Author(s): Laasasenaho, K.; Lensu, Anssi; Lauhanen, R.; Rintala, J.

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

Year: 2019

Version: Accepted version (Final draft)

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Please cite the original version:

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. https://doi.org/10.1016/j.seta.2019.01.006

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.

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.
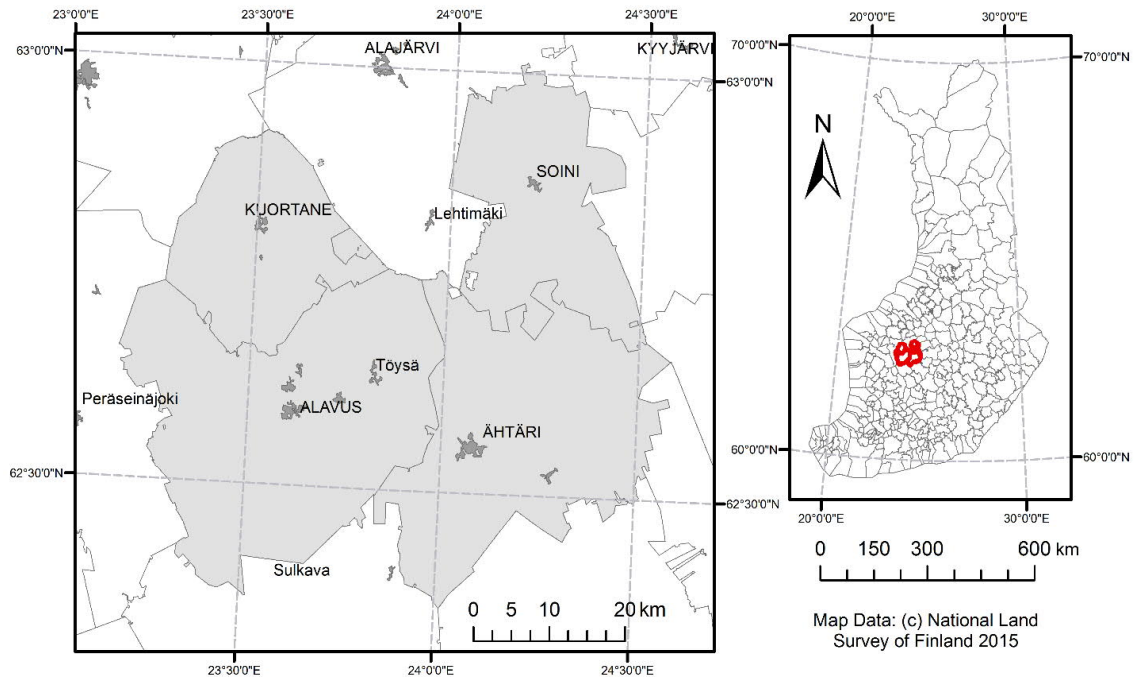
126

127 Figure 1. Location of the studied Kuudestaan 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_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]

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^3/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
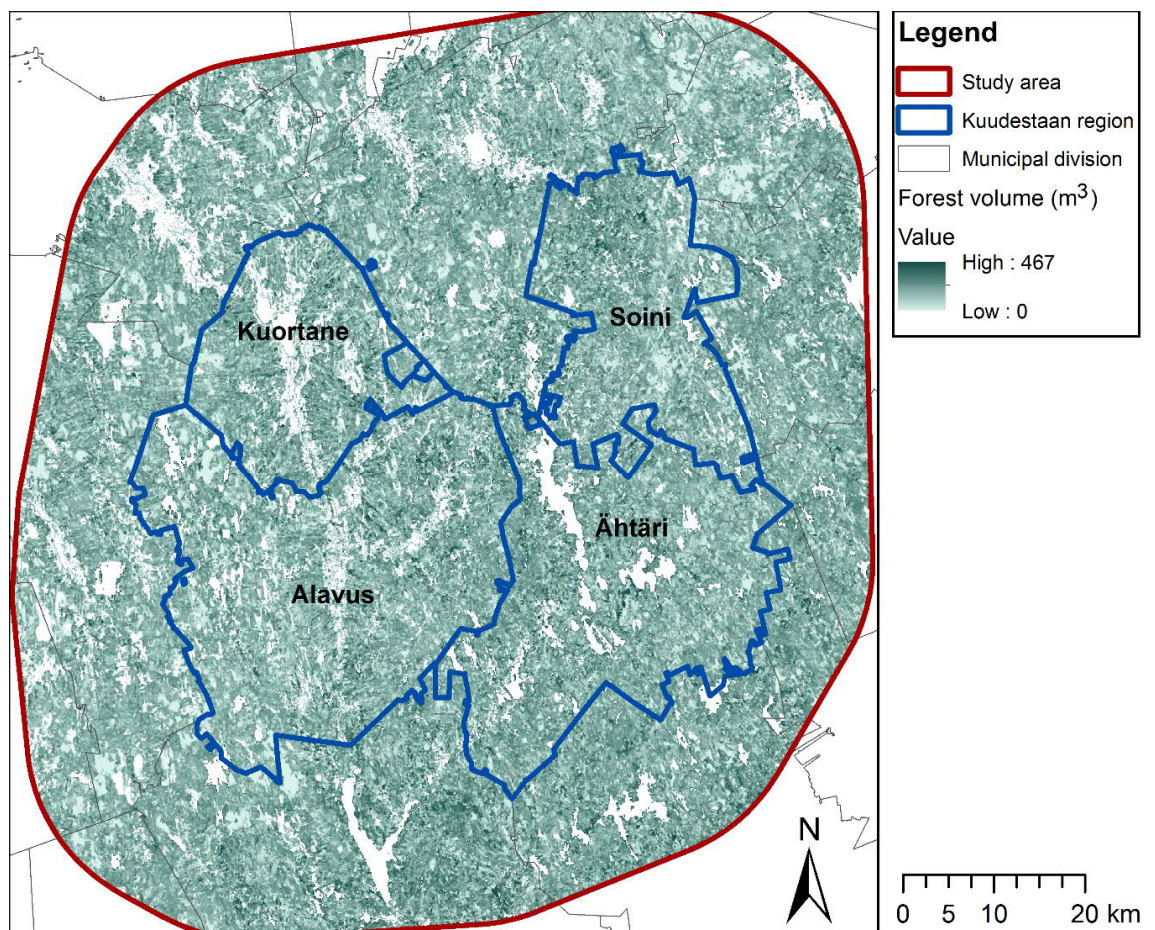
170   Figure 2. Forest inventory data in the study area (forest inventory data [37]; municipal

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-

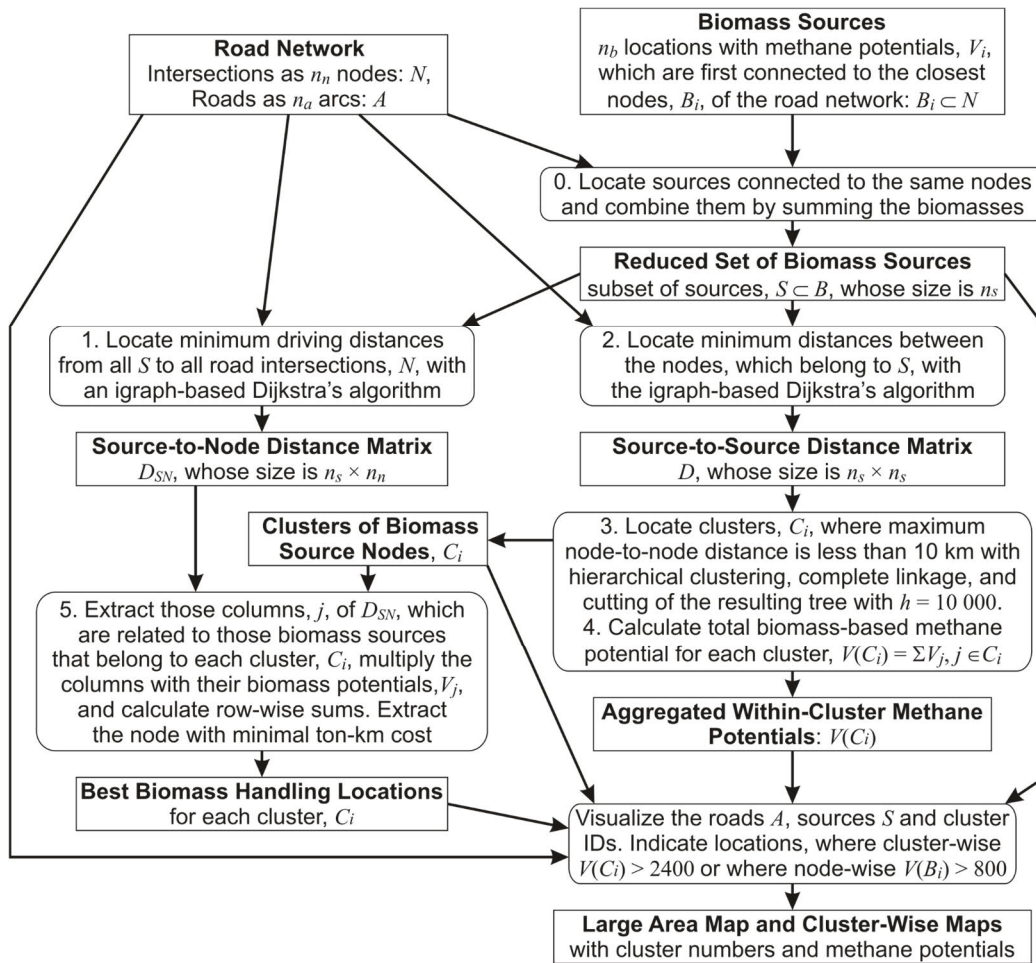186 programmed location optimization tool then used the following approach (Fig. 3):

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

Road Network
Intersections as n_n nodes: N,
Roads as n_a arcs: A

Biomass Sources
n_b locations with methane potentials, V_i, which are first connected to the closest nodes, B_i, of the road network: $B_i \subset N$

0. Locate sources connected to the same nodes and combine them by summing the biomasses

Reduced Set of Biomass Sources
subset of sources, $S \subset B$, whose size is n_s

1. Locate minimum driving distances from all S to all road intersections, N, with an igraph-based Dijkstra's algorithm

2. Locate minimum distances between the nodes, which belong to S, with the igraph-based Dijkstra's algorithm

Source-to-Node Distance Matrix
D_{SN}, whose size is $n_s \times n_n$

Source-to-Source Distance Matrix
D, whose size is $n_s \times n_s$

Clusters of Biomass Source Nodes, C_i

3. Locate clusters, C_i, where maximum node-to-node distance is less than 10 km with hierarchical clustering, complete linkage, and cutting of the resulting tree with $h = 10\,000$.
4. Calculate total biomass-based methane potential for each cluster, $V(C_i) = \Sigma V_j, j \in C_i$

5. Extract those columns, j, of D_{SN}, which are related to those biomass sources that belong to each cluster, C_i, multiply the columns with their biomass potentials, V_j, and calculate row-wise sums. Extract the node with minimal ton-km cost

Aggregated Within-Cluster Methane Potentials: $V(C_i)$

Best Biomass Handling Locations
for each cluster, C_i

Visualize the roads A, sources S and cluster IDs. Indicate locations, where cluster-wise $V(C_i) > 2400$ or where node-wise $V(B_i) > 800$

Large Area Map and Cluster-Wise Maps
with cluster numbers and methane potentials

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
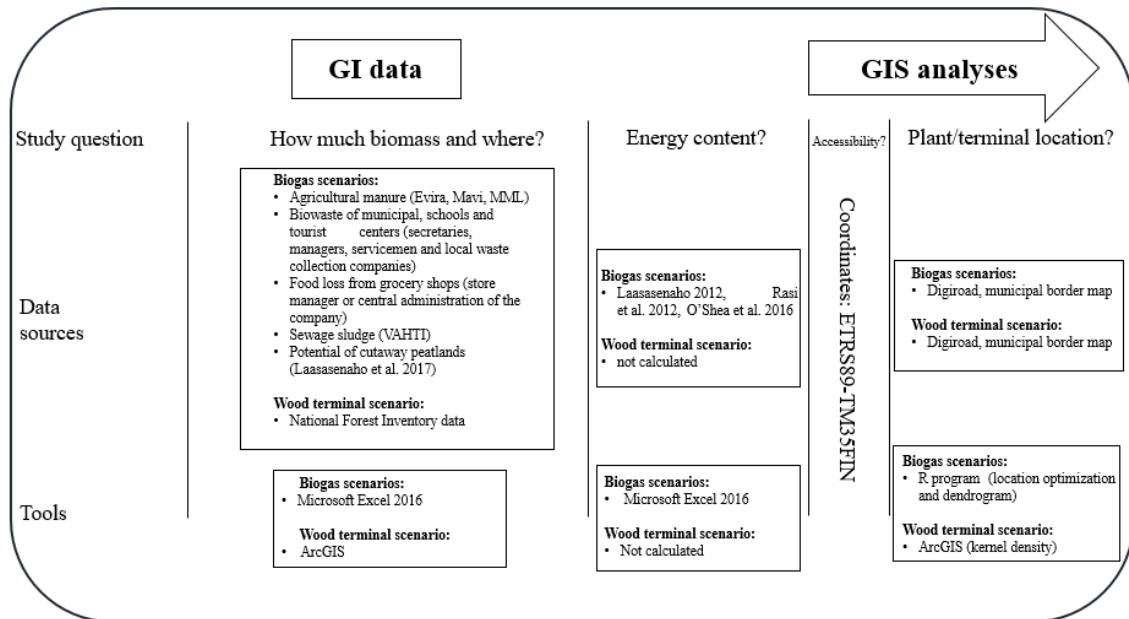
Figure 4. GIS process for determining the optimal locations of biogas plants and wood

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

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.
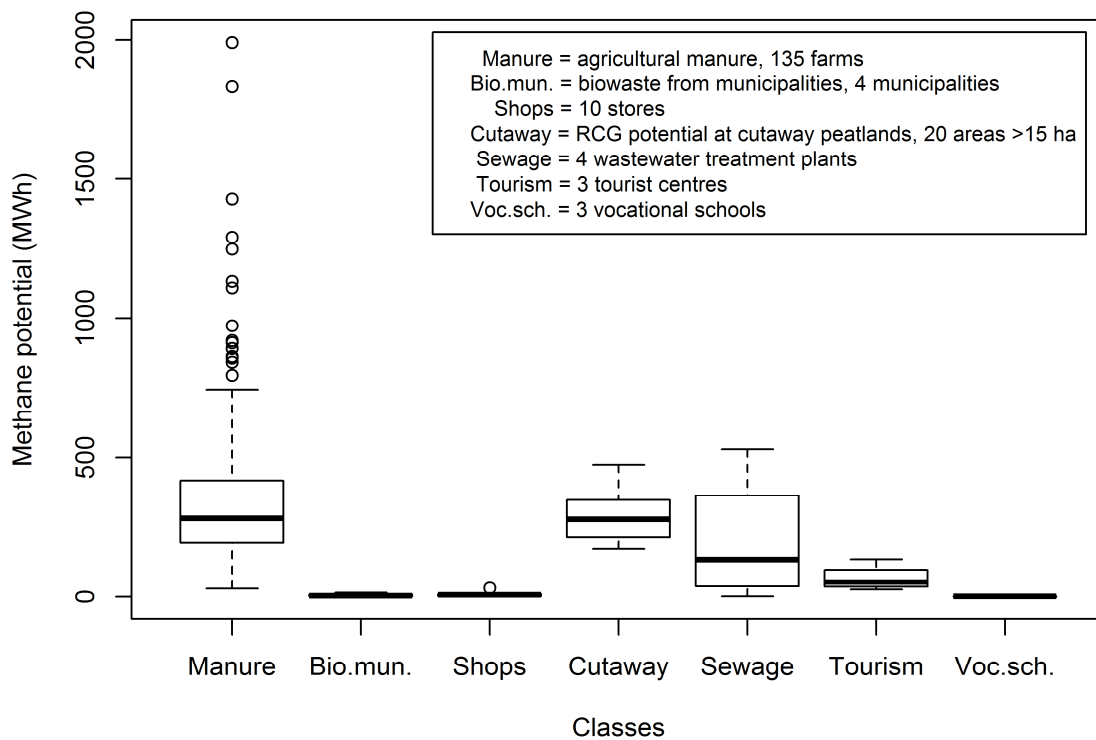
294

295   Figure 5. Studied feedstocks and their gross biogas potentials (MWh) in the study

296   region as box-and-whiskers plots.
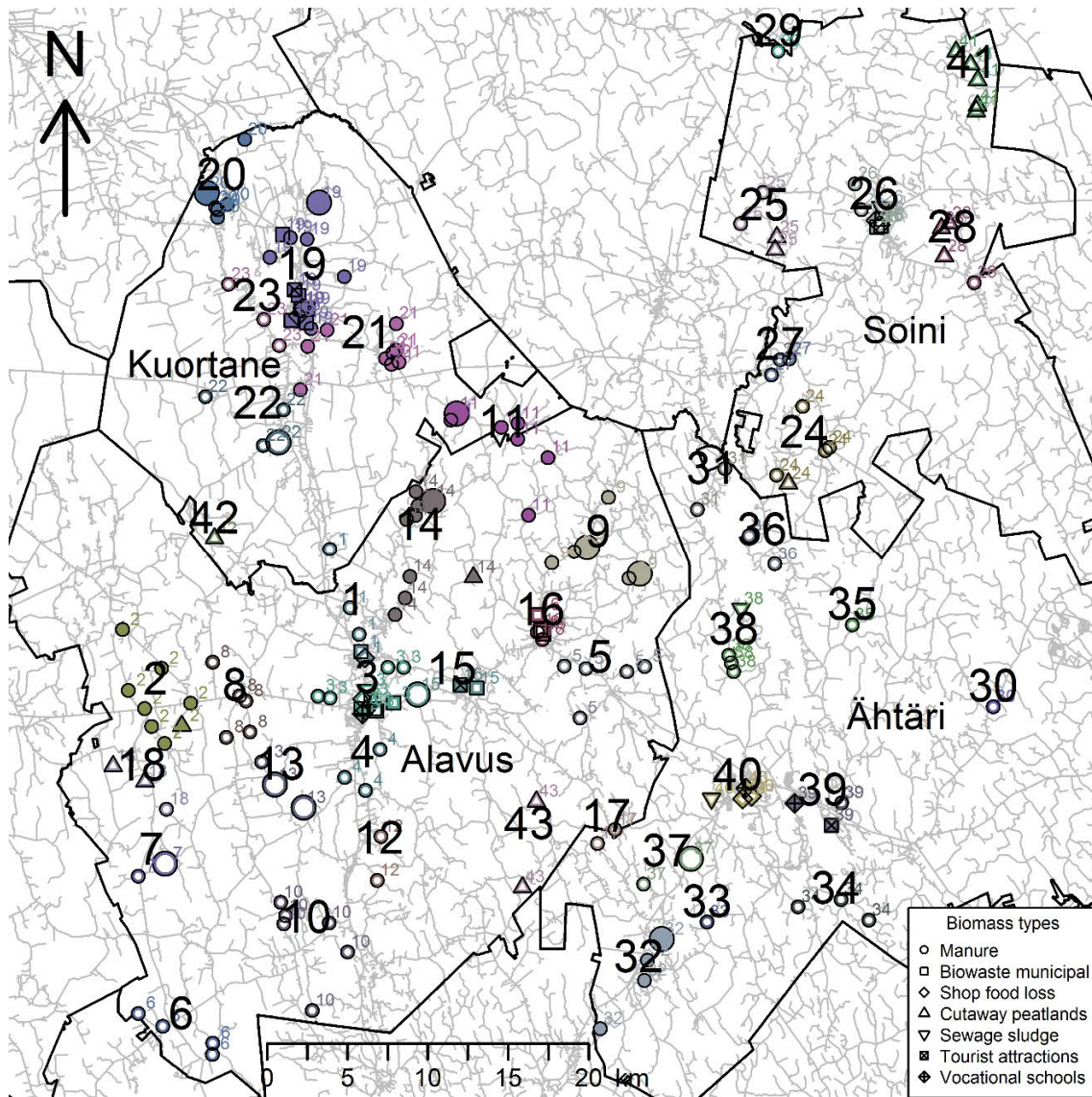
297

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).

301
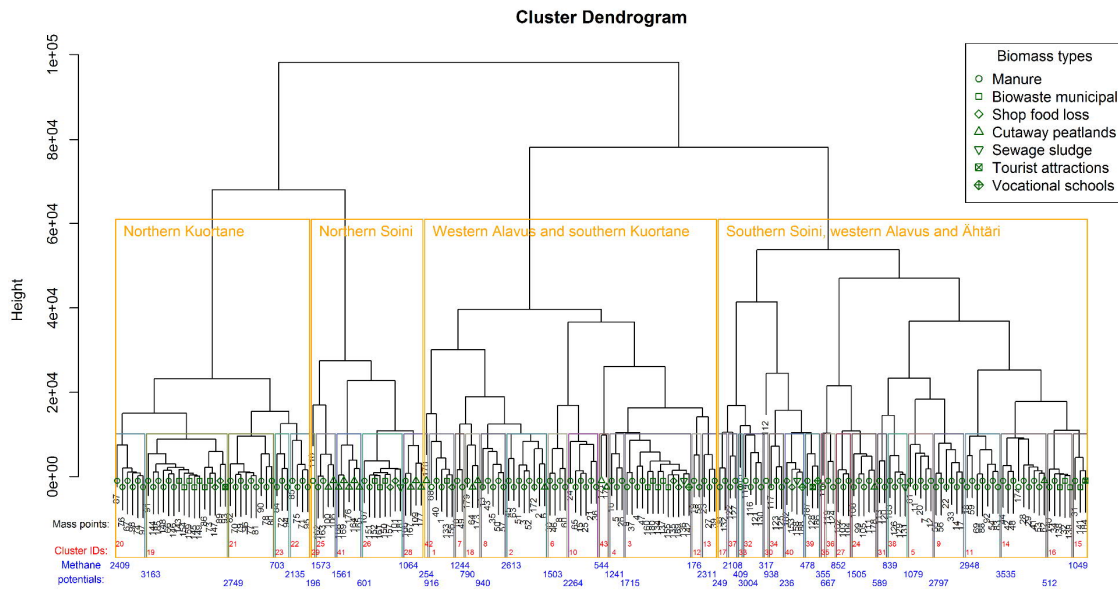
Figure 7. Dendrogram presenting centralized biogas plant clusters according to a transportation threshold of 10 km in the study region. Agglomerative clustering based on complete linkage was applied to combine biomass production sites as clusters when threshold distance was not exceeded. Rectangles are 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.
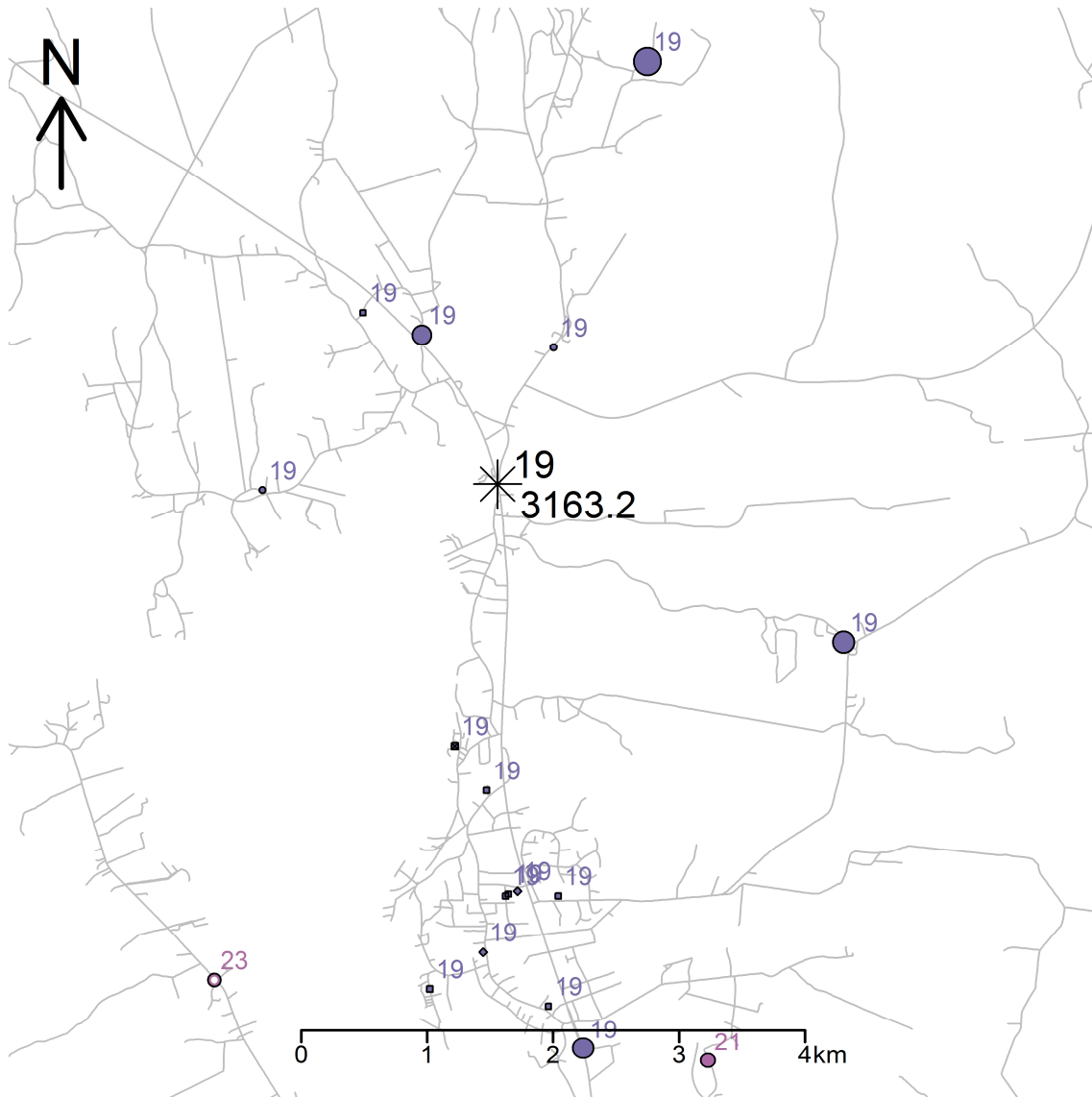
310

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.
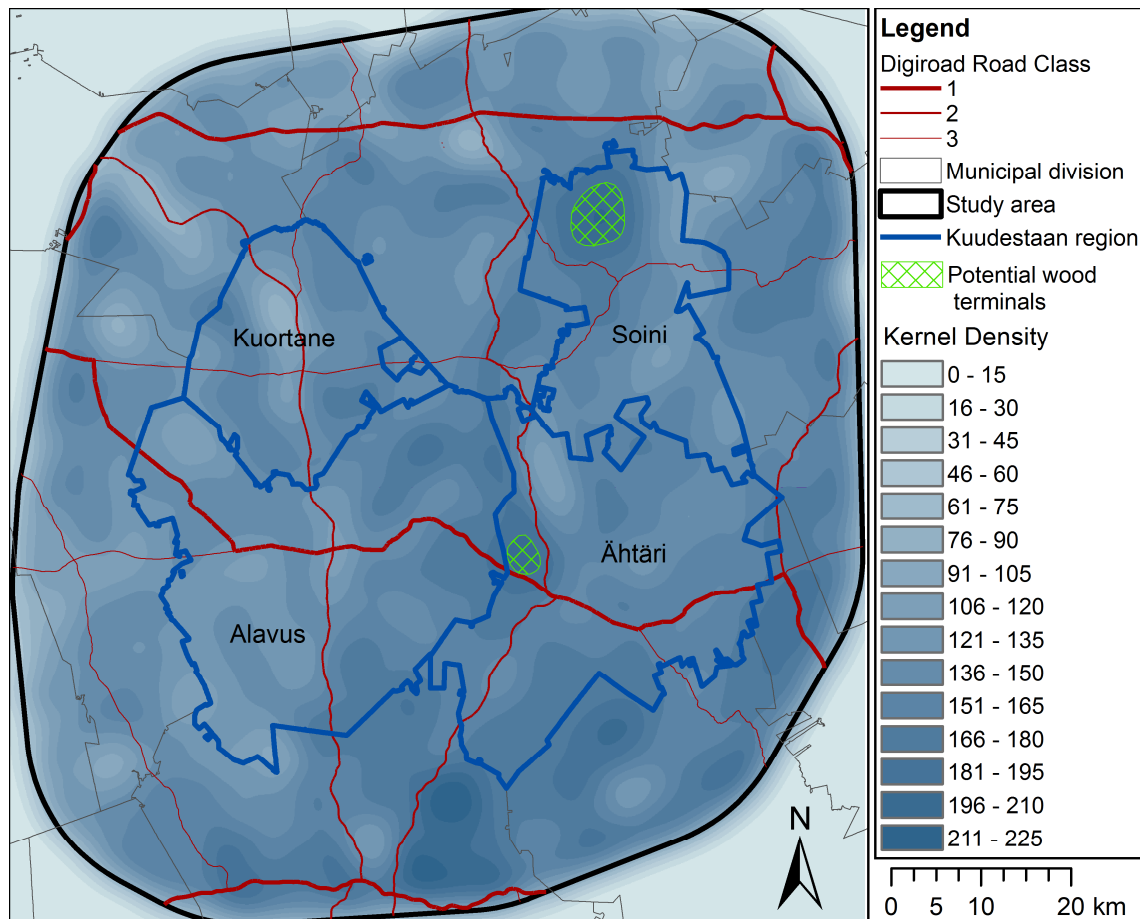
343

344 Figure 9. Kernel density map of wood resources (tree stand volume in m^3 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

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 **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]

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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