2018.11.25

Version 1

689229

Deliverable D3.9

Results of the spatial approach for designing the decentralised urban biowaste valorization network

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 689229.

DECISIVE

A DECENTRALISED MANAGEMENT SCHEME FOR INNOVATIVE VALORISATION OF URBAN BIOWASTE

This project has received funding from the European Union’s Horizon 2020
research and innovation program under grant agreement No 689229.

A Decentralised Management Scheme for Innovative Valorisation of Urban Biowaste

D3.9 - Results of the spatial approach for designing the decentralized urban biowaste valorization network

Grant Agreement N°	6689229		
Acronym	DECISIVE		
Full Title	A Decentralised Management Scheme for Innovative Valorisation of Urban Biowaste		
Work Package (WP)	WP 3.3		
Authors	Thiriet Pierre		
Document Type	Report		
Document Title	D3.9 - Results of the spatial approach for designing the decentralised urban biowaste valorization network		
Dissemination Level	**CO**	Confidential, only for partners of the Consortium (including the Commission's Services)	
	PU	Public	**X**
	PP	Restricted to other programme participants (including the Commission Services)	
	RE	Restricted to a group specified by the Consortium (including the Commission Services)	

1. DOCUMENT HISTORY

version	date	editor	modification
Draft 01	15/09/2018	Pierre Thiriet	
Review	22/11/2018	Pierre Thiriet	Revision (AMB case study)

2. CONTRIBUTORS

	Name	Organization	Contact
Written by	Pierre Thiriet	**IRSTEA** Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture, Rennes, France	pierre.thiriet@irstea.fr
With the contribution of	Thierry Bioteau	**IRSTEA** Institut national de recherche en sciences et technologies pour l'environnement et	thierry.bioteau@irstea.fr

	Name	Organization	Contact
		l'agriculture, Rennes, France	
	Jessica.Schermuly Phillipp Lüssenhop Steffen Walk	**TUHH** Hamburg University of Technology, Hamburg, Germany	jessica.schermuly@tuhh.de phillipp.luessenhop@tu-harburg.de steffen.walk@tuhh.de
	Veronica Martinez Sanchez Rosaria Chifari	**ENT** Fundació ENT, Barcelona, Spain	vmartinezs@ent.cat rchifari@ent.cat
Reviewed by	Gisela Sommer Teresa Guerrero	**ARC** Agència de Residus de Catalunya	tguerrero@gencat.cat gsommer@gencat.cat
	Marc Iriani	**ENT** Fundació ENT, Barcelona, Spain	miriani@ent.cat
For approval by	Coordinator Anne Tremier	**IRSTEA** Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture, Rennes, France	anne.tremier@irstea.fr

3. ABSTRACT

The growing need of biowaste valorization through a more circular economy raises new challenges for the waste management at the territorial scale. This study, conducted in the framework of the H2020 DECISIVE project, aimed at testing on the the metropolitan area of Lyon (Grand Lyon-GL, France), the Metropolitan Area of Barcelona (AMB, Spain) and the city of Hamburg (Germany) a method to design decentralized and micro-scale Anaerobic Digestion (mAD) networks in urban and peri-urban areas.

The method developed by IRSTEA (Deliverable D3.8 – application to the Lyon case) combines a mixed integer linear program (MILP) and Geographic Information System (GIS). The MILP aims at lowering the impacts of biowaste and digestate transportation by minimizing the payload-distances while taking into account the technical constraints of the system. The GIS methodology is designed to feed the MILP model with very fine-scale data about the location and the characterization of the biowaste sources, of the digestate outlets (agricultural areas) and the potential sites for mAD.

The application of the method on GL, AMB and Hamburg underlines the challenges for conducting the GIS inventories. The data availability and heterogeneity remain key issues which imply a continuous adaptation of the initial method that increases the level of uncertainties. On the other hand, the MILP model was easily and quickly applied in the new case studies without requiring significant modification of the initial code. An optimal decentralized mAD network was found in each territory which recovers the quantity of biowaste targeted (10% of the total biowaste of the territory), but also with the addition of central treatment units if relevant. Therefore, the study confirms the possibility of spatially optimizing decentralized mAD treatment network and it proved the replicability of the method in different EU geographical contexts with the proper adaptation of the inventory step.

The networks designed in the different case studies present significant similarities: the mAD were mainly located on the urban periphery (close to both biowaste sources and digestate outlets), each mAD treated a low quantity of biowaste (53t/y to 86t/y) and mainly made up of household and assimilate kitchen waste. The first two points are directly related to the criteria for selecting the potential treatment sites and the objective function of the MILP model.

Table of content

Abbreviations and acronyms

AD	Anaerobic Digestion
ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie (The French Environment and Energy Management Agency)
AMB	Metropolitan Area of Barcelona
BTN25	Base Topográfica Nacional 1:25000 (Spain)
ARC	Agència de Residus de Catalunya
DB	Database
CHP	Combined Heat and Power
D	Deliverable
DECISIVE	DECentralised management Scheme for Innovative Valorization of urban biowastE
DEM	Digital Elevation Model
FW	Food Waste
GEOBIA	GEOgraphic-Object-Based Image Analysis
GIS	Geographic Information System
GL	Grand Lyon
IGN	Institut national de l'information géographique et forestière (National Institute of Geographic and Forest Information)
INSEE	Institut National de la Statistique et des Etudes Economiques (National Institute of Statistics and Economic Studies)
LAU	Local Administrative Units. LAU level 2 : municipalities or equivalent units in the 28 EU Member States
Lidar	Light Detection And Ranging
mAD	Micro Anaerobic Digestion
MCDA	Multiple-criteria Decision Analysis
MILP	Mixed Integer Linear Programming
nDSM	Normalised digital surface model
NUTS	NUTS classification (Nomenclature of territorial units for statistics) – NUTS 1: major socio-economic regions – NUTS 2: basic regions for the application of regional policies – NUTS 3: small regions for specific diagnoses
OSM	OpenStreetMap
POI	Point Of Interest
RPG	Registre parcellaire graphique (Graphical Parcel Register)
SE	Stirling Engine
SIREN	Système d'identification du répertoire des entreprises (Establishments and facilites national database)
SSF	Solid State Fermentation
t	metric ton or Mg
WP	Work Package
y	year

I. Introduction

By developing and testing a decentralized small scale AD valorization network, the H2020 DECISIVE project is contributing to the evaluation of new biowaste management schema. The project aims to develop a biowaste management system, hereinafter referred to the DECISIVE system (Figure 1), in which the biowaste sources, the treatment sites, and the product outlets are brought closer to create local biowaste valorization loops. The proposed system relies on decentralized and small-scale solutions currently under development: micro Anaerobic Digestion (mAD), combined heat and power (CHP) Stirling Engine (SE), Solid-State Fermentation (SSF). The shift to a decentralized system also implies to network numerous small scale treatment units to handle the biowaste production of a territory.

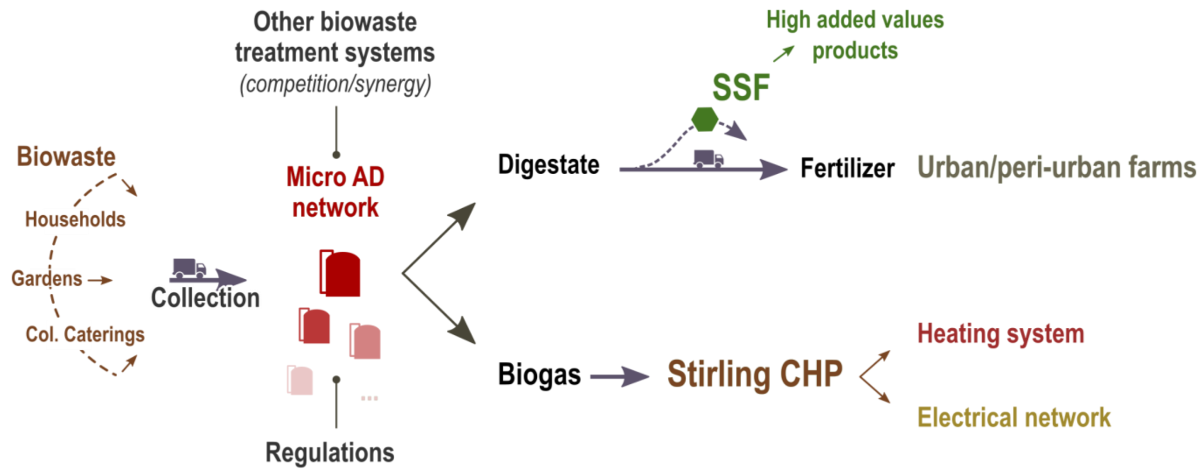


Figure 1: Simplified scheme of the DECISIVE system.

The design of biowaste treatment networks consists in solving location-allocation problems as defined by Scott (Scott, 1970); the location of the treatment plants and the allocation of the corresponding biowaste sources and outlets. In the literature (e.g. Ghiani et al., 2014), the methods described are mostly based on mathematical programming approaches and more specifically on Mixed-Integer Linear Programming (MILP). A method combining GIS and MILP was then specifically designed by Irstea for optimizing a decentralized biowaste valorization network compliant with the DECISIVE system guidelines. The overall method is detailed in the deliverable D3.8. It comprising 5 steps as described in Figure 2. The DECISIVE system targets the food waste generated by households, restaurants, canteens of public and private activities (*e.g.* schools, hospitals, public administrations and companies) and the green waste from private or public gardens (Degueurce, 2017; Manns et al., 2017). The locations of the biowaste sources and their annual production have to be accurately estimated (Figure 2a). Once collected, the biowaste is treated in mAD and the biogas is valorized with a combined heat and power (CHP) Stirling engine. The mAD and the CHP are enclosed in the same treatment unit. mAD is designed to process from 50 to 200 t/y (Degueurce, 2017) and needs to be fed by a regular stream of biowaste. Thus, alternative sources should be identified to buffer negative consequences due to fluctuations of non-permanent biowaste sources (*e.g.* school canteens). Similarly, the fraction of green waste processed should also be restricted as mAD is primarily designed to use food waste. Biowaste quality is also of importance for the viability of mAD with respect to operability, yield and quality of the outputs, even though for the purpose of the present model an even high quality of the biowaste input is assumed. Such mAD characteristics directly impact the shape of the biowaste treatment network and have to be explicitly included for designing the optimization model. The locations of the potential mAD sites are restricted by environmental regulations and urban planning rules but also by proximity constraints related to its accessibility for vehicles and the heat valorization. These sites have to be identified with an appropriate GIS multi-criteria analysis (Figure 2c). The digestate is further processed to extract a bio-pesticide through SSF (Cerda Llanos and Colmenar-Santos, 2017). The relative number of mAD units per SSF is still not defined. Thus, the SSF stage is not included in this analysis. The digestate is then exported to agricultural lands located near-by the mAD. The amount of digestate that can be used locally has to be estimated based on the agricultural surface and the legal threshold of organic nitrogen fertilization (Figure 2b). The efficiency of the system depends partly on the transport distance of the biowaste and the digestate which have to be minimized. To increase the accuracy of the analysis, these distances have to be estimated based on real road infrastructures (Figure 2d). Finally, the MILP model is built based on all GIS data previously gathered and solved (Figure 2e).

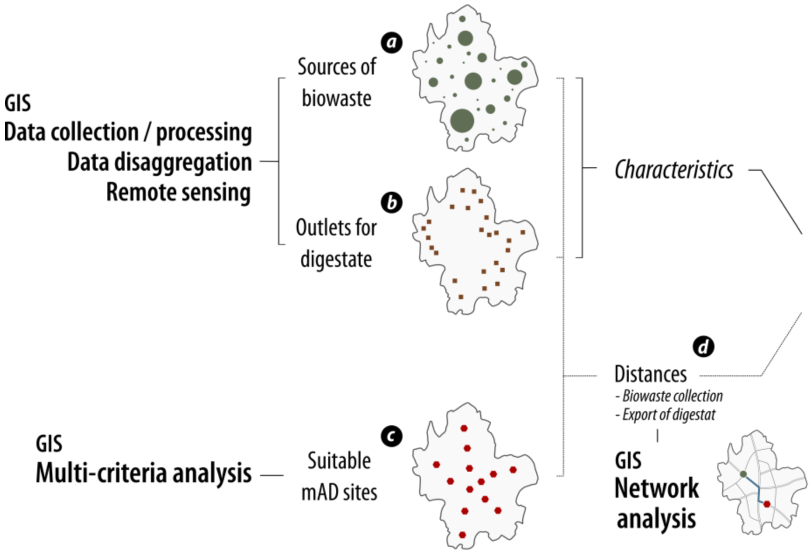


Figure 2: Flowchart of the overall method developed for designing decentralized micro-AD network: a) and b) the GIS method for the identification and characterization of the biowaste sources and the outlets for digestate, c) the GIS multi-criteria analysis for the identification of the potential mAD sites, d) the network analysis for the estimation of the transportation distances and e) the MILP for the network optimization.

The methodology was successfully tested for the case study of Grand Lyon (GL), a French territorial collectivity located in the region of Auvergne-Rhône-Alpes. However, the DECISIVE project has a wider scope, and the approach developed should remain valid in at least the 6 countries of the project partners. Hence, this study aims to assess the use of the method in new geographical contexts and to compare the different mAD networks designed. To that end, the method was tested on two new case studies, the Metropolitan Area of Barcelona (AMB), a metropolitan area in Catalonia, north of Spain and Hamburg, a city and a region (Länder) located in northern Germany. It must be noted that it was initially planned to apply the method also to the city of Lübeck (Germany), however lack of data availability prevented to achieve the method application.

The overall method is described in chapter 2. Its application to the AMB and Hamburg is summarized in chapter 3, with the addition of the GL case study for comparison purposes (extracted from deliverable D3.8). The strength and weaknesses of the method and their impacts on its potential replication are discussed in chapter 4. In the same chapter, the mAD treatment networks of the different case studies are compared to identify their similarities and potential difference.

II. Material & Methods

The following paragraph summarizes the overall method to optimize mAD networks. Some modifications were done to the original approach described in the D3.8 to include lessons learned on the MILP and to simplify the data collection.

A. MILP optimization model

Figure 3: Simplified diagram of the DECISIVE biowaste treatment system with the MILP model notation.

The optimization model aims to minimize the payload-distances under the constraint fixed by the DECISIVE system: 1) the network should handle a target amount of biowaste decided by stakeholders while being well integrated within the existing management systems (*e.g.* centralized systems, composting), 2) the mAD plants treat a quantity of biowaste that fits with their capacity , 3) for technical reasons, the quantities of biowaste from non-permanent sources (*e.g.* school canteens) and the quantity of green-waste cannot exceed a target proportion of the mAD capacity and 4) if needed, the maximal biowaste collection distance can be restricted to take into account walking distance limits for example.

The objective and the constraints are converted into a linear combination of the decision variables. The set of data, the decision variables, and the model parameters are listed in Table 1 and the model equations are described in Table 2. Figure 3 summarizes the system with the notation used for the MILP. The quantity $Fw_{i,j}$ of biowaste is transported from the sources $i \in I$, producing a quantity q_i of biowaste, over a distance $d_{i,j}$ to the processing plant $j \in J$. The processing plant j has capacity Pw_j and produces a quantity of digestate which is function of the biowaste treated and the treatment technology. The quantity $Td_{j,k}$ of digestate is then transported from the plant j to the outlets k that have a reception capacity o_k.

The objective of the optimization is given by equation *(1)*. It minimizes the payload distance, i.e. the sum of the distances and the quantity of biowaste and digestate transported. The biowaste and the digestate transport are considered equivalent; they are supposed to involve similar vehicles with similar impact per unit of weight transported and distances.

All distances are estimated based on the real road network to properly model the heterogeneity of infrastructures. The transportation of biowaste or digestate in the DECISIVE system is described by the graph $G = \{N, E\}$. The nodes N represent the locations of the biowaste sources I, the candidate sites for mAD and the current central biowaste treatment plants J, and the outlets for digestate K. The edge $e_{m,n} \in E$ is the shortest path between the nodes n and m; $d_{n,m}$ is the corresponding driving distance, calculated with the Dijkstra's algorithm (Dijkstra, 1959) and the OpenStreetMap road network (available worldwide).

Equation *(2)* sets the target quantity of biowaste to be treated in a specific area ($\sum_i q_i$). The equations *(3)* and *(4)* are the mass flow constraints from the biowaste sources to the treatment plants. The biowaste from a source included in the network is treated by a single plant only. The equations *(5)* and *(6)* describe the capacity of biowaste treatment of the plants according to their technology. The equations *(7)* and *(8)* set a limit for the contribution of non-permanent sources (*e.g.* school canteens) and green waste sources to the total biowaste supplied to a mAD. The equation *(9)* sets a list of treatment units that need to be included in the final network, such as those centralized or mAD units already installed. The equations *(10)* and *(11)* are the mass flow constraints of digestate between the treatment plants and the outlets for digestate; they take into account the loss of mass due to the biowaste treatment.

Table 1: Set of data, decision variables and model parameter of the DECISIVE model.

Sets	
I	Set of biowaste sources
J	Set of biowaste treatment units
$J_{open}, J_{mAD}, J_{Digestate} \in J$	Treatment units already open or that are mAD or producing digestate
K	Set of digestate outlets

Indices	
$i \in I$	Biowaste source
$j \in J$	Treatment facility
$k \in K$	Outlet

Decision variables	
$Fw_{i,j} \in \mathbb{R}^+$	Quantity of biowaste transported from source i to the treatment facility j
$Fd_{j,k} \in \mathbb{R}^+$	Quantity of digestate transported from the treatment facility j to the outlet k
$Pw_j \in \mathbb{R}^+$	Quantity of biowaste processed by the treatment facility j
$bS_i \in \{0,1\}$	Binary variable for the inclusion or exclusion of source i
$bFw_{i,j} \in \{0,1\}$	Binary variable for the link between the source i and the treatment facility j
$bP_j \in \{0,1\}$	Binary variable for the inclusion or exclusion of the treatment facility j

Model parameters	
q_i	Quantity of biowaste produced by the source i
$d_{i,j}$	Distance between the source i and the treatment facility j
$d_{j,k}$	Distance between the treatment facility j and the outlet k
o_k	Quantity of digestate usable in the agricultural area k
cap_j^{min}	Minimal capacity of the treatment facility j
cap_j^{max}	Maximal capacity of the treatment facility j
α	Proportion of biowaste produced in the territory treated by the network
γ_{np}	Maximal proportion of non-permanent biowaste sources
γ_{gw}	Maximal proportion of green waste sources
β	Quantity of digestate produced per biowaste treated

Table 2: Model equations of the DECISIVE MILP.

Model equations	*Equation numbers*
Objective function	
$Minimize \sum_{i \in I} \sum_{j \in J} Fw_{i,j}\, d_{i,j} \times \sum_{j \in J} \sum_{k \in K} Fd_{j,k}\, d_{j,k}$	*1*
Subject to:	
$\sum_{i \in I} \sum_{j \in J} Fw_{i,j} \geq \alpha \sum_{i \in I} q_i$	*2*

$$\sum_{j \in J} Fw_{i,j} = bS_i \, q_i \quad \forall\, i \in I \qquad (3)$$

$$Fw_{i,j} = bFw_{i,j} \, q_i \quad \forall\, i \in I, \ \forall j \in J \qquad (4)$$

$$\sum_{i \in I} Fw_{i,j} = Pw_j \quad \forall\, j \in J \qquad (5)$$

$$\begin{cases} Pw_j \geq bt_j \, cap_j^{min} \\ Pw_j \leq bt_j \, cap_j^{max} \end{cases} \quad \forall\, j \in J \qquad (6)$$

$$\sum_{i \in I_{np}} Fw_{i,j} \leq \gamma_{np} \, Pw_j \quad \forall\, j \in J_{mAD} \qquad (7)$$

$$\sum_{i \in I_{gw}} Fw_{i,j} \leq \gamma_{gw} \, Pw_j \quad \forall\, j \in J_{mAD} \qquad (8)$$

$$bt_j = 1 \ \forall j \ \in J_{open} \qquad (9)$$

$$\sum_{k \in K} Fd_{j,k} \leq \beta \, Pw_j \quad \forall\, j \in J_{Digestate} \qquad (10)$$

$$\sum_{j \in J_{Digestate}} Fd_{j,k} \leq o_k \quad \forall\, k \in K \qquad (11)$$

The level of details targeted by the inventory is very high and, as a consequence, biowaste sources, mAD sites, and outlets to include in the model are numerous. The number of possible combinations can reach 10^6 to 10^9, according to collection distance threshold. The method was specifically tailored to build a MILP model with a large number of input data and it relies on *JuMP*[1], a dedicated package for modeling linear programming in *Julia* language[2].

The parameters of the model allow fine adaptation to the specific needs of the analysis: 1) the type of biowaste sources (*e.g.* households only) and the quantity of biowaste to be treated by the decentralized valorization network, 2) the maximum collection distances thresholds (*e.g.* walking distances) and 3) the technical constraints of mAD such as their treatment capacity or new restrictions for the biowaste sources (*e.g.* non-permanent or green-waste sources). These parameters make possible to define and compare a wide range of biowaste treatment scenarios: biowaste from households only combined with a suitable threshold for walking distances; the restaurants and canteens only combined with longer collection distance; etc.

B. GIS data collection

The MILP model is implemented on a targeted territory based on data collected with a specific GIS methodology. This approach allows the extraction of information of the biowaste sources, the mAD potential location and digestate outlet at the suitable spatial scale.

1. INVENTORY OF BIOWASTE SOURCES

a) Household food waste

The food waste generated by households is estimated with the number of inhabitants and the ratio of food waste production per capita provided by the literature (*e.g.* 83 to 101 kg/y per capita, (Manns et al., 2017)). The food waste production at the building scale is then calculated by disaggregating the census data at the building scale (L. Létinois, 2013).

---

[1] https://github.com/JuliaOpt/JuMP.jl

[2] https://julialang.org/

The residential buildings are extracted from topographic databases according to their main use or function. If the number of dwellings is not provided, it is estimated with the floor surface (surface of the building times the number of floors). The surface of the buildings is calculated with their shape and the number of floors is estimated with their height. Below 5 m, a building is a single story house and above 5 m, each floor is supposed to be 3 m high (L. Létinois, 2013). The method for estimating the number of dwellings is described in Figure 4.

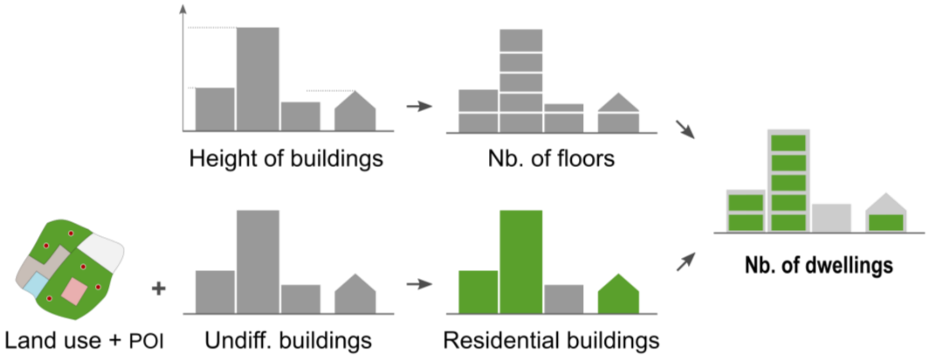


Figure 4: Allocation of the population based on the identification of the residential buildings and the estimation of the number dwellings.

The population census is allocated according to the floor surface of the buildings. Finally, the quantity of food waste generated in each construction is estimated *(equation 12)* with a ratio of production per capita and per year and the source separation efficiency.

$$Q_{fw_{ij}} = q \times SSE_s \times P_j \times \frac{FSA_{ij}}{\sum_i FSA_{ij}} \qquad (12)$$

$Q_{fw_{ij}}$: Food waste generated by the building i in census unit j
q : Food waste generated per capita / year
SSE_s : Source separation efficiency for household
P_j : Population of the census unit j
$FSA_{ij} = S_i \times Nf_i$: Floor surface area of the building i (surface S and a number of floors Nf) in the census unit j

b) Green waste

The lawn areas from public parks and private gardens are identified with remote sensing approach, a method used for extracting spatial objects from aerial or satellite images (Campbell and Wynne, 2011). According to the location, the analysis is based on aerial or satellite images. The aerial images have higher spatial resolution (less than 1 m compared to 10 m for Sentinel 2A) than satellite images but the latter usually include near infra-red data, very useful for extracting vegetation and are provided for a wider range of date (e.g. to avoid dry summer period for grass identification). Several studies ((Bork and Su, 2007), (Rampi et al., 2014), (Parent et al., 2015)) also showed that the accuracy of the image classification can be greatly improved by the integration of Lidar data or nDSM (normalized digital surface model) to the multispectral imagery. If available, the Lidar data are then included in the study.

With high resolution images, the pixels can be smaller than the spatial objects studied (*e.g.* garden, building, trees) and they only characterize a small part of them (Blaschke, 2010). In this context, the image classification methods based on the properties of pixels provide suboptimal results. They present a form of noise that is called ‘salt-and-pepper’ effect (Blaschke et al., 2000). To overcome these issues, a geographical object-based image analysis (GEOBIA) is applied in this study. The core idea of this method consists in grouping similar pixels (image segmentation) into meaningful image-objects, based on their spectral properties: color, size, shape, and texture and the ones from the surrounding pixels (Blaschke and Strobl, 2001). The objects (or segments) are then classified using features and criteria set by the user with a supervised classification method.

The images combined with an nDSM, if available, are segmented with the SAGA GIS tool (Figure 5a). The segments are filtered to extract those located around residential areas with land use information to ensure that no natural or agricultural grasslands will be identified as lawn. A training sample of segments is used to characterize the different types of land cover based on their spectral and height values with a *Maximum likelihood* method (SAGA GIS with the *Supervised Classification for shape* tools). This characterization supports the final classification of all the segments into the targeted category of land covers (Figure 5 d). The segments under the shadow of trees or buildings can hardly be identified (Wan et al., 2012). If required, a simple de-shadowing method is applied in this study by reclassifying the segments under shadow according to the type of surrounding land covers.

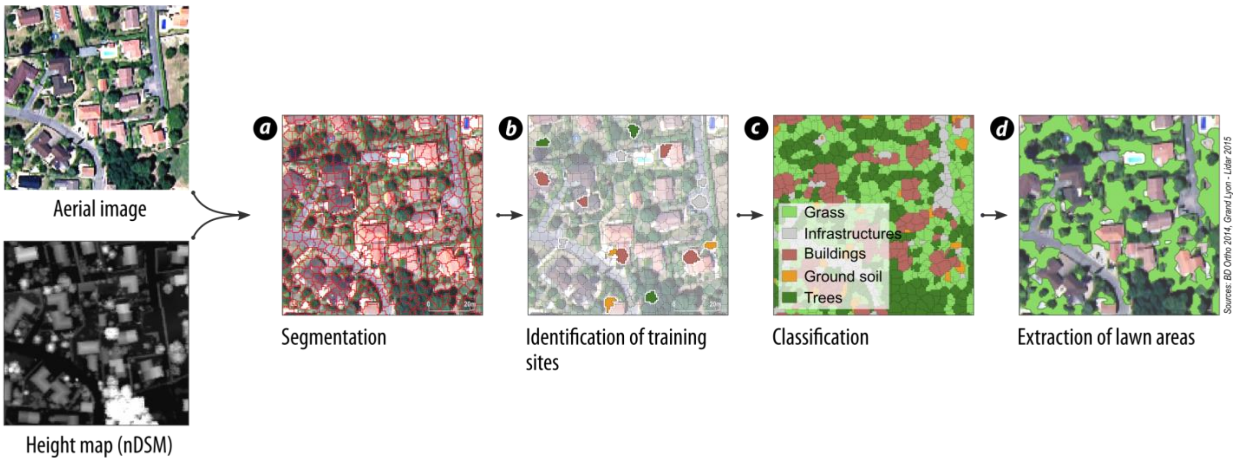


Figure 5: Object-based analysis method with, a) the segmentation of an aerial image combined with an nDSM and Supervised, b) identification of training site, c) classification of the segments and c) extraction of the lawn areas.

The accuracy of the image classification is assessed with a confusion matrix (e.g. see the method developed by Schoepfer and Lang (2012). This matrix shows the correspondence between the classification results and a reference image for a sample of points already identified in the field.
The quantities of grass from private or public garden available for valorization are finally estimated with the surfaces of lawn previously identified using the production of grass per surface (1 kg/m² of lawn) and a ratio of green waste collectable *(equation 13)* (ADEME, 2013).

$$Q_{Gw} = S \times 1_{kg/m^2.y} \times Gw_{collectable} \qquad (13)$$

Q_{Gw}: Quantity of green waste of a given area
S: Surface of grass for the area
$Gw_{collectable}$: ratio of green waste collectable

c) Catering food waste

The present inventory includes the following catering activities in urban areas: school and health facility canteens, restaurants, administrative and company canteens. Due to the complexity of getting estimates, the biowaste is assessed as a whole, without distinction between the different types of food waste (food preparation, leftover, cooking oil, etc.).

The different catering facilities are identified and located. The biowaste generation is estimated with the number of meals served and the amount of food waste produced per meal according to the type of catering service *(equation 14)*.

$$Q_{fw} = Nb_{meals/y} \times q_{fw\ meals} \times SSE_s \qquad (14)$$

Q_{fw}: Food waste sorted per year
Nb_{meals}: Number of meals served per year
$q_{fw\ meals}$: Food waste generated per meal
SSE_s : Source separation efficiency

(1) Canteens of schools

The list of schools and their location are usually provided by the relevant administration. If not available, this information can be extracted from OpenStreetMap (OSM) database. The number of meals served in the canteens is provided by administrative services or estimated with the number of students present (official databases, websites about the educational system) and the number of meals taken per students and per day.

The number of meals served per school is then calculated based on the type of school, the number of students, and the number of meals per day and per student estimated *(equation 15).*

$$Nb_{meals/y} = Nb_{students} \times Nb_{meals/student/day} \times Nb_{days\ of\ schools/y} \tag{15}$$

(2) Canteens of hospitals

The lists of health facilities are usually provided by the relevant administration or it can be extracted from the OSM. The number of meals is calculated with the number of patients taking the meals in each facility. The number of patients is estimated using the number of beds installed in each facility, the bed occupancy and assuming that the hospital runs all year long (365 days/year). Information on the number of beds installed can be provided by the appropriate administration or by websites gathering detailed data on health facilities (e.g. www.sanitaire-social.com in France). The number of meals eaten by the patients is calculated with the number of beds in a given facility, multiplied by the number of meals served per year *(equation 16)*. Only the lunch and the dinner are considered for determining the food waste production.

$$Nb_{meals\ patients/year} = N_{beds} \times 2_{meals/day} \times 365_{days/y} \tag{16}$$

(3) Restaurants and collective catering services

The list of restaurants and catering services is extracted from the official register of companies or from OSM database. The distinction between the two types of restaurants is done in the Companies Registry but usually not in other source of data such as OSM. The Fast-foods are not included in this inventory because: 1) the food waste is usually collected with packaging and 2) some consumers take away their food and thus waste is disposed of in unknown locations and, 3) the food waste from preparation is considered negligible (e.g. use of industrial food).

A careful analysis of the data is done to avoid a double counting of the restaurants in schools or hospitals that are managed by a catering company. Where both pieces of information exist, the estimation of biowaste generation is based on the method developed for the school and hospital to keep a single approach for each kind of facility.

The number of meals is estimated with the number of employees of the restaurants (kitchen staff) and the number of meals served per employee *(equation 19)* (ADEME, 2013).

$$Nb_{meals/y} = Nb_{employees} \times Nb_{meals/employee/y} \tag{19}$$

The number of meals served per employee is greater in collective catering services than in restaurants (ADEME, 2013) (*e.g.* 14,840 meals/year and 2,920 meals/year, respectively in France). This approach provides only rough estimates, but it remains the most accurate with the data currently commonly available. The number of employees is available in the official Companies Registry. When data are missing or too expensive, the number of employees is estimated with an average value for the restaurants in the study zone.

2. INVENTORY OF THE DIGESTATE OUTLETS

The digestate is the remaining solid and liquid fractions of the biowaste after the AD process. It contains most of the nutrients from the input material and it can be used as a fertilizer or an organic amendment for agriculture. To close the organic nutrient loop locally, the digestate has to be used in farms located near the mAD units. This proximity is achieved by targeting in priority the urban or peri-urban agricultural (UPA) areas. The Food and Agriculture Organization of the United Nations (FAO) defines UPA as “the growing of plants and the raising of animals within and around cities” (“FAO’s role in Urban Agriculture,” n.d.). The UPA usually includes the farms located near the urban areas, the vegetable farms located in urban areas, the micro-urban farms, the community gardening, and the emerging rooftop and indoor farming. The different UPA are deeply embedded in the urban context and they would be the closest places to use the digestate coming from the mAD. However, in this study, we only focused on the peri-urban farm that are similar to conventional farms but located close or inside the urban fabric. The urban farming is a promising approach that may help tackling some of the current food and environmental stakes. It is, however, a new field and it is still mostly at the demonstration stage. A prospective study is hardly possible due to the lack of common information and the suitability of the digestate for urban farming cannot be evaluated currently. As a consequence, the urban farms are not included in the inventory of outlet for the digestate.

It is important to note that the EU regulation *n°889/2008* allows using digestate in organic farming if the digestate comes from household biowaste and if the raw material is sorted at source and only contains animal or vegetable elements (atee Club Biogaz, 2017). Except if local regulation state otherwise, there is no legal restriction at EU level to use the digestate from the mAD for organic farming.

a) Inventory of peri-urban agricultural areas

The location of the farms and more specifically the location and the shape of the agricultural plots are recorded in an official register of the *Common Agricultural Policy (CAP).* If this information is not available, the agricultural areas are extracted from the land use database (Corine Land Cover) or from national databases.

b) Estimation of the amount of digestate spreadable

The estimation of the amount of digestate that can be spread is related to the digestate properties, the regulations, the crop management technique, the soil properties, but also the organic matter already applied (*e.g.* cattle or pig manure). This amount of digestate usable is estimated with a simplified calculation based on the following three key parameters: 1) the nitrogen content of the digestate from mAD units, 2) the agricultural land available and 3) the current local nitrate loadings from livestock and waste water treatment units.

Only the fertilizing properties of the nitrogen contained in the digestate are taken into account. The content of mineral N was estimated to 10 g/kg of raw digestate based on analyses of digestate from kitchen waste done by Irstea (data not published) and the data published in the expertise MAFOR (Benoît et al., 2014)). No distinction is done between the crops cultivated and their respective nitrogen needs.

All agricultural areas are supposed to be located inside Nitrate Vulnerable Zones (NVZ) (European Commission, 2018) with restrictions for organic fertilization (170 kg of N organic/ha) and it is assumed that no mineral nitrogen sources are used. The Nitrate directive limits the use of organic fertilizer in agricultural plots presenting a high risk of nitrate pollution. The details of the regulation are specific to each country, but usually two criteria are included: the slopes and the distance to surface water. High values of slopes increase the risk of nitrate runoff, whereas higher proximity to water courses increases the risks of water pollution. The average slope of each agricultural plot is estimated with a digital elevation model. The surface waters are extracted from national or OpenStreetMap databases. Moreover, local regulation generally states that the spreading should not occur close from housing.

The estimation of the nitrate loadings from livestock and waste water treatment units was only conducted in the GL (summarized in III.A.2 and detailed in the D3.8) due to the time and the data required for such analysis. It was found that the local nitrogen loading for the two above sources was about 22.8 kg of nitrogen/ha/year. It will be assumed that the nitrogen load is similar for the other case studies.

The potential quantity of nitrogen from the digestate that can be used in each agricultural plot is estimated with the equation *(20)*.

$$Q_{N\ spread\ i} = S_{Agri\ suit.\ i} \times 170 - Q_{avg\ N\ load} \tag{20}$$

With $Q_{N\ spread\ i}$: Nitrogen from digestate usable in the field i

S_{Agri_i}:	Surface suitable for organic fertilization of the field i
$Q_{avg\ N\ load}$	Average of N load (22.8 kg of nitrogen/ha/year)

3. POTENTIAL LOCATION FOR MICRO-AD UNITS

To optimize the location of mAD units, the data gathered previously and described above (sources and outlets) are mobilized and implemented in the MILP model. In addition, several constraints have to be considered for the mAD candidate sites. Although the mAD units are small, especially compared to industrial ones, their installation is restricted to a limited number of suitable locations. The sites have to comply with the regulation that sets distance limits with surrounding elements, to be close to a heat outlet, to be accessible and to be large enough to cover the space needs of the processing unit.

a) Regulation

In France, the AD installations are included in the list of *Installation Classified for the Protection of the Environment* (ICPE) *heading 2781* (“2781. Méthanisation de déchets non dangereux ou de matière végétale brute | AIDA,” n.d.) and they have to comply with the corresponding regulation. In particular, the *Ministerial Order of the 26 November 2009* (*Arrêté du 10 novembre 2009 relatif aux prescriptions générales applicables aux installations classées de méthanisation soumises à déclaration sous la rubrique n° 2781-1*, n.d.) restricts their establishment close to water bodies (*e.g.* open water or ground water) and close to living places or to places open to public. The legal distances thresholds are described in the Table 3 and they are set to avoid water pollution and the nuisance or risk for the local population.

Table 3: Distance threshold for AD units in France (Ministerial Order of the 26 November 2009).

Topic	Description	Mini. distance
Water	Water catchment: wells and drilling outside the site, spring	**35 m**
	Waterworks (free flow)	
	Buried or half-buried water storage used for drinking water, for agri-food industries, irrigation of vegetable or hydroponic crops	
	Shores and river banks	
Population	Dwellings*	**50 m**
	Establishments open to the public* (administration, hostel, etc.)	
	Official camp site	

**Except the one supplying the installation or benefiting from the heat*

The plants producing gas should comply with the relevant gas storage regulation described in the *ICPE heading 1411-2* (“1411. Gazomètres et réservoirs de gaz comprimés renfermant des gaz inflammables | AIDA,” n.d.). In the DECISIVE mAD, the gas storage is limited, currently estimated lower than 1 t and is not subject to any additional authorization or constraint. The municipalities or the collectivities also set specific rules related to their land use planning in the *Local Urbanism Plan* (LPU). Among these rules, the 500 m protective perimeter set around any historical monuments applies in all French municipalities. Inside this perimeter, new constructions are very restricted and it is assumed that the installation of mAD will be difficult if not impossible. The protective areas (decrees for the protection of biotopes, natural reserve, etc.) are also considered not suitable for the mAD plants to prevent environmental risks.

b) Accessibility

The mAD units have to be accessible for the different waste suppliers, the users of digestate or any transportation services as required by the safety regulation. There are no official criteria to qualify the accessibility in this context and the maximum distance from the roads has been defined at 50 m.

c) Proximity to outlets

The biogas produced by the mAD is valorized by cogeneration. For this study, it is assumed that the cogeneration cannot be connected to a district heating for technical reasons or because it doesn’t exist (the district heating covers only 10 % of the total heat demand in Europe (Colmenar-Santos et al., 2016)).

The mAD CHP have to be connected directly to the heat consumers which could be residential buildings, industries, swimming pools, etc. To minimize the size of the pipe network, the mAD are supposed to be connected to only a few but large heat consumers. Due to the amount of power generated and the heat losses in the pipes, the heat can only be transported on short distances. According to experts, the mAD should not be located at more than 100 m from the potential consumers. The electrical power generated is only used to feed the mAD unit. So, no additional spatial constraints are considered for the electrical valorization.

d) Size of the installation

The mAD and all the related equipment aim at being gathered in a single *40ft* standard container (12.2 m × 2.4 m). With the additional free spaces required around the container (delivery operations from waste producers and the entrance of digestate users) the potential sites should be at least about 75 m² (15 m×5 m). Moreover, the sites too narrow to accommodate mAD installations are removed based on a criterion combining their surfaces and their compactness (ratio between the shape area and the area of the minimum bounding circle). The different criteria of the multi-criteria analysis are combined to identify suitable sites (Figure 6)

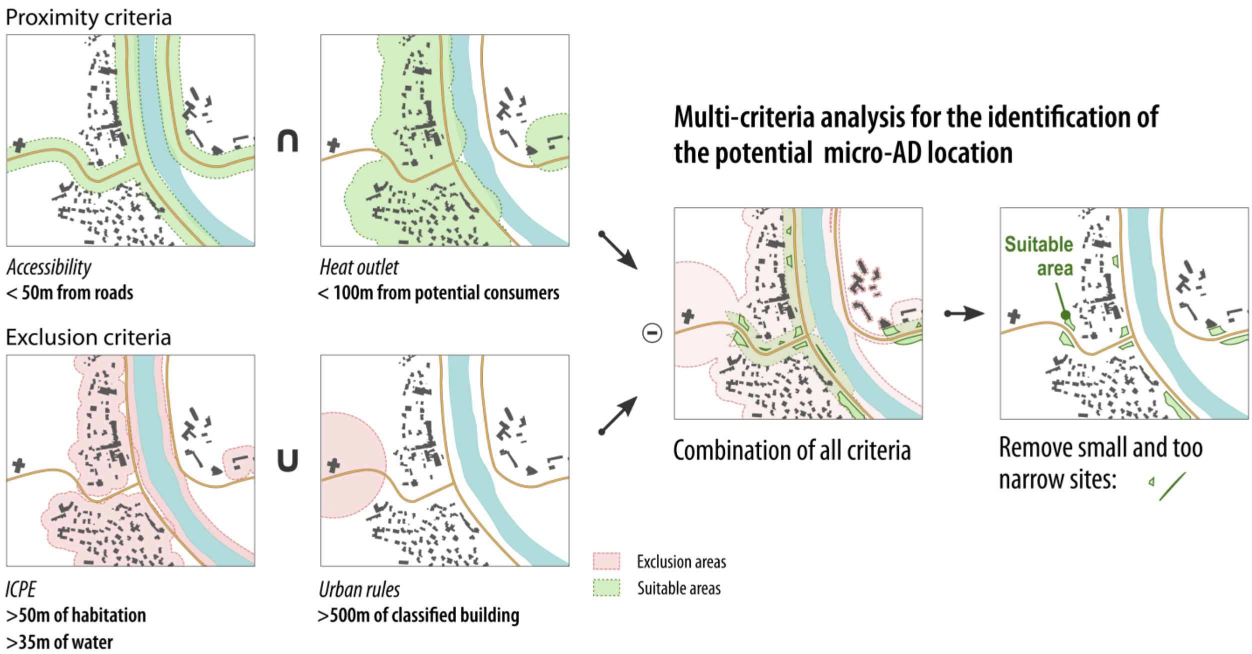


Figure 6: Simplified drawing of the criteria used for identifying the potential mAD sites.

III. Case studies

The following chapter presents the application of the method for optimizing a mAD network to the new cases study of AMB and Hamburg and a summary of the GL one (described in deliverable D3.8). Due to the difference of data availability and quality, the initial method required adaptations to the studied territories. Those differences significantly impact the results of the GIS analysis, mainly the estimation of the biowaste sources generation. Hence, the values of biowaste inventory should not be directly compared between the case studies. The analyses of the resulting mAD network are gathered in the discussion, chapter 4.

A. Metropolitan Area of Barcelona (AMB)

The AMB (Figure 7) is located in southern Europe, in Catalonia, in the middle of the Mediterranean corridor that connects Spain with the rest of the continent. This privileged position has allowed it to become the epicenter of Catalonia. Its territory includes the agricultural areas of the Llobregat Delta, the fully urbanized areas of the Barcelona plain and the large green areas of the massifs of Garraf and Collserola and the Marina mountain range. To the north-west of Collserola, there are several extensive agricultural areas in both Vallès Oriental and Vallès Occidental.

The metropolitan area (636 km²) occupies 2 % of total area of Catalonia, while its population (3.2 million inhabitants) represents 42.8 % of the total population. The average population density is slightly over 5,000 inh/km², but can reach over 20,000 inh/km^2 in the biggest municipalities. The AMB is one of the largest and most populated metropolitan areas in Europe and occupies an important place in the Mediterranean.

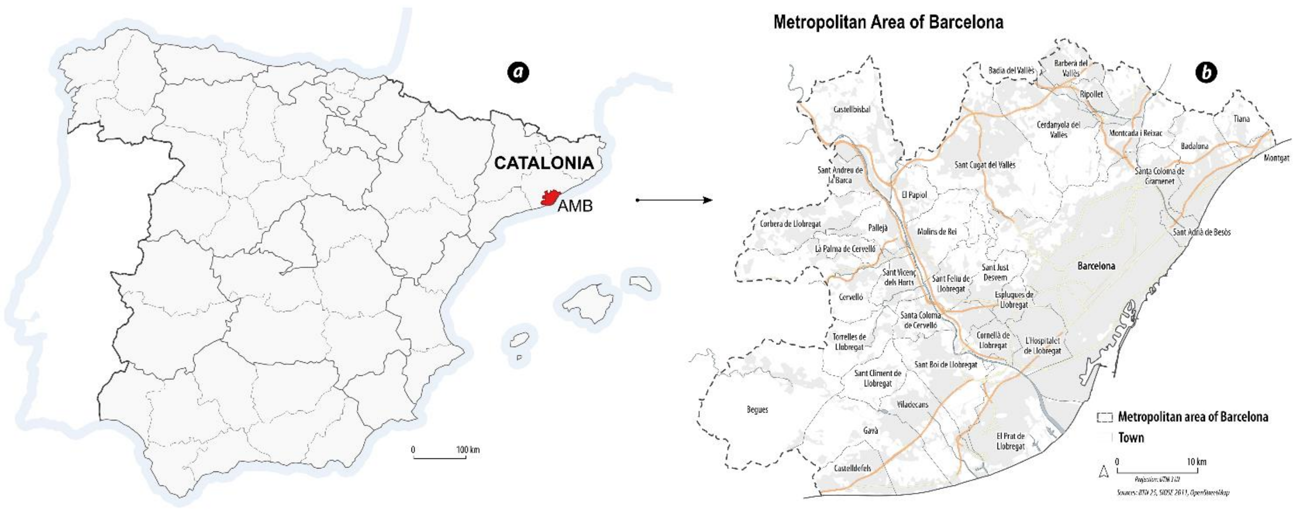


Figure 7: Location of AMB in Spain (a) and detailed map of AMB (b).

The most common collection scheme for MSW in the AMB is the kerbside Bring Bank system, where the citizens bring the waste to publicly accessible container banks. Two municipalities of the municipal area Tiana and Torrelles de Llobregat, have a Door-to-Door collection system fully rolled out, whereas Barcelona has recently implemented a system that combines the bring bank system with areas of Door-to Door collection in the Sarrià District in the north of the city, covering around 4.000 households.

In AMB, 5 fractions are usually collected separately: glass, paper and cardboard, packaging, organic and residual fraction. There are also 4 municipalities that sort waste into 4 fractions: glass, paper and cardboard, biowaste and inorganic fraction. The latter is a stream of packaging combined with the residual fraction.

In AMB, 4 facilities treat the biowaste collected separately. Two facilities (Ecoparc 1 and Ecoparc 2) treat the biowaste by anaerobic digestion followed by a composting step to obtain compost. In a separate biological treatment line, they stabilize the organic output from the mechanical treatment of residual waste. The resulting material cannot be used as compost, as it does not meet the requirements for application in agriculture. There are also 2 composting plants that treat exclusively biowaste separated at source and subject to separate collection. (Sant Cugat and Torrelles)

1. INVENTORY OF THE BIOWASTE SOURCES

The Agència de Residus de Catalunya (ARC) has a very comprehensive set of information about the biowaste in AMB. Hence, ARC has accurately estimated their collection rate for biowaste without the green waste, at about 36 % in 2018 for all the sources considered in the study (biowaste separately collected compared to biowaste generated according to waste analyses). For this study, the biowaste generation is however estimated with the methodology developed in the framework of the WP3.3 and not with the data available in ARC. It allows testing the methodology in a new geographical context. Moreover, the use of real waste collection data would have required a specific desegregation method to reach the targeted spatial scale which was not the aims of the present analysis.

The very detailed official cadastral database allows an easy and accurate estimation of the household biowaste generation Due to the climatic conditions in the Mediterranean great lawn extensions are not traditional gardening or park elements. The average production of lawn cutting per unit of area in AMB appeared to be very low and difficult to estimate. Green waste was therefore excluded from the potential biowaste sources for the AMB case. The lack of official census for students per schools was addressed by collecting information from a private website or using the average of student per school according to their grade. The list of hospitals and their capacity was extracted from official publication. Detailed databases about restaurants were too expensive. Instead, OSM database was used to identify the location of restaurants, and the number of employees was assumed to be the same for all establishments and estimated based on the median value of number of employees for the restaurant in Catalonia (INE, 2018). OSM didn't allow the distinction between the different types of catering activities. The administrative and the company canteens were then considered as regular restaurants.

The location and the biowaste generation in AMB were estimated with the data described in the **Erreur ! Référence non valide pour un signet.** and Table 5.

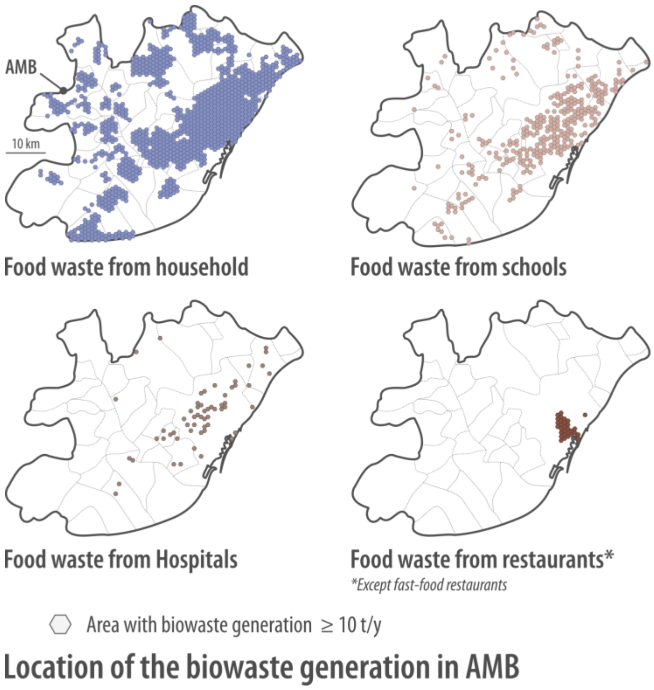
Table 4: Description of the dataset used for the characterization of the biowaste generation in AMB.

Biowaste sources	Data	Sources	
Household	Location of residential buildings and number of dwellings	Spanish Ministry of Finance and Civil Service	www.catastro.minhap.es
	Census data	Instituto Nacional de Estadística (INE), Census sections 2011	http://www.ine.es
Green waste	NA (production likely to be too low for real valorization)	NA	NA
Schools	Schools locations and number of student per grade	Educateca (private service because no official information available)	http://www.educateca.com
Health facilities	Locations and Number of beds	Catálogo Nacional de Hospitales 2017, Ministerio De Sanidad, Servicios Sociales E Igualdad	www.mscbs.gob.es/ciudadanos
Restaurants	Location	OpenStreetMap	www.openstreetmap.org
	Number of employees	Median of employee per restaurant (2.5) based on the statistics from INE values for Catalonia	http://www.ine.es
Admin. and company canteens	Specific information not available (mixed with restaurants in OSM)	NA	NA

Table 5: Parameters used to estimate the biowaste generation of the different sources and the total for AMB.

Biowaste sources	Biowaste generation			Sorting rate		Total bw sorted (t/y)
	Parameters	Values	Ref.	Value	Ref.	
Household	BW ratio	147 kg/capita.y	*(Agència de Residus de Catalunya, 2014)*			**169,503**
Green waste	_	_	_			**NA**
School canteens	BW ratio	185 g/meal (primary) 280 g/meal (second.) 315 g/meal (higher grade)	*(ADEME, 2013)*			**4,883**
	Day of school	177 days/y	*School calendar*	36%	*ARC*	
	Students taking meal in canteen	59% (primary) 63%.(secondary) 28% (higher grade)	*(ADEME, 2013)*			
Canteen of Hospitals	BW ratio	276 Kg/bed.y	*(Institut Cerdà, 2014)*			**1,780**
Restaurants	BW ratio	170 g/meal	*(Pujol and Lladó, 2013)*			**892**
	Meals per employee	2,920 meals/empl.y	*(ADEME, 2013)*			

Based on the methodology used for the inventory, the biowaste potentially collected from the targeted sources in AMB was estimated at 177,058 t/y. The map Figure 8 and the graphic Figure 9 summarize the results for each source (detailed map in Annex, Figure 23 – Figure 26).



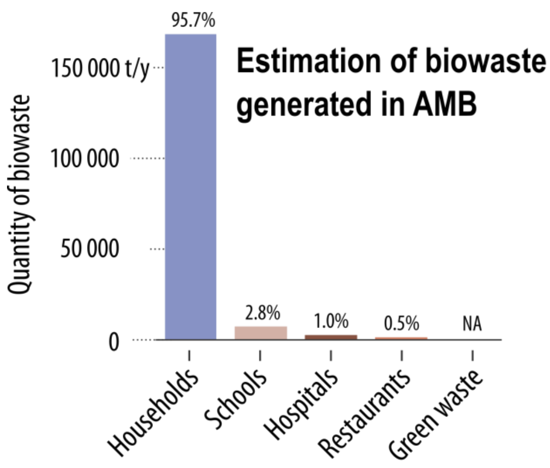


Figure 8: Location of the biowaste generation of the targeted sources in AMB.

Figure 9: Quantification of the biowaste generation of the targeted sources in AMB.

2. INVENTORY OF THE OUTLETS: THE PERI-URBAN FARMS

The location and the shape of the agricultural parcels were extracted from the official register of agricultural parcel, the SIGPAC 2016[3], published by the government of Catalonia. The extraction was done in AMB and in a 10km radius. The agricultural areas were filtered based on the Catalan decree 136/2009 (Catalunya, 2009) related to the application of organic fertilizers. The criteria are presented in the Table 6: List of criteria for the application of organic fertilizer (extracted from Catalan decree 136/2009).

Table 6: List of criteria for the application of organic fertilizer (extracted from Catalan decree 136/2009).

Criteria	Data	Distance	
Livestock farms	Not included (information not available)	>50m	
Manure management centers		>25m	
Points of water caption for human consumption	- BTN25: Water sources	>50m	
Populated areas	- BTN25: Populated area	>100m	
Isolated houses, industrial areas, working and leisure areas	- Cadastral parcels (www.catastro.minhap.es): buildings residential, office, retail and public services buildings - BTN25: leisure and industrial areas	>75m	
Water surface - Distinction according to the slope	(Official Digital Terrain Model 25)	Slope	
		<10%	>10%
- Natural water courses / masses defined in 1:250,000 of Cartographic Institute of Catalonia (ICC)	- Topo 250: rivers	>35m	>50m
- Natural water courses / masses not in 1:250,000 of ICC	- BTN25: Shoreline, lakes, rivers, streamline (only permanent), riverbeds	>10m	>25m
Artificial water courses	- BTN25: artificial water course	>2m	

About 8,106ha of agricultural areas were found suitable for organic fertilization in AMB and in the surroundings areas (Annex, Figure 27).

3. POTENTIAL LOCATION FOR MICRO-AD UNITS

The Catalan Environmental Department stated that the current environmental regulation does not define clearly restricted areas for AD or small-scale AD implementation. The authorizations are provided on a case-by-case basis.

To comply with the optimization model requirement, the number of potential sites for mAD was limited by applying the multi-criteria analysis used in the GL case. This solution also ensures that the location selected respects a minimal set of social and environmental criteria.

Table 7 summarizes the criteria for the potential locations for mAD units in AMB.

Table 7: List of criteria and the corresponding data used to select the suitable mAD sites in the AMB.

Criteria	Description	Data	Distance
Regulation *-Water*	Water catchment (wells, spring, etc.), water storage for drinking water, rivers, shoreline	- BTN25: Shoreline, lakes, rivers, streamline (only permanent), artificial riverbeds, wells, water sources, underground water storage, reservoir (dam).	>35 m
	Wetland	- BTN25: Wetland	>10 m
-Population	Dwellings, establishments open to the public* (administration, hostel, museum, etc.) Official campsites	- Cadastral parcels (www.catastro.minhap.es): residential buildings or building with dwellings or buildings for public services, office or retail - BTN25: Camping, cemeteries, sport filed or areas	>50 m
Protected area	Natural reserve, protection plan, regional / national park, natural reserve, etc.	- www.protectedplanet.net	None (not in)

[3] https://analisi.transparenciacatalunya.cat

Buildings	All buildings or construction not listed previously for "Population"	- Cadastral parcels (www.catastro.minhap.es): buildings without dwelling or agricultural and industrial buildings	
Urban plan. rules	No applicable	_	_
Infrastructure	Roads	- OpenStreetMap: Highway ('motorway', 'trunk') / Other roads	>10 m or 2 m
	Railways	- OpenStreetMap: Railways	>6 m
Accessibility	Roads	- OpenStreetMap: roads	< 50 m
Heat outlet	Collective housing	- Cadastral parcels (www.catastro.minhap.es): Residential buildings with more than 1 dwelling	< 100 m
	Building open to the public (not open air places)	- Cadastral parcels (www.catastro.minhap.es): buildings for public services, office, retail or agricultural and industrial buildings	

About 6,081 sites were identified by the multi-criteria analysis (Annex, Figure 28), ranging from 76 m² to 394,665 m². Each site was considered as a single potential site. As in the GL case, the suitable sites are mainly around commercial or industrial areas or on the outskirts of the residential neighborhoods. In dense areas, there are only a few areas and often located in or close to public gardens.

4. RESULTS OF THE MILP OPTIMIZATION MODEL

The scenario studied targeted 10% of the biowaste from AMB, all sources of food waste included (except green waste), with a maximal biowaste collection distance of 500m. The final model included 13,742 biowaste sources, 4,740 potential mAD sites and 4,137 outlets.

The optimal decentralized treatment network returned by the MILP method and shown in Figure 10 involved 298 mAD plants. Such a network would handle 25,870 t/y of biowaste for a payload-distance of 7,126 km-t and a total collection distance of 780 km. The digestate would be valorized in 466 agricultural plots, for a payload-distance of 23,134 km-t and a total transportation distance of 1,404 km.

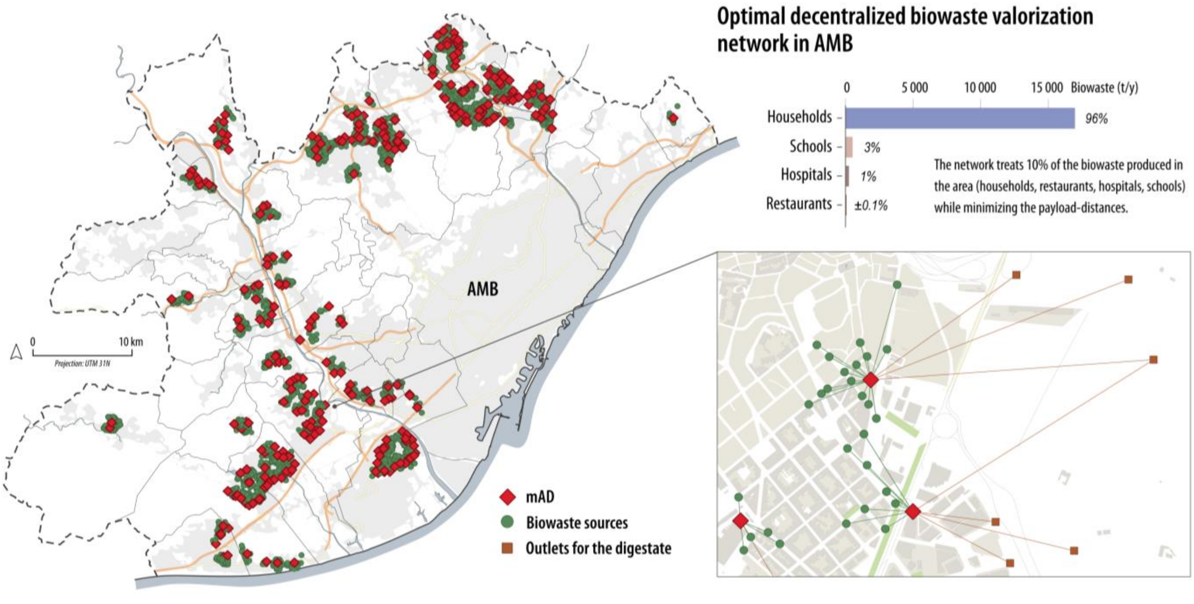


Figure 10: Map of the optimal network treating 10% of the biowaste identified in AMB and the chart of the quantities treated per type of waste.

The biowaste treatment network collects almost exclusively household kitchen wastes (96%, Figure 10). In average, the mAD treats 79t/y of biowaste, a value on the lower range of the treatment capacity possible (50 to 200t/y).

Currently, the biowaste stream in AMB is partially treated in two anaerobic digestion plants, Ecoparc 1 & 2 and two composting plants, Sant Cugat and Torrelles with a respective treatment capacity of 72,000t/y, 76,000t/y, 6,700t/y and 4,600t/y. The optimization model was adapted to include those facilities and their treatment capacities were set between their current capacities and their official maximal capacities[4].

The model was set to retrieve more than 99%[5] of the biowaste identified in AMB. Figure 11 shows the resulting treatment network.

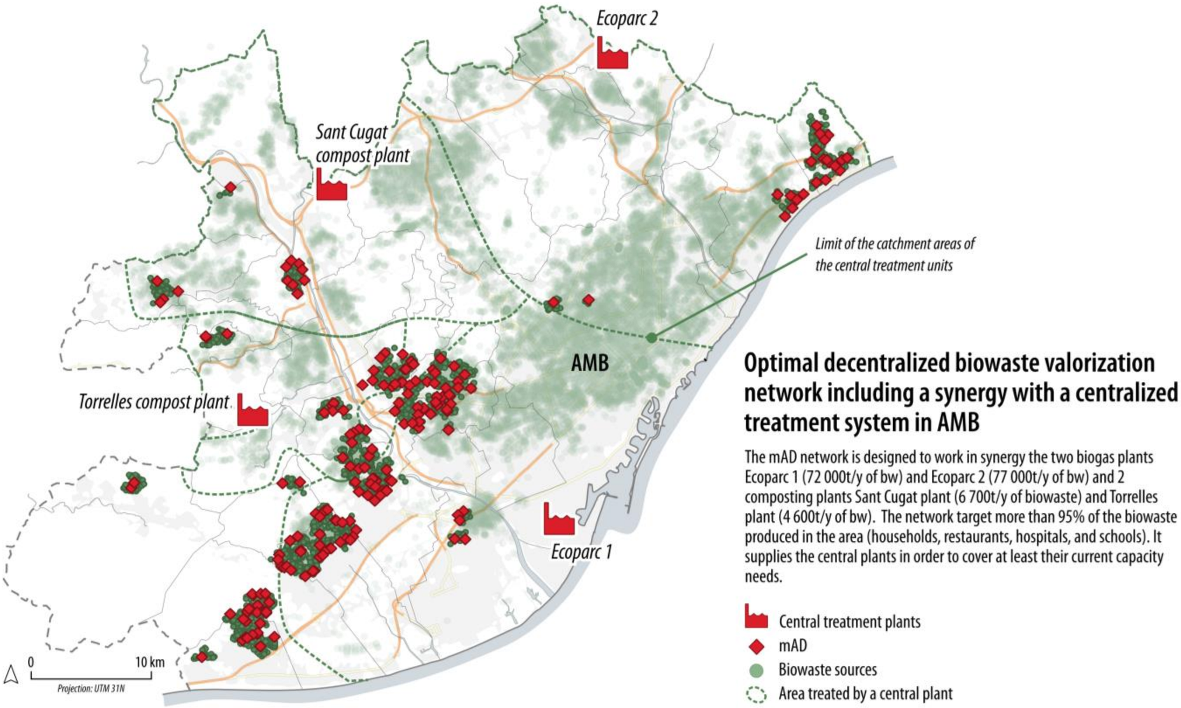


Figure 11: Map of the optimal mAD network working in synergy with the central treatment plants (Ecoparc 1 & 2, Sant Cugat and Torrelles compost plant) to treating more than 95% of the biowaste identified in AMB.

The MILP ensured first the supply of the 4 plants up to their minimal treatment capacities. Once this constraint was fulfilled, the mAD were then preferably selected by the model due to their higher proximity with sources and outlets. In the proposed network, the central units are only running at their current capacity (considered as the minimal capacity), but in AMB, they still handle 91% of the targeted biowaste due to a good match between the treatment capacity and the biowaste generation. The mAD are preferably located in the urban periphery and mostly at a distance from the central units.

B. Hamburg

Hamburg is a city and a region (Länder) located in northern Germany and is surrounded by the states of Schleswig-Holstein to the north, and Lower Saxony to the south (Figure 12). With an area of 755 km², it is the second smallest state in Germany but it is also the second most populous city in Germany (1.8 million inhabitants in 2018). The population density is 2,464 inh/km² but it can reach 30,000 inh/km² in the most populated areas. Located on the Elbe river, Hamburg hosts the third largest port in Europe. It is also an important financial center and a major industrial city where most of the processing and manufacturing industries are represented.

[4] http://residus.gencat.cat/ca/ambits_dactuacio/planificacio/atencio_pla_territorial_sectorial_dinfraestructures_de_gestio_de_residus/

[5] At the current level of the MILP model development, it is not possible to target 100% of biowaste (technical limitation)

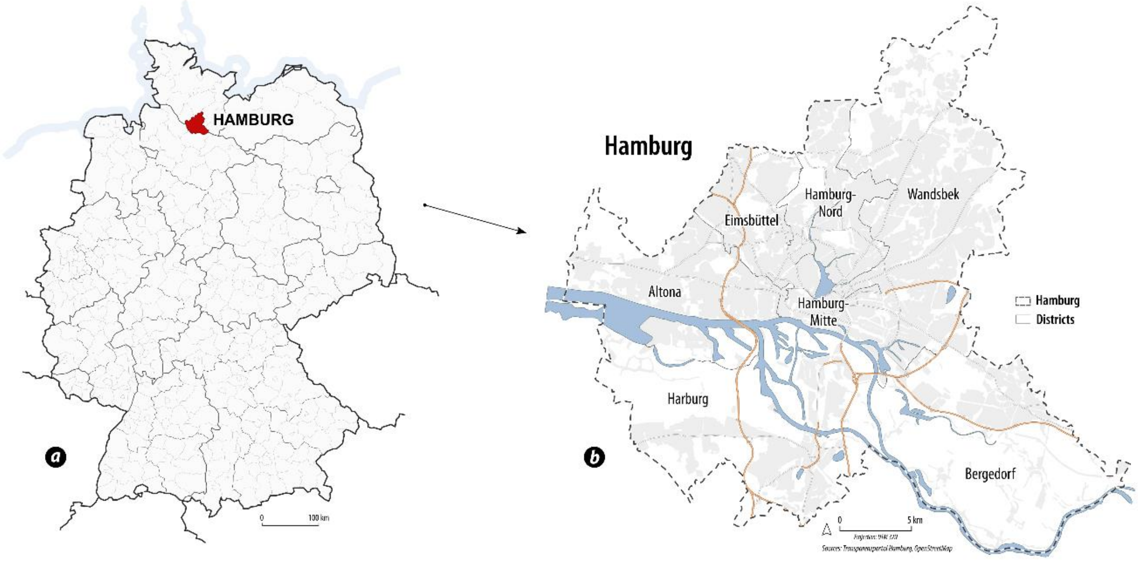


Figure 12: Location of Hamburg in in Germany (a) and detailed map of Hamburg (b).

In Hamburg, 5 fractions are collected separately: glass, recyclables, paper, biowaste, and residual fraction and biowaste. Glass collection relies on Bring-Point while the other fractions are collected Door-to-Door. About 60% of the households are now connected to the biowaste collection system. The green wastes that do not fit in the bio bin have to be brought to a collection center. The biowaste is treated in Bützberg plant trough AD and compost process. The biogas is purified and fed to the gas network.

1. INVENTORY OF THE BIOWASTE SOURCES

The location and the biowaste generation in Hamburg were estimated with the data described in Table 8 and the parameters in Table 9. This inventory included the biowaste stream already handled by the current waste management of Hamburg. It is assumed that a part could still be processed through decentralized valorization network.

The description of the buildings, their use and height, and the very fine scale census data were provided by the Hamburg data portal and help for an accurate estimation of household biowaste generation. The lack of Lidar data and some issues with the official aerial images (e.g. unsuitable season and time of day) have led to the use of the satellite images from Sentinel-2 (10m ×10m of resolution in the visible spectrum and near infrared). Their resolution did not allow the delineation of small gardens but the near-infrared band and the derivate Normalized difference vegetation index (NDVI) lead to more robust results. The list and the detailed information of schools and hospital were extracted from the Hamburg data portal. The restaurants were identified with OSM to avoid buying expensive database on companies. The average number of employees per restaurant could not be identified. It was estimated as the average of the values found in GL and AMB case (2 employees per restaurant, based on an average of 2.5 in AMB and 1.5 in GL). OSM didn't allow the distinction between the different types of catering activities. The administrative and the company canteens were then considered as regular restaurants.

Table 8: Description of the dataset used for the characterization of the biowaste generation in Hamburg.

Biowaste sources	Data	Sources	
Household	Location, type and height of buildings	ALKIS - ausgewählte Daten (Landesbetrieb Geoinformation und Vermessung Hamburg)	http://suche.transparenz.hamburg.de
	Census data	Statistisches Amt für Hamburg und Schleswig-Holstein 2017	Sent by the relevant service
Green waste	Sentinel-2 (Satellite Images)	Copernicus Open Access Hub	https://scihub.copernicus.eu/

	Delineation of land parcels and land use	ALKIS - ausgewählte Daten (Landesbetrieb Geoinformation und Vermessung Hamburg)	http://suche.transparenz.hamburg.de
Schools	Schools locations and number of student per grade	Behörde für Schule und Berufsbildung	http://suche.transparenz.hamburg.de
Health facilities	Locations and Number of beds	Behörde für Gesundheit und Verbraucherschutz	http://suche.transparenz.hamburg.de
Restaurants	Location	OpenStreetMap	www.openstreetmap.org
	Number of employees	No data available. Estimate with the avg of employees in GL and AMB	NA
Admin. and company canteens	Specific information not available (mixed with restaurants in OpenStreetMap)	NA	NA

Table 9: Parameters used to estimate the biowaste generation of the different sources and the total for Hamburg.

Biowaste sources		**Biowaste generation**		**Sorting rate**		**Total bw sorted (t/y)**
		Value	Source	Value	Source	
Household	Ratio of production	80 kg/capita.y	(Hafner and Barabosz, 2012)	50 %		74,513
Green waste	Ratio of production	1 kg/m².y of lawn	*(Schneider and Le Bozec, 1995 and internal report from Irstea),*	20 %		12,486
School canteens	Ratio of production	151 g/meal	*Considered similar to restaurant*			1,832
	Nb. day of school	186 days/y	*(official school calendar)*	70 %	*(ADEME, 2013)*	
	Student taking meal in canteen	69% for primary 27%.for secondary	(Arens-Azevedo, 2015)			
Canteen of Hospitals	Ratio of production	151 g/meal	*Considered similar to restaurant*	70 %		919
	Hospital occupancy	83,6%	(Statistisches Bundesamt, 2018)			
Restaurants	Ratio of production	151 g/meal	(Müller, 1998)	70 %		1,832
	Nb. meal per employee	2,920 meals/empl.y	*(ADEME, 2013)*			

The biowaste generated and sorted by the targeted sources in Hamburg was estimated at 90,777 t/y. The map Figure 13 and the graphic Figure 14 summarize the results for each source (detailed map in Annex, Figure 29 to Figure 33)

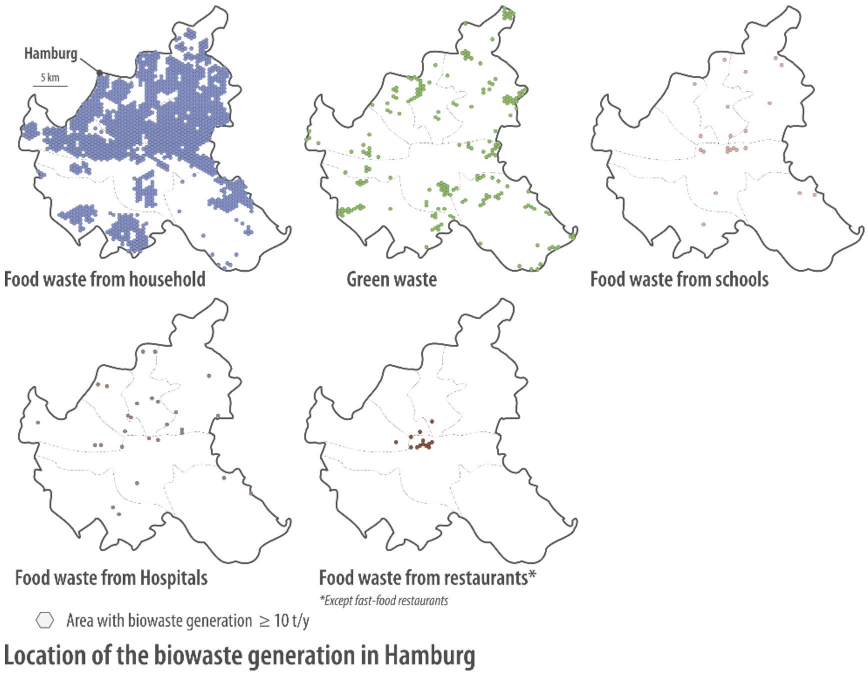


Figure 13: Location of the biowaste generation of the targeted sources in Hamburg.

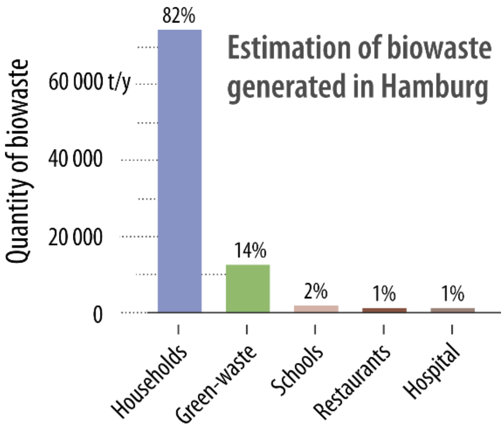


Figure 14: Quantification of the biowaste generation of the targeted sources in Hamburg.

2. INVENTORY OF THE OUTLETS: THE PERI-URBAN FARMS

Hamburg provides an exhaustive description of the agricultural areas for its own territory[6]. To ensure that digestate is exported to the closest agricultural areas, the land surrounding Hamburg has also to be included in the inventory. However, the detail databases for the land located in Schleswig-Holstein or Lower Saxony länders, were only available for a price not compatible with the project budget. The locations of the agricultural areas were then extracted from the Corine Land Cover[7] (inventory of land cover available at the EU scale) and improved with information about infrastructures, rivers, and lakes.

Table 10: List of criteria and the corresponding data used to select the suitable mAD sites in Hamburg.

Description	Data
Land use	- Corine Land Cover 2012 (Arable land, Heterogeneous agricultural areas and Pastures)
Water surfaces (rivers, lakes, etc.)	- OpenStreetMap: Water wand waterway
Roads, Railways	- OpenStreetMap: Highway

Restricted areas of 3m around the surface waters or 10m for parcels with slope greater than 10%, were set to respect the water protection guidelines for organic fertilization (Heidemeier and Schulz, 2012).

About 96,758ha of agricultural areas were found suitable for organic fertilization in Hamburg and in the surroundings areas (Annex, Figure 34).

3. POTENTIAL LOCATION FOR MICRO-AD UNITS

The current German legislation (Bundesministerium, 2002) concern only units that treat more than 10t of waste per days. In such case, the biogas plant has to be in line with regulations of the emission protection law (§ 3 (5c) BImSCHG / BImSCHV) and general restrictions of fire safety regulations. For smaller facilities such as the mAD, there is not a clear set of rules for their implementation and the authorizations are given based on the relevance of each specific project. Therefore, mAD could be potentially implemented in a very wide range of locations (basement, parking, etc.) as long as the relevant authority agrees.

However, the optimization model is designed to choose between a limited number of potential sites and not between infinite possibilities. Their number was then limited by applying the multi-criteria analysis used in the GL case. This solution also ensures that the location selected respect social and environmental criteria which could help for submitting a mAD project the authorities.

---

[6] http://transparenz.hamburg.de/, ALKIS database
[7] https://land.copernicus.eu/pan-european/corine-land-cover

Table 11 summarizes the criteria for the potential locations for mAD units in GL.

Table 11: List of criteria and the corresponding data used to select the suitable mAD sites in Hamburg.

Criteria	Description	Data	Distance
Regulation -Water	Water catchment (wells, spring, etc.), water storage for drinking water, rivers	- OpenStreetMap: river banks, rivers, streams, canals, spring, water well, water tower, reservoir, drinking water points	>35 m
-Population	Dwellings, establishments open to the public* (administration, hostel, museum, etc.) Official campsites	- ALKIS Liegenschaftskartes: residential building and building open to public, commercial building, cemetery, sports field, campsites	>50 m
Protected area	Natural reserve, protection plan, regional / national park, natural reserve, etc.	- www.protectedplanet.net	Not locate inside
Buildings	All buildings or construction not listed previously for "Population"	- ALKIS Liegenschaftskartes: All buildings not listed for "Population"	2m
Urban plan. rules	No applicable	_	_
Infrastructure	Roads	- OpenStreetMap: Highway ('motorway', 'trunk') / Other roads	> 4 m or 2 m
	Railways	- OpenStreetMap: Railways	>6 m
Accessibility	Roads	- OpenStreetMap: roads	< 50 m
Heat outlet	Collective housing	- ALKIS Liegenschaftskartes: cluster of dwellings or isolated dwellings if the floor surface > 100m²	< 100 m
	Building open to the public (not open air places)	- ALKIS Liegenschaftskartes: industrial, commercial and administrative buildings	

With the multi-criteria analysis, about 5,710 sites were identified (Annex, Figure 35), ranging from 76 m² to 638,000 m². Each site was considered as a single potential site. As for the GL case, the suitable sites are mainly around commercial or industrial areas or on the outskirts of the residential neighborhoods. In dense areas, there are only a few areas and often located in or close to public gardens.

4. RESULTS OF THE MILP OPTIMIZATION MODEL

The scenario studied targeted 10% of the biowaste from Hamburg, all biowaste sources included, with a maximal collection distance of 500m. The final model included 35,000 biowaste sources, 5,372 potential mAD sites and 6,352 outlets.

The optimal decentralized treatment network returned by the MILP method and shown in Figure 15 involved 147 mAD plants. Such a network would handle 9,078 t/y of biowaste for a payload-distance of 2,781 km-t and a total collection distance of 1,307 km. The digestate would be valorized in 111 agricultural plots, for a payload-distance of 4,688 km-t and a total transportation distance of 243 km.

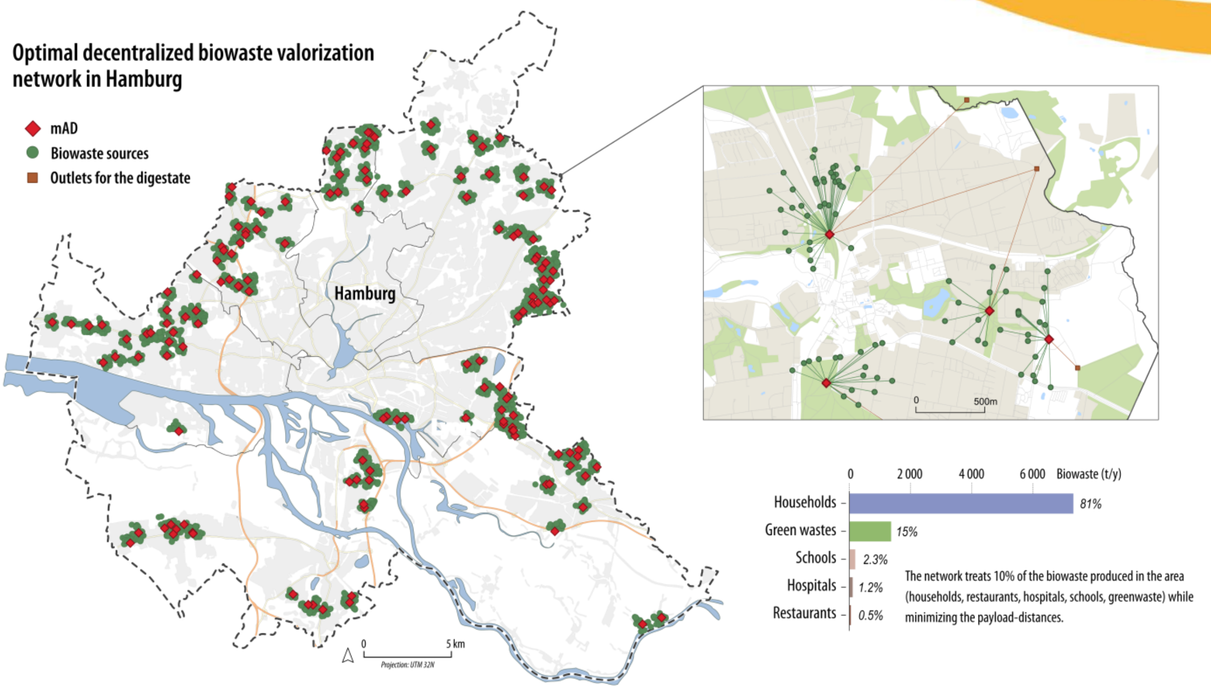


Figure 15: Map of the optimal network treating 10% of the biowaste of Hamburg and the chart of the quantities treated per type of biowaste.

The biowaste treatment network collects mainly household kitchen wastes (61 %, Figure 15). In average, the mAD treat 62t/y of biowaste, a value on the lower range of the treatment capacity possible (50 to 200 t/y).

In Hamburg, the biowaste is treated in the Bützberg biogas and composting plant that treats up to 70,000t/y. This plant was included in the optimization model assuming that the minimum treatment capacity was about 80% of the maximal capacity. The target quantity of biowaste to retrieve was set to 90% of the biowaste identified in Hamburg. Figure 16 shows the resulting treatment network.

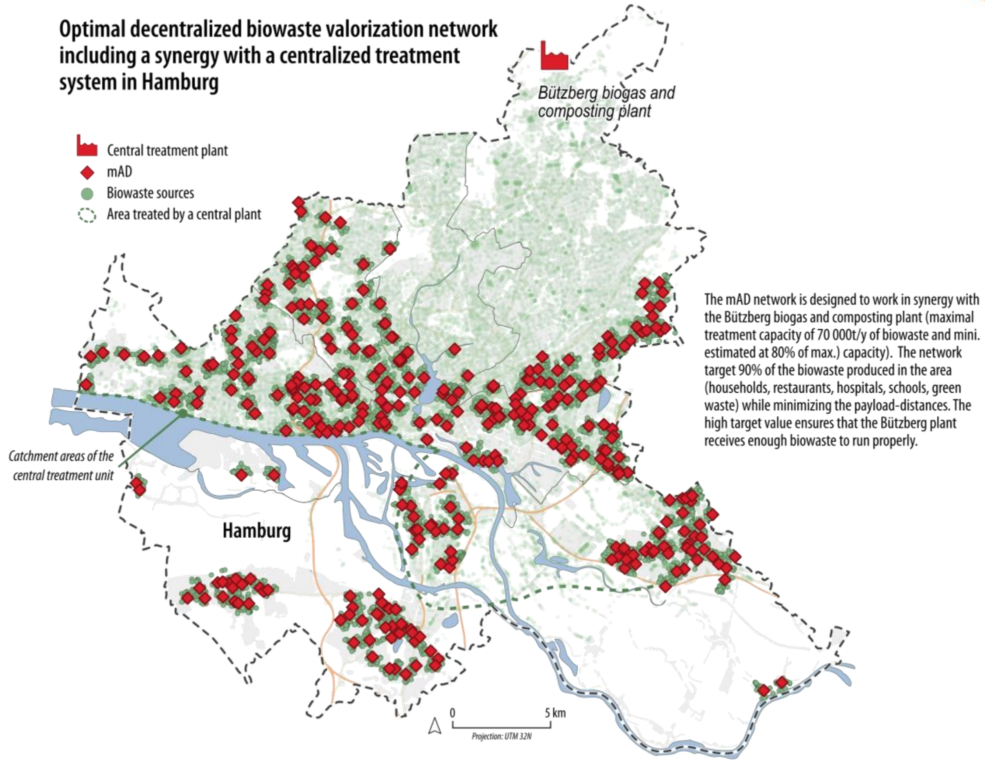


Figure 16: Map of the optimal mAD network working in synergy with the Bützberg central treatement plant (biogas and composting) to treating 60% of the biowaste of Hamburg.

In the new treatment network, the *Bützberg* plant covers most part of the city located in the north of Elbe. The MILP model ensures that the central plant treats enough biowaste to cover its minimal capacity requirement (estimated at 80% of the maximal capacity). The remaining biowaste is treated troughs mAD.

A. Grand Lyon Metropole

The Lyon Metropole, the Grand Lyon (GL) is a local authority comprising 59 municipalities around Lyon and located in the Rhône Department and the Auvergne-Rhône-Alpes region (Figure 17). The GL covers 534 km² and in 2014 its population was 1.3 million inhabitants, which represent about 600,000 households. It is located within a greater urban area of 2.2 million inhabitants, the second largest in France. The population GL density is 2,383 inhabitants/km², with central city Lyon having a density of 10,583 inhabitants/km². The GL is the most important urban area in France for industry. Pharmaceuticals, chemical, petrochemical, automotive, glass and food industries are the most prominent. The agricultural land covers about 10,000ha, corresponding to 20 % of the GL surface area. Most of the usual agricultural sectors are represented: cereal crops, stock rearing, arboriculture, horticulture and vegetables.

Figure 17: Location of the GL in France.

The GL separately collects from households recyclables (paper, cardboard, plastics, glass), bulky and hazardous waste. The remaining waste is collected as residual waste, in containers for each individual household or building. There is currently no separated collection of the biowaste which is disposed in the residual waste bin.

1. INVENTORY OF THE BIOWASTE SOURCES

The location and the biowaste generation in GL were estimated with the data described in the Table 12 and the parameters in Table 13.

The household biowaste generation was estimated with a very detailed census data and the floor surfaces of the habitation extracted from the official location of the buildings, several data sources about their function and an estimation of their height with Lidar data. The green waste was estimated with remote sensing method applied on aerial images and Lidar data. The list and the detailed information of schools and hospital were extracted from the official French data portal and completed with ancillary data. The database about companies (SIREN) identified the catering services, their type and their size (number of employees) which allows an accurate estimation of their biowaste. The availability of this database has also made it possible to include the employees in the calculation of the number of meals served in hospitals (ADEME, 2013).

Table 12: Description of the dataset used for the characterization of the biowaste generation in GL.

Biowaste sources	Data	Sources	
Household	Location and type of buildings	IGN BD Topo	professionnels.ign.fr/bdtopo
	Height of dwellings	Lidar	data.grandlyon.com
	Census data	INSEE IRIS (2013)	www.insee.fr
Green waste	High-resolution aerial images	IGN BD Ortho	professionnels.ign.fr/bdortho
	Official delineation of land parcels	IGN BD Parcellaire	professionnels.ign.fr/bdparcellaire
	Land use (urbanized areas)	Local Urban Plan of Grand	data.grandlyon.com
Schools	Schools locations and number of student per grade	French ministry of education (List of primary and secondary schools)	data.gouv.fr
		Other web sources	www.onisep.fr, etc.
Health facilities	Health facilities locations	FINESS database	finess.sante.gouv.fr
	Number of beds	Website: sanitaire-social	www.sanitaire-social.com

Restaurants	Location and number of employees	SIREN database	www.sirene.fr
Admin. and company canteens	Location and number of employees	SIREN database	www.sirene.fr

Table 13: Parameters used to estimate the biowaste generation of the different sources and the total for GL.

Biowaste sources	Biowaste generation			Sorting rate		Total bw sorted (t/y)
	Parameters	Values	Ref.	Value	Ref.	
Household	BW ratio	100 kg/capita.y	*(ADEME, 2013)*	50%	*(ADEME, 2013)*	**67,173**
Green waste	BW ratio	1 kg/m².y of lawn	*(Schneider and Le Bozec, 1995 and internal report from Irstea)*	20%		**16,599**
School canteens	BW ratio	185 g/meal (primary) 280 g/meal (secondary)	*(ADEME, 2013)*	70%		**1,014** (primary) **2,527** (second.)
	Day of school	144 days/y (primary) 180 days/y (secondary)				
	Students taking meal in canteen	59% (primary) 63%.(secondary)				
Canteen of Hospitals	BW ratio	185 g/meal	*(ADEME, 2013)*	70%		**2,034** (Hospital) **2,000** (Other facilities)
	Occupancy	100% (365 days/year)				
	Meals/day	2 meals/day				
Restaurants	BW ratio	185 g/meal	*(ADEME, 2013)*	70%		**5,503**
	Meal per employee	2,920 meals/empl.y				
Admin./ company canteens	BW ratio	180 g/meal	*(ADEME, 2013)*	70%		**5,163**
	Meals/employee	14,840 meals/empl.y				

The biowaste generated and sorted by the targeted sources in GL was estimated at 102,013 t/y. The map Figure 18 and the graphic Figure 19 summarize the results for each source (detailed map in Annex, Figure 36 – Figure 41).

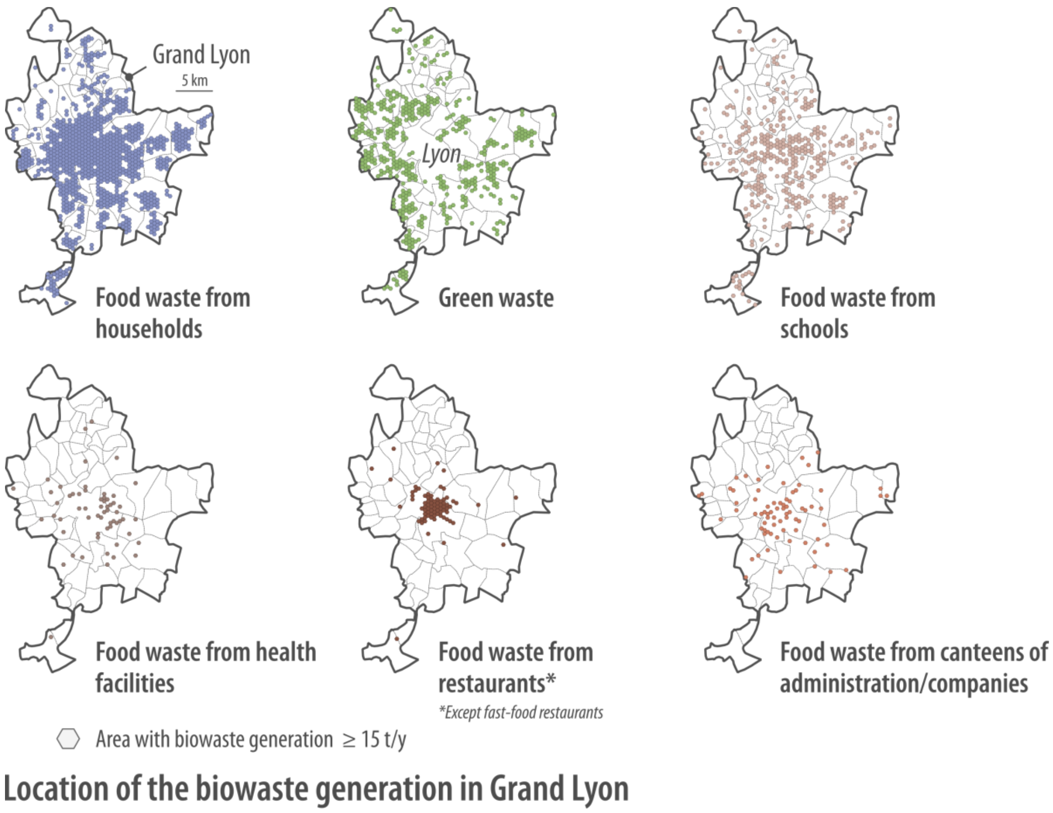


Figure 18: Location of the biowaste generation of the targeted sources in Grand Lyon.

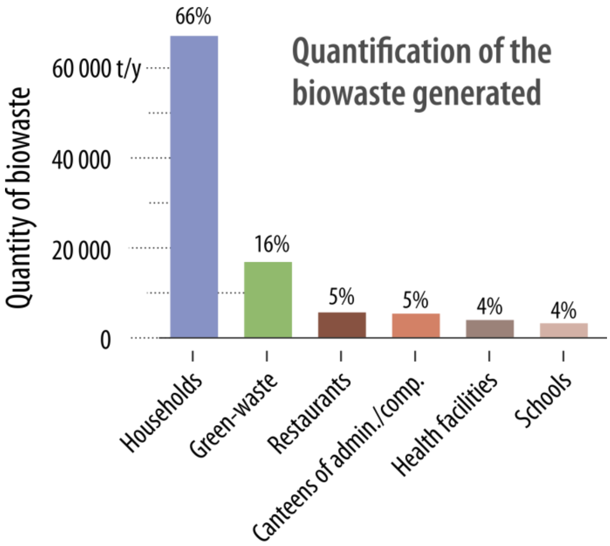


Figure 19: Quantification of the biowaste generation of the targeted sources in Grand Lyon.

2. INVENTORY OF THE OUTLETS: THE PERI-URBAN FARMS

The location and the shape of the agricultural parcels were extracted from the Graphical Parcel Register (RPG), freely available through the official governmental French portal. The RPG was completed for the vegetable farms with the SIREN database for their locations and an average of crop surfaces of the farms in the Rhône department from the *Agreste* database[8]. In GL, 64 % of the agricultural lands were located inside a NVZ, and, as stated in the methodology, all farms will be considered under the directive nitrate regulation. Based on the water protection guidelines for organic fertilization, a restricted area of 35m around surface waters was defined (IGN BD Topo) and the agricultural plot with an average slope greater than 10% were excluded (IGN BD Alti). The total of agricultural land in GL was estimated at 10,035 ha based on RPG data. After filtering those lands with the previous set of criteria (slope, regulation distances), 9,085 ha (91 %) were found suitable for the use of organic fertilization.

A balance was calculated gathering the current loads of Nitrogen and the potential spreadable N from digestate in order to put predictions in perspectives. For more detailed information, refer to deliverable D3.8.

Current nitrogen loading from livestock activity

Based on the official livestock census (Agreste) and the ratio of nitrogen production per capita (Laurent, 2015), the total production of nitrogen from the livestock is estimated to be 104.8 t/year. With 9,085 ha of agricultural land in GL, the nitrogen load from livestock was about 11.2 kg of N/ha. If farmers would use only the manure to reach the 170 kg of N/ha from organic fertilizer, they could cover the need of 617 ha which would be about 7 % of the total of agricultural land available.

Current nitrogen loading from sludges of wastewater treatment plants

The location and characteristics of the wastewater (2015) were made available free of charge by the Ministry of Ecological and Solidarity Transition[9]. The analysis was simplified by selecting only the plants located inside GL, even if a part of the wastewater from the territory can be treated in plants outside and conversely. Reported to the agricultural land of the territory (9,085ha), the average nitrogen loads from sludge products would be 11.6 kg/ha per year.

The nitrate loading from livestock and wastewater sludge in GL was then about 22.8 kg of nitrogen/ha/year. The quantity of organic fertilizer available in the territory was substantially lower than the

---

[8] http://agreste.agriculture.gouv.fr/

[9] *http://assainissement.developpement-durable.gouv.fr/services.php*

legal threshold of 170 kg/ha/year of nitrogen even if the analysis shows some spatial heterogeneity over the territory (higher values along the west and south-west border).

Digestate potentially spreadable

The potential quantity of digestate spreadable was calculated with the assumption that the digestate contains 10 g N/kg of raw material (unpublished value from Irstea, 2017). In average, there was a potential of about 14.7 t/y of digestate per hectare of agricultural area and a total of 132,641 t/y for the GL territory. The potential production of digestate was estimated at 51,000 t/y if all the biowaste of GL were treated by AD and considering 50 % of mass reduction during the AD process (unpublished value from Irstea, 2017). Consequently, the digestate produced by the mAD network seemed to be usable inside the territory without a risk of nitrogen overload.

3. POTENTIAL LOCATION FOR MICRO-AD UNITS

Table 14 summarizes the criteria for the potential locations for mAD units in GL.

Table 14: List of criteria and the corresponding data used to select the suitable mAD sites in the GL.

Criteria	Description	Data	Distance
Regulation -Water	Water catchment (wells, spring, etc.), water storage for drinking water, rivers	- IGN BD Topo: watering place, reservoir, stream section ("Permanent"), water surface	>35 m
	Wetland	- Data.GrandLyon: Wetland of Gran Lyon	>10 m
-Population	Dwellings, establishments open to the public* (administration, hostel, museum, etc.) Official campsites	- IGN BD Topo: undifferentiated (only dwellings), remarkable and industrial buildings (commercial building only), cemetery, sports field, POI leisure (campsites)	>50 m
Protected area	APPB, Natural reserve, national / regional park, RAMSAR site	- DREAL Rhône-Alpes	NA (none in GL)
Buildings	All buildings or construction not listed previously for "Population"	- IGN BD Topo: lightweight construction, aerodrome, reservoir, industrial (not commercial) and undifferentiated buildings (not dwellings)	
Urban plan. rules	Protection perimeter around classified monument	- Wikipedia (list and location of classified monument for the Grand Lyon)	>500 m
Infrastructure	Roads	- IGN BD Topo: Highway/ Other roads	>10 m or 2 m
	Railways	- IGN BD Topo : Railways	>6 m
Accessibility	Roads	- IGN BD Topo: roads	< 50 m
Heat outlet	Collective housing	- IGN BD Topo: undifferentiated buildings habitation and Height > 8m	< 100 m
	Building open to the public (not open air places)	- IGN BD Topo: industrial (commercial or industrial buildings and greenhouses) and remarkable buildings (town hall, etc.)	

About 6,529 sites were identified by the multi-criteria analysis (Annex, Figure 43), ranging from 76 m² to 254,000 m². Each site was considered as a single potential site. The suitable sites are mainly around commercial or industrial areas or on the outskirts of the residential neighborhoods. In dense areas, there are only a few areas and often located in or close to public gardens.

4. RESULTS OF THE MILP OPTIMIZATION MODEL

The scenario studied targeted 10% of the biowaste from GL, all biowaste sources included, with a maximal collection distance of 5,000m. The final model included 27,169 biowaste sources, 3,351 potential mAD sites and 921 outlets.

The optimal decentralized treatment network returned by the MILP method, Figure 20, involved 170 mAD plants. The network would handle 9,135 t/y of biowaste for a payload-distance of 2,882 km-t, a total collection distance of 1,363 km and a distance per ton of waste collected of 149 m /t. The digestate would be valorized in 194 agricultural plots, for a payload-distance of 855 km-t and a total transportation distance of 52 km.

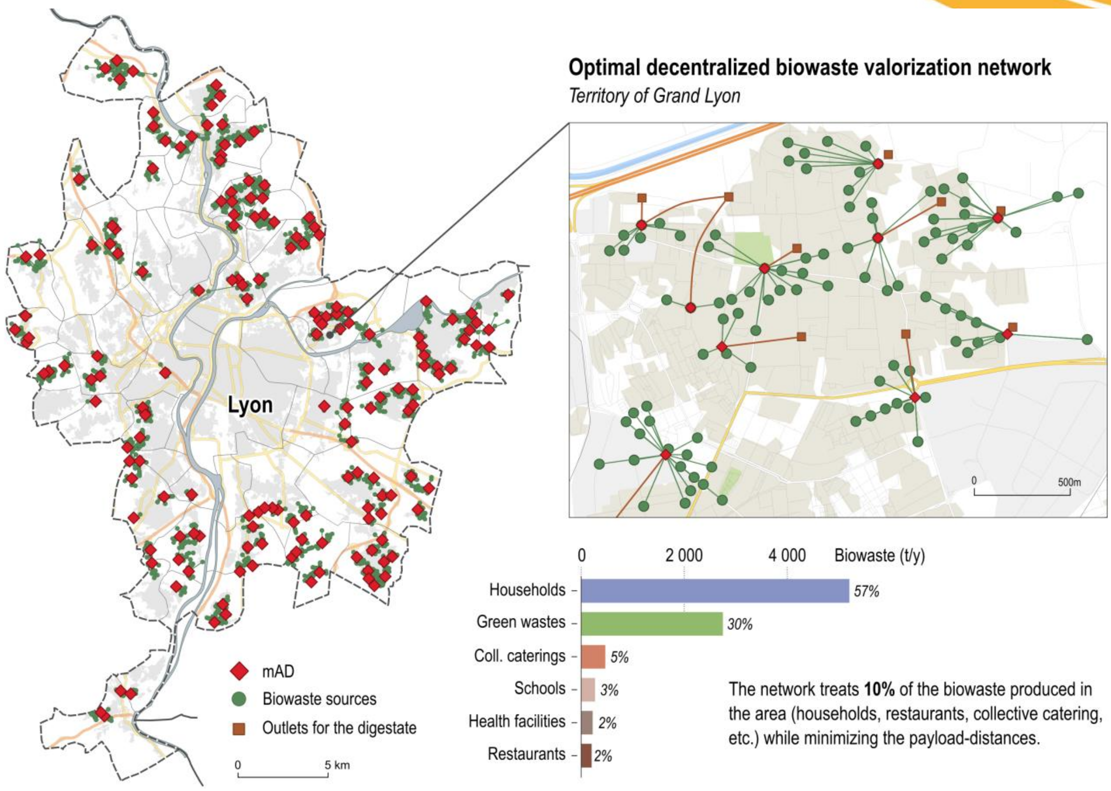


Figure 20: Map of the optimal network treating 10% of the biowaste of the GL and the chart of the quantities treated per type of waste.

The biowaste treatment network collects mainly household kitchen wastes (57 %, Figure 20). In average, the mAD treat 53 t/y of biowaste, a value on the lower range of the possible treatment capacity (50 to 200 t/y).

IV. Discussion and Conclusion

A. Discussion on the method

The application of the optimization method on new case studies confirms the first conclusions of the deliverable D3.8: 1) the inventory step is clearly the main bottleneck of the methodology, while 2) the MILP model is easy to implement as long as the input data are properly shaped.

Even if the three area- studies have a clear policy for open data, the data availability still differs greatly according to location or topics concerned. In the frame of this study, France appears to be the most compelling country. Table 15 summarizes the complexity and the uncertainties related to the inventories in the 3 case studies. The topographical database (IGN Topo) is easily available, accurate and up-to-date. The SIREN database provides for free an exhaustive reference of all companies, including the different type of collective caterings. The health and educational administration provide most of the data required for the analysis. Hamburg publishes a very exhaustive set of data through their open data portal[10] but information about companies and in particular about restaurants is still missing. Moreover, information about agricultural lands, free for Hamburg, were very expensive in the surrounding Länder (Lower Saxony and Schleswig-Holstein), even for research purpose. In Catalonia, most of the databases were available except for companies and more remarkably for the schools census. The different data gaps were filled based on ancillary data and some simplification of the method. Among those gaps, the lack of detail information about the different restaurants was the most problematic. The restaurants may be an important target for the DECISIVE system but, except for France, there is no accurate and detailed information or it is very expensive. In any case, the data heterogeneity among EU countries (even inside a country) makes necessary an adaptation of the method to each cases study.

Concerning the quality of the inventory, the sources of biowaste were generally accurately located. However, the estimation of the biowaste generation was much more prone to errors that were complex to quantify.

The estimation of green waste production raises other issues. The remote sensing analysis is a complex task that required good quality data, suitable tools, but also a high level of expertise. The timespent for this task and the quality of the results must be weighed against the comparatively low importance of the green waste for the mAD supply. Even if the quality of the lawn areas extracted for GL and Hamburg appear to be acceptable, the time spent for this analysis seems high for the assessment of a co-substrate.

Table 15: Comparison of the uncertainties in the inventory for the different case studies (the text in bold give an estimation of the level of uncertainty ranging from low to high and the complexity of the method in parenthesis, from simple to complex).

Biowaste source	GL	AMB	Hamburg
Household	**Average (*Slightly complex*)**	**High (*Simple*)**	**High (*Simple*)**
	Building with habitation not clearly defined, height of building not always provided Census data very detailed	Building with habitation identified and number of floor provided. Census data very detailed	Number of dwelling per building provided (cadaster) Census data detailed but not very pu-to-date(2011)
Canteen of schools	**Average (*Simple*)**	**Low (*Complex*)**	**Low (*Simple*)**
	Official list of schools with the nb of student. Partial information about the real number	No official census of schools. Information partially retrieved with a private website.	Official list of schools with the number of student.

[10] http://transparenz.hamburg.de/

	of meals served.		
Canteen of Hospitals	**Average-high (*Slightly complex*)**	**Low-Average (*Simple*)**	**Low-Average (*Simple*)**
	Official list of hospitals but without the nb of beds. Nb beds collected on private website.	Official list of hospitals with the nb of beds.	Official list of hospitals with the nb of beds.
Restaurants	**Average-High (*Slightly complex*)**	**Low (*Slightly complex*)**	**Low (*Slightly complex*)**
	Official list restaurants with their type and the nb of employees (given in range)	List of restaurants from OSM. Statistics on the nb of employee in Catalonia	List of restaurants from OSM.
Green waste	**Low (*Complex*)**	NA	**Low (*Complex*)**
	Suitable high resolution aerial image and Lidar data	NA	Sentinel 2A multi-spectral data

In the proposed method, the inventory does not rely on real waste data that can be difficult to retrieve from the corresponding stakeholders. However, in areas such as Catalonia, the biowaste generation from households and some commercial circuits are well referenced and accurately located. In these cases, the method and the MILP model could be adapted to make the best use of this information.

The outlets for digestate are located accurately, but it remains difficult to estimate the quantity of digestate spreadable. Some simplifications were done compared to the original method. The nitrogen load was considered similar to the GL one without further calculation. Deeper study (e.g. including crop management, fertilization guideline, and mineral fertilization) would improve the final results. However, there are some questions about the added value on a more detailed approach due to the current uncertainties on other critical processing information (e.g. quantity of digestate produced by the mAD and its exact nitrogen content).

The MILP model required time to be properly developed, but its application to new case studies is easy. With the inventory data well shaped, the model could run without any adaptation of the original programming code.

B. Discussion on the design of the micro-AD networks

1. SIMILARITY BETWEEN MICRO-AD NETWORKS

The case studies are located in three different geographical contexts with distinct shape of the urban areas. Despite these differences, the mAD networks designed by the MILP model present great similarities: 1) the mAD are mainly located in the urban periphery, 2) the mAD are mainly fed by household food waste, 3) the capacities of the mAD selected are in the lower values of the possible range and, if included, the central treatment plants are always set to their minimal capacity.

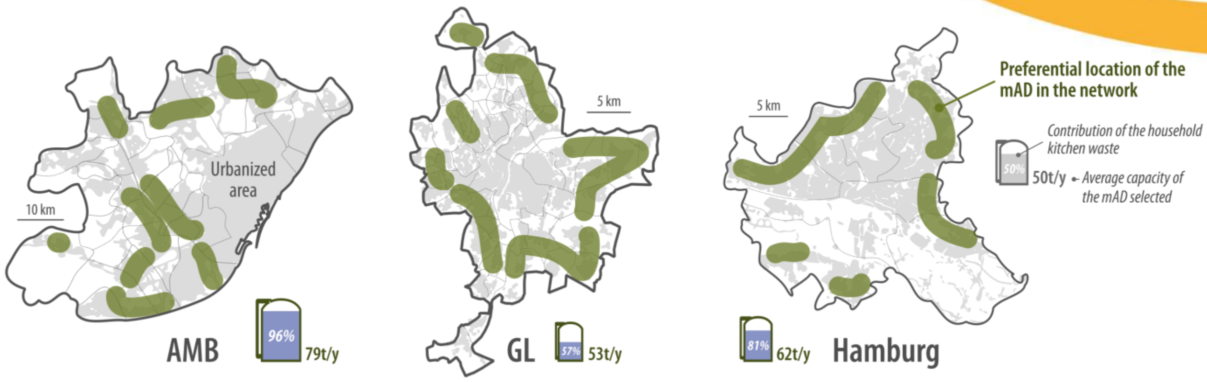


Figure 21: Location of the mAD in the treatment network for the 3 case studies (10% of biowaste targeted), average treatment capacity of the mAD and proportion of the household kitchen waste in the biowaste mix treated.

The location of mAD in the treatment network is constrained by the potential sites identified with the GIS multi-criteria analysis and the MILP model. For the 3 case studies, the potential sites were extracted based on the same set of criteria defined by the French regulation (e.g. distances to water surfaces, dwellings). The German and Spanish legislation does not currently provide specific regulation for small-scale AD and the authorizations are provided on case-by-case analysis. The lack of proper distance threshold in these two countries offers a greater flexibility for implementing mAD. This situation led to a very high number of potential sites for mAD, which is not suitable for the MILP model. Their number was thus reduced by the use of the French regulation, the most restrictive one. It also ensures that in all the case studies, the potential sites do not show high environmental or social risks (distance to water and dwelling respectively). The exclusion zone around habitations or buildings opened to the public and the minimum surface area required prevent the installation of mAD in very dense urban areas. Conversely, the criteria adopted impose proximity between the infrastructure and the potential outlets for the heat. Together, these two set of criteria are restricting the potential sites to the low density or industry areas, mainly in the urban periphery. At the optimization stage, the MILP model minimizes simultaneously the transport of biowaste and digestate. The model will then choose preferentially the treatment sites located close to agricultural areas, in the urban periphery or peri-urban areas.

The household kitchen waste was the main biowaste source of the treatment network in all the case studies (57% to 96% of the total treated, Figure 21). Indeed, the household kitchen waste was the biggest biowaste source identified in the inventory step (66% to 95% of the total targeted). The households and the corresponding biowaste production were also more evenly distributed in the territory than any other biowaste sources (cf. Figure 18, Figure 8, Figure 13). Hence, it provides more flexibility to the optimization model for minimizing the overall transport distances.

In the 3 case studies, the mAD units treated in average from 53t/y to 79t/y (Figure 21) of biowaste which is on the low range of the possible capacities (50t/y to 200t/y). Selecting numerous small treatment units allows reducing the transport distance, by locating them closest to the biowaste sources and to the digestate outlets. For the current MILP model, this solution is optimal. However, increasing the number of mAD may have a significant impact on the investment and the running cost of the treatment network. This issue could be mitigated by shifting the MILP objective function from payload distance to a broader range of economic variables (e.g. transport cost, running cost).

The previous remark on the mAD size also explains the restriction of the central treatment plant to their minimal capacity. Due to the constraints defined, the model will first try to feed the centrals plants up to their minimal treatment capacity and then the model will select preferably the mAD that are closer to their sources and outlets.

2. MAIN DIFFERENCE BETWEEN MICRO-AD NETWORKS

The proximity between biowaste sources and mAD differs according to the geographical context. In the treatment network designed for AMB, the ratio between the sum of collection distances and the total of biowaste collected (± 50 m/t) is significantly lower than the ones of Hamburg and GL (144 m/t and 149 m/t respectively). The most suitable mAD sites in AMB are supplied by biowaste sources located closer than the ones in the two others cases. The households are the most important sources in all the 3 territory and the population density around the sites (1,173 inhab./km² in AMB, 639 inhab./km² in Hamburg and 317 inhab./km² in GL) explains in large part the differences observed.

In AMB, the mAD network designed formed very dense clusters. Hence, a mAD is located in average at about 300m of the closest other mAD of the network. In Hamburg and GL, the values are higher, 639m and 734m respectively which reflects the differences in local population density as explained above. The very high proximity of mAD raise the issues of the selection of numerous small mAD by the MILP model. The payload-distance is optimal, but the cost or the management of such system maybe not, as already underlines in chapter 1IV.B.1. This, jointly with the limitation of applying digestate to soil, is why it was considered to treat the biowaste generated in the area of Barcelona city in a centralised plant instead of distributing numerous mAD plants in the city.

3. DECISIVE PILOT SITES AND MICRO-AD NETWORK

To some extent, the suitability of the DECISIVE pilot site locations can be assessed in regard of a potential optimal treatment network of their territory. For example, in GL, a pilot mAD will be installed in the Refarmers sites (Écully) and it will process mainly biowaste from the restaurants located nearby. The MILP model targeting restaurants in GL showed that this site was not selected in the final network (Figure 22, a)). A new network was designed to include the Refarmers site (Figure 22, b)). The new network showed a similar shape compared to the default results and a very similar performance, with an increase of only 0.07% of the payload distance. Therefore, the location of the DECISIVE pilots mAD in GL allows its smooth integration into an optimized treatment network. This analysis also showed that there are several mAD with very similar performance.

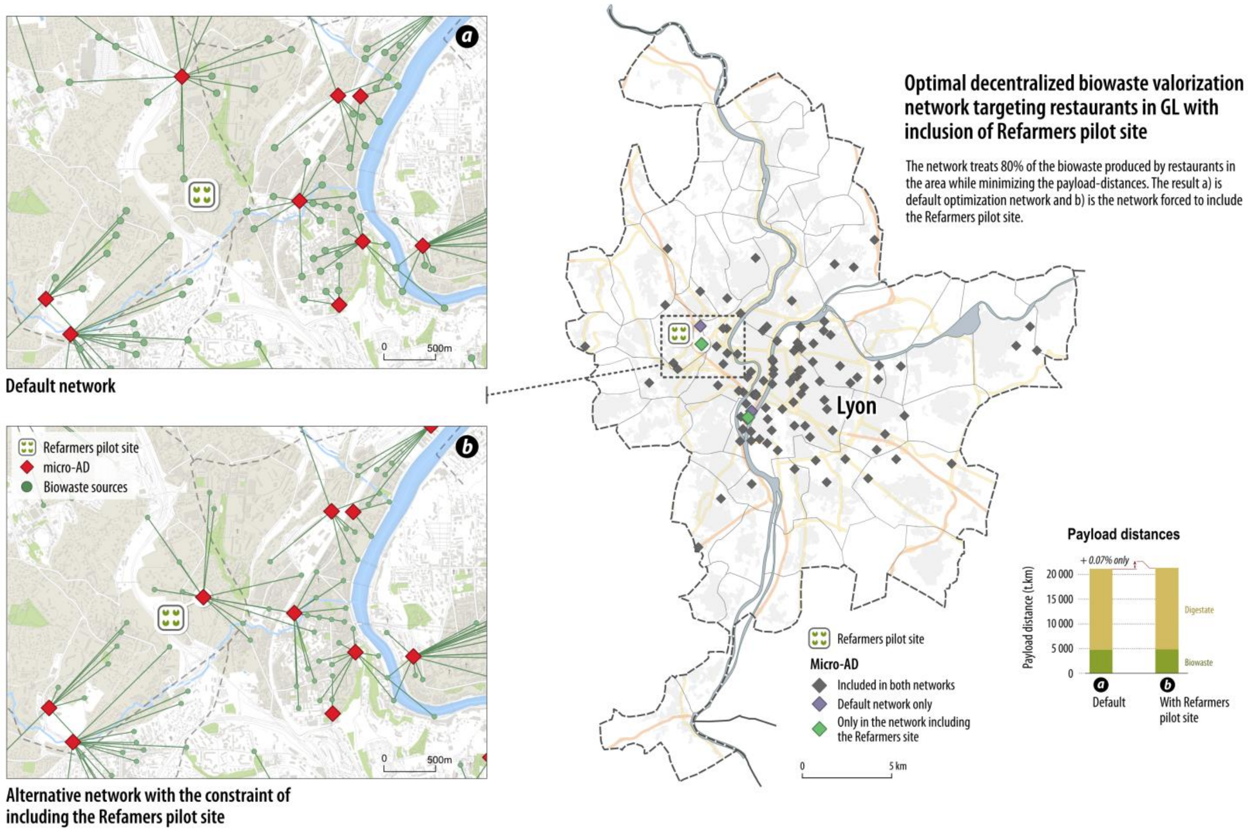


Figure 22: Comparison of a) the default optimal network treating 80% of the biowaste from restaurants in GL and b) an alternative one that is constrained to locate a mAD in the Refamers pilot site. The chart shows the difference in payload-distance between the two biowaste treatment networks.

In the above example, the MILP model redistributed the biowaste among mAD according to the new model constraints to keep a low payload distance while avoiding competition between the treatment sites.

However, this approach is less suitable when testing sites that have only one single and already well defined biowaste source (one to one relationship). In that case the question of competition between mAD is less significant as the resource is already allocated and the results of the optimization method do not really provide valuable conclusions about these sites. The pilot site in AMB illustrates this situation. The mAD should be located in UAB campus to treat the biowaste from university restaurants. There is no real competition with alternative mAD sites. In this case, the suitability analysis of the AMB pilot based on MILP model seems not fully relevant.

C. Conclusions

The method developed in the framework of DECISIVE project for designing optimal mAD networks has been successfully applied in the case studies of GL, AMB, and Hamburg. The development and the application of the method demonstrate that 1) a significant fraction of the biowaste generated in urban or peri-urban areas can be recovered through a decentralized small-scale treatment system including regulation constraints and, 2) the mAD network can be designed to minimize the transport of the biowaste and the digestate. It is important to underline that the method does not prove the overall feasibility or the economic, social and environmental relevance of the DECISIVE system. These analyses will be conducted with a suitable set of methods (e.g. LCA) by other project partners. If the DECISIVE system demonstrates its advantages, the optimization methods can help to design decentralized network at the territorial level.

The method links a detailed GIS data and a MILP and this approach proved to be an efficient solution for optimizing local and small valorization loops while covering the need of a large territory. The flexibility of the MILP and its combination with GIS analysis make it a very powerful approach for optimizing numerous kinds of waste management systems. However, the application of the method is still challenging, mostly related to the inventory of the biowaste sources. The current trends for open data will most probably ease the process in the near future. But at the moment, the development of more automated tools will require simplification of the method and more important use of OpenStreetMap data. On the other hand, the MILP model can be very easily applied in a new case study if the proper databases are well shaped.

The similarity between the mAD networks in different contexts underlines the impact of the initial design of the model. Hence, the current objective function minimizes the transport distances that lead to a selection of numerous very small size mAD located in urban periphery. The minimization of economic or environmental impacts would modify the final network shapes.

The optimization model and the results have demonstrated their potential strength. A further step would consist in applying the method in collaboration with key stakeholders of the waste management. Their knowledge of the territory and their own development strategy would improve the selection of the potential mAD sites and refine the parameter of the MILP model. The resulting network would be then more in line with the territorial context and more useful for the decision makers.

V. References

1411. Gazomètres et réservoirs de gaz comprimés renfermant des gaz inflammables | AIDA [WWW Document], n.d. URL https://aida.ineris.fr/consultation_document/10451 (accessed 6.11.18).

2781. Méthanisation de déchets non dangereux ou de matière végétale brute | AIDA [WWW Document], n.d. . Ministère Environ. Energ. Mer Réglementation Prév. Risques Prot. Environ. URL https://aida.ineris.fr/consultation_document/10757 (accessed 6.11.18).

ADEME, 2013. Estimation des gisements potentiels de substrats utilisables en méthanisation.

Agència de Residus de Catalunya, 2014. PRECAT20 Programa general de prevenció i gestió de residus i recursos de catalunya 2020 - Annex 11, Estudi de composició de la bossa tipus de residus municipals a Catalunya.

Arens-Azevedo, 2015. Qualität der Schulverpflegung – Bundesweite Erhebung.

Arrêté du 10 novembre 2009 relatif aux prescriptions générales applicables aux installations classées de méthanisation soumises à déclaration sous la rubrique n° 2781-1, n.d.

atee Club Biogaz, 2017. Lettre digestat du Club Biogaz ATEE Novembre 2017.

Benoît, P., Brugère, H., Casellas, M., Dabert, P., Fuchs, J., Giamberini, L., Patureau, D., Pons, M.-N., Pourcher, A.-M., Topp, E., 2014. Rapport final de l'ESCo "Matières fertilisantes d'origine résiduaire", Chapitre 2. Caractéristiques physico-chimiques et biologiques des Mafor 249.

Blaschke, T., 2010. Object based image analysis for remote sensing. ISPRS J. Photogramm. Remote Sens. 65, 2–16. https://doi.org/10.1016/j.isprsjprs.2009.06.004

Blaschke, T., Lang, S., Lorup, E., Strobl, J., Zeil, P., 2000. Object-oriented image processing in an integrated GIS/remote sensing environment and perspectives for environmental applications. Environ. Inf. Plan. Polit. Public 2, 555–570.

Blaschke, T., Strobl, J., 2001. What's wrong with pixels? Some recent developments interfacing remote sensing and GIS. GIS – Z. Für Geoinformationssysteme 14, 12–17.

Bork, E.W., Su, J.G., 2007. Integrating LIDAR data and multispectral imagery for enhanced classification of rangeland vegetation: A meta analysis. Remote Sens. Environ. 111, 11–24. https://doi.org/10.1016/j.rse.2007.03.011

Bundesministerium, 2002. Erste Allgemeine Verwaltungsvorschrift zum Bundes–Immissionsschutzgesetz, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit.

Campbell, J.B., Wynne, R.H., 2011. Introduction to Remote Sensing, Fifth Edition. Guilford Press.

Catalunya, 2009. DECRET 136/2009, d'1 de setembre, d'aprovació del programa d'actuació aplicable a les zones vulnerables en relació amb la contaminació de nitrats que procedeixen de fonts agràries i de gestió de les dejeccions ramaderes. [WWW Document]. Portal Juríd. Catalunya. URL http://portaljuridic.gencat.cat/ca/pjur_ocults/pjur_resultats_fitxa/?documentId=478701&action=fitxa&versionId=1346987 (accessed 10.17.18).

Cerda Llanos, A., Colmenar-Santos, A., 2017. DECISIVE-D4.5 Report of the possibilities of digestate (and other wastes) as raw materials for SSF processes to obtain certain bioproducts. UAB.

Colmenar-Santos, A., Rosales-Asensio, E., Borge-Diez, D., Blanes-Peiró, J.-J., 2016. District heating and cogeneration in the EU-28: Current situation, potential and proposed energy strategy for its generalisation. Renew. Sustain. Energy Rev. 62, 621–639. https://doi.org/10.1016/j.rser.2016.05.004

Degueurce, 2017. DECISIVE-D4.1 Deliverable 4.1 Definition of general specifications for micro-anaerobic digestion in a oncept of decentralised management of urban biowaste.

Dijkstra, E.W., 1959. A note on two problems in connexion with graphs. Numer. Math. 1, 269–271. https://doi.org/10.1007/BF01386390

European Commission, 2018. Nitrates - Water pollution - Environment [WWW Document]. Eur. Comm. URL http://ec.europa.eu/environment/water/water-nitrates/index_en.html (accessed 10.17.18).

FAO's role in Urban Agriculture [WWW Document], n.d. . Food Agric. Organ. U. N. URL http://www.fao.org/urban-agriculture/en/ (accessed 3.14.18).

Ghiani, G., Laganà, D., Manni, E., Musmanno, R., Vigo, D., 2014. Operations research in solid waste management: A survey of strategic and tactical issues. Comput. Oper. Res. 44, 22–32. https://doi.org/10.1016/j.cor.2013.10.006

Hafner, Barabosz, 2012. Determination of discarded food and proposals for a minimization of food wastage in Germany. University Stuttgart.

Heidemeier, Schulz, 2012. Good agricultural practice: the legal basis current situation & BEP measures Implementation of the Nitrates Directive in Germany - Umweltbundesamt.

INE, 2018. Empresas por CCAA, actividad principal (grupos CNAE 2009) y estrato de asalariados [WWW Document]. URL http://www.ine.es/jaxiT3/Tabla.htm?t=298 (accessed 10.22.18).

Institut Cerdà, 2014. Estudi sobre la generació de residus comercials a Catalunya.

L. Létinois, 2013. Méthodologie de répartition spatiale de la population.

Laurent, F., 2015. Optimisation fonctionnelle et spatiale de scénarios de méthanisation centralisée selon une approche systémique territoriale couplée à l'analyse du cycle de vie. Université de Rennes 1.

Manns, Schermuly, Kjerulf Petersen, Körner, 2017. DECISIVE-WP3.5 Survey on waste collection systems with evaluations for decentralised applications.

Müller, 1998. Recycling von Lebensmittelabfällen in Deutschland.

Parent, J.R., Volin, J.C., Civco, D.L., 2015. A fully-automated approach to land cover mapping with airborne LiDAR and high resolution multispectral imagery in a forested suburban landscape. ISPRS J. Photogramm. Remote Sens. 104, 18–29. https://doi.org/10.1016/j.isprsjprs.2015.02.012

Pujol, Lladó, 2013. Quantificació del residus organics generats al bar restaurant del campus del baix llobregat i valorització de la fo per compostatge 151.

Rampi, L.P., Knight, J.F., Pelletier, K.C., 2014. Wetland Mapping in the Upper Midwest United States. Photogramm. Eng. Remote Sens. 80, 439–448. https://doi.org/10.14358/PERS.80.5.439

Schneider, P., Le Bozec, A., 1995. La Production des déchets végétaux des espaces verts publics : résultats d'une enquête nationale auprès des villes françaises, Etudes.$3102212 Equipements pour l'eau et l'environnement ; 22.

Schoepfer, E., Lang, S., 2012. Object fate analysis - A virtual overlay method for the categorisation of object transition and object-based accuracy assessment. Object-Based Image Anal.

Scott, A.J., 1970. Location-Allocation Systems: A Review. Geogr. Anal. 2, 95–119. https://doi.org/10.1111/j.1538-4632.1970.tb00149.x

Statistisches Bundesamt, 2018. Grunddaten der Krankenhäuser - Fachserie 12 Reihe 6.1.1 - 2016.

Wan, C.-Y., King, B.A., Li, Z., 2012. An assessment of shadow enhanced urban remote sensing imagery of a complex city-Hong Kong.

VI. Annexe – Map Atlas

A. Metropolitan area of Barcelona (AMB)

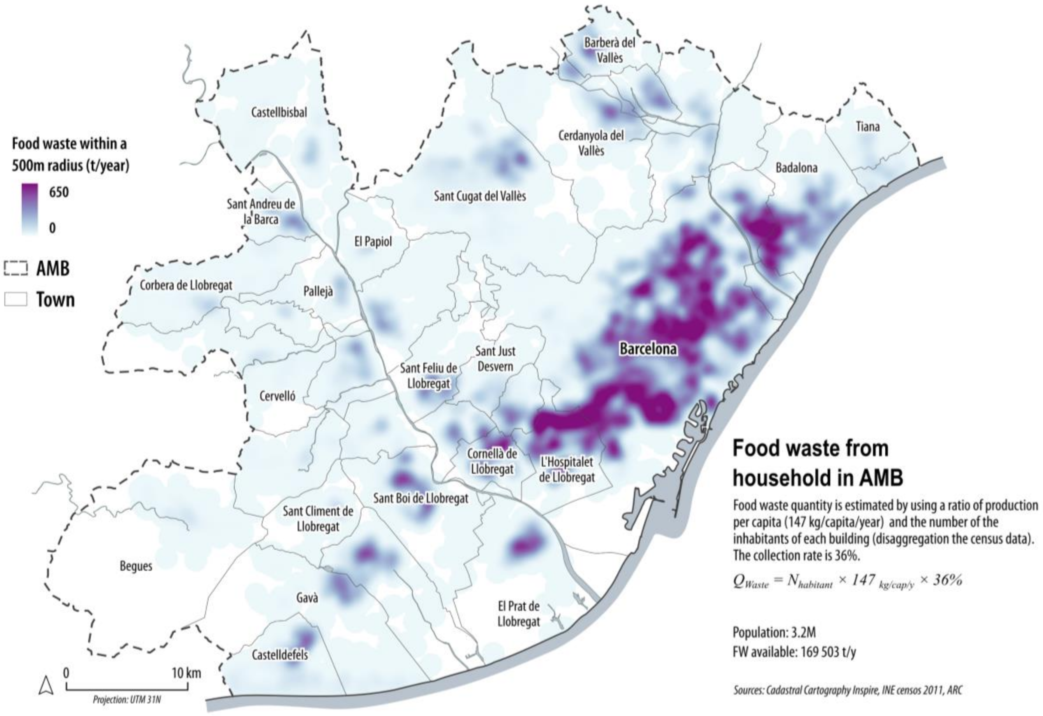


Figure 23: Heat map of the quantities of food waste sorted by household in AMB. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

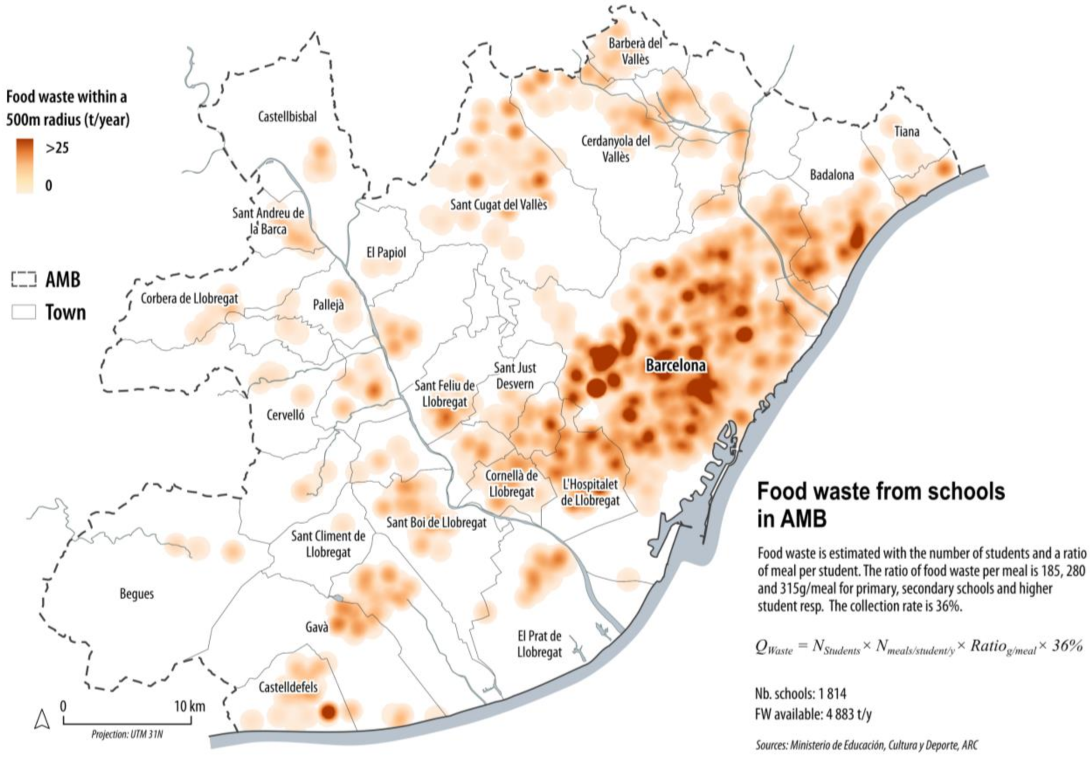


Figure 24: Heat map of the quantity of food waste sorted in schools of AMB. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

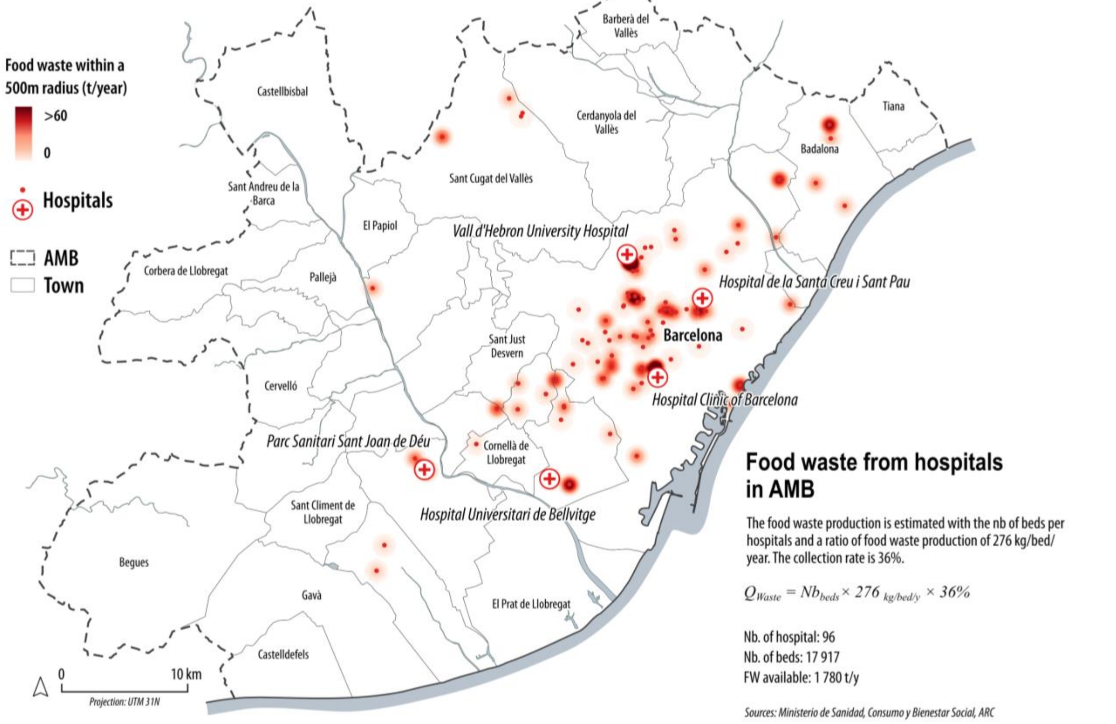


Figure 25: Heat map of the quantity of food waste sorted in health facilities of AMB. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

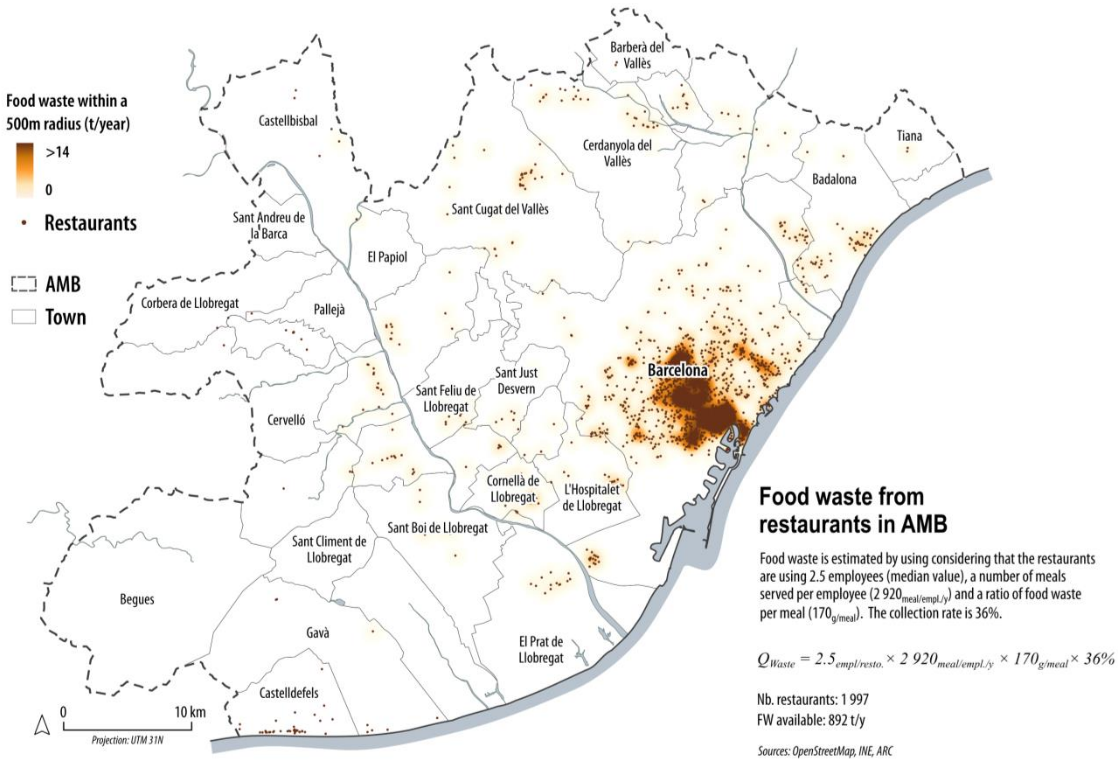


Figure 26: Heat map of the quantity of food waste sorted in the restaurants located in AMB. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

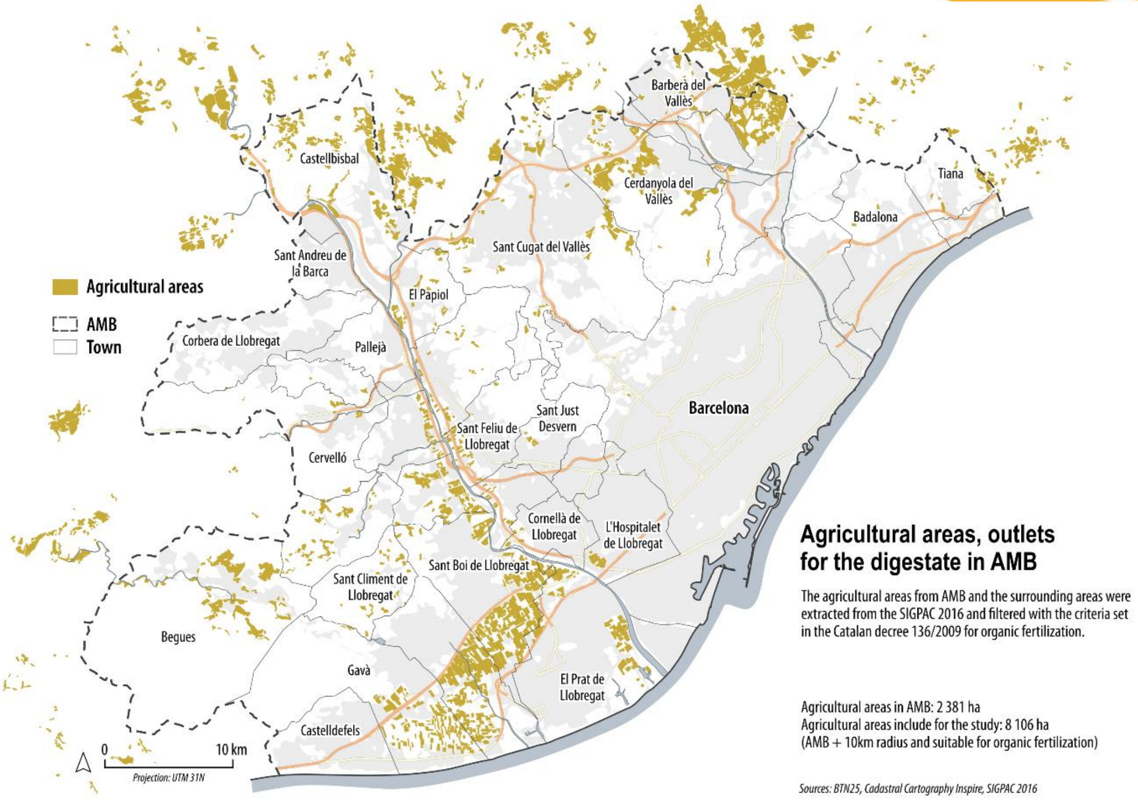


Figure 27: Map of the location of the agricultural areas in and around AMB (potential outlet for the digestate).

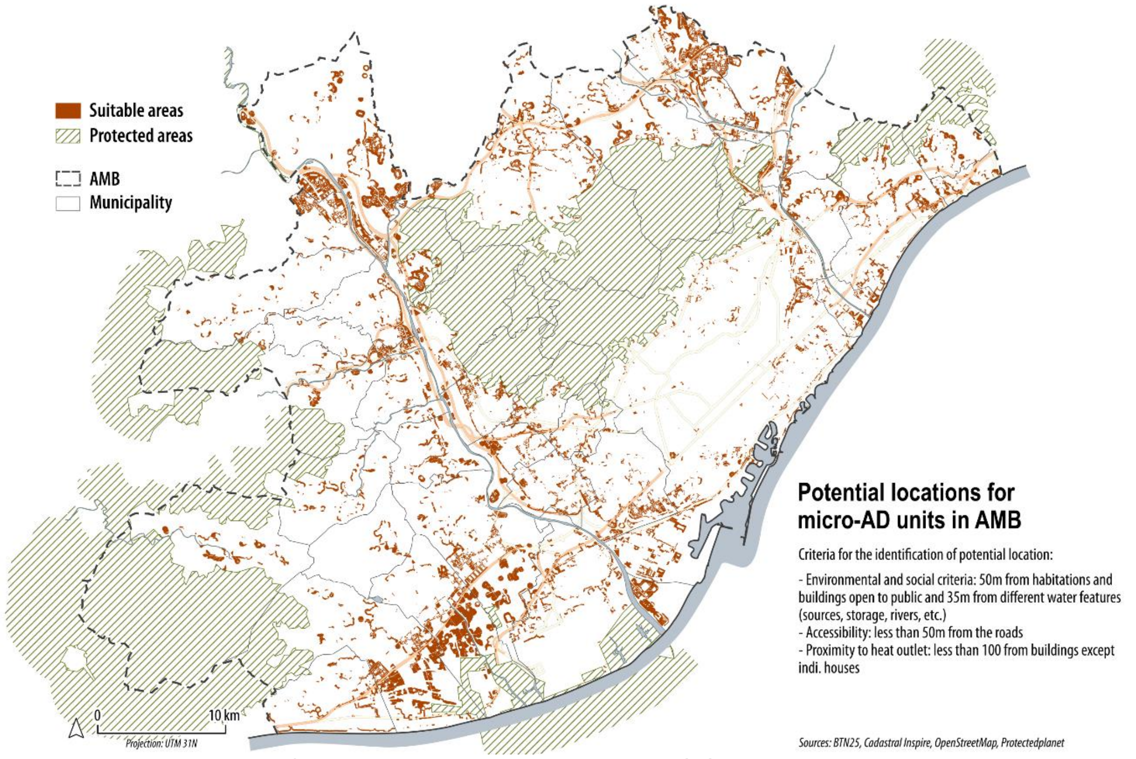


Figure 28: Potential locations for micro-AD units in AMB based on GIS multi-criteria analysis.

B. Hamburg

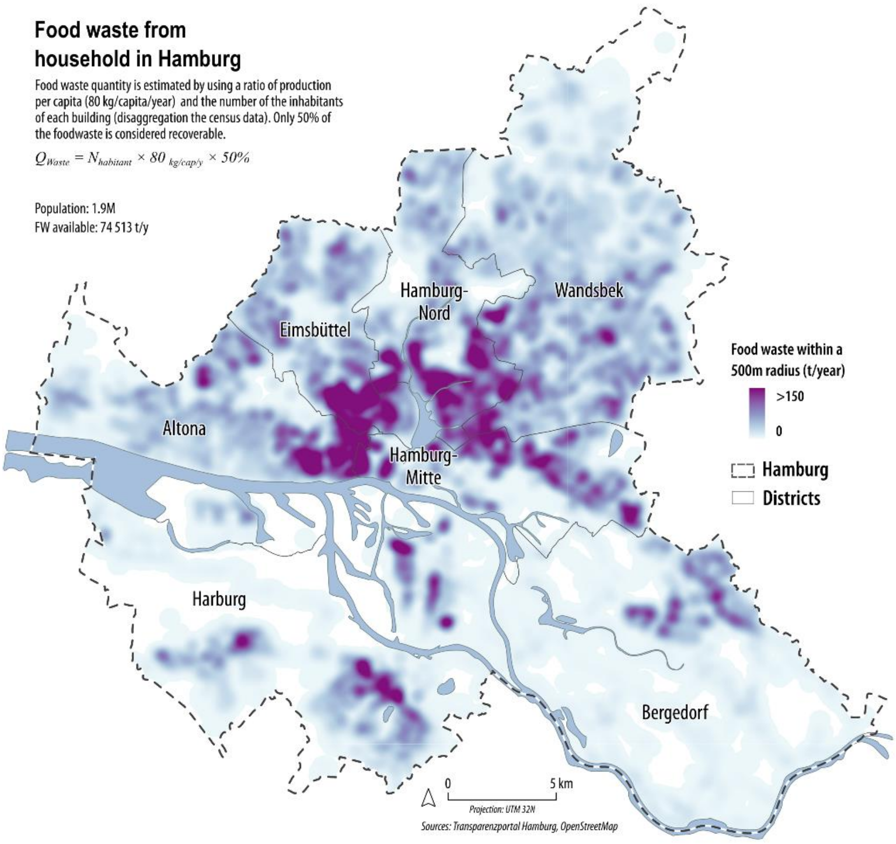


Figure 29: Heat map of the quantities of food waste sorted by household in Hamburg. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

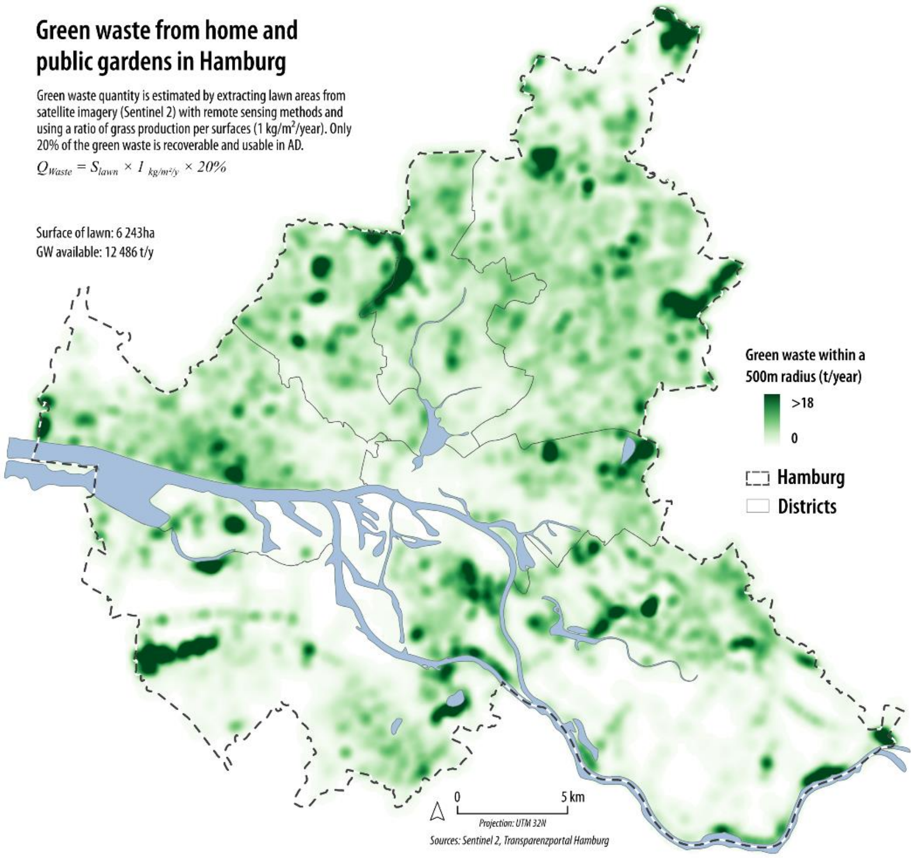


Figure 30: Heat map of the quantity of green waste (lawn cutting) collectable in Hamburg. The intensity of the color represents the quantity of green waste available at specific location and proximity (local density).

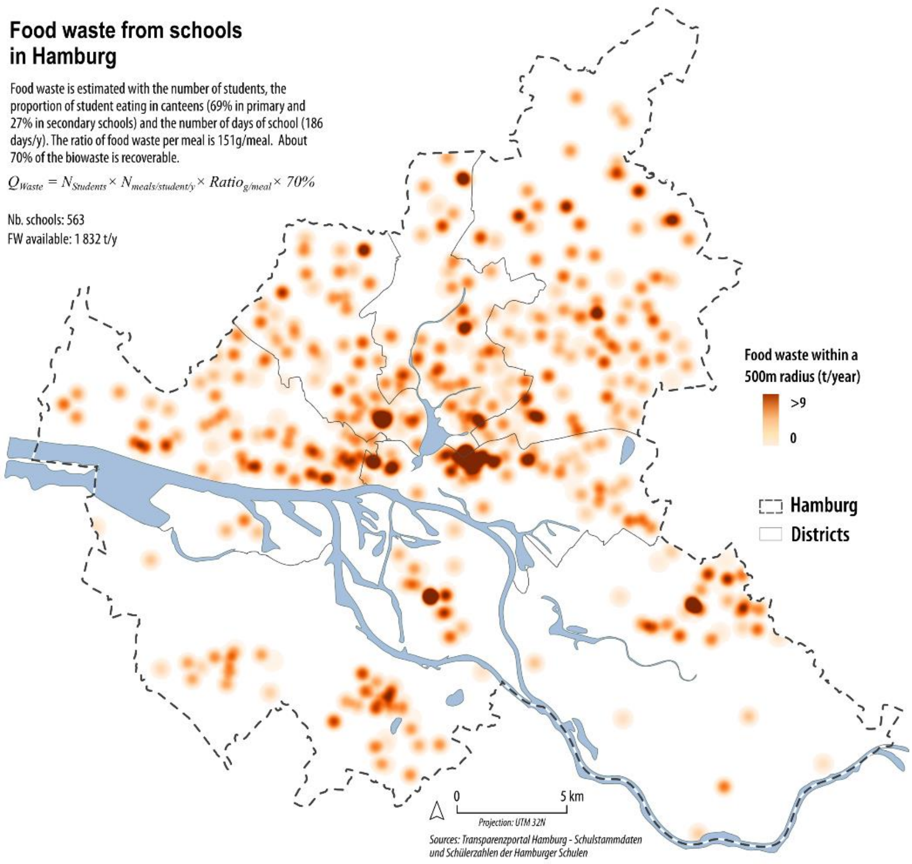


Figure 31: Heat map of the quantity of food waste sorted in schools of Hamburg. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

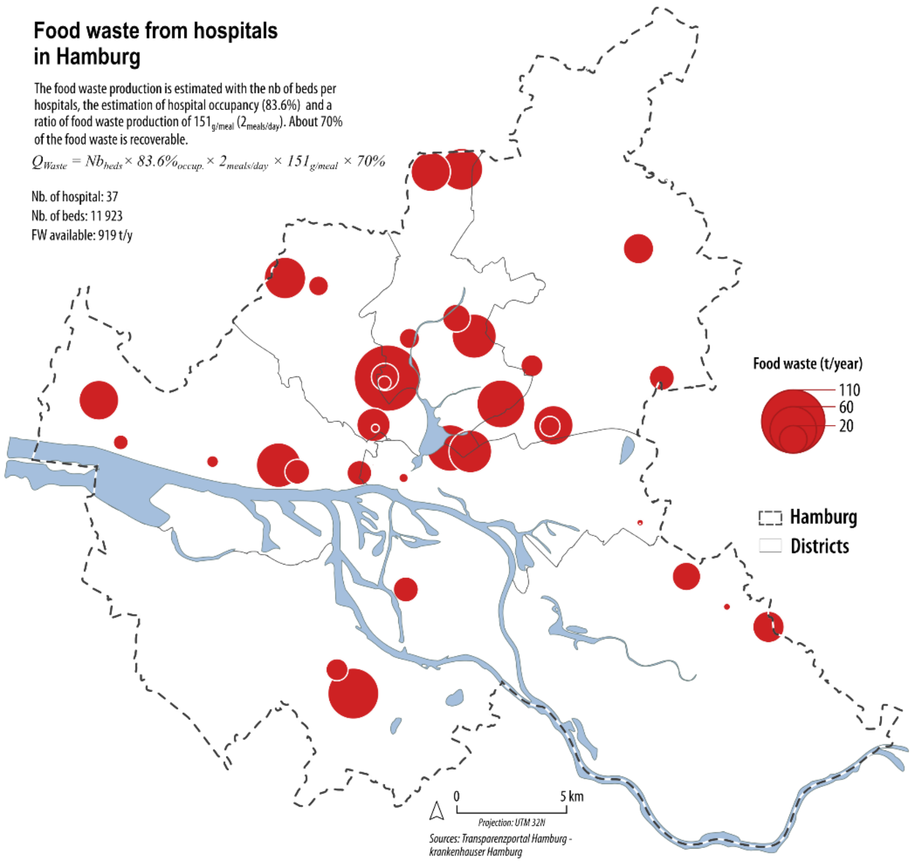


Figure 32: Map of the quantity of food waste sorted in hospitals of Hamburg.

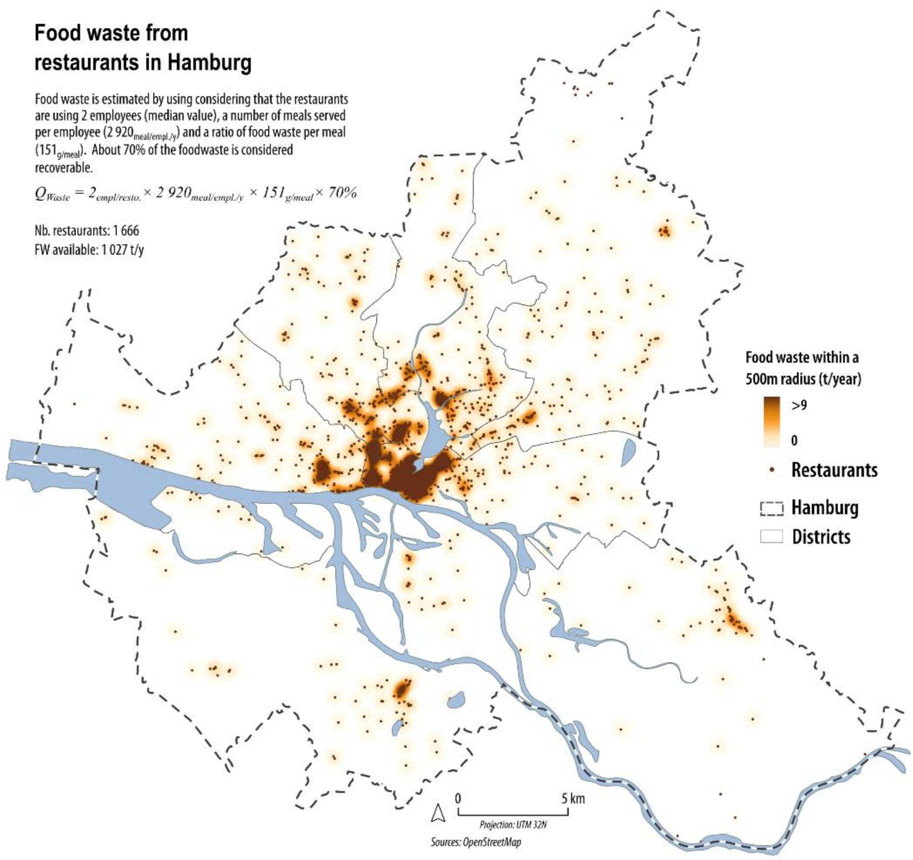


Figure 33: Heat map of the quantity of food waste sorted in the restaurants located in Hamburg. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density).

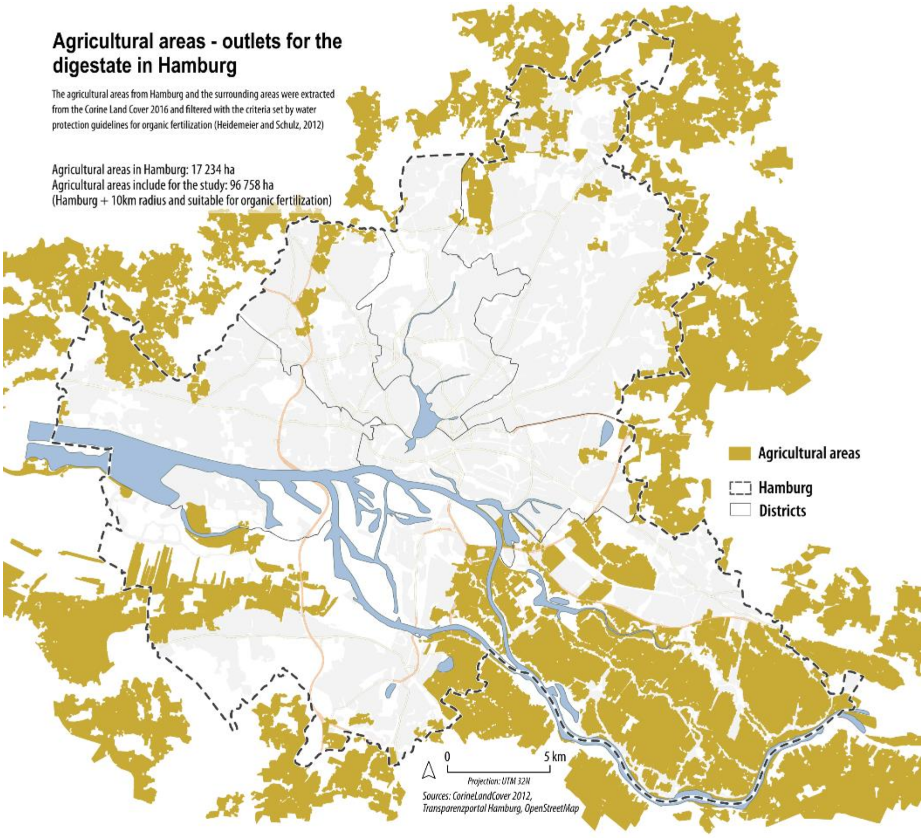


Figure 34: Map of the location of the agricultural areas in and around Hamburg (potential outlet for the digestate).

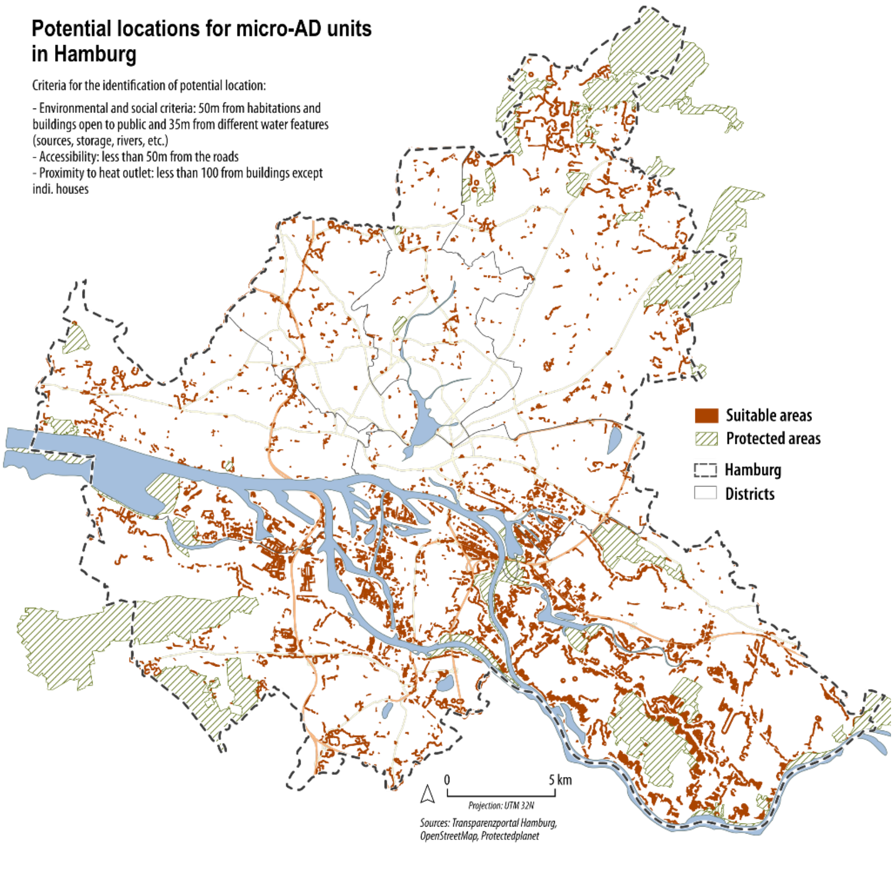


Figure 35: Potential locations for micro-AD units in Hamburg based on GIS multi-criteria analysis.

C. Grand Lyon

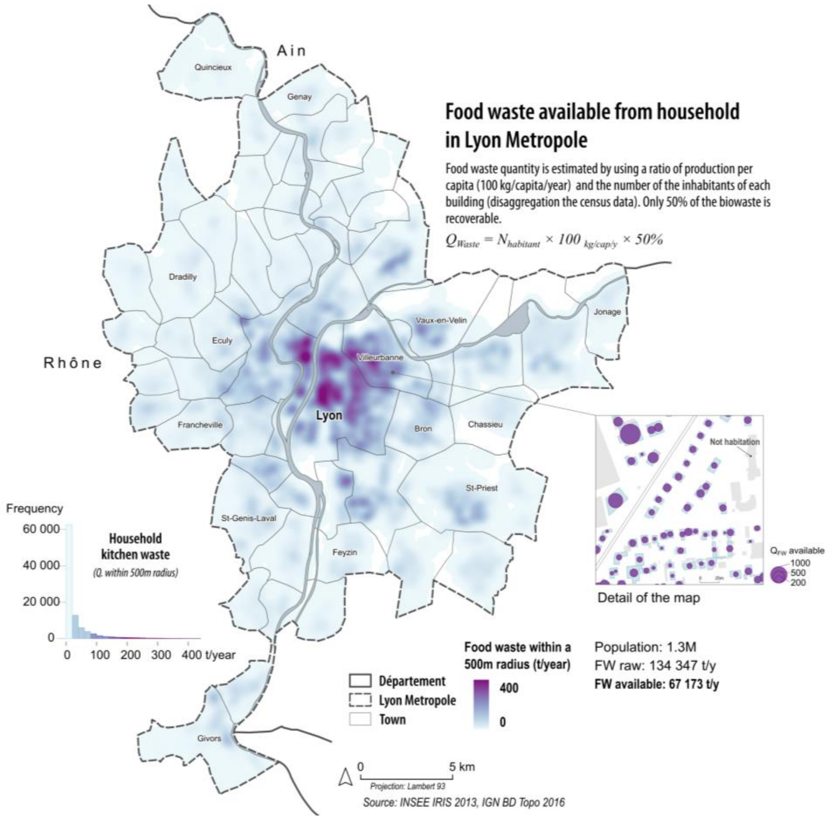


Figure 36: Heat map of the quantities of food waste sorted by household in GL. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density). The detail of the map shows the quantity of food waste estimated at the scale of the buildings. The histogram shows the food waste quantity available at proximity, given in number of pixels of the main map.

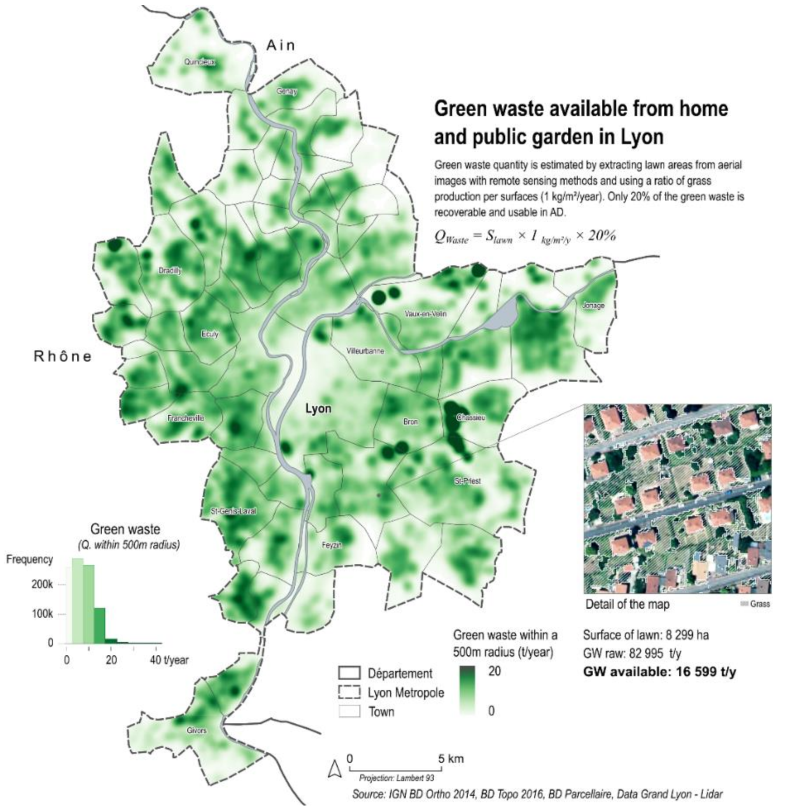


Figure 37: Heat map of the quantity of green waste (lawn cutting) collectable in GL. The intensity of the color represents the quantity of green waste available at specific location and proximity (local density). The insert map show details of the lawn location identified with the remote sensing analysis. The chart on the left of the map is the histogram of the green waste quantity available at proximity, given in number of pixels of the main map.

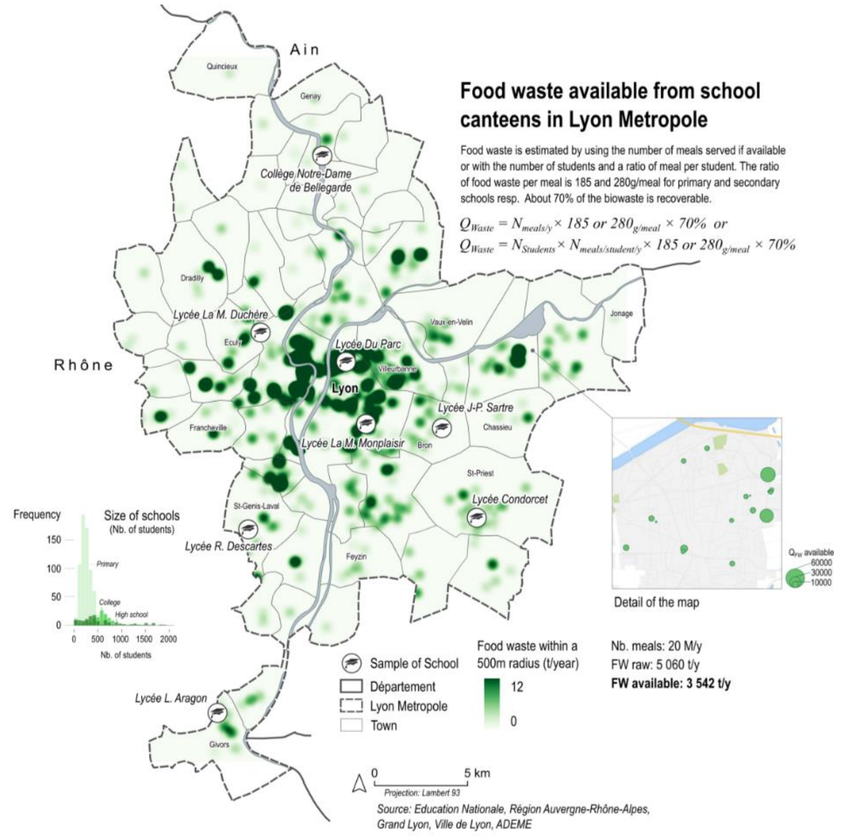


Figure 38: Heat map of the quantity of food waste sorted in schools of GL. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density). The insert map provides details of the school locations and the estimated quantity of sorted food waste. The histogram provides information about the size of the different types of schools in GL.

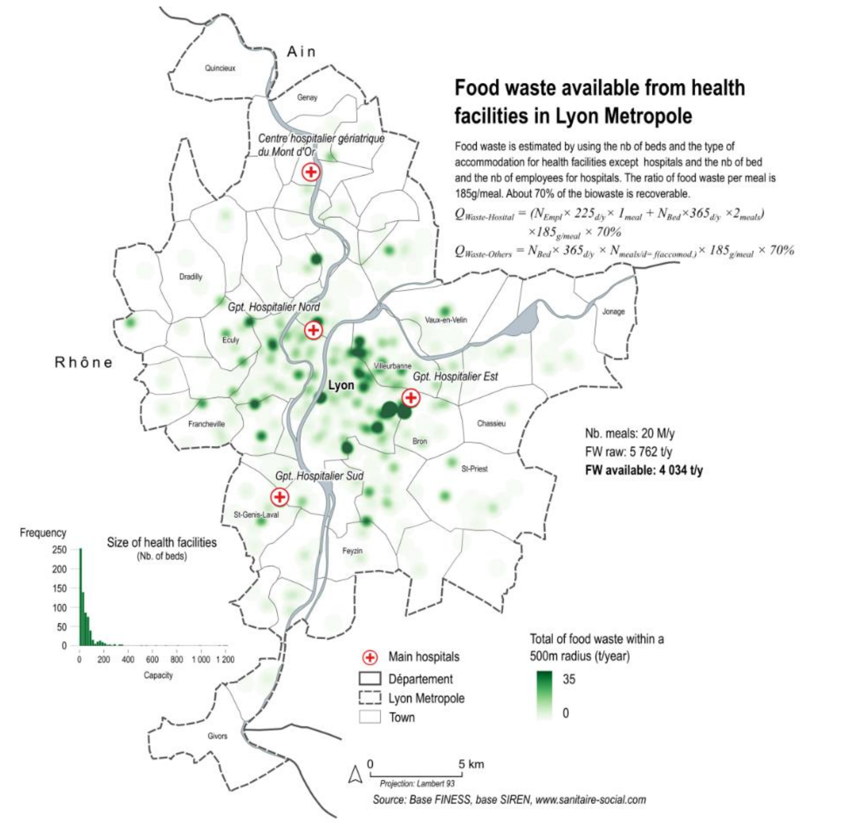


Figure 39: Heat map of the quantity of food waste sorted in health facilities of GL. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density). The chart on the left of the map is the distribution of the size of the hospitals in GL based on the number of beds available.

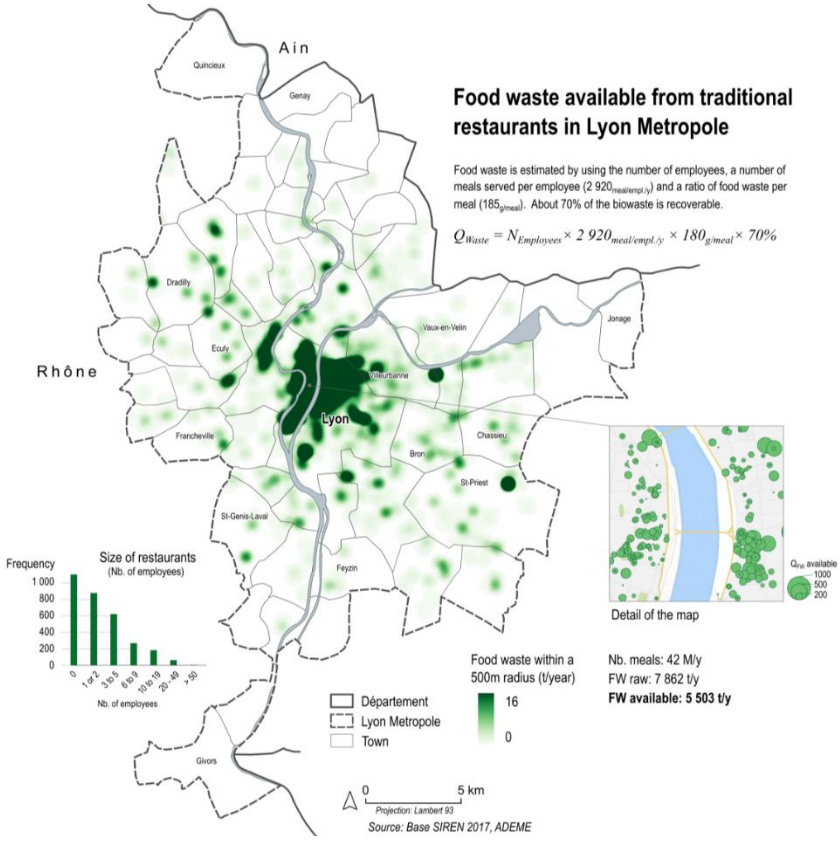


Figure 40: Heat map of the quantity of food waste sorted in the restaurants located in GL. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density). The insert map provides details of the location of the restaurants and the quantity of food waste estimated. The chart on the left of the map is the distribution of the size of the restaurants in GL based on the number of employees.

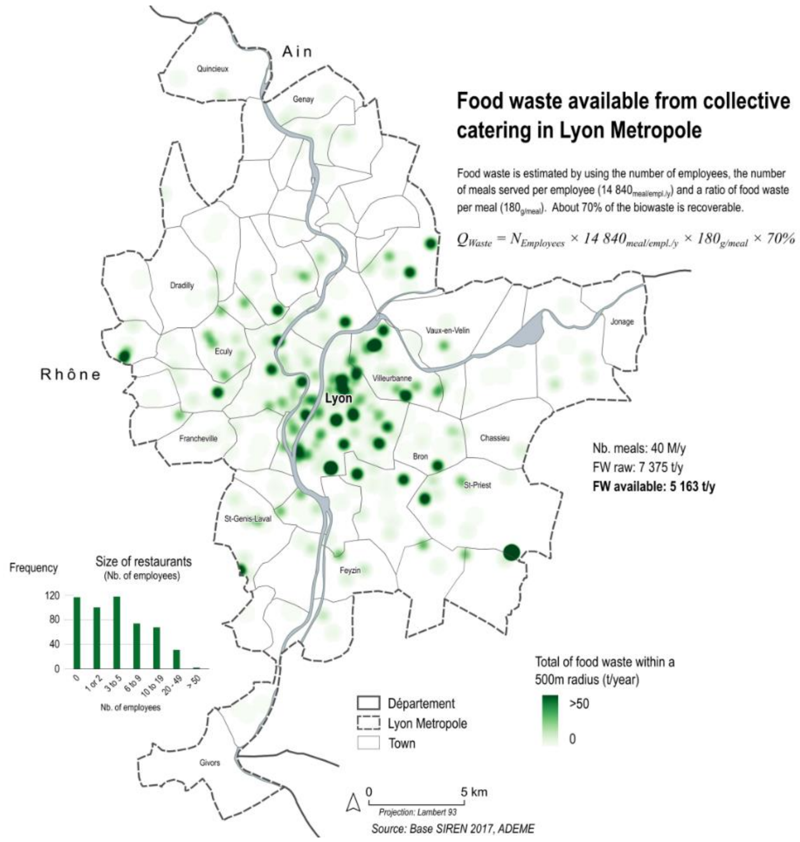


Figure 41: Heat map of the quantity of food waste sorted in the administrative or company canteens located in GL. The intensity of the color represents the quantity of food waste available at specific location and proximity (local density). The figure on the left of the map is the distribution of the size of the collective caterings services in GL based on the number of employees.

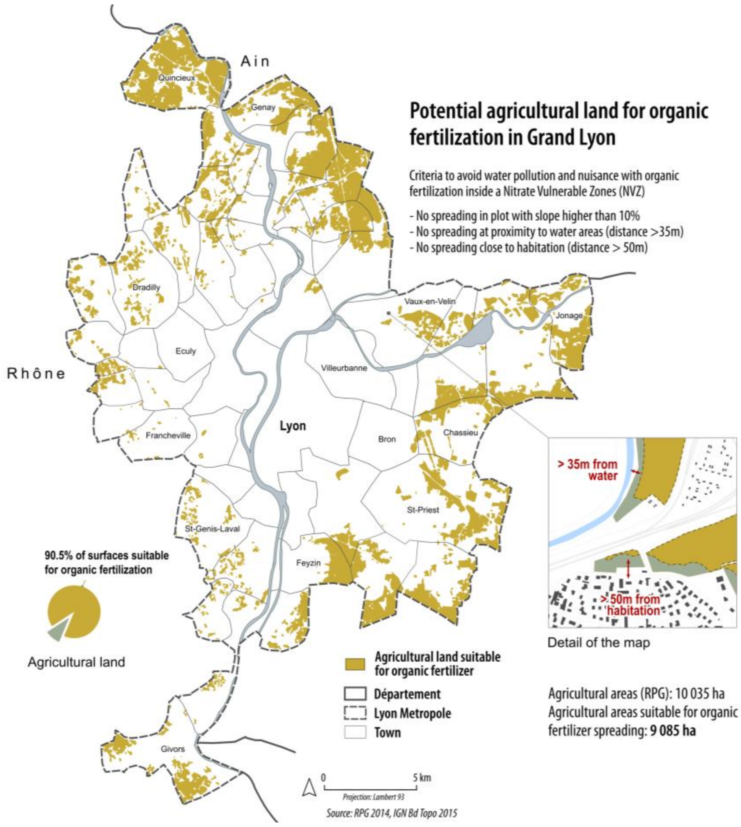


Figure 42: Location of the agricultural areas suitable for organic fertilization (Nitrate Vulnerable Zones criteria)

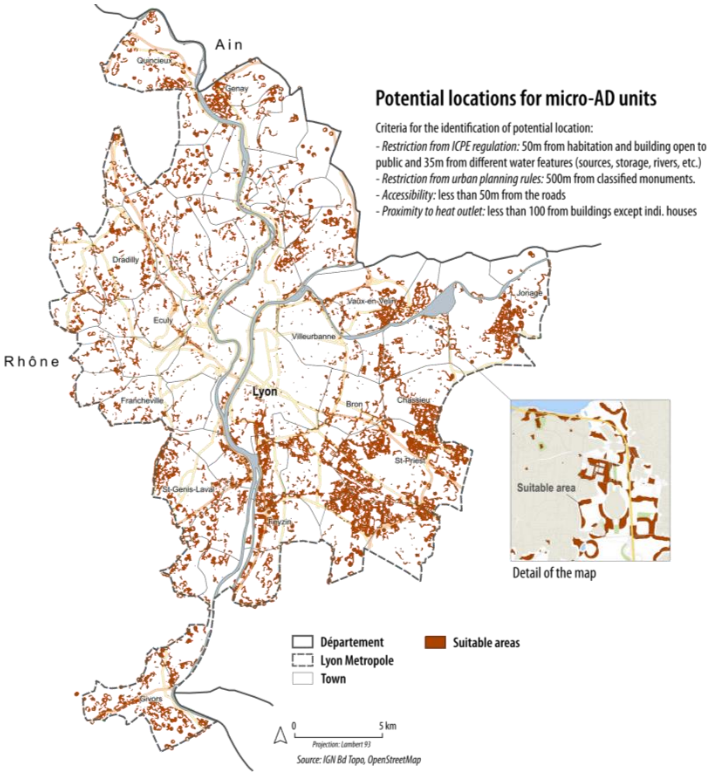


Figure 43: Potential locations for micro-AD units in GL.

Contact

Thiriet Pierre

pierre.thiriet@irstea.fr

Bioteau Thierry

thierry.bioteau@irstea.fr

Irstea Rennes

17 Avenue de Cucillé,
35000 Rennes
France