minimizing nodes were selected as the optimal locations for the centralized  
204 biogas plants for the chosen clusters.

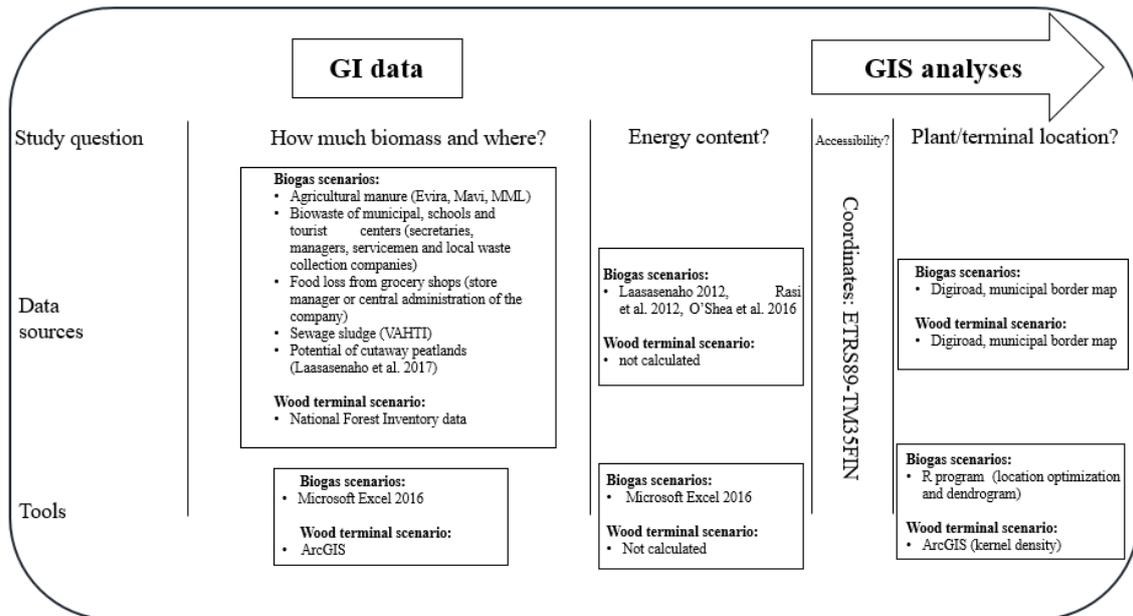
205 In the wood terminal scenario, raster data on forest wood volume were fed into the  
206 ArcGIS software, v. 10.5.1 (ESRI Inc., Redlands, CA). First, raster data were converted  
207 to points using the raster-to-point tool. The raster size in the kernel density analysis was  
208 chosen as 1 km,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

212



213

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



218

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

## 222 3 Results and discussion

### 223 3.1 Biogas plant scenario

224 Potential locations for farm biogas plants (>100 kW) and centralized biogas plants  
 225 (>300 kW) were determined in the study area using GIS-based optimization tools. Total  
 226 gross methane potential in the area was 57.1 GWh per year (Fig. 5). Of the different  
 227 feedstocks, the largest gross methane potential in the area came from livestock manure,  
 228 ranging from 30 MWh to 1,991 MWh per farm annually.

229 In the scenario of farm-scale biogas plants, sufficient biomass was available for  
 230 13 farm biogas plants (with a >100-kW energy production potential) in the study area  
 231 (Fig. 6). The highest gross methane potential for one farm was 1,991 MWh/a (Fig. 5).  
 232 The median value was about 300 MWh/a/farm. The total gross methane potential in  
 233 these 13 potential farms was 15.5 GWh/a, representing 27.1% of the total gross methane

234 potential in the area. The largest gross methane potential is found from farms located in  
235 rural villages, as indicated in Fig. 6. Seven of these are located in Alavus municipality,  
236 four in Kuortane municipality, and two in Ähtäri municipality.

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

246 The study area can be divided into four large domains or groups based on  
247 accessibility by road network: northern Kuortane belongs to the first group; northern  
248 Soini to the second group; western Alavus and southern Kuortane to the third group;  
249 and southern Soini, western Alavus, and Ähtäri to the fourth group (Fig. 7). The eight  
250 clusters with the highest methane energy production potential for centralized biogas  
251 plants were clusters 2, 9, 11, 14, 19, 20, 21, and 32 (Fig. 6). Specifically, their gross  
252 methane potentials ranged from 2,409 MWh/a, which is equal to a nominal power of  
253 301 kW (cluster 20 in Kuortane), to 3,535 MWh/a, which is equal to a nominal power  
254 of 442 kW (cluster 14 in Alavus). The total gross methane potential of the eight clusters  
255 was 23.2 GWh, representing 40.6% of the total gross methane potential of the area. The  
256 clusters included from 4 to 9 large farms.

257 Optimal locations for the biogas plants were then computed inside each cluster  
258 based on the road network. As an example, the localization of cluster number 19 is

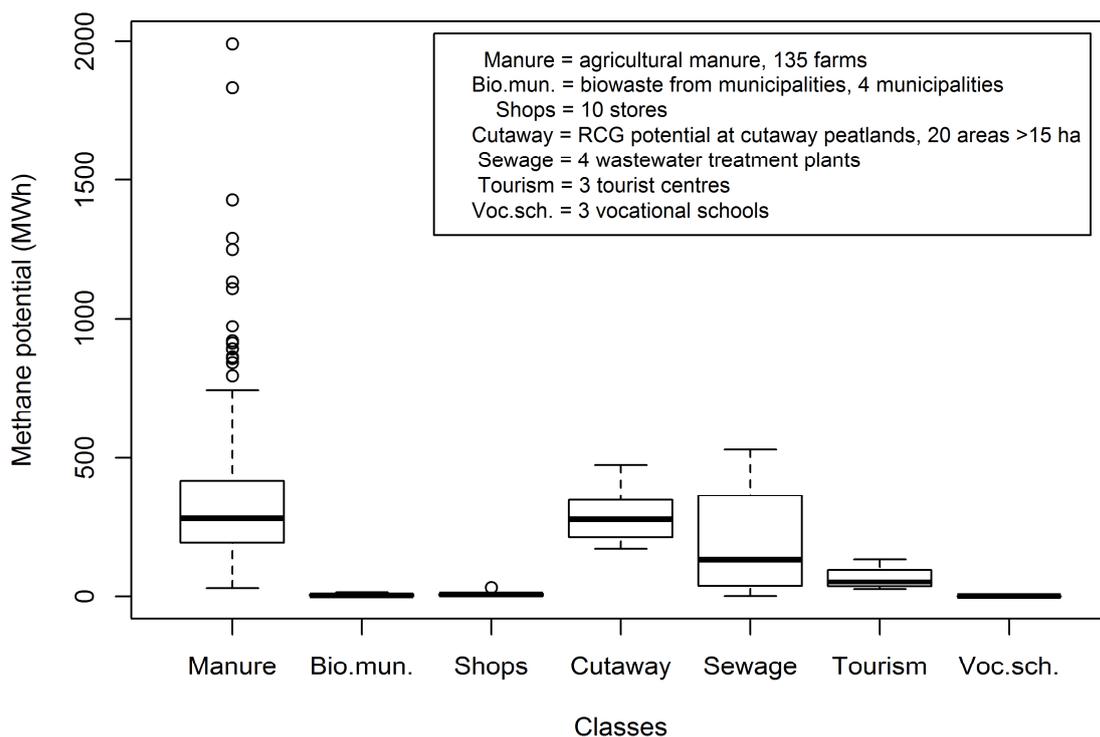
259 illustrated in Fig. 8, where the optimal biogas plant location was defined based on 6  
260 farms, organic waste from 7 municipal sources, 1 tourism centre, and 2 grocery stores.

261         Livestock manure was the largest source of biomass to the potential biogas  
262 plants. However, in Alavus and Kuortane, a significant increase of methane potential  
263 was achieved through combining manure with biowaste and potential RCG cultivation  
264 in cutaway peatlands. The largest methane energy production potential is in the western  
265 part of the region, whereas no potential locations for biogas installations were identified  
266 in the Soini municipality (Fig. 6). In particular, large-scale farms (over 50 heads of  
267 cattle) have an important role in future biogas production in the study area. Only about  
268 20 % of the dairy farms have over 50 heads of cattle in Finland and the number of small  
269 farms is constantly decreasing [41]. For example, in Denmark, the largest farms were  
270 also identified, in most cases, as relevant and vital for future biogas production; average  
271 farm size in Denmark has increased from 131 heads of cattle to 238 heads per farm in  
272 ten years (from 1999 to 2009 [10]). Agricultural residues, including slurries and crops  
273 produced for energy, have also been found to be important biomass sources in other  
274 regional GIS-based biogas analyses, representing from 50% to over 90% of total biogas  
275 potential [13-14] in studied rural areas.

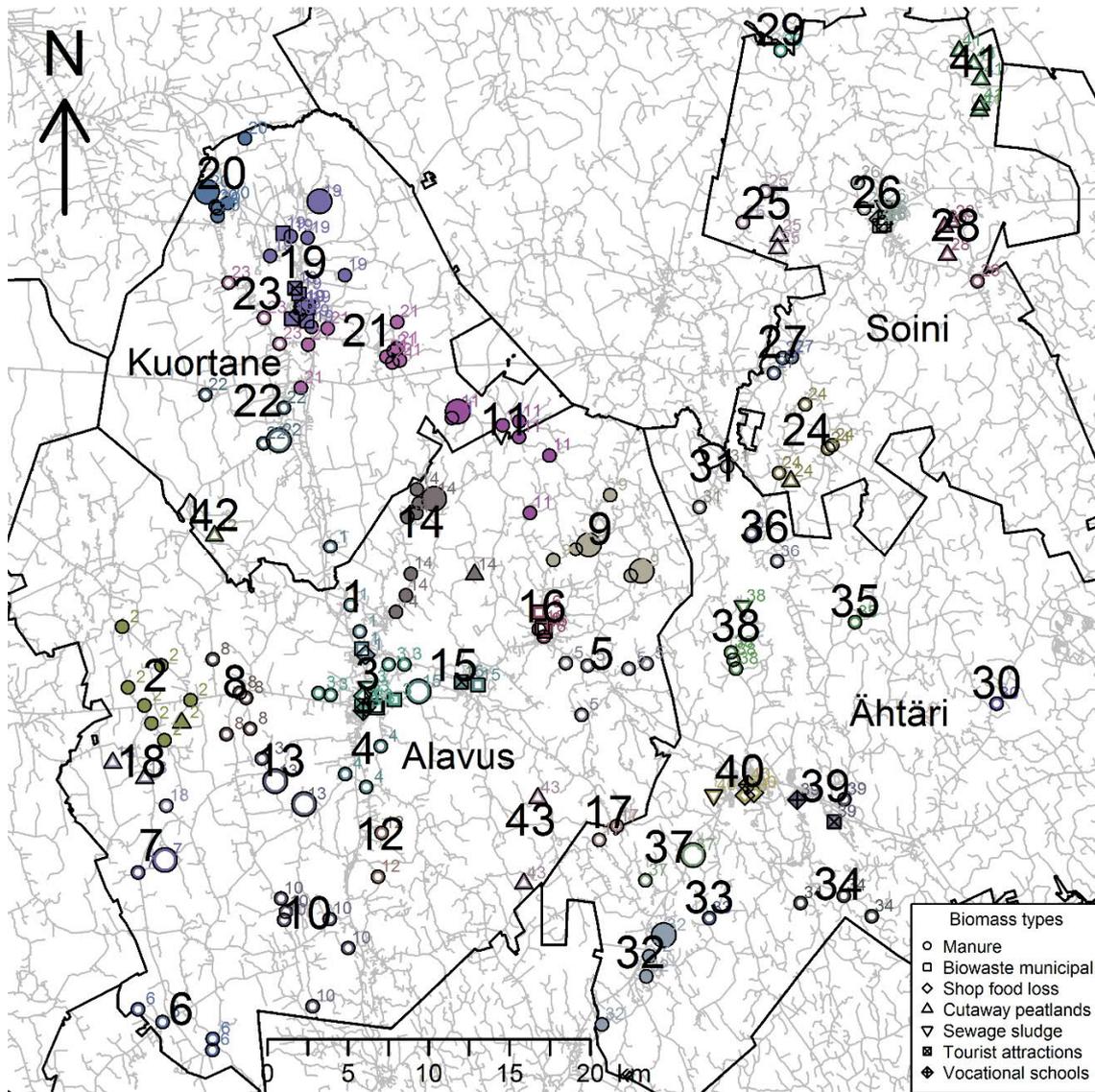
276         Notably, the cultivation of RCG on prior cutaway peatlands was confirmed as a  
277 potential feedstock source for a biogas plant in an area of intensive peat extraction. In  
278 Alavus, there were two areas where cultivation of RCG on prior cutaway peatlands  
279 could increase local biomass resources (Fig. 6). However, the cutaway peatlands are  
280 usually located over 10 km away from farms, which can make the logistic arrangements  
281 difficult (Fig. 7). Also, certain limitations of cutaway peatlands must be addressed, such  
282 as the difficulty of cultivating agricultural crops in these areas because of typical high  
283 water levels [42]. Alternatively, forest biomass could be considered on remote cutaway

284 peatlands, and in fact landowners generally prefer forestry as an after-use alternative  
285 instead of energy crop production [30].

286 The fact that sludge generated in wastewater treatment plants and biowaste  
287 generated in municipalities and tourist centres are often located far away from large-  
288 scale farms complicates the location of the biogas plant. However, in Kuortane, the  
289 increase of energy potential is achieved from combining the joint methane potential of  
290 biowaste (from one tourist centre, grocery stores, and municipal collection facilities)  
291 and large-scale farms near the town centre (Fig. 8). Finally, the GIS tools used in the  
292 present study allocated biomasses according to reasonable transportation distances (10  
293 km) and helped to plan biogas plants sizing.



294  
295 Figure 5. Studied feedstocks and their gross biogas potentials (MWh) in the study  
296 region as box-and-whiskers plots.



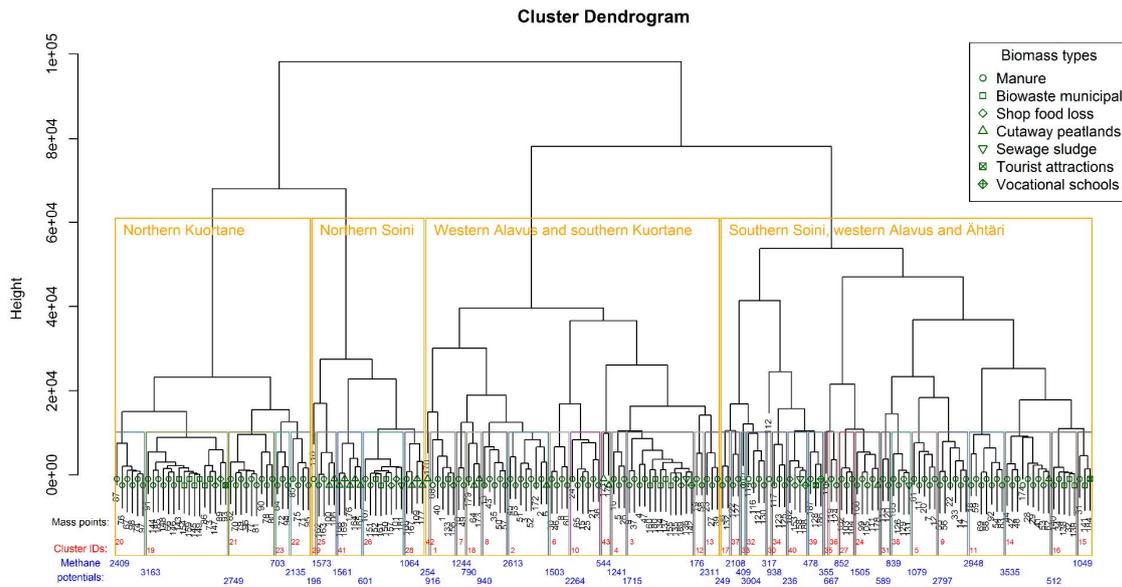
297

298 Figure 6. Feedstock production sites and their division into clusters (given as numbers)

299 for the 13 potential farm biogas plants (larger circles) (>100 kW) and eight potential

300 centralized biogas plant clusters (filled with colour) (>300 kW).

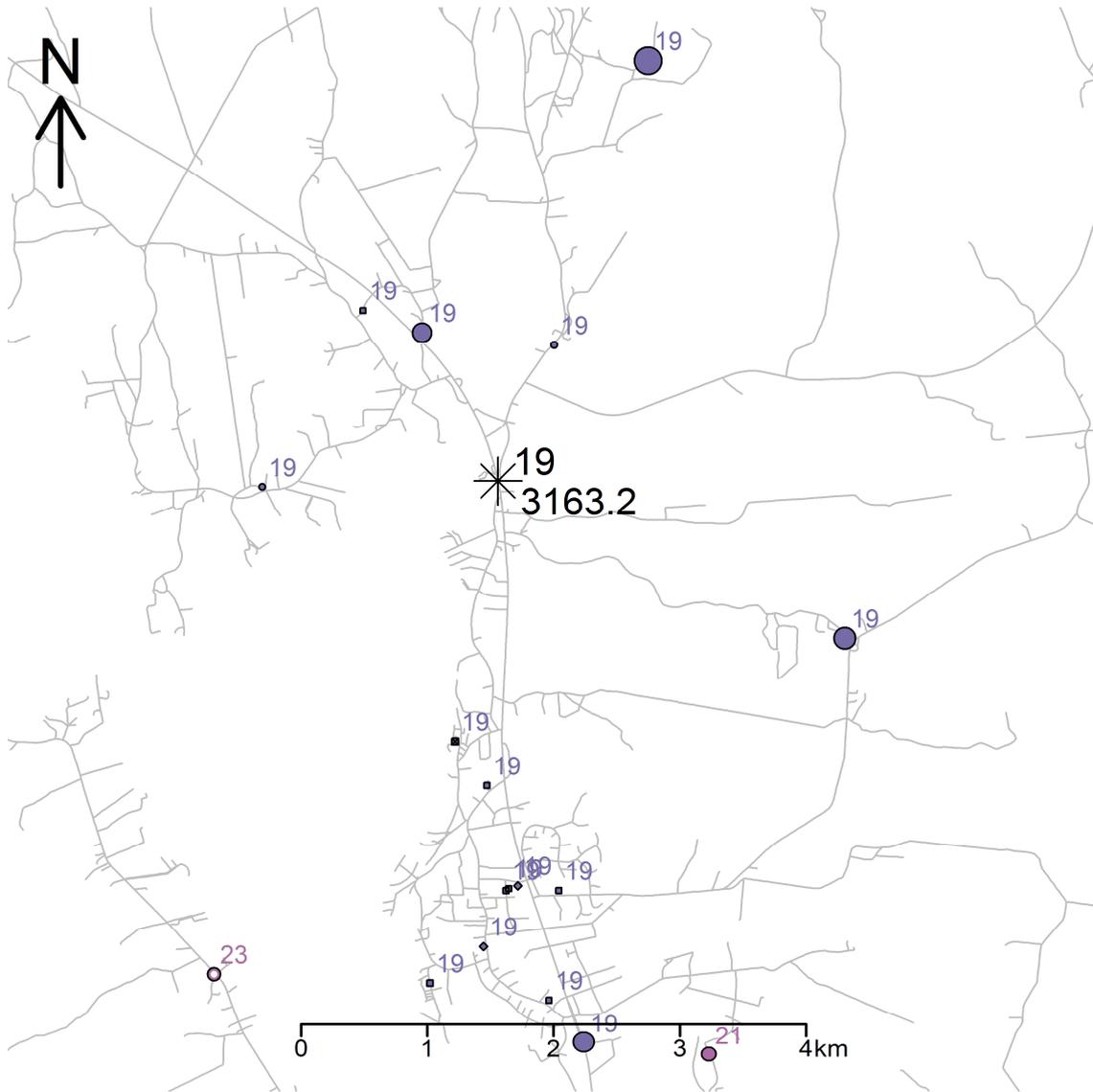
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302

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

309



310

311 Figure 8. Example of the self-programmed optimization tool for identifying a suitable  
 312 location for a power plant by minimizing transportation distance when biomasses are  
 313 sparsely distributed in a potential biogas production area (cluster 19). The model  
 314 minimizes the sum of total transportation needs. The potential plant location is  
 315 illustrated as an asterisk (energy potential indicated below the asterisk in MWh/a). The  
 316 biomass sources are denoted with symbols explained in the legend of Fig. 7.

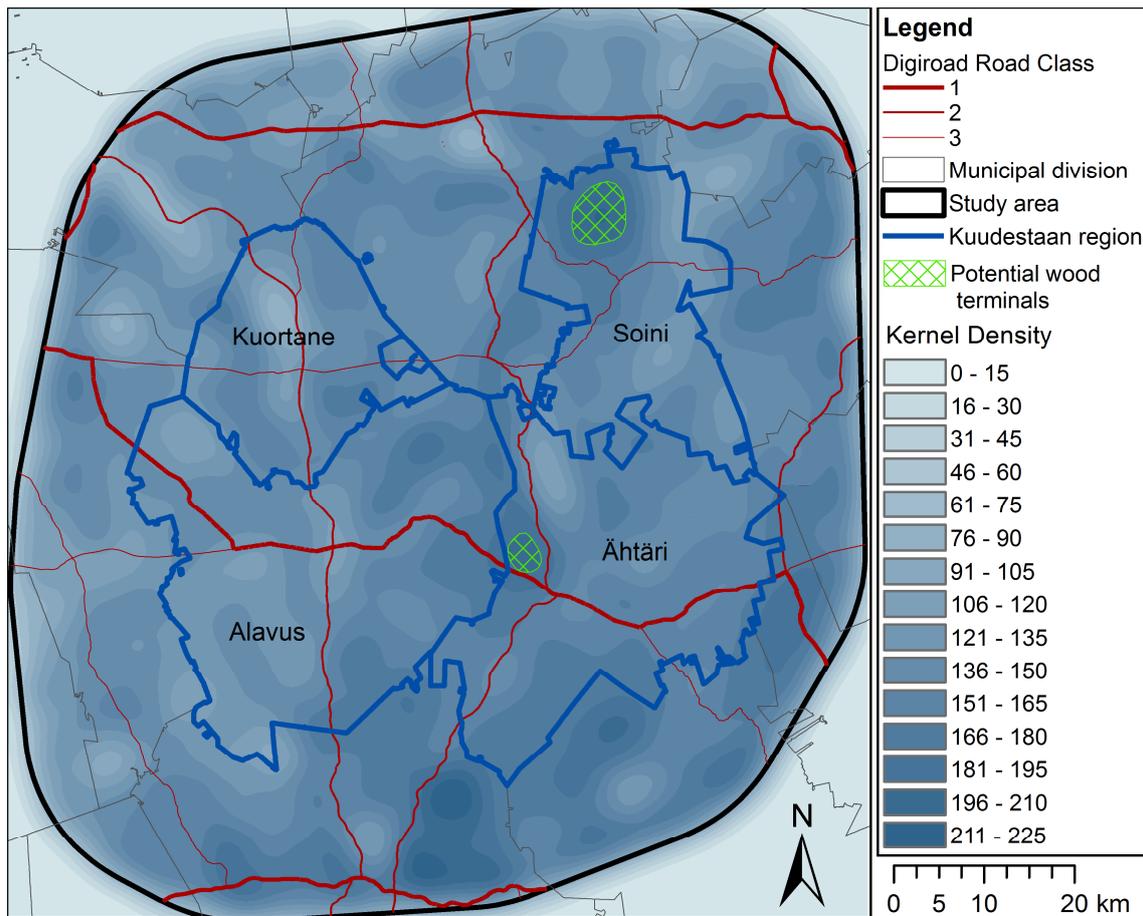
### 317 **3.2 Wood terminal scenario**

318 The optimal locations of wood terminals in the study area were determined based on

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

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

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



343

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

349

### 350 ***3.3 Feasibility of the methods for defining the locations of bioenergy plants***

351 The present study developed and assessed methods consisting of route optimization,  
 352 hierarchical clustering, location optimization, and kernel density estimation for  
 353 identifying biomass processing or storing locations in cases of multiple feedstock such  
 354 that transportation distances are minimized. The methods optimize biomass

355 transportation from the collection point to non-predefined power plant location, which  
 356 shows the progress together with previous studies using different GIS on bioenergy  
 357 plant planning as summarized in Table 3. The goal was to achieve the highest potential  
 358 bioenergy production and plant size with short transportation distances from collection  
 359 points to all other locations in the road network. The results show that these methods are  
 360 suitable for allocating biomass for bioenergy in rural areas and the methods can be  
 361 considered as decision-making tools to help plan power plant size.

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

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

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

GIS method	The method can be used for	Reference
Markov chain model	Forecasting the <b>spatial distribution</b> of Danish livestock intensity and future biogas plants	[10]
Mixed integer linear programming model	Biorefining plant <b>location optimization</b> by remote sensing and road network	[16]

GIS – Analytical Hierarchy Process – Fuzzy Weighted Overlap Dominance (GAF) model	Decision support on <b>suitable locations</b> for biogas plants	[12]
Kernel density and p-median problem	Pinpointing <b>areas with high biomethane concentration</b> (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 <b>biomass supply catchments</b> (an extension to the p-median model)	[9]
Modified Dijkstra algorithm	A systemic approach to <b>optimizing animal manure supply</b> 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) <b>in biogas plants site selection.</b>	[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 <b>siting of anaerobic co-digestion plants</b>	[13]

375

376           The method described in the present paper can be useful for municipal-level  
377 business developers and for promoting business activity in rural areas. The method  
378 helps to recognize energy potentials by clustering the feedstocks and by finding  
379 hotspots with kernel density analysis. In particular, the biogas plant optimization  
380 scenario was useful for identifying potential areas for bioenergy production given  
381 multiple potential feedstocks. Further, the self-programmed tool can help to optimize  
382 biogas plant locations by minimizing transportation costs, especially in situations when  
383 candidate biogas plant locations have not been defined in advance. Many GIS tools,  
384 such as e.g. Closest Facility and Location-Allocation in ArcGIS, require such candidate

385 points. One clear advantage of this method is also that the configuration of biomass  
386 sources can be easily changed and the analysis can be re-run if some farms decide to  
387 leave out from proposed cooperatives.

388         The assessed optimization model can make location determination easy when  
389 centralized biogas plants are planned. Different network analyses and adjusting the  
390 transportation threshold limit (10 km) lower or higher could provide different  
391 allocations or logistical solutions for biogas plant location. For example, by adjusting  
392 the threshold limit to 12 and 15 km, the number of potential clusters increases to 9 and  
393 11, respectively. The biogas plants are often placed near the spatial mean of biomass  
394 sources, because in many cases there are several rather large biomass sources. In these  
395 cases, the transportation distances would still be less than 10 km, because the distances  
396 from biomass sources to the centrally located plant are usually smaller than the  
397 maximum distance between the biomass sources. Also, it is possible to balance  
398 biomasses between clusters afterwards to reach an even more even distribution of  
399 locations considering biogas potential among all clusters.

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

409 farm biogas plant. In these cases, a large amount of manure has to be moved along  
410 roads from point to point, which increases the cost of transportation and emissions.

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

420         The accuracy of GIS analyses varies greatly depending on spatial and temporal  
421 resolution and data simplification. Early and seasonal variation in biomass quantities,  
422 because of weather conditions and soil quality, are demanding for GIS analyses [12,  
423 16]. In this study, all of the organic waste types have yearly variations that are affected  
424 by several factors, such as population size and animal grazing. It is important that a  
425 continuous, cost effective, feedstock for bioenergy is available throughout the year [47].  
426 However, agricultural manure, for example, is a relatively stable potential biomass  
427 source for biogas plants, or at least the manure from large-scale farms.

428         In the case of wood terminals, the utilized forest inventory data included large  
429 forest conservation areas and small-sized local forests or protected aquatic ecosystems  
430 [36] where logging cannot be performed. These areas should be considered, and their  
431 possible effect on practical optimization solutions should be taken into account [45-46].  
432 Also, peatland forests are usually only suitable for logging operations when the terrain  
433 is frozen with snow cover [44].

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

448           In practice, the existence and availability of required data may be limited  
449 because of legislation. In Finland, information on farms is given only for scientific  
450 purposes. In any case, these types of studies can be carried out with the involvement of  
451 research organizations and with farms that are willing to share information. The next  
452 step could involve finding potential farmers to participate in cooperative ventures and in  
453 making more detailed logistical optimizations based on actual biomasses. In the case of  
454 wood, the amount of forest biomass based on data from the Finnish [36] is freely  
455 available online, making these data easy to access and utilize. With respect to  
456 cooperative-based centralized biogas plants, several co-actors would be necessary to  
457 ensure that local biogas yields are high enough. It might be beneficial for business  
458 developers to begin from the clusters with fewer large actors, such as cluster 32 (Fig. 6),

459 to avoid complex situations with many small participants. Finally, more detailed  
460 analyses of the economic profitability of bioenergy plants should be performed to assess  
461 if such plans are realistic: considering e.g. transportation mode (truck and train) and  
462 location of energy users.

463

## 464 **5 Conclusions**

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

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

482 In the studied rural area, 13 farm biogas plants (>100 kW) and eight centralized  
483 biogas plants (>300 kW) considering a threshold distance of 10 km were identified. The

484 results suggest that the co-digestion of biowastes and potential RCG from cutaway  
485 peatlands could be logistically reasonable in three centralized biogas plants. The kernel  
486 method also suggests that two wood terminals could be located in the study area to  
487 provide a constant wood supply for bioenergy production.

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