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Public report

Regional feedstock potentials and preference regions for HTL projects

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Project Information

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Public Report – Report on regional feedstock potentials and preference regions for HTL projects

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Abstract:

The hydrothermal liquefaction process (HTL) can convert a wide range of organic feedstock into transportation biofuels. So far, there are only few studies available that present spatially explicit data on feedstock availability specifically for HTL. The report investigates the potential availability for a selection of 14 individual types of promising biomass feedstock for HTL processes at the European (countries from EU-28 plus countries outside EU-28 but in continental Europe) and also at the regional level, including residue and waste streams with high moisture content. The spatially explicit data on feedstock availability is presented in form of feedstock density maps, which are suitable to identify preference regions for the development of future commercial HTL plants in Europe. Finally, a biofuel conversion model is applied to derive spatially explicit biofuel production potentials from the feedstock density maps. The results indicate that, assuming **100% exploitation rate**, between 40 million tonnes and 59 million tonnes HTL based fuel could be derived from the selected biomasses, which is at par with the current European jet fuel demand of about 57 million tonnes in 2017.

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Executive Summary

The hydrothermal liquefaction process (HTL) can convert a wide range of organic feedstock into transportation biofuels. However, there are only few studies available yet, that present figures for feedstock availability specifically for conversion processes based on hydrothermal liquefaction (HTL). The objective of this report is to provide information about the methodology for evaluating spatially explicit data on potential feedstock availability and to derive feedstock density maps, biofuel potentials and preference regions for the development of future HTL plants.

This report on regional feedstock potential and preference regions for HTL plants closes a knowledge gap regarding the potential feedstock availability for hydrothermal liquefaction. The regional availability of biomasses that are in particular suitable for HTL conversion, such as residue and waste stream with high moisture content, is often not known on a European scale. The assessment described in this report is based on results from a previous deliverable report of the HyFlexFuel project (D1.1 Report on results of feedstock potentials for selected HTL feedstock, confidential), which includes a list of aggregated feedstock availability for 54 individual biomass types on a European level. A downselection process condensed 14 individual biomass types according to several selection criteria such as total availability or market structures. In addition, feedstock which are currently scarcely used in Europe, but which show significant future potential, such as algae and miscanthus, are investigated in a combined quantitative and qualitative manner with respect to land availability and suitability.

The results indicate that, assuming a **100% exploitation rate** of the investigated feedstock, between 40 million tonnes and 59 million tonnes HTL based fuel could be derived from the selected biomasses, which compares to a current European jet fuel consumption of about 57 million tons in 2017. These values indicate that a considerable fraction of the annual jet fuel demand could potentially be supplied by HTL fuels within Europe.

Table of Contents

1. Introduction

Hydrothermal liquefaction (HTL) based conversion of biomass to renewable fuels is a highly promising conversion technology. Consequently, the whole process chain of HTL is part of significant research activities. The core advantage of HTL lies in its feedstock flexibility, as almost all biogenic carbon sources (such as sewage sludge, manure, agriculture and forest residues), as well as various crops can be used as input [1]. This very heterogeneous portfolio opens up the question, where relevant quantities of suited feedstock are available. As part of this process chain and within the activities of WP1 in the HyFlexFuel project, this report has the goal of providing a region - specific assessment of the promising biomass potentials already defined in Task1.1 (D1.1 – Report on screening results of feedstock potentials for selected HTL feedstock). Within the biomass potential assessment of HyFlexFuel, the theoretical biomass potential is considered as the total physical amount of an individual biomass type [2]. The technical biomass potential is considered as the result of the theoretical biomass potential minus specific indicators ensuring sustainable resource use, availability or technical restrictions.

The main objectives of Task 1.2 “Regional feedstock potential and preference regions for HTL projects” are:

- a region - specific assessment of the biomass potentials and availability for the feedstock defined in Task 1.1
- identification of suitable hot-spot regions as well as technical parameters and requirements regarding the HTL process
- development of parameters and requirements for the identification of regions suitable for the production of feedstock that are currently produced only in small quantities

The results of the previous Task 1.1 activity indicate that there is a considerable biomass potential in Europe. In total, 54 single types of biomass have been evaluated in Task 1.1. For full account of the screening of the European potential of biomass relevant for use as HTL feedstock, please refer to D1.1 (Report on screening results of feedstock potentials for selected HTL feedstock).

Please note that we use different approaches to assess the potential of waste and residue streams (sewage sludge, animal excretion, agricultural residues, etc.) on the one hand, and cultivated biomass (miscanthus, algae) on the other hand. First, we describe how the potentials for waste and residue streams are assessed, secondly the approach for determining available and suitable areas for cultivated biomass is explained. In terms of setting a context of the here presented approach, the technical potential of the biomasses is converted to HTL derived kerosene via a HTL conversion model. Although HTL process is able to generate a variety of different fuels, the jet fuel sector is seen as very promising.

The results indicate that, assuming an **100% exploitation rate** of the investigated feedstock, between 40 million tonnes and 59 million tonnes HTL based fuel could be derived from the described biomasses, which represents in the best case about 100 %

of Europe`s jet fuel, when comparing to Eurostat energy balance data from 2017 (51 Mt for international, and 6 Mt for national aviation)[1] [3].

The bandwidth is a result from the use of minimum and maximum calculation values (such as excretion rates or dry matter contents). However, it indicates that there is a tremendous potential available for HTL technology. Although it has to be mentioned, that current use of the resources is not part of this study. This will be examined in following supply-chain analysis for identified hot spots in the upcoming task 1.3.

[1] Note that the there is a slight mismatch between the countries analyzed in this study, and the number of total jet fuel demand cited here. While the total jet fuel demand is related to the EU-28, we also take into account European countries outside of the EU, such as Switzerland and Norway. Thus, the total jet fuel demand named here shows slightly lower figures, then if we would include all countries analyzed here.

2. Methodology for spatial assessment

To identify the biomass-based potential in on large geographic extents for further HTL processing, a three-stage process was used, illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**. First (STAGE 1A), biomass resource information was compiled, comprising the combination of calculation elements and the corresponding statistical data (Table 9 in Annex A). The potentials for the individual biomasses have been determined on a dry matter basis in tons.

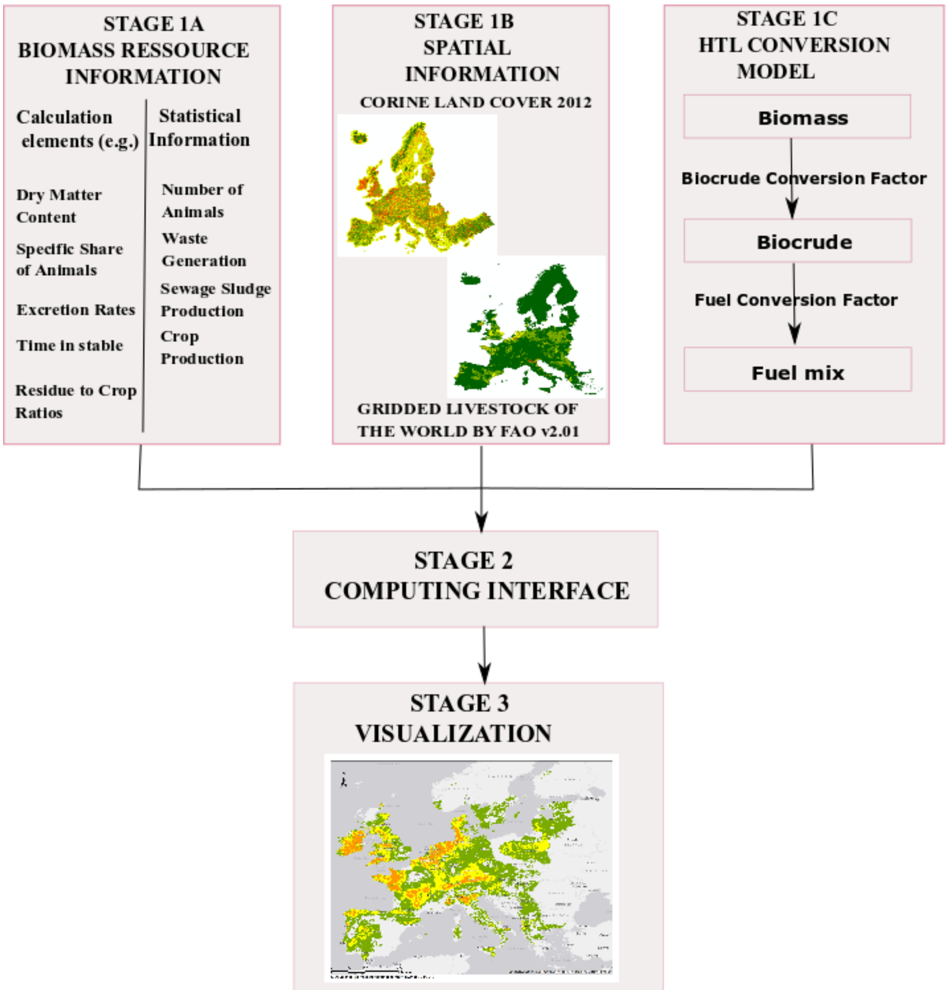

Figure 1 Process Scheme of methodology

STAGE 1A comprises the compilation of necessary data from reports, databases and literature. STAGE 1B includes the compilation of spatial information of areas associated with the production of the respective biomass (settlement area and cultivation area [4] as well as livestock distribution of cattle, pigs and poultry [5]). The third component comprises a HTL biomass feedstock to biofuel conversion model (STAGE 1C). The three different data inputs (STAGE 1 A-C) act as input for STAGE 2. Here, the different datasets are merged using Geographic Information System (GIS) software. Finally, the results are visualized in STAGE 3 as biomass potentials per square km.

2.1 Biomass resource information (Stage 1A)

In order to concentrate on the most promising feedstock, the preliminary list of 54 individual biomass types produced in Taks1.1 has been further condensed. The selection was performed according to, first, the suitability for HTL process and, second, the availability in terms of reported theoretical biomass potentials. Finally, feedstock, which are tied to functioning, markets, such as products or residues made from wood, have not been considered. As a result, for the spatially explicit distribution of feedstock for biofuel conversion through HTL processes, the following biomasses have been selected:

- Excretions from cattle, pigs and poultry including breakdown into solid dung, manure and slurry
- Cereal straw including straw from wheat, barley, oat and rye
- Sugarbeet leaves
- Biowaste including breakdown in separately and not separately collected
- Maize stover
- Oilseed rape straw
- Sewage sludge
- Rice straw
- Sunflower straw

The above-mentioned biomasses are currently seen as the most promising ones and have been further analyzed in Task 1.2. Chemical characterization of these most promising feedstock identified during the biomass potential assessment is part of Task 1.4.

Besides the biogenic wastes and residues mentioned above, several energy crops (e.g. miscanthus and algae) would be suitable as feedstock for HTL process with regard to the raw material properties. However, the biomass potential of these biomasses is difficult to determine, as other criteria for land suitability and sustainability have to be applied. We will elaborate this in more detail further below.

Within the biomass potential assessment presented here, minimum and maximum values are shown for biomass potentials from livestock excretions and agricultural by-products. This is due to the diverging information that can be found regarding excretion rates and dry matter contents. Consequently, giving a range as outcome of biomass potential assessment seems more appropriate as single values.

2.1.1 Feedstock definition and data sources

In order to ensure a common understanding of the biomasses that are further analysed, this chapter presents their definitions for the context of HyFlexFuel. Furthermore, the data sources for the following spatial analysis are presented. A detailed overview on the numeric values used is given in Table 9 of Annex A.

Sewage Sludge

According to Kaltschmitt et el. (2016) sewage sludge is considered as the residue produced from primary (physical and/or chemical), secondary (biological) and tertiary (often nutrient removal) wastewater treatment processes where liquids and solids are separated [6]. Its handling is a major challenge within densely populated areas. Within this study, numbers presented for sewage sludge potential encompass primary, secondary and tertiary treated sewage sludge, as a distinction of the three different types of sludge is not feasible at European level due to missing data. Data for the biomass potential assessment are taken from population statistics [7] and sewage sludge per capita production [8]. Both figures are available on national level. Current utilization pathways encompass agricultural use, composting, landfill or incineration with varying share within the European Union. The specific utilization is not determinable at the European level now due to a lack of data. Even though exact numbers are not available, it can be stated that sewage sludge is predominantly treated using anaerobic digestion and/or incineration [9].

Biogenic Municipal Waste

Biogenic municipal waste (biowaste) is considered as the biogenic fraction of municipal waste from households. Within this study, waste from industry and restaurants or supermarkets is not considered due to a lack of European-wide data. Within this category, separated and unseparated biogenic municipal waste is considered. Currently, municipal waste is landfilled, incinerated, composted or recycled in the European Union with a strong trend towards less landfilling and more efficient ways of waste treatment, framed by a plurality of legislation. Figures for biomass potential calculation of biogenic municipal waste on European level was available for municipal waste generated per capita [10], total country population [7], the share of organic content and the share of biowaste being collected separately [11] on national level. Finally, dry matter content was assumed equal for all countries [12].

Animal Excretions

To assess the amount of animal excretions within the European Union, the “Gridded Livestock of the World” dataset from the Food and Agriculture Organization of the United Nations (FAO) was taken as basis for animal heads [13]. A further distinction between different animal types has been performed on national level. Within this study the term animal excretions include solid dung, slurry and manure from pigs and cattle as well as slurry and solid dung from poultry. According to Eurostat, solid dung is excrements with or without litter of domestic animals including possibly a small amount of urine. In addition, Foged et al. (2012) states that solid dung “normally having a dry matter content of 20-30 % and being removed from the livestock stables on a daily basis, and placed in a manure pad with drains to collect effluents and rain water” [14].

Slurry is manure in liquid form (mixture of excrements and urine) and according to Foged et al. (2012) “usually a mix of faeces and urine from livestock, bedding material with small structure like sawdust or chopped straw, washing water, water spill, etc. and originating from stables with whole or partly slotted floors. Normally having a dry matter content of 2-10 %, and flowing out of the livestock stables via piping systems by gravity or pumping, and placed in a liquid manure tank, in some cases with cover in order to reduce ammonia emissions” [14].

Manure (or liquid manure) is considered as “normally having a dry matter content of 2-10 %, and flowing out of the livestock stables via piping systems by gravity or pumping, and placed in a liquid manure tank, which is closed/with cover in order to reduce ammonia emissions” [14].

Cattle

In order to determine the most accurate biomass potential information on a European level, this study distinguishes seven different types of cattle (bovine < 1 year, bovines 1-2 years male, bovines 1-2 years female, bovines > 2 years, heifers > 2 years, dairy cows and other cows) and their share on national level [5]. Furthermore, the excretion is distinguished between solid dung, slurry and manure on a national level [14]. Excretion rates and dry matter content are given with a minimum and maximum value each to determine a sound bandwidth [15–17]. To determine the technical biomass potential, the time in stable (in %) is multiplied with the theoretical biomass potential where data was available on NUTS2 level [18].

Pigs

Analog to the assessment of cattle excretion biomass potential, three different types of pigs were distinguished (sows, piglets, other pigs) with their respective share being available on national level [5]. Type of excretion was distinguished between solid dung, slurry and manure on national level [14]. Excretion rates and dry matter content are given with a minimum and maximum value each to determine a sound bandwidth according to the methodology used for cattle excretions [15–17]. To determine the technical biomass potential, the time in stable is taken into consideration where data was available on NUTS2 level [18].

Poultry

Poultry excretions is only distinguished between slurry and solid dung due to non-availability of manure from poultry [14]. Within this study poultry is distinguished on national level between three different types (broilers, laying hens and other poultry) [5]. Excretion rates and dry matter content are given with a minimum and maximum value each to determine a sound bandwidth according to the methodology used for cattle excretions [15–17]. Analog to cattle and pig excretions, time in stable is taken into consideration where data was available on NUTS2 level [18].

Agricultural by-products

In this study, cereal straw, maize stover, sunflower straw, oilseed rape straw, rice straw and sugarbeet leaves are considered. In a broader sense, straw can be seen as a predominantly dry plant by-product. It is generated from a large variety of plants during harvesting, such as maize, wheat or rice [19].

Cereal straw is considered to be the above-ground part of the cereal plant. It consists mainly of cellulose, hemicellulose and lignin combined in the parts that remain after the nutrient grain or seed have been removed by grain harvesting [20]. Maize stover is considered as the leaves and stalks of maize crops. It stands out through a high nutrient content but low feeding value due to a low concentration of digestible dry matter and proteins [21].

Sunflower straw, oilseed rape straw and rice straw are analogously considered as residual leaves and stalks of their respective plants after harvesting. Sugarbeet leaves originate from the production of sugar from sugar beets. In most cases, the leaves are left in the fields as fertilizer since they are not of use for sugar production. In contrast to most types of straw, sugar beet leaves have a high water content. Dried, they are comparable to leaves of other plants, such as seaweed or banana leaves [22].

For calculating the biomass potential of straw and other agricultural residues, national figures for production area and yield were used [23]. Specific residue-to-yield ratios were used for cereal straw, maize stover, oilseed rape straw, rice straw and sunflower straw [24], as well as sugarbeet leaves [25] on European level. Dry matter content as well as sustainable removal rate have been considered on a European level [26,27]. Detailed numeric values used for the calculation can be found in Table 9 of Annex A.

2.2 Spatial information (Stage 1B)

Next, the resource data explained above is combined with spatial information using the CORINE Landcover dataset and FAO Gridded Livestock of the World dataset.

CORINE (Coordination of Information on the Environment) Land Cover (CLC) is an inventory initiated in 1985 by the European Commission. It provides a uniform classification of land cover. Since 1985, updates have been performed regularly. The inventory is produced by mainly visual interpretation of high resolution satellite images. A minority of the inventory is produced via semi-automatic approaches. Currently, 44 uniform land cover classes are available for Europe. The data has a thematic accuracy of ≥ 85 %, geometric accuracy of better than 100m and a minimum mapping unit of 100m. Classifications used for the potential assessment encompass the following land cover classes:

Table 1 CORINE Land Cover classes

Level 1	Level 2	Level 3
1 Articial Surfaces	11 Urban fabric	111 Continuous urban fabric
		112 Discontinuous urban fabric
	12 Industrial, commercial and transport units	121 Industrial or commercial units
		122 Road and rail networks and associated land
		123 Port areas
		124 Airports
	13 Mine, dump and construction sites	131 Mineral extraction sites
		132 Dump sites
		133 Construction sites
	14 Artificial, non-agricultural vegetated areas	141 Green urban areas
		142 Sport and leisure facilities
2 Agricultural areas	21 Arable Land	211 Non-irrigated arable land
		212 Permanently irrigated land
		213 Rice fields
	22 Permanent crops	221 Vineyards

		222 Fruit trees and berry plantations
		223 Olive groves
	23 Pastures	231 Pastures
	24 Heterogenous agricultural areas	241 Annual crops associated with permanent crops
		242 Complex cultivation patterns
		243 Land principally occupied by agriculture, with significant areas of natural vegetation
		244 Agro-forestry areas

For the biomass potential assessment of sewage sludge and biowaste, the land cover classes 111 and 112 have been used, as the emergence of these two biomass categories are strongly related to settlement areas. For the biomass potential assessment of the plant based individual biomass types, the land cover categories 211, 212, 213 (for rice straw only), 241, 242 and 243 have been used. Their individual definition is shown in *Table 1*.

The FAO Gridded Livestock of the world is provided as grids with data on livestock density as heads per square kilometer. The 2012 version of this data has been used for the biomass potential assessment within HyFlexFuel. Basically, sub-national livestock statistics are collected and cross-referenced with other sources and then linked to the respective GIS data of this area (e.g. environmental data and spatial data). Next, the two data sources (statistics and GIS data) serve as Input to Global Livestock Impact Mapping System (GLIMS), a FAO owned software program to further process and manage the data. More detailed information can be found in [13]. Today, the mentioned livestock grids are available for cattle, pigs, chicken, sheep and goats. Since sheep and goats are mainly grown on open land, their excretions cannot be collected effectively and where thus neglected.

2.3 HTL conversion model

While the previous chapter discussed biomass feedstock potentials, this chapter focuses on biofuel potentials. In order to present biofuel potentials biomass potentials are converted to biofuel potentials using a HTL conversion model. This is explained in this chapter in more detail. Since biocrude is the primary target product in the HTL process, biocrude yield is often used as central metric to measure process efficiency. The biocrude yield is expressed as ratio of the feedstock input (dry matter) to the obtained biocrude:

$$Y_{bc} = \frac{m_{FS}}{m_{bc}} \tag{1}$$

Where:

Y_{bc} : biocrude yield

m_{FS} : mass (dry matter) of the feedstock

m_{bc} : mass (dry matter) of the bioocrude

To determine the biocrude yield of various waste biomasses we used a linear regression model developed by Wang et al. [28] which turned out to be a suitable prediction of biocrude yield. This model uses as input carbohydrate (X_C), protein (X_P) and lipid content (X_L) of the biomass and was initially developed for the use of sewage sludge in continuous HTL plants, but can also be applied to other feedstocks. The biocrude yield for a balanced distribution of the components lipids, protein and carbohydrates ((X_p<30, X_L<20, X_C<80) can be calculated according to the model as follows:

$$\boldsymbol{Y_{bc,1}} = \big((\mathbf{16.701} * \boldsymbol{X_L} + \mathbf{8.8709}) + (\mathbf{1.1828} * \boldsymbol{X_P} + \mathbf{3.5485}) + (-\mathbf{0.7014} * \boldsymbol{X_C} + \mathbf{71.543})\big)/3 \quad (2)$$

Where:

X_L : mass fraction lipis

X_P : mass fraction proteins

X_C : mass fractioncarbohydrates

For feedstock with a high protein content (X_p>30 wt%) as well as for feedstock with high carbohydrate (X_C>80) content equation 3 was used:

$$\boldsymbol{Y_{bc,2}} = \big((\mathbf{0.0333} * \boldsymbol{X_L} + \mathbf{33.565}) + (\mathbf{0.1341} * \boldsymbol{X_P} + \mathbf{27.059}) + (-\mathbf{0.0984} * \boldsymbol{X_C} + \mathbf{37.114})\big)/3 \quad (3)$$

Results for biocrude yield are shown in Table 3. Please note that the model is subject to a certain degree of uncertainty, as biocrude production of different feedstock differs not only in their biochemical composition but also in other characteristics such as their macroscopic structure, ash composition or water content. Additionally it has to be mentioned that the biocrude yield and composition also depend on selected process conditions. The effect of pressure and temperature on reaction kinetics is not represented in this model.

The fuel conversion factor F_{fuel} includes both: the quantity and the quality of the produced biocrudes.

$$\boldsymbol{F_{fuel}} = \boldsymbol{Y_{bc}} * \boldsymbol{Y_{fuel}} \quad (4)$$

Where:

F_{fuel} : fuel conversion factor

Y_{fuel} : fuel yield

X_P : mass fraction proteins

X_C : mass fractioncarbohydrates

For calculating the fuel yield, we refer to the composition of experimentally obtained biocrudes. The chemical analysis of the biocrudes pruduced by HTL using manure, sewage sludge and lignocellulosic is shown in Table 2.

Table 2 Composition and HHV of different biocrudes

Feedstock group	Composition (daf)							HHV	Ref
	water	ash	C	H	N	S	O	in MJ/kg	
Manure	-	-	71.2	9.5	3.7	0.12	15.6	34.7	[1]
Sewage sludge	14.0	28.4	58.2	6.5	2.4	0	5.9	60.40	[29]
Lignocellulosic	18.3	2.8	68.5	7.3	1.2	0	17.7	71.09	[30]

For a first approximation, our approach considers only the carbon content in the biocrude, since ash, water, and heteroatoms should be completely removed during upgrading. Fuel yield Y_{fuel} and carbon yield C_{Yfuel} can be described according to equations 5 & 6:

$$Y_{fuel} = \frac{m_{fuel}}{m_{bc}} \tag{5}$$

Where:
F_{fuel} : fuel conversion factor
m_{fuel} : mass (dry matter) of the fuel

$$CY_{fuel} = const. = \frac{m_{C,fuel}}{m_{C,bc}} = \frac{x_{C,fuel} * m_{fuel}}{x_{C,bc} * m_{bc}} = \frac{x_{C,fuel}}{x_{C,bc}} * Y_{fuel} \tag{6}$$

Where:
CY_{fuel} : carbon yield
$m_{C,fuel}$: mass (dry matter) of carbon in the fuel
$m_{C,bc}$: mass (dry matter) of carbon in the biocrude
$X_{C,fuel}$: mass fraction of carbon in the fuel
$X_{C,bc}$: mass fraction of carbon in the biocrude

This results in fuel yield Y_{fuel}:

$$Y_{fuel} = CY_{fuel} * \frac{x_{C,bc}}{x_{C,fuel}} \tag{7}$$

In the model described, the assumption has been made that carbon yield corresponds to a fixed value. Based on a carbon balance developed by Castello et al. [31] a value of 87 wt.% is selected for carbon yield CY_{fuel} of balanced and high protein feedstock and a value of 78 wt.% for lignocellulosic feedstock. The carbon content of the fuel mix is considered 84.6 wt.%. These assumptions result in the linear equation 8 for the calculation of the fuel yield, which depends on biocrude carbon content:

$$Y_{fuel} = 1.037 * X_{C,bc} \tag{8}$$

The composition of experimentally obtained biocrude was used to calculate the fuel yield. Biocrude of miscanthus was used as lignocellulosic representative, as this energy grass is similar in composition to lignocellulosic residual currents and results for this feedstock on a continuous HTL are available [32]. For manure, biocrude compositions based on results from HTL batch experiments were used [1]. Using animal excretions in a continuous HTL plant, slightly different compositions are to be expected. However, this data is sufficient for an estimation of the yield of fuel mix.

Table 3 Conversion factors for biocrude and upgraded fuel

Feedstock group	Represented waste stream	Biocrude yield Y_{bc} [-]	Fuel yield Y_{fuel} [-]	Fuel conversion factor F_{fuel} [-]
Balanced	Sewage sludge	0.387	0.694	0.27
High protein	Manure	0.331	0.599	0.20
Lignocellulosics	Wheat straw	0.298	0.632	0.19

The model is based on the calculation of the biocrude yield of different feedstocks described above. Since this model is already subject to uncertainties depending on the application, a reliable statement regarding the fuel yield is additionally challenging.

2.4 Computing

The above described input (STAGE 1A – STAGE 1C) has been further processed in a GIS using ESRI software according to the methodology used in [33,34]. Here, the qualitative data from statistics, reports and scientific literature has been intersected with the spatial data from CORINE land cover and FAO Gridded Livestock of the world, respectively. This process will be explained in more detail using the example of sewage sludge

2.4.1 Data intersection using the example of sewage sludge

First, data about considered feedstock was gathered, more specifically statistical data of sewage sludge per capita per country, which is available as figures on national level in Europe, has been derived from Eurostat. Next, this data was multiplied with population information. Because of the need to be displayed spatially, the data was connected to NUTS3 population layer provided by the European Commission (Figure 2).

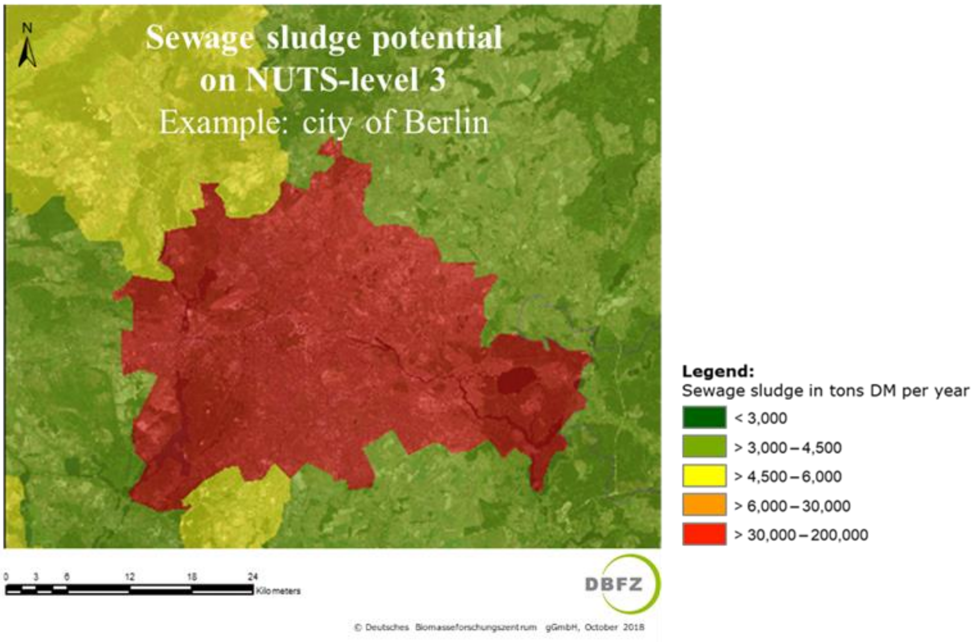

Figure 2: *Example of sewage sludge potential on NUTS3 level*

Next, spatially explicit information about wastewater concentration and collection areas was needed. For the case of sewage sludge, the settlement area was chosen as the regional scale of analysis, where wastewater and thus sewage sludge is produced. Furthermore, wastewater treatment plants, where the sewage sludge is collected, are closely located to settlement areas because of the high water content and hygiene problems regarding wastewater transport.

For this purpose, data from CORINE land cover has been taken due to its high spatial and thematic resolution. CORINE land cover provides a large set of different thematic layers. Determining the settlement area, classes 111 and 112 have been selected and connected to the NUTS3 layer with sewage sludge potential per NUTS3 polygon. As a result, one has information about the settlement area in one NUTS3 polygon (Figure 3).

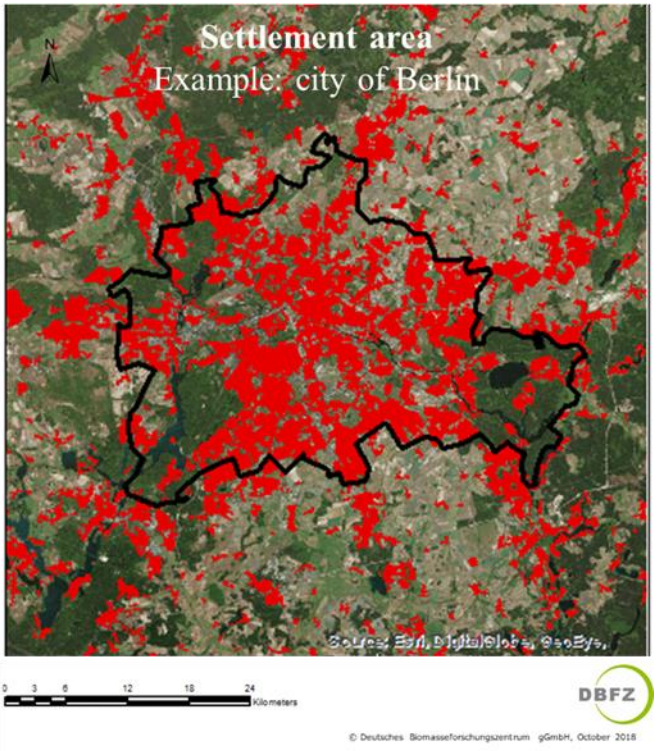

Figure 3 Settlement area in Berlin

Based on the information of sewage sludge production per settlement area in one NUTS3 polygon (division of total settlement area in NUTS3 polygon and total sewage sludge per NUTS3 polygon), the sewage sludge production per km² can be derived. This information again is used to calculate the sewage production in each settlement polygon (size in km² is known) of each NUTS3 region in Europe. With regard to further data processing, the information was transferred to a grid. Thus, the centroid of each settlement area has been computed and connected to the biomass potential information of its former polygon.

Another reason for the conversion of vector based data (settlement area polygons) to raster cells is the possibility to further use this data for catchment area analysis. This has been done using neighbourhood analysis tools from ESRI GIS software. Here, values for raster cells within a predefined circle are accumulated. Finally, one has generated catchment area based biomass potential maps. The grid cells from which the catchment area analysis has been started are the common basis and have been created for each individual biomass types. This allows a future intersection of different feedstock.

Using ESRI GIS software, the results of the combination STAGE 1A and 1B are further multiplied with the conversion factors from the HTL conversion model explained in chapter 2.3. Finally, results are visualized in maps.

2.4.2 Calculation of spatially explicit biomass potentials

In the following, the equations for the determination of the biomass potentials on a dry matter basis are shown:

Sewage sludge potential calculation

Biomass based potential from sewage sludge was estimated calculating the sum of the sewage sludge potential of each polygon of CORINE Landcover data from classes 111 (continuous urban fabric) and 112 (discontinuous urban fabric) in Europe using equation 9 & 10:

$$\boldsymbol{THP_{SW} = \sum p\ (PO_p\ x\ SW)} \quad (9)$$

with

$$\boldsymbol{PO_p = \frac{A_p}{A_N}\ x\ PO_N} \quad (10)$$

Where:
THP_{SW} : theoretical biomass potential of sewage sludge
PO_p : population per polygon p
p : polygons from CORINE Landcover classes 111 and 112
SW: sewage sludge per capita as dry matter
A_p : area per Polygon
A_N : area per NUTS3 Region
PO_N : population per NUTS3 Region

Because of missing data on local use of sewage sludge across Europe, only the theoretical biomass potential was calculated.

(Not) separately collected biowaste potential calculation

CORINE Landcover classes 111 and 112 have also been used for the estimation of biomass based potential derived from biowaste, either separately collected or collected without prior separation in EU. The methodology for biomass based potential calculation has been derived from the S2Biom project incorporating theoretical as well as technical biomass potentials [12]. Within this study, biowaste is distinguished between separately collected and unseparately collected biowaste. The latter one is estimated by adding a *biowaste fraction* element to the calculation which is available on national level. The theoretical biomass potential has been calculated using equation 11:

$$\boldsymbol{THP_{BW} = \sum p\ (PO_p\ x\ MSW\ x\ BF\ x\ DM)} \quad (11)$$

The technical biomass potential has been calculated following equation 12 and encompassing a factor for the percentage of biowaste that is collected separately within the EU. These numbers are derived from [11]. Table 9 of Annex A shows the relevant numerical values and assumptions.

$$\boldsymbol{TEP_{BW} = (THP_{BW}\ x\ SCF)} \quad (12)$$

Where:
THP_{BW} = Theoretical biomass potential of (un)separately collected biowaste
p : polygons from CORINE Landcover classes 111 and 112
PO_p : population per polygon p
MSW = Municipal solid waste per capita
BF = Biogenic Fraction
DM = Dry matter content
TEP_{BW} = Technical biomass potential of (un)separately collected biowaste
SCF = Share of separate collection

Excretions from livestock production

The biomass based potential from livestock production is divided into three animal classes, namely cattle, pigs and poultry. A further division was made between solid dung, slurry and liquid manure. As the calculation of these biomass potentials are similar a summarizing calculation approach is used here. Equation 13 illustrates the calculation of the theoretical biomass potential for the different types of livestock considered within this study.

$$\boldsymbol{THP_{AE} = \sum(N_{AH}\ x\ AH_S\ x\ EF_S\ x\ DM)} \qquad (13)$$

The technical biomass potential has been calculated combining the theoretical biomass potential and information about housing of the specific type of animal head formulated in equation 14. Used numerical values and assumptions are shown in Table 9 of Annex A.

$$\boldsymbol{TEP_{AE} = \sum(THP_{AE}\ x\ HT_{AE})} \qquad (14)$$

Where:
THP_{AE} = theoretical biomass potential of animal excretions (tonnes DM/year)
N_{AH} = Animal heads
AH_S = Specific share of animal heads
EF_S = Specific Excretion Factor of each specific animal head type
DM = dry matter content
TEP_{AE} = Technical biomass potential of animal excretions
HT_{AE} = Specific housing type of each respective animal head

Plant based biomass potential

Cereal Straw (wheat, oat, barley and rye), sunflower straw, sugarbeet leaves, rice straw, oilseed rape straw and maize stover form the group of plant based potential for HTL based processes. As their biomass potential is calculated very similarly, they are summarized within this group. The calculation of biomass based potential from this group has been done for the theoretical biomass potential as well as technical biomass potential. Equation 15 illustrates the calculation for the theoretical biomass potential.

$$\boldsymbol{THP_{PB}} = \sum(\boldsymbol{PA_{PS}}\ \boldsymbol{x}\ \boldsymbol{SY}\ \boldsymbol{x}\ \boldsymbol{RYR}\ \boldsymbol{x}\ \boldsymbol{DM}) \tag{15}$$

In order to assess the technical biomass potential, the sustainable removal rate was considered for each type of agricultural by-product assessed here. This concept follows the respective biomass potential calculation proposed by S2Biom project (Base potential) and encompasses the biomass part that can be removed while keeping the soil organic carbon constant (Equation 16). Used numerical values and assumptions are shown in Table 9 of Annex A.

$$\boldsymbol{TEP_{PB}} = \sum(\boldsymbol{THP_{PB}}\ \boldsymbol{x}\ \boldsymbol{SRR_{PS}}) \tag{16}$$

Where:
THP_{PB} = Theoretical biomass Potential Plant based biomass
PA_{PS} = Plant specific Production Area
SY = Specific Yield
RYR = Specific Residue to Yield Ratio
DM = Dry matter content
SRR_{PS} = plant specific sustainability removal rate
TEP_{PB} = Technical biomass potential plant based biomass

3. Results

The 14 different single biomasses have been partially aggregated for result visualization in order to reduce the number of figures to be shown. Lignocellulosic single biomasses (different types of straw and sugarbeet leaves) have been aggregated to agricultural by-products. Animal excretions in form of solid dung, slurry and liquid manure have been aggregated for their respective type of animal. Sewage Sludge and biowaste are shown individually. In this section the theoretical as well as the technical biomass potentials are shown in tons dry matter (except for sewage sludge due to low data availability) , whereas the biofuel potential is expressed in tons. Biocrude potentials are not presented as this is only an intermediate product.

For the visualization of the results, the biomass and biofuel potentials are presented in a certain catchment area. This is done to better visualize potential distribution. Agricultural by-products are presented within a catchment area of 50km, animal excretions within 10km, sewage sludge and biowaste within 20km.

For the purpose of better illustration the values 0 – 299 tons dry matter have been removed from the figures (0-49 at poultry excretions). The reason for this is the high concentration of values in this bandwidth. Displaying all values would decrease readability of the feedstock potential maps.

3.1 Agricultural By-products

The here presented single biomasses of maize stover, rice straw, wheat straw, sunflower straw, rapeseed straw and sugarbeet leaves are aggregated to agricultural by-products. As the calculation element residue-to-yield ratio is given within a bandwidth, the results are presented as minimum (MIN) and maximum (MAX) values for a 50km catchment area.

The theoretical biomass potential of agricultural by-products is shown in Figure 21 and Figure 22 of Annex C. The theoretical potential for a catchment area of 50km is tremendous and about 4,200,000 tons dry matter. Here, the difference between minimum and maximum is not very significant since calculation elements only show little variance. After the application of the technical restriction factors for agricultural by-products, the technical biomass potential shown in Figure 23 and Figure 24 of Annex C is between 1,900,000 and 2,100,000 tons dry matter. With regard to the HTL biomass to fuel conversion model, the available fuel potential is shown in Figure 4 and Figure 5, and amounts to 350,000 and 400,000 tons biofuel. Preference regions for the use of agricultural by-products are highlighted in orange and red color and can be found in regions such as northern and western France, parts of Romania and Bulgaria and in Denmark. Regarding the maps shown in Figure 21 and Figure 22 only little variance can be observed in terms of color mapping. This is due to the small bandwidth for agricultural by-products potential.

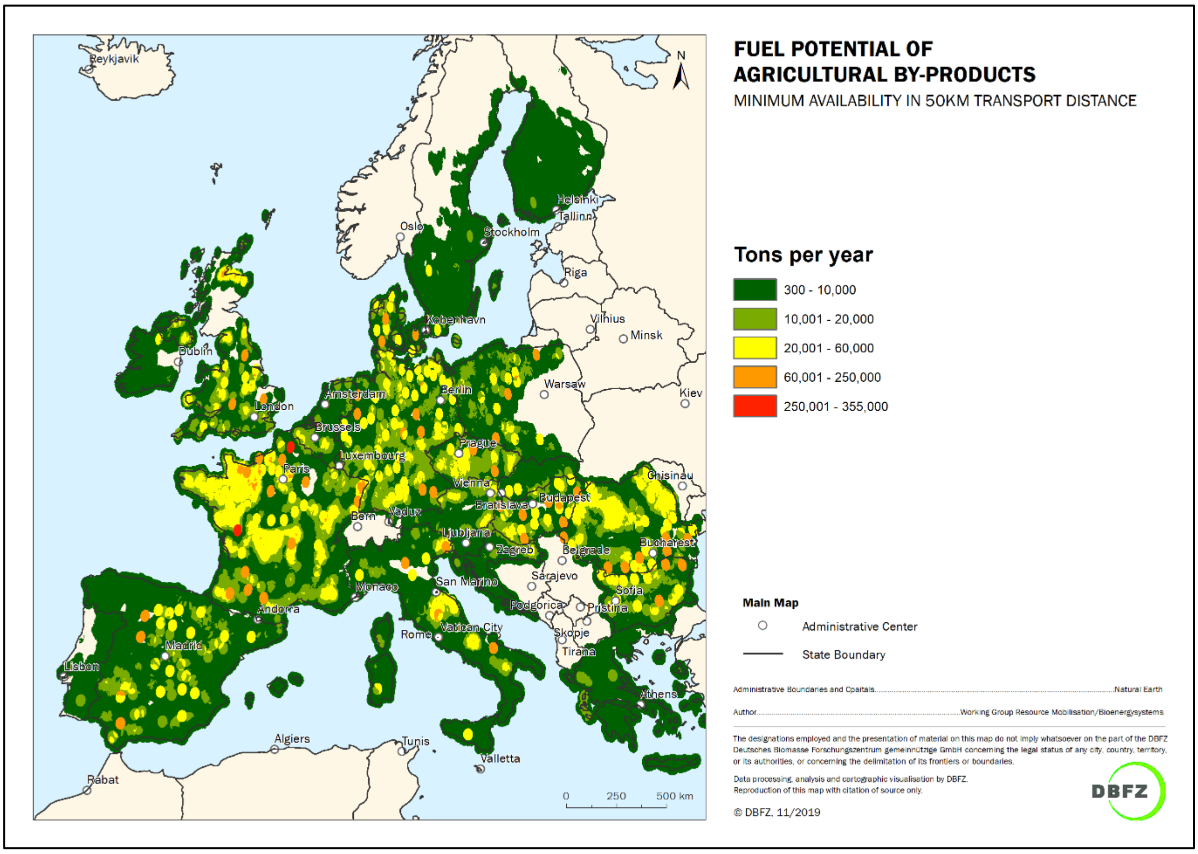

Figure 4 Minimum biofuel potential from agricultural by-products

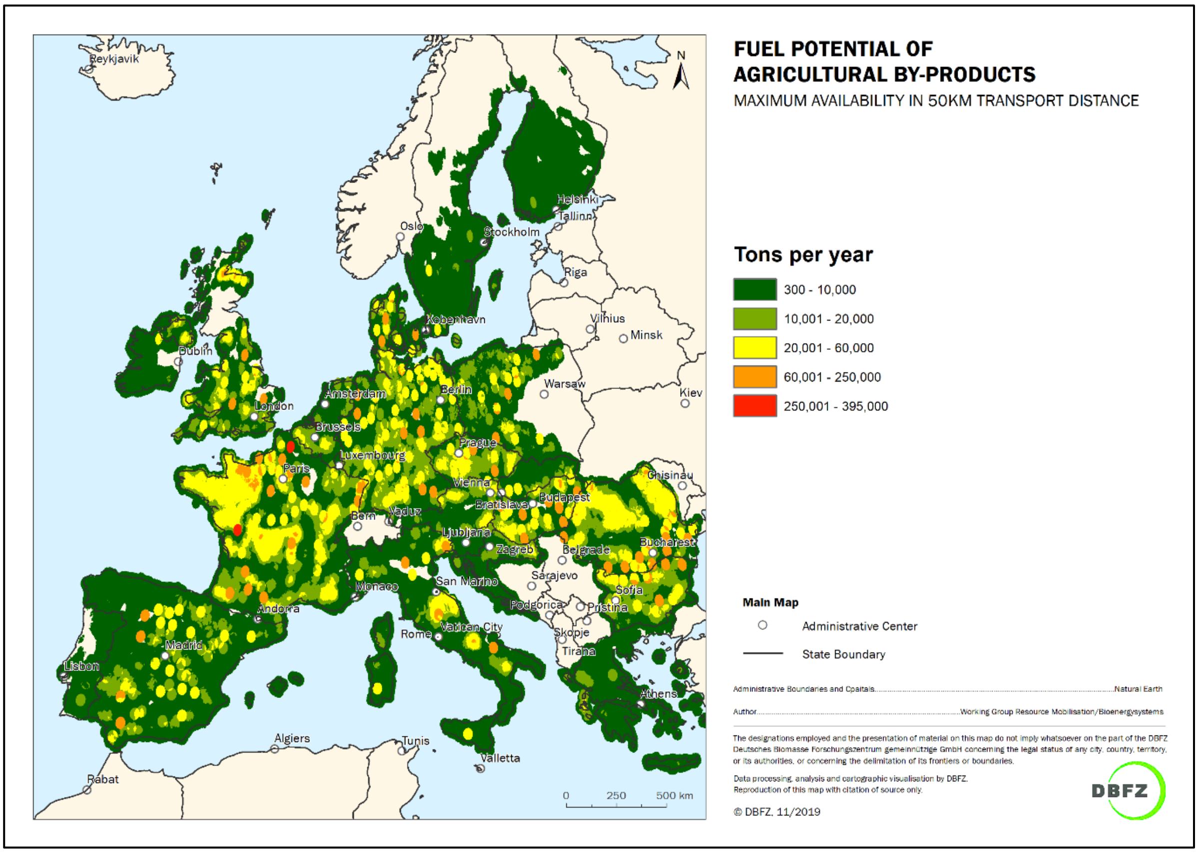

Figure 5 Maximum biofuel potential from agricultural by-products

3.2 Animal Excretion

3.2.1 Cattle

Animal excretions from cattle have been aggregated from the animal classes bovine < 1 year, bovines 1-2 years male, bovines 1-2 years female, bovines > 2 years, heifers > 2 years, dairy cows and other cows and the different excretion types liquid manure, slurry and solid dung. Because animal specific excretion factors vary in the literature, potential figures of cattle excretions are presented with a bandwidth. The theoretical potential of cattle excretions is given in Figure 25 and Figure 26 of Annex C, which roughly ranges from 150,000 to 350,000 tons dry matter within each catchment area. Applying the technical restriction factor of time in stable results in a technical potential between 84,000 and 192,000 tons dry matter (Figure 27 and Figure 28 of Annex C). A further reduction of those potential figures to HTL derived biofuel results in a bandwidth between 17,000 and 42,000 tons biofuel (Figure 6 and Figure 7). Preference regions for the HTL based production of biofuel from cattle excretions are seen in the northern parts of Italy and several parts of the Benelux countries.

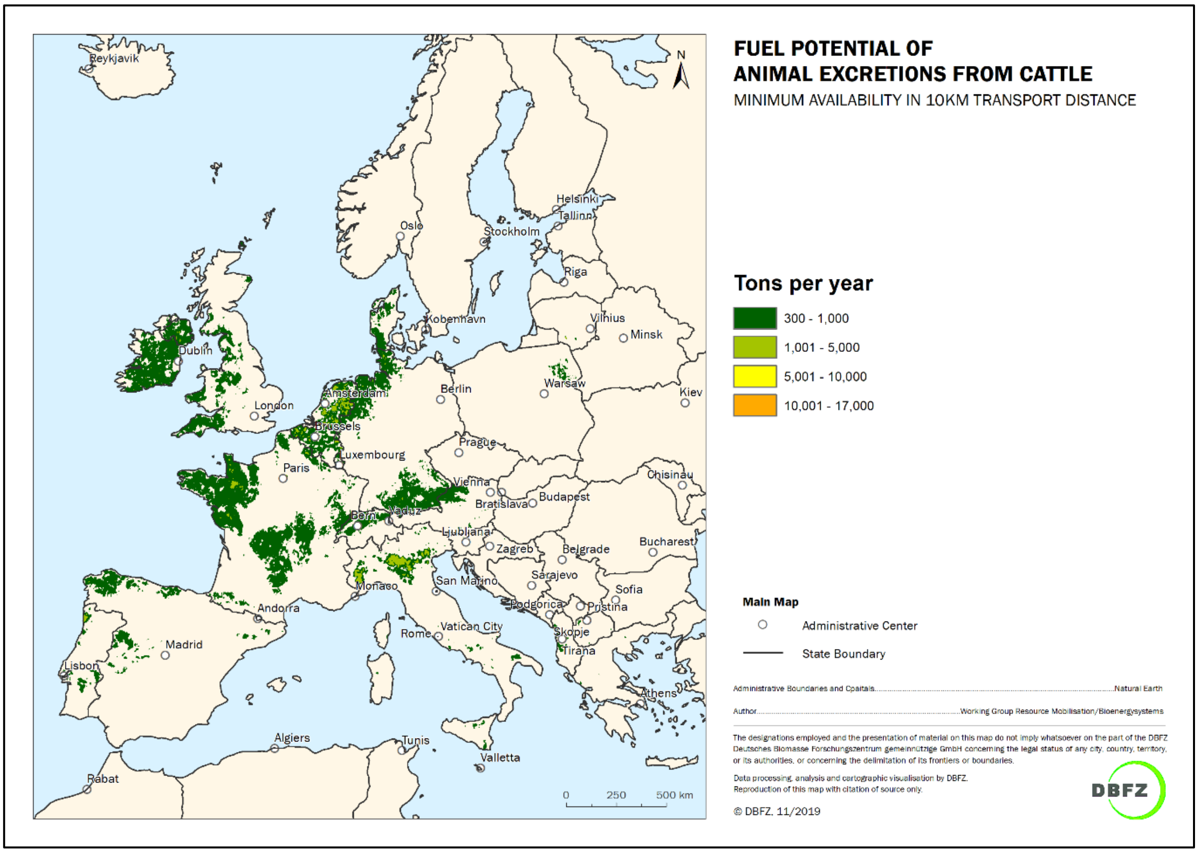

Figure 6 Minimum biofuel potential from cattle excretions

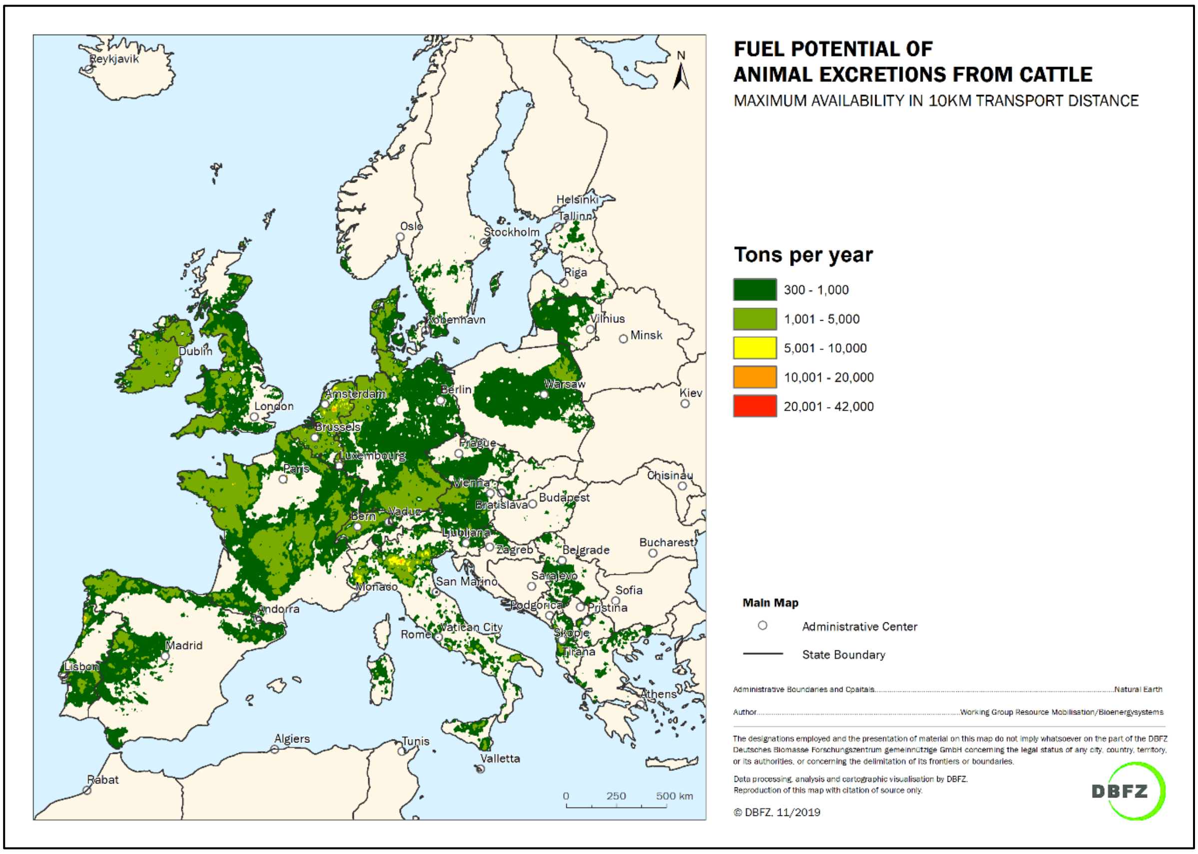

Figure 7 Maximum biofuel potential of cattle excretions

3.2.2 Pigs

Animal excretions from pigs have been aggregated from the animal classes piglets under 20kg, breeding sows over 50kg and others and the different excretion types liquid manure, slurry and solid dung. Because animal specific excretion factors vary in the literature, potential figures of pigs excretions are presented with a bandwidth. The theoretical potential of pigs excretions is given in Figure 29 and Figure 30 of Annex C, amounting to 21,000-81,000 tons dry matter within each catchment area. Applying the technical restriction factor of time in stable results in a technical potential between 21,000 and 80,000 tons dry matter (Figure 31 and Figure 32 of Annex C). A further reduction of those potential figures to HTL derived biofuel results in a bandwidth between 4,100 and 16,000 tons biofuel (Figure 8 and Figure 9). Preference regions for the HTL based production of biofuel from cattle excretions are seen in the northern parts of Italy, eastern parts of the Benelux countries, northwestern parts of Spain and several regions in Denmark.

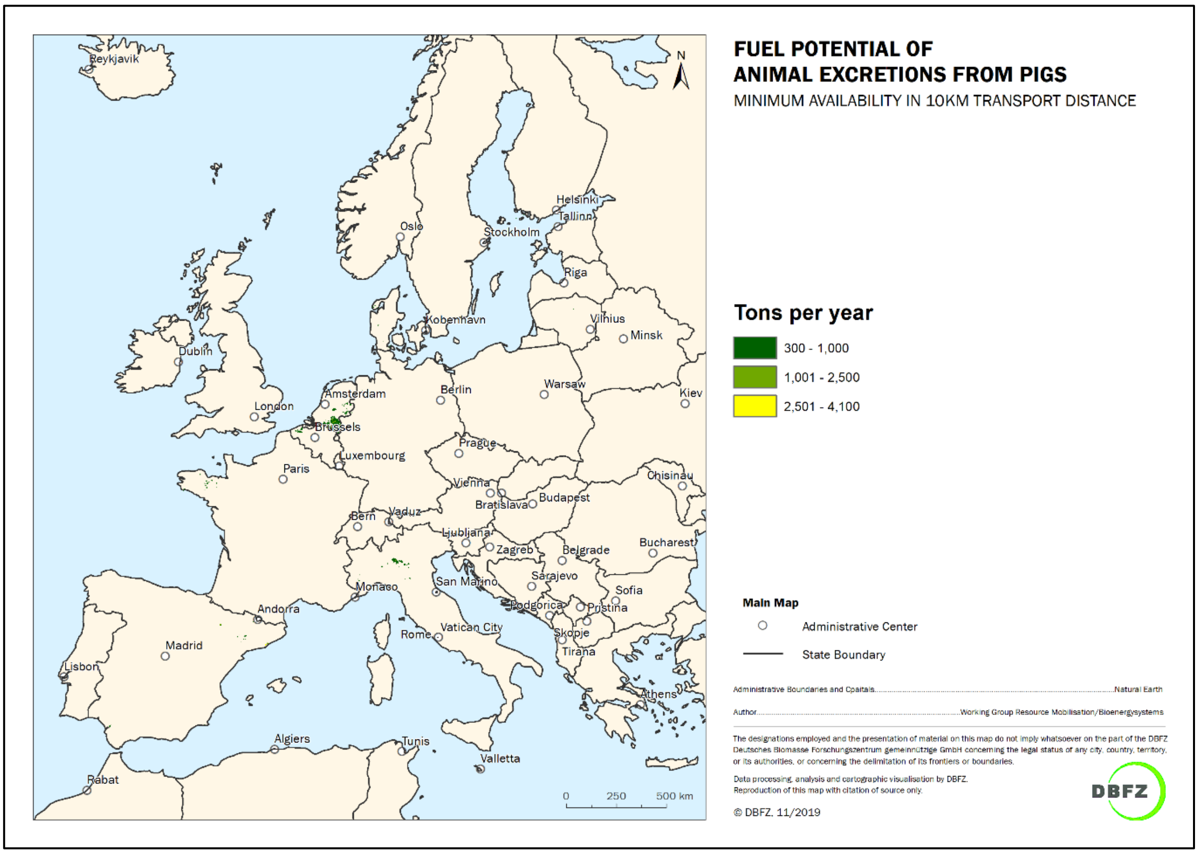

Figure 8 Minimum biofuel potential of pig excretions

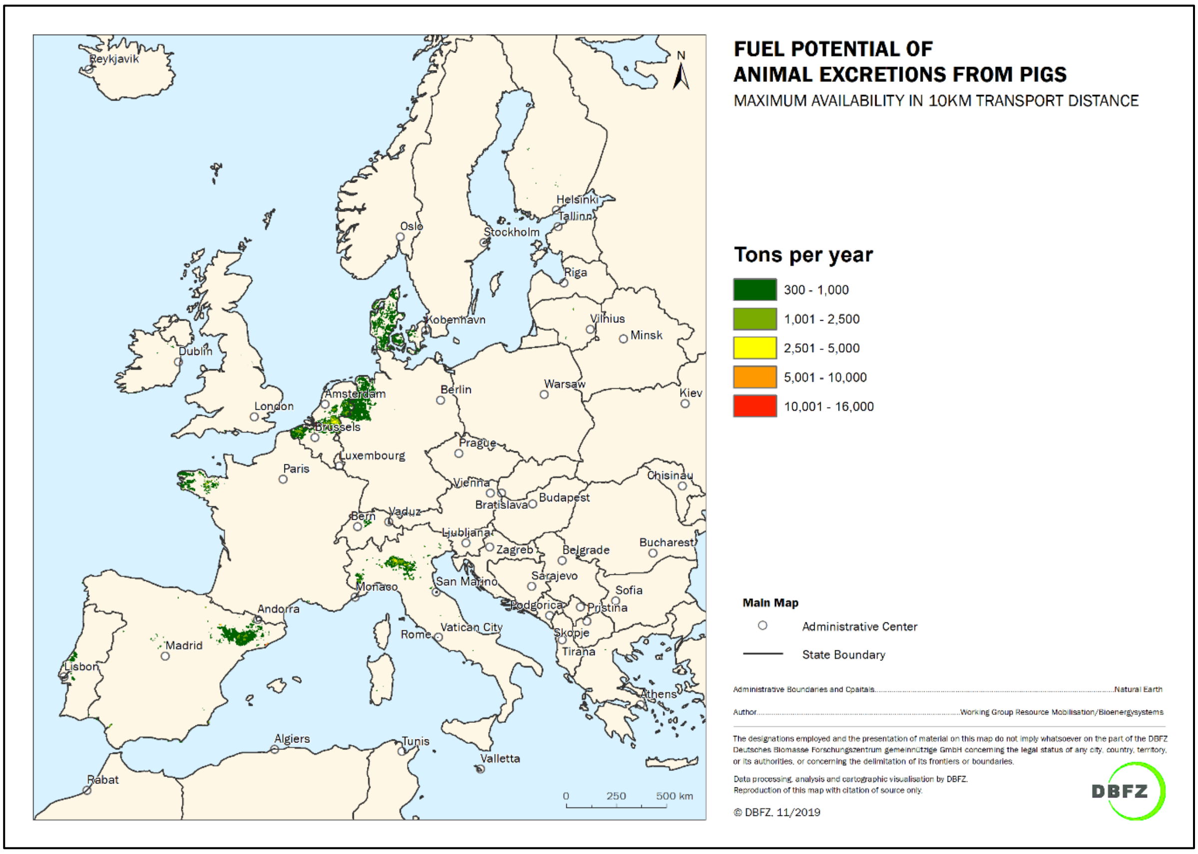

Figure 9 Maximum biofuel potential of pig excretions

3.2.3 Poultry

Animal excretions from poultry have been aggregated from the animal classes broilers, laying hens and others and the different excretion types liquid manure and slurry. Because animal specific excretion factors vary in the literature, potential figures of poultry excretions are presented with a bandwidth. The theoretical potential of poultry excretions is given in Figure 33 and Figure 34 of Annex C. It is between 107,000 and 120,000 tons dry matter within each catchment area. Applying the technical restriction factor of time in stable results in a technical potential between 1,050 and 1,200 tons dry matter (Figure 35 and Figure 36 of Annex C). A further reduction of those potential figures to HTL derived biofuel results in a bandwidth between 150 and 240 tons biofuel (Figure 10 and Figure 11). Preference regions for the HTL based production of biofuel from poultry excretions are seen in the eastern parts of the Benelux countries and northern parts of Italy.

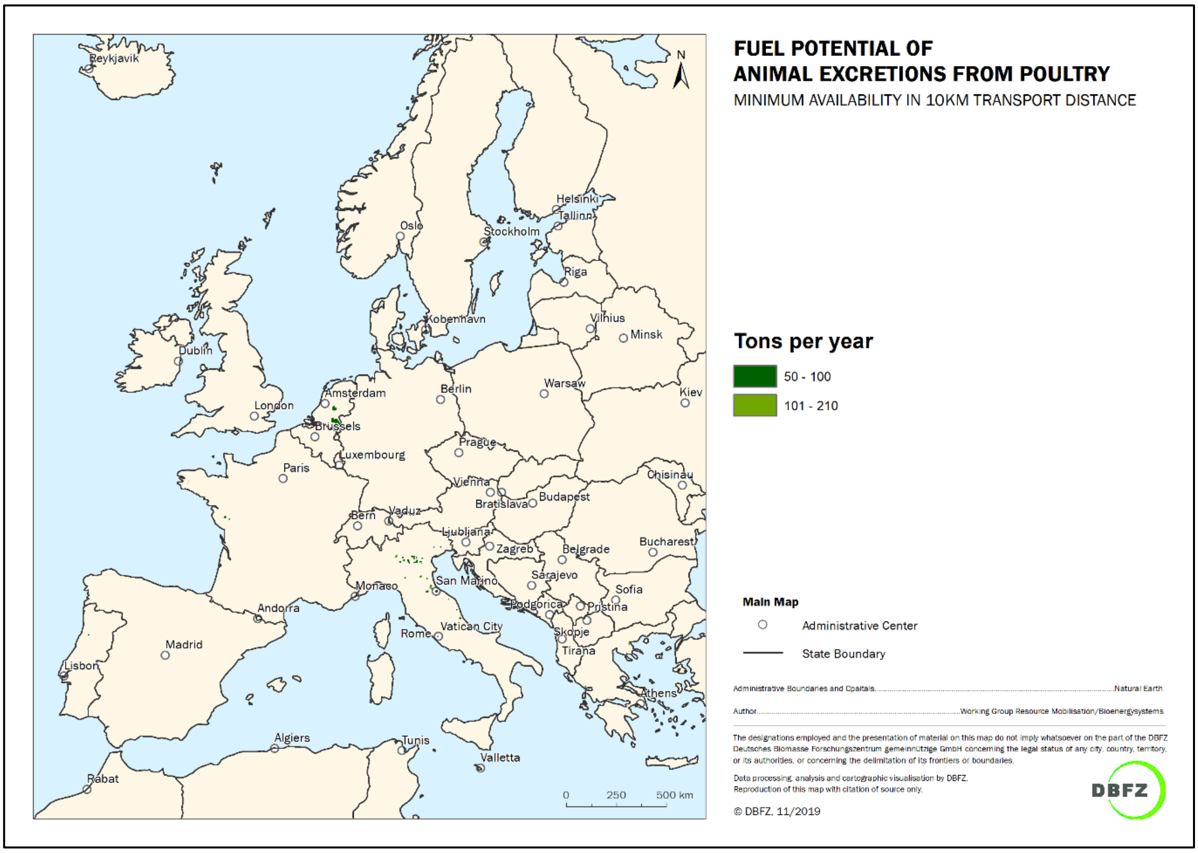

Figure 10 Minimum Biofuel Potential from poultry excretions

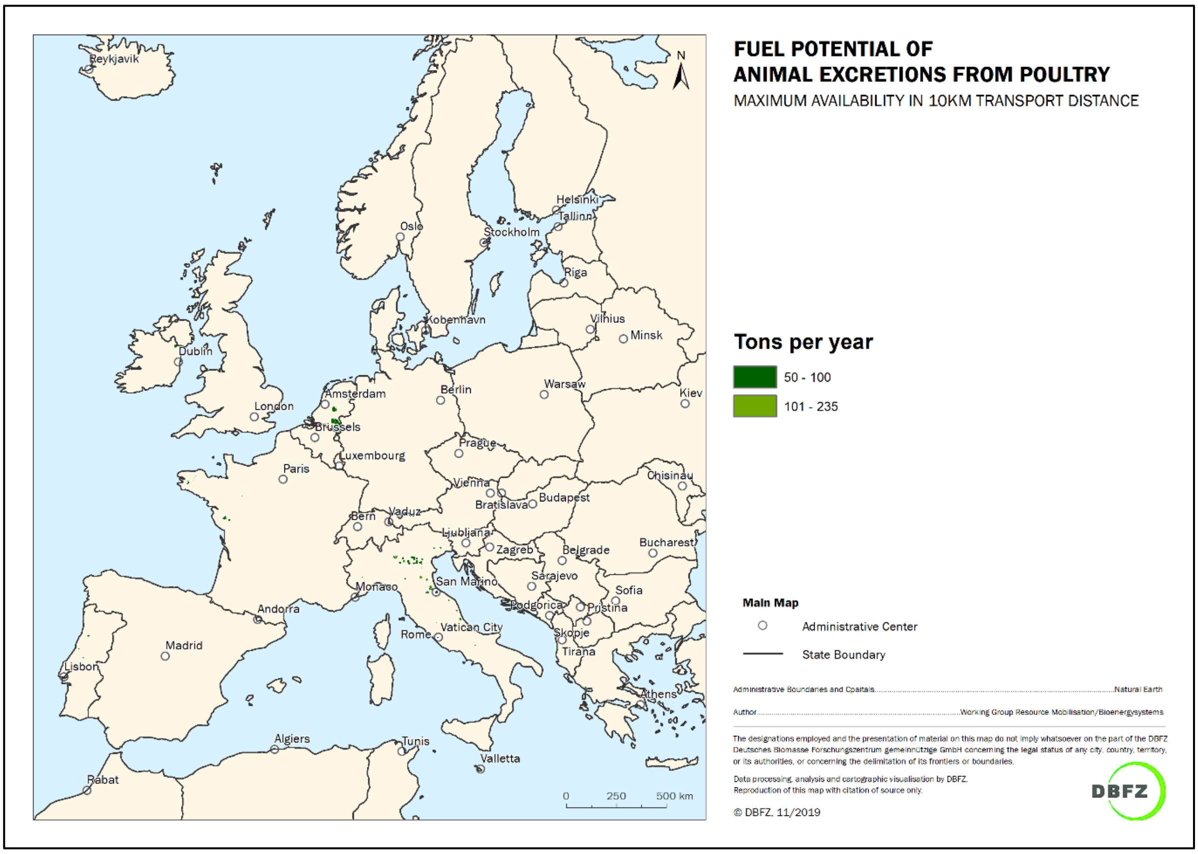

Figure 11 Maximum Biofuel Potential from poultry excretions

3.3 Sewage Sludge

The here presented potential figures have been calculated for a catchment area of 20km in order to best-possible visualize centralized collection systems of wastewater. Biomass and biofuel potential of sewage sludge are available in centralized urban areas with a significant number of inhabitants and large-scale wastewater treatment systems. Consequently, the theoretical potential of sewage sludge is large in mainly western European urban areas. In the larger catchment areas of those urban areas theoretical potentials of about 5,000 to 10,000 tons dry matter can be found (Figure 37 of Annex C). Biofuel potentials follow this pattern, of course. Here, biofuel potentials of about 10,000 – 19,000 tons can be found in major European cities such as Berlin, Copenhagen, London, Madrid and Vienna (Figure 12).

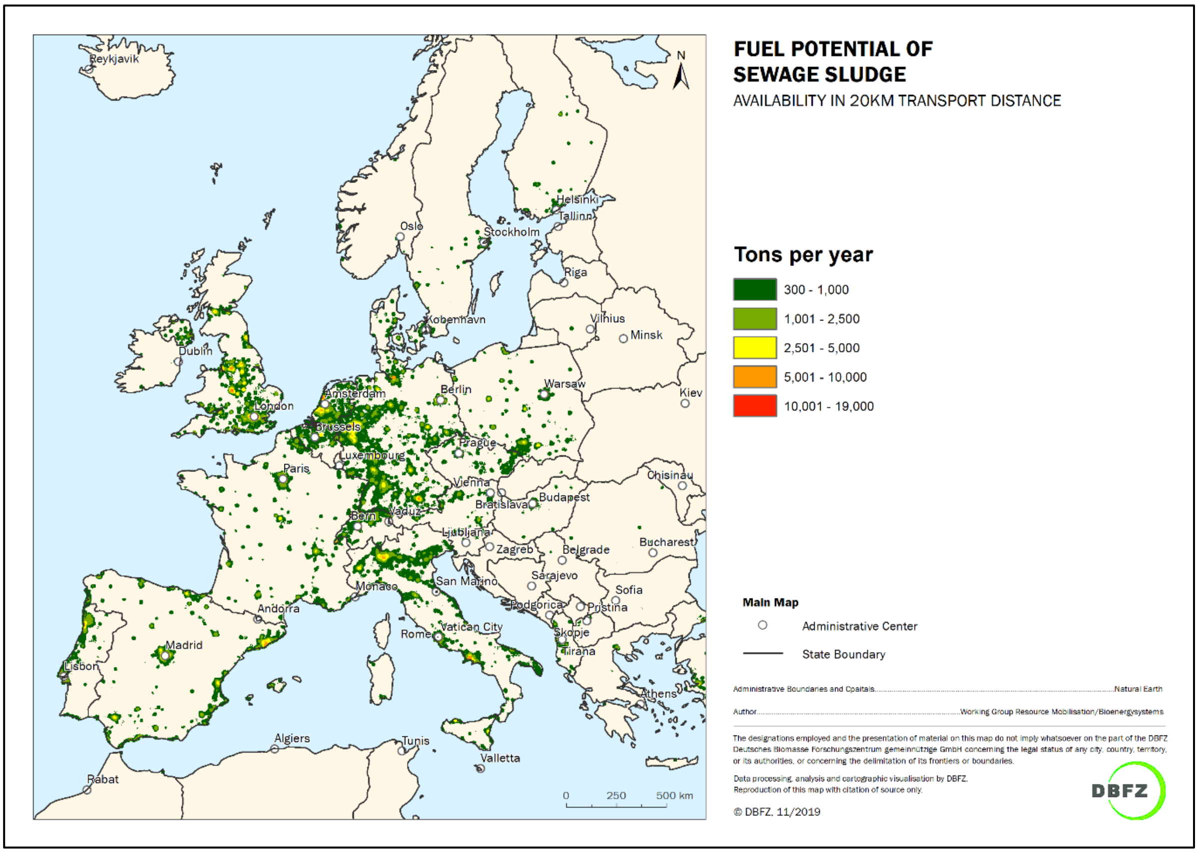

Figure 12 Biofuel potential from sewage sludge

3.4 Biowaste

The category biowaste encompasses the single biomass organic fraction of municipal solid waste from households. The theoretical potential illustrated in Figure 38 of Annex C shows that there is a tremendous amount of biowaste existent in Europe. The potential was derived for a catchment area of 20km to capture large-scale collection systems as well. Of course, centers of this biomass are centralized urban areas. The technical potential for biowaste includes the factor of separate collection. This has been included as the not separated use of municipal solid waste is currently not feasible due to economic (cost intensive pre-processing) and process side reasons. Incorporating the issue of separate collection of biogenic share of organic fraction of municipal solid waste reduces the overall available potential. Figure 39 of Annex C shows the technical potential for separately collected biowaste. Here, it becomes obvious that the separate collection of the organic share of municipal solid waste is not part of all waste collection systems in European countries and their urban and rural regions. Figure 13 shows the final fuel potential from the separate collection of biowaste. Up to 19,000 tons fuel could be produced by HTL at single locations. Preference regions for this biomass are located in centralized urban areas across Western Europe with widely available potential of 10,000 – 50,000 tons dry matter. Highly concentrated potential above 50,000 tons dry matter and 10,000 tons fuel is available in major European cities such as Berlin, London, Madrid. Copenhagen and Vienna.

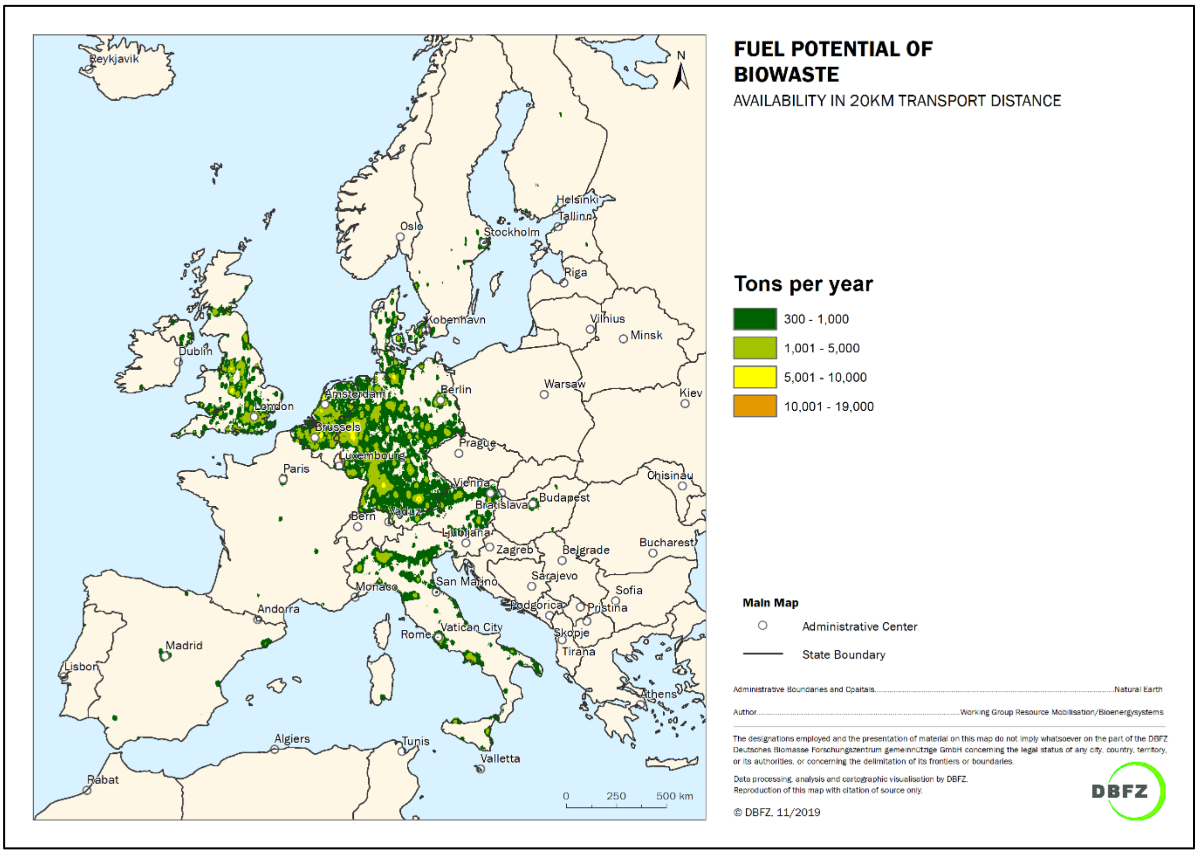

Figure 13 Biofuel Potential from Biowaste

3.5 Summary of potential assessment results

The results indicate that, assuming an **100% exploitation rate** of the investigated feedstock, between 40 million tonnes and 59 million tonnes HTL based fuel could be derived from the described biomasses, which represents about 100 to 150 % of Europe`s jet fuel demand (Table 4).

Table 4 Summarized Potential figures for Europe in kilo tons (dry matter; for the case of sewage sludge, theoretical potential has been calculated; figures have been rounded)*

Feedstock	Agricultural by-products	Animal Excretions			Sewage Sludge	Biowaste
		Cattle	Pigs	Poultry		
Technical Potential MIN	140,000	45,250	5,690	415	10,740*	9,830
Technical Potential MAX	154,000	107,580	22,130	465	10,740	9,830
Biocrude Potential MIN	41,000	14,980	1,880	137	4,150	2,370
Biocrude Potential MAX	46,000	35,610	7,320	154	4,150	2,370
Biofuel Potential MIN	26,000	8,970	1,130	82	2,880	1,420
Biofuel Potential MAX	29,000	21,330	4,390	92	2,880	1,420
SUM MIN	40,482					
SUM MAX	59,112					

4. Discussion

This research does not come without limitations. First, not all possible biogenic feedstock have been taken into account, due to various reasons such as current non-availability of necessary data quantity and quality or too low reported overall potential. Further, we give only an estimate of fuel production potentials without determining how many HTL plants could be effectively built. In other words, it is unlikely that the totality of feedstock could be used for HTL fuel production, as some regions might be characterized by low feedstock density. In those regions, it might be uneconomical to build HTL plants, so that feedstock of those regions would not be used. Future research could dig deeper into this topic and assess the minimum regional feedstock requirements for economically feasible HTL investments. Further, a still existing lack of a harmonized methodological approach including minimum requirements for biomass potential assessment can be identified, as already raised before by other authors such as [35,36]. This missing methodological harmonization leads to a gap between biomass, biocrude, and biofuel potentials presented here with those potentials from previous studies. Consequently, we stress the necessity for international effort towards unified minimum standards for biomass potential calculation.

Biomass potential figures are usually within a reasonable bandwidth because of manifold definitions of the term potential itself, different assumptions of calculation elements, different spatial scopes, varying time references and inconsistent methodologies. The biomass potential figures presented within HyFlexFuel are illustrated in Figure 14. The presented bandwidths have been compared to biomass potential figures from European studies such as S2Biom and scientific literature. This is explained in more detail in this section, including the respective references. The yellow boxes represent the bandwidth determined through the biomass potential assessment presented in this report. The black line in Figure 14 at 100% represents a respective value from largely a comparable study (regarding methodology and scope) or a mean value from various comparable studies. In the following section, this is explained for the assessed biomasses. References are made to the studies that were used for the comparison.

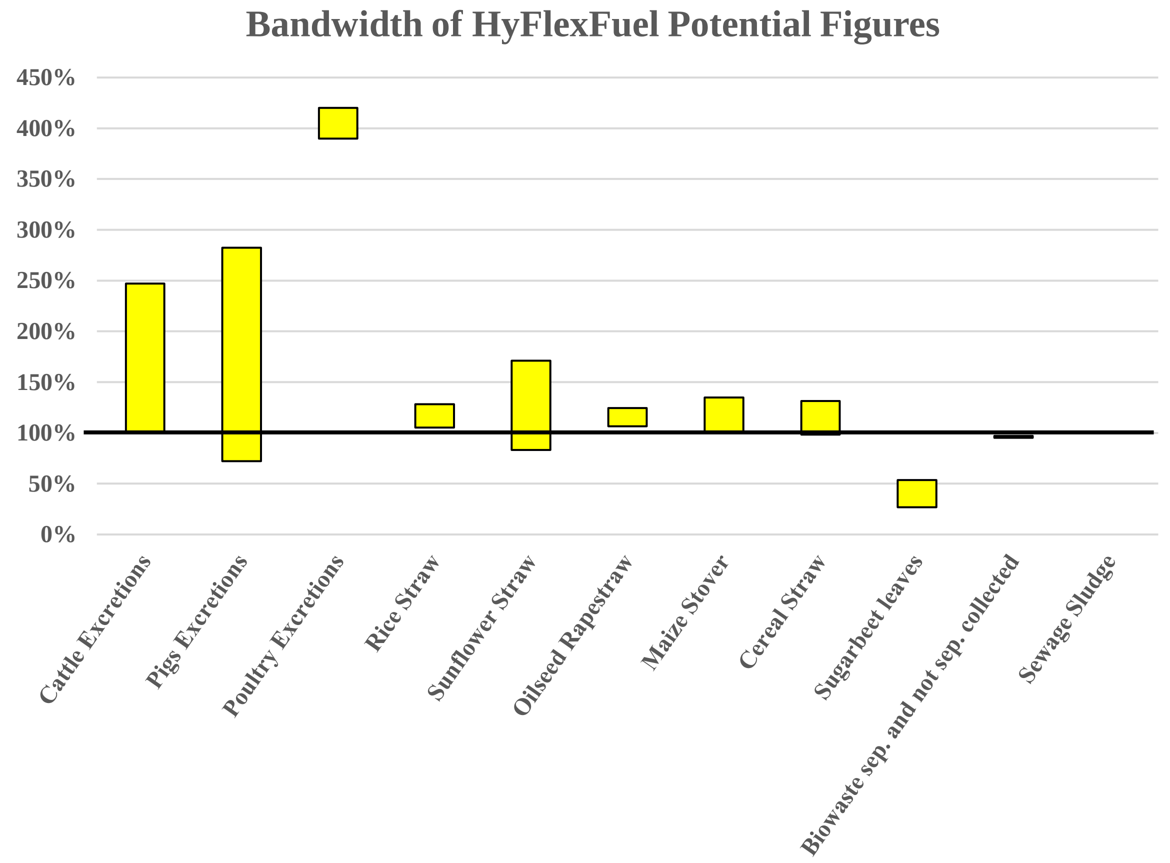

Figure 14 HyFlexFuel potential figures compared to associated studies with European scale (100 % reference)

Animal Excretions

Bandwidths of potentials of livestock excretions (cattle, pigs and poultry) has been compared to biomass potential figures from [14,15,37]. It gets obvious that the low (minimum) biomass potential figures proposed for cattle excretions meet the figures from the comparative study or are close to this, respectively. The high (maximum) biomass potential figures are in a range of 250 – 270 % higher than values from the comparative study. Reasons are different assumptions for excretion rates per type of animal. Whereas the comparative study only used a single excretion value, the here proposed assessment used different excretion rates depending on the type of animal (e.g. heifer, beef cow, dairy cow). Consequently, regarding the intensive production of beef and dairy products in the EU and thus the amount of beef cows and dairy cows with a higher amount of excretion compared to young heifers, this results in a higher value (maximum). The same applies for pigs (share of sows). The values presented here shall not be considered more precise as values from other studies, but more reasonable as a bandwidth is presented in which the exact value is located.

Biomass based potential figures for poultry excretions can be seen as an outlier regarding comparative values from [14,37]. The calculated sums are about four times higher than those of comparative values. The used data indicates a significant change of the farming method. Figures used for housing types of livestock are from 2009 as no more recent data is available. Since then, farming methods changed from cage rearing to free-range husbandry in many farms. As a result, less poultry excretions can be gathered which is why less biomass based potential from poultry livestock is available.

Agricultural By-products

Biomass based potential figures for plant based straw potentials are seen within a reasonable deviation. The bandwidths calculated for HyFlexFuel project represent the value from the comparative study [12] in an acceptable way. Potential figures of sugarbeet leaves assessed within HyFlexFuel are about 25% lower than reported in comparative studies such as S2Biom and represent a smaller deviation in comparison to other agricultural by-products. Shown deviations result from different methodologies of the comparative study and the here presented approach. Whilst the comparative study of S2Biom used a model called CAPRI, the here presented approach relied on statistical data on production, yields and agricultural area from EUROSTAT. The advantage of the approach used here is its transparency and reproducibility. In turn, the CAPRI model is very extensive and considers a plurality of other measures.

Biowaste

Deviations from the comparative value of [12] are within a range of 2 %. The deviation results from using more recent data than the comparative study (population data). Due to missing data on chemical composition of biowaste (lipids, carbohydrates and proteins) it is currently not possible to convert biomass potentials from tons dry matter to HTL derived biofuel.

Sewage Sludge

Currently, there are no figures available for the potential of sewage sludge on European level. Therefore, the presented value cannot be compared. Because the calculation of sewage sludge potential is very similar to biowaste potential calculation and figures used are from official statistical databases such as EUROSTAT, the calculated values are seen as very accurate. Due to a lack of data on European level it is currently not possible to assess the technical potential of sewage sludge. Therefore, theoretical potential has been used for the conversion to HTL derived biofuels.

5. Cultivated biomass

As discussed in the introduction, we focus on waste and by-product streams, because of several advantages they show in comparison to cultivated biomass when it comes to the technical process.

Further, assessing the sustainable feedstock potential for cultivated biomass is more complex than for waste and by-product streams. This is mainly due to the fact that, by definition, cultivated biomass is produced on suited land in the quantity that is required or desired. In turn, it is difficult to determine an upper boundary of production potential.

Additionally, the definition of sustainable production potential for cultivated biomass is a complex endeavour, because the use of (arable) land for biomass production has various effects on the used areas itself (direct land use changes), and on land use systems in general (indirect land use change).

We thus follow a different approach when discussing feedstock potentials for cultivated biomass. First, we differentiate between algae cultivation and miscanthus cultivation. These two cultivated biomass feedstock show such different properties, that a uniform analysis would give limited insights. Second, we do not quantify the theoretical and technical potential of these feedstock, but rather assess the amount of suitable land on which these feedstock could be usefully cultivated.

As miscanthus can be considered as a usual arable crop, we determine the suitable cultivation area by matching the climatic requirements of miscanthus with the climatic conditions of global agricultural areas, with a focus on Europe. Algae suitable locations for a future development of microalgae cultivation are qualitatively discussed and combined with the review of a doctoral thesis on spatially explicit potential analysis of future microalgae fuel production

5.1.1 Miscanthus

The methodology to assess availability and suitability for miscanthus consists of two stages. First, the amount of *available* land, second the amount of *suitable* land is determined.

The assessment of land availability was conducted through a bottom-up approach [38,39], comprising a set of restricting criteria to exclude land that is unsuitable and/or not accessible for agriculture. The following land classes were excluded from the assessment for reasons of climatic or physical constraints or of sustainability concerns:

- Inland water bodies (MODIS 500-m Map of Global Urban Extent) [40]
- Forest areas (Global Forest Resources Assessment 2005) [41]
- Constrained habitats, i.e. regions that are too cold, too dry or too steep for sustainable agriculture (Food Insecurity, Poverty and Environment Global GIS Database) [42]
- Protected areas (World Database on Protected Areas) [43]
- Settlement areas (MODIS 500-m Map of Global Urban Extent) [40]

The assessment was carried out in a layer-based geographic information system (GIS) processing georeferenced data with the highest available spatial resolution of up to 15 arcsec. As a result, the potential for available agricultural land area could be quantified (illustrated in Figure 15 for Europe). Note that on figure 15, pixels with forest areas are only excluded if forest occurrence surpasses 75%. In turn we do not exclude pixel with moderate percentages of forest occurrence. Based on the raster-coded datasets, values can be aggregated to larger areas, such as continents and individual countries, but also for sub-national regions. As examples, the potential agricultural land availability in Belgium and Denmark at NUTS 2 regional level is presented in **Table 5** and **Table 6**, respectively.

Table 5: Potentially available agricultural land in Belgium at NUTS 2 level. Percentage share of potentially available agricultural land in each NUTS 2 region is given in parentheses. (Data adapted from ref. [38,39])

Nuts_ID	Nuts_region	Potentially available agricultural land [km²]
BE10	Région de Bruxelles-Capitale / Brussels Hoofdstedelijk Gewest	16 (10%)
BE21	Prov. Antwerpen	2276 (79%)
BE22	Prov. Limburg (BE)	2030 (84%)
BE23	Prov. Oost-Vlaanderen	2553 (85%)
BE24	Prov. Vlaams-Brabant	1739 (82%)
BE25	Prov. West-Vlaanderen	2843 (90%)
BE31	Prov. Brabant Wallon	993 (90%)
BE32	Prov. Hainaut	3318 (87%)
BE33	Prov. Liège	3316 (86%)
BE34	Prov. Luxembourg (BE)	3651 (82%)
BE35	Prov. Namur	3088 (84%)

Table 6: Potentially available agricultural land in Denmark at NUTS 2 level. Percentage share of potentially available agricultural land in each NUTS 2 region is given in parentheses. (Data adapted from ref. [38])

Nuts_ID	Nuts_region	Potentially available agricultural land [km²]
DK01	Hovedstaden	2128 (83%)
DK02	Sjælland	7220 (99%)
DK03	Syddanmark	12007 (99%)
DK04	Midtjylland	12674 (96%)
DK05	Nordjylland	7270 (92%)

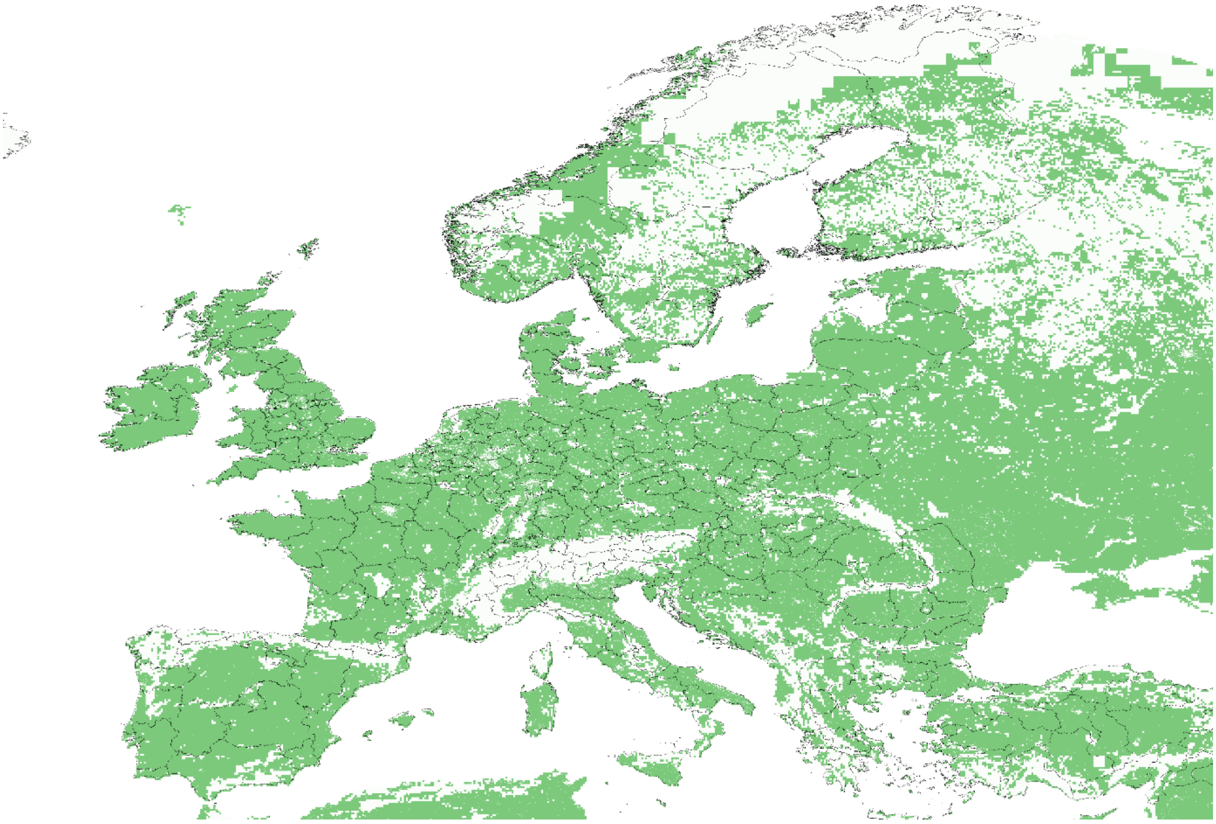

***Figure 15: Potentially available agricultural land in Europe (in green). Source: BHL* [1]**

As georeferenced information of climatic and edaphic conditions for every pixel of potentially available agricultural land is included in the data set, the application of biomass suitability models enables the estimation of local, regional, national or global suitability, which will be discussed in the next paragraph.

Agro-climatic Resources

For the global agro-ecological zones assessment GAEZ v3.0 [44], time series data are used from the Climate Research Unit (CRU) at the University of East Anglia. Seven climatic variables are required for GAEZ climate analysis: mean 24-hour temperature, diurnal temperature range, sunshine fraction, wind speed, relative humidity, wet day frequency and precipitation. The precipitation data used was obtained from the German Weather Service (Global Precipitation Climatology Centre – GPCC[2]) and the Johann Wolfgang Goethe-University Frankfurt (Institute for Atmosphere and Environment).

Original monthly CRU 10 arc-minute and GPCC and CRU 30 arc-minute latitude/longitude climatic surfaces were interpolated to a 5 arc-minute grid for all years between 1961 and 2000 with a bilinear interpolation method. For temperatures, a lapse rate was applied to calculate temperature values adjusted to sea level at original resolutions, followed by a bilinear interpolation to 5 arc-minutes. Subsequently a lapse rate and a 5 arc-minute resolution digital elevation model (DEM) were used to calculate temperatures at actual elevations.

From these resulting 5 arc-minute grids of the climate parameters, a number of climate indicators were compiled representing agronomically relevant thermal regime data,

[2] See: https://www.dwd.de/EN/ourservices/gpcc/gpcc.html

moisture regime data and growing period data for individual years between 1961 and 2000 and baseline climate (1961-1990) (Figure 16).

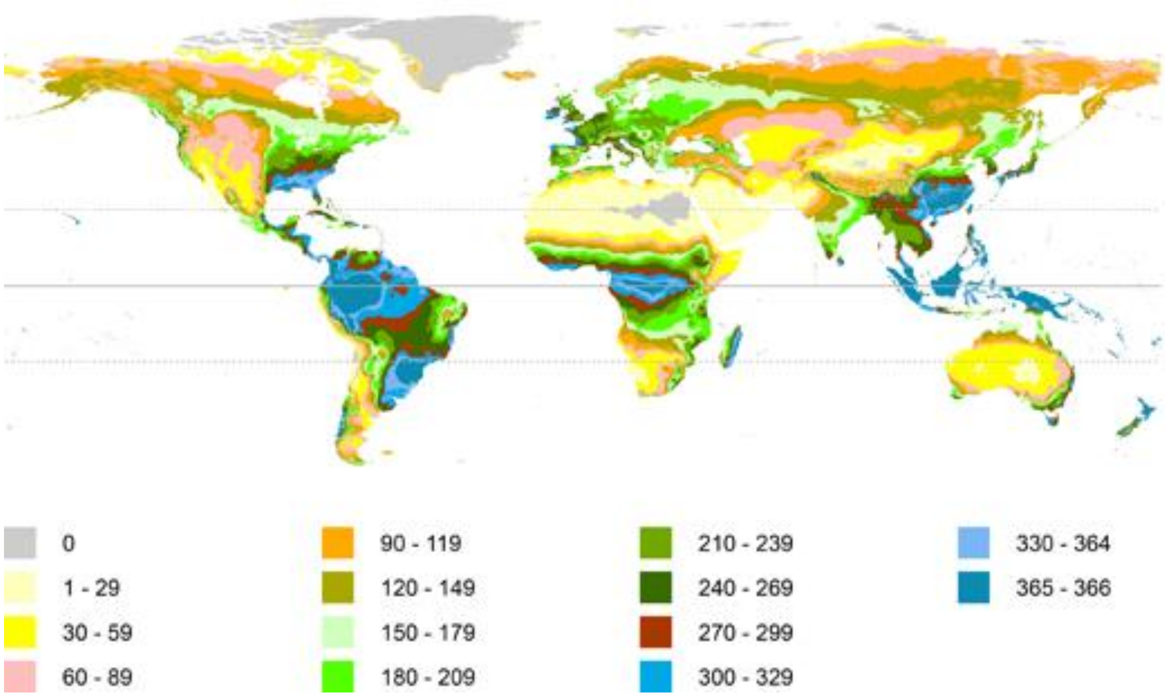

Figure 16: Reference length of growing period in days (1961-1990)

Agricultural Suitability

For the assessment of rain-fed land suitability, a water-balance model is used to determine the beginning and duration of the period when sufficient water is available to sustain crop growth. Soil moisture conditions together with other climate characteristics (radiation and temperature) are used to determine if a certain crop can effectively grow in these conditions. For the assessment of irrigated land suitability, each crop growth cycle length is matched with the period with temperatures conducive for crop growth. The calculated potential of agro-climatic yields are subsequently combined with a number of reduction factors directly or indirectly related to climate (e.g., pest and diseases), and with soil and terrain conditions.

The reduction factors, which are successively applied to the potential suitability index, vary with crop type, the environment (in terms of climate, soil and terrain conditions) and depend on assumptions regarding level of inputs/management. In order to ensure that the results of the suitability assessment relate to suitability on a long term basis, (i) fallow periods have been imposed, and (ii) terrain slopes have been excluded when inadequate for the assumed level of inputs/management or too susceptible to topsoil erosion. In essence, the GAEZ v3.0 assessment provides a comprehensive and spatially explicit database of crop suitability and related constraint factors.

Agro–climatic suitability

The constraint-free crop suitability calculated in the AEZ biomass model reflect suitability with regard to temperature, radiation and moisture regimes prevailing in the respective grid-cells. The model requires the following crop characteristics: Length of growth cycle (days from emergence to full maturity); length of yield formation period; maximum rate of photosynthesis at prevailing temperatures, leaf area index at maximum growth rate; harvest index; crop adaptability group; sensitivity of crop growth cycle length to heat provision; development stage specific crop water requirements, and coefficients of crop yield response to water stress. Agro-climatic suitability was calculated at crop/LUT level for three input levels (high, intermediate and low) and three water supply system types (rain-fed, rain-fed with water conservation, and irrigation).

Climate yield constraints

Apart from providing estimates of agro-climatically attainable crop suitability, the model provides information on the climate-related constraints affecting crop suitability. These constraints include temperature constraints, moisture constraints, and yield constraints due to pests, diseases and workability. Crop water deficits (rain-fed conditions) or crop irrigation water requirements (irrigated conditions) are provided as model output

Agro-ecological suitability

Adequate agricultural exploitation of the climatic potentials and maintenance of land suitability largely depend on soil fertility and the management of soils on an ecologically sustained basis. Soil fertility is concerned with the ability of the soil to retain and supply nutrients and water in order to enable crops to maximally utilize the climatic resources of a given location. The fertility of a soil is determined by both its physical and chemical properties. An understanding of these factors and insight in their interrelations is essential for the effective utilization of climate, terrain and crop resources for optimum use and production. From the basic soil requirements of crops, a number of soil characteristics have been established related to crop suitability. For most crops and cultivars, optimal, sub-optimal, marginal and unsuitable levels of these soil characteristics are known. Beyond critical ranges, crops yields cannot be expected to be satisfactory unless special precautionary management measures are taken. Soil suitability classifications are based on knowledge of crop requirements, of prevailing soil conditions, and of applied soil management. In other words, soil suitability procedures quantify to what extent soil conditions match crop requirements under defined input and management circumstances. The agro-ecological suitability is presented for four input levels (high, intermediate, low and mixed), five water supply system types (rain-fed, rain-fed with water conservation, gravity irrigation, sprinkler irrigation and drip irrigation), at crop level (49 crops) for baseline climate (1961-1990) and future climate conditions (Figure 17). In addition, comprehensive crop summary tables by administrative units are available for viewing and download[3].

[3] See: http://www.fao.org/nr/gaez/en/

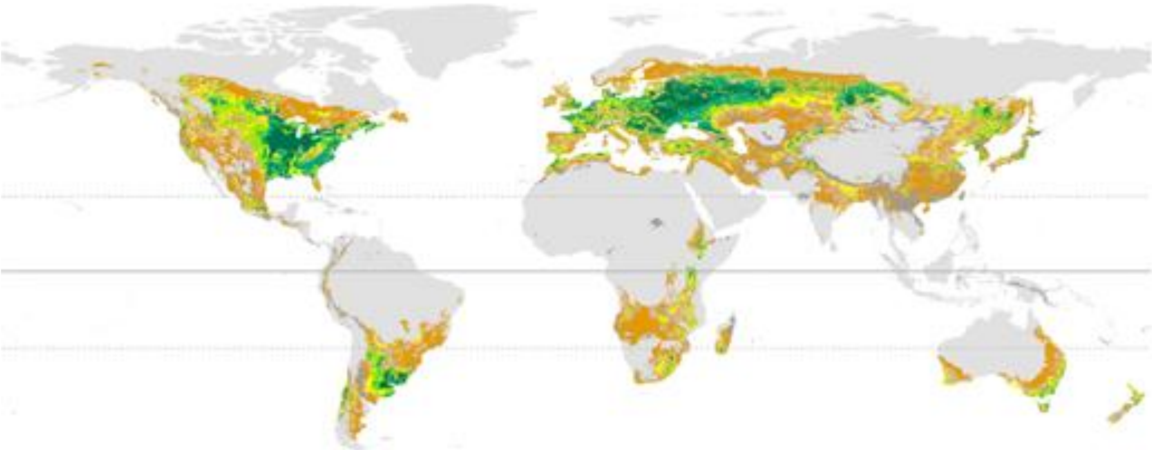

Figure 17: Crop Suitability Index (mixed input level) Rain-Fed Wheat, Baseline period: 1961-1990, available at: http://www.fao.org/nr/gaez/about-data-portal/agricultural-suitability-and-potential-yields/en/

Edaphic suitability

After the assessment of climatic suitability, we now turn towards edaphic suitability. For this, we first assess which types of soils are suited for Miscanthus cultivation. The classification of the world's soils into suitable and unsuitable soils for miscanthus is based on data from the FAO Ecocrop database [45]. Ecocrop provides data for a variety of plants regarding:

- Soil texture
- Soil drainage
- Soil depth
- Soil pH
- Soil salinity

The description of soil requirements in the Ecocrop database can be translated into soil characteristics found in the Harmonized World Soil database (HWSD) as shown in *Table 7*. The HWSD is the most detailed global soil database currently available [42]. The HWSD consists of a map data set in raster format with a resolution of 30 arcsec and an associated attribute database in Microsoft Access format. For the sake of simplicity and clarity, only the dominant ground within a map unit, and only the subsoil (30-100 cm) for pH value and salinity were taken into account.

Table 7: Parameter values of edaphic suitability, derived from the Ecocrop database

Miscanthus: (*Miscanthus giganteus*)	**Soil drainage**	**Soil texture incl. optimum**	**Soil pH**	**Soil salinity**	**Soil depth**
Description of soil requirements in Ecocrop	Good	Opt.: humus-loam soils; very heavy soils unsuitable	*M. sinensis*	High salt tolerance	Medium and profound
Classification of soil characteristic in HWSD	4, 5	Medium, coarse/ 1, 2	*4,3-8,5*	<32	

Based on this information, edaphic suitability maps can be generated, depicting whether the local soil characteristics meet the minimum soil requirements of Miscanthus are met. “0” stands for “not suitable”, “1” stands for “suitable”.

The combination of availability of agricultural land and climatic/edaphic suitability for miscanthus are shown in Figure 18 and Figure 19. Figure 18 depicts the availability and suitability on pixel basis, showing that larger continuous areas can be found in Ireland, western France, central Germany, southern Spain, and the lowland of the Po River in Italy, to name just a few. However, this type of illustration makes it difficult to assess which regions are characterized by a high share of eligible land. Thus, we calculated the share of suitable and available area by NUTS 2 region, as depicted in Figure 19.

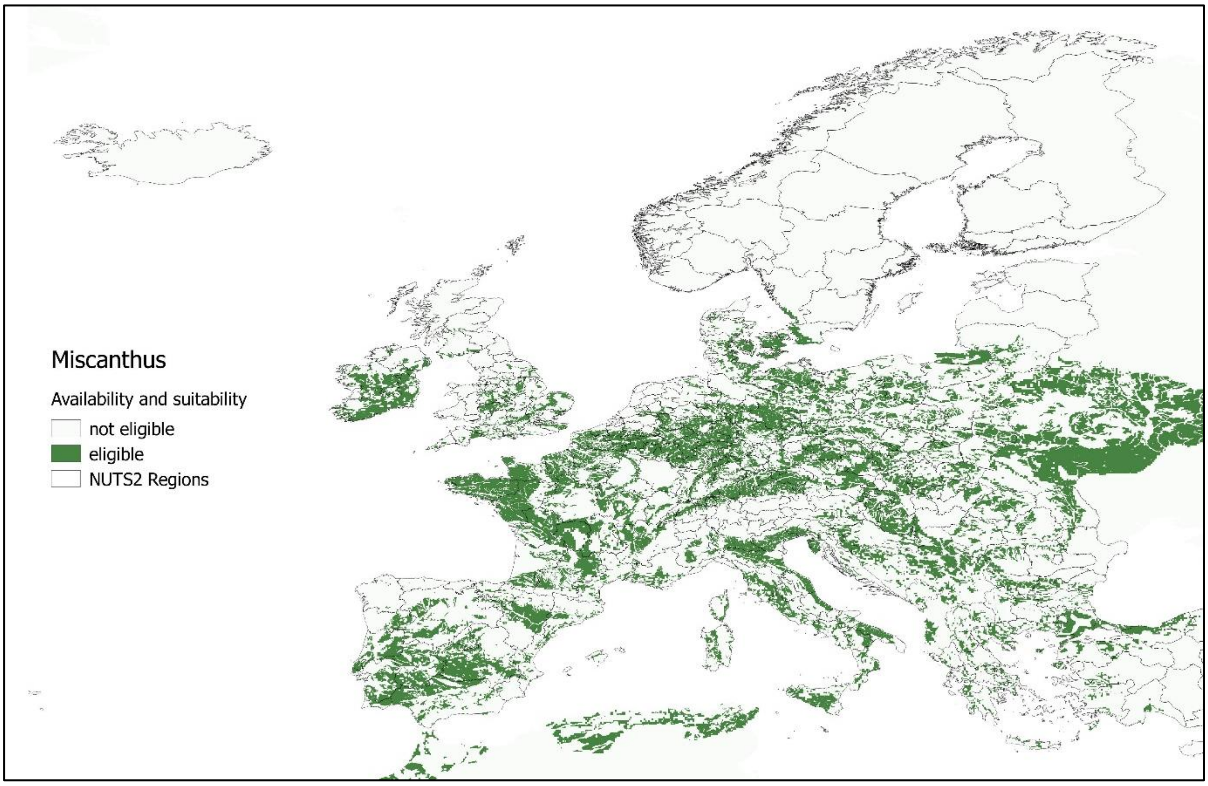

Figure 18: Binary representation of suitable and available areas for Miscanthus in Europe

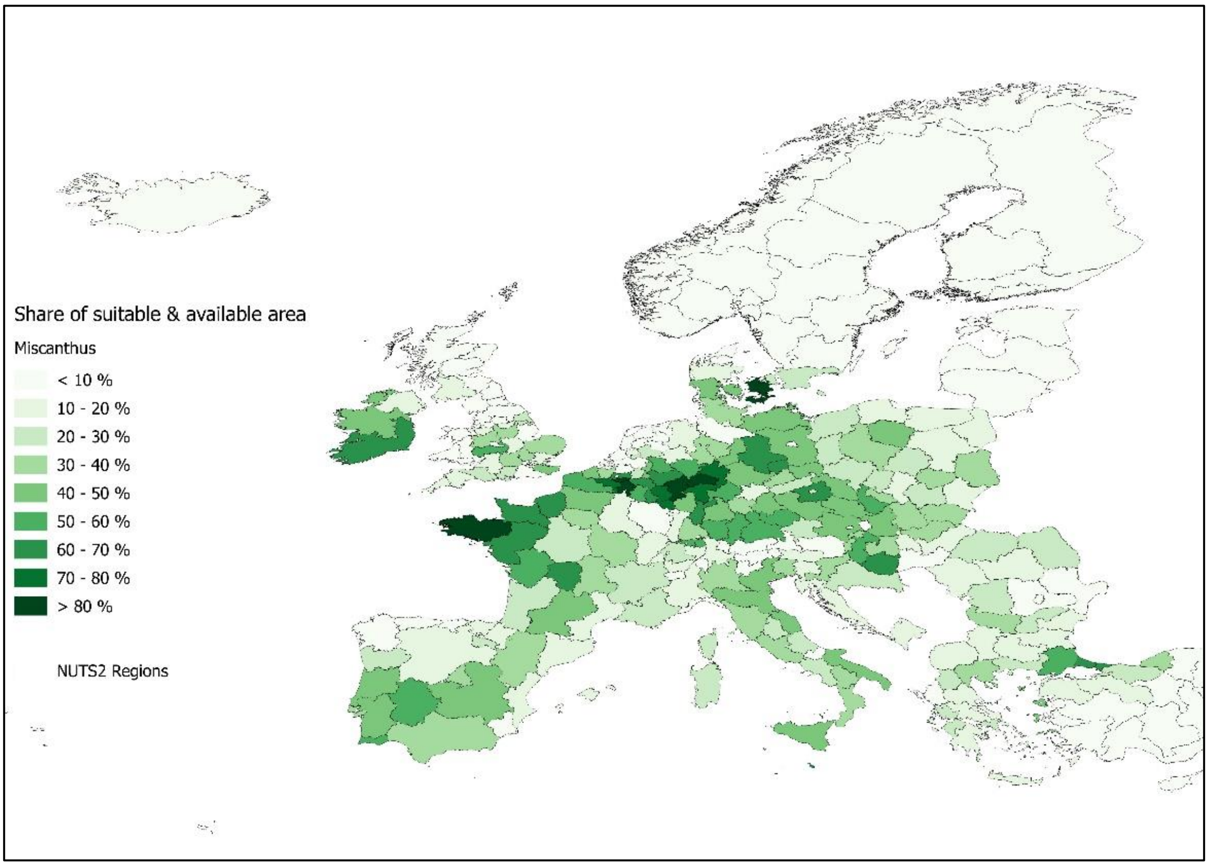

Figure 19: Share of suitable and available areas by NUTS 2 regions

5.1.2 Algae

Finally, the present report assesses the potential availability of algae feedstock for hydrothermal liquefaction. Our investigations of the current microalgae production in Europe, including the HyFlexFuel model feedstock Spirulina, did not reveal an existing biomass production that is relevant for HTL fuel conversion. Consequently, there is no near-term availability of algae biomass that could be meaningfully assessed in the framework of this deliverable report. Instead, we qualitatively discuss suitable locations for a future development of microalgae cultivation. Furthermore, we review a doctoral thesis on spatially explicit potential analysis of future microalgae fuel production.

General characteristics of algae cultivation

Microalgae offer growth rates that significantly exceed the growth rates of traditional agricultural plants (see below). Furthermore, biomass production does not require arable land as microalgae are cultivated in artificial water bodies like open pond systems (e.g. raceway ponds) or closed photobioreactors. The specific design of the cultivation system introduces uncertainty in the assessment of the future availability of algae biomass. Furthermore, proposals for mass cultivation of microalgae usually involve additional CO_2 supply to achieve high growth rates. CO_2 is a gaseous commodity that is not generally available, unless CO_2 is directly captured from air. In the following, we review a doctoral thesis by Johannes Skarka (Karlsruhe Institute of Technology) [46] which evaluated a future technical potential of 41 Mt/yr algal biomass in the EU-27 considering CO_2 availability. It is important to distinguish this value that represents a future technical potential, from the values in Section 3 that quantify actual biomass potentials. Achieving the above mentioned technical potential for algae cultivation would require a rapid scale-up of algae production capacities. However, such a scale-up is currently not observed. Therefore it is unlikely that the technical potential will be approached in the near-term future. We attribute this to the still limited technical maturity of large-scale cultivation, harvesting and processing of algae biomass, and to the high effort for algae production, that presumably keeps economic production potentials far below technical potentials unless the current state-of-art is significantly improved by research and innovation.

Area yields for algae fuel production and preferable production sites

Figure 20 quantifies the area yields of algae biomass of up to 175 t/ha*yr, where 70-140 t/ha*yr is a more common value for European production sites. These values may be compared with yields of up to 25 t/ha a for high yield energy crop cultivation such as short rotation coppice [47]. The estimated yields in Skarka are evaluated for closed photobioreactors, but the author states that comparable yields should also apply to open pond systems.

The HyFlexFuel partner Bauhaus Luftfahrt evaluated the area yield for flat plate closed bioreactors in the framework of a German national funded research project[4]. Endres et al. identified an area yield between 55 t/ha*yr (Phoenix, Arizona) and 115 t/ha*yr (Sacramento, California) for six representative sites in the USA, based on a detailed growth model considering temperature and light distribution within flat panel photo-bioreactors [48]. The area yield in the work of Endres roughly supports the area yield evaluations by Skarka [46]. A notable difference is the area yield in hot and arid climates (represented by Phoenix, Arizona within this study) where reactor overheating brought biomass production to halt for elongated periods of time. This result is specific to the chosen reactor technology, nevertheless it may be concluded that preferable production sites for microalgae cultivation offer a high level of solar irradiation on one hand, but also temperate climatic conditions since micro-algae production is strongly inhibited when reactor temperatures fall outside of a relatively narrow temperature optimum[5]. A further important consideration for preferable production sites is the local availability of a suitable CO_2 source.

Skarka evaluates geographic production potential based on four submodels [46]. The submodels consider biomass yield, land availability, the selection of specific sites with respect to CO_2 supply. The microalgae biomass yield is modelled using climate data, while land availability is determined according to slope and land use. The CO_2 supply model considers the demand at specific algae production sites and their distance to existing industrial CO_2 sources. The results of the evaluated technical production potentials are displayed in Figure 20 and add up to a total technical potential of 41 Mt/yr algal biomass in the EU-27. The map further shows that preference regions are located in southern Mediterranean regions with high solar irradiation and temperatures that allow for biomass cultivation also in winter month. The cultivation period is less than six month for all production sites north of 50° latitude according to the modelling of Skarka [46].

[4] German Federal Ministry of Education and Research (Project: Advanced Biomass Value, 03SF0446C)

[5] Active temperature control (heating or cooling) introduces additional techno-economic penalties.

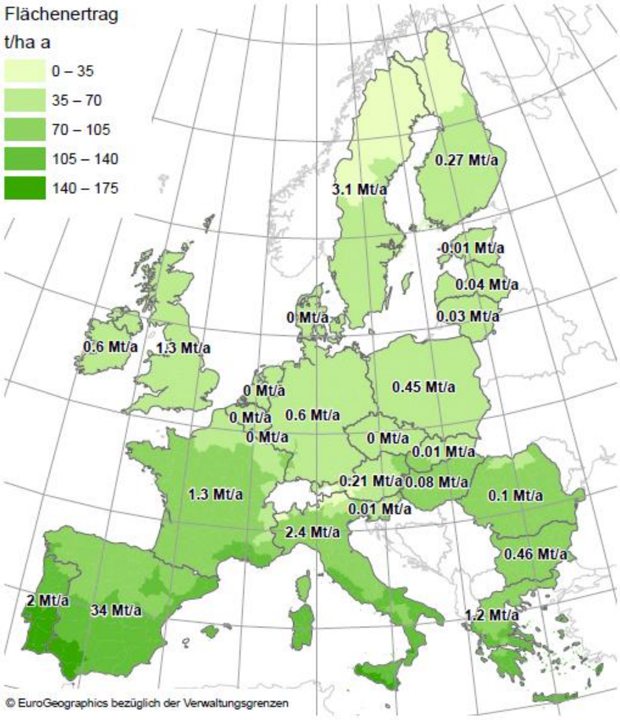

Figure 20: Area yields and future technical production potentials for for algae biomass cultivation in EU-27 Member States. Screenshot from Figure 4.1 in [46]

Another important consideration both for production potentials and preferable production sites is the availability of a suitable and sustainable CO_2 source. The assessment of Skarka considered CO_2 provision of all industrial sources, consequently the analysis is dominated by CO_2 provision from coal and natural gas fired power plants. The EU directive on the promotion of the use of energy from renewable sources (Renewable Energy Directive) acknowledges that so-called recycled carbon fuels can contribute towards decarbonisation of the transport sector where they fulfil the appropriate minimum greenhouse gas emissions savings threshold of 65% [49]. However, such recycled carbon fuels should not be counted towards the overall Union target since they are not fully renewable (RED Art. 89). As a consequence, preferable algae biomass production sites should also involve a regenerative CO_2 source, such that the final HTL fuel product qualifies as a renewable fuel according to current EU directives.

6. Conclusions

The work presented here sought to estimate fuel production potentials from HTL based biomass conversion by analyzing the geographical distribution of a variety of biogenic feedstock. For this, high quality spatial data covering 14 different feedstock was converted to liquid fuel production potentials by using a HTL conversion process model.

Generally speaking, the results show that substantial amounts of biofuel could be produced from waste and residue feedstock, with animal excretion from cattle representing the largest share.

According to [3], kerosene consumption in the European Union in 2017 decreased to 57 million tonnes per year (from 42.8 million tonnes in 2006). From this, almost 100% was imported from Middle East and Pacific-Asia. With regard to the results of the here presented approach, a considerable amount of Europe’s annual kerosene demand could be supplied by HTL derived fuels from the here presented biomass feedstock, assuming an encompassing exploitation of the feedstock (Table 8). The results indicates that, assuming an 100% exploitation rate of the investigated feedstock, between 40 million tonnes and 59 million tonnes HTL based fuel could be derived, which represents about 100% of Europe`s jet fuel demand. Of course, a 100% exploitation rate is not very realistic, nevertheless it is important to show the maximum possible HTL derived fuel potential regarding the here presented assessment. Decreasing the mobilisation rate to more realistic figures of 50%, 25% and 10% result in possible kerosene substitution in Europe of 35 to 52% (50% mobilization rate), 18 to 26% (25% mobilisation rate) and 7 to 10 % (10% mobilisation rate). This shows that even with a mobilization rate of one quarter of the here presented feedstock, a significant amount of fossil kerosene could be substituted (range of 18 to 26%).

Table 8 Possible kerosene substitution by HTL matrix

40 to 59 million tons HTL derived fuel - What does that mean					
		HTL fuel [million tons]		Kerosene substitution Europe [%]	
		MIN	MAX	MIN	MAX
Mobilisation rate	100%	40	59	70	104
	50%	20	30	35	52
	25%	10	15	18	26
	10%	4	6	7	10

Further measures influencing a possible mobilisation rate of the feedstock are amongst others the current use of the feedstock, which is currently not part of this assessment, cost structure of feedstock mobilization, infrastructure and stakeholders.

Next steps in analyzing location-specific feedstock potential after having identified hot-spot regions across Europe, is identifying and visualizing the interrelations of resource potential and transport distances at different local sites identified during the hot-spot analysis presented here. This will be integral part of the upcoming task 1.3 within WP1 of HyFlexFuel project. Another interesting issue is the possible combination of single feedstock for the HTL process such as lignocellulosic feedstock and sewage sludge. This finding will be integrated in task 1.3, too.

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8. Glossary

Abbreviation / Acronym	Description
HTL	Hydrothermal liquefaction
GIS	Geographic Information System
FAO	Food and Agriculture Organization of the United Nations
NUTS	Nomenclature des unités territoriales statistiques
CORINE	Coordination of Information on the Environment
CORINE LAND COVER	CLC
LUT	Land Utilization Types
MIN	MINIMUM
MAX	MAXIMUM
GAEZ	global agro-ecological zones assessment
CRU	Climate Research Unit
GPCC	Global Precipitation Climatology Centre
DEM	digital elevation model
HWSD	Harmonized World Soil database

9. Annexes

9.1 Annex A

Table 9 Detailed overview on calculation elements used

Calculation Element	Unit	Value / Data source	Spatial Level	Reference
CATTLE				
Total amount of animals		FAO Gridded Livestock of the world	0.00833333 Decimal Degree	[13]
Specific share of animals	heads per km²	Breakdown into: Bovine < 1 year [15%- 40%] Bovines 1-2 years male [1% - 15%] Bovines 1-2 years female [3% - 18%] Bovines > 2 years [.3% - 6%] Heifers > 2 years [2% - 10%] Dairy cows [15% - 63%] Other cows [.5% - 32%]	National Level for EU27	[5]
Total area	km²		NUTS 3	[50]

Animal specific excretion factor	tons per year per animal class	Breakdown into: Bovine < 1 year [1.5- 5] Bovines 1-2 years male [3.3 - 11] Bovines 1-2 years female [4.6 - 13] Bovines > 2 years [3.6 - 14] Heifers > 2 years [4.6 - 15] Dairy cows [10 - 25] Other cows [9 - 14]	European Level	[16,51]
Specific share of excretion	%	Breakdown into: Liquid manure [5 %] Slurry [41 %] Solid Dung [26 %]	European Level	[18]
Dry matter content	%	Breakdown into: Liquid manure [12 %] Slurry [2 %] Solid Dung [23 %]	European Level	[18]
Time in stable	%	Breakdown into: Dairy Cows indoor [25% - 93%] Beef Cows indoor [29% - 63%]	NUTS2	[18]

PIGS

Total amount of animals		FAO Gridded Livestock of the world	0.00833333 Decimal Degree	[13]
Specific share of animals	heads per km²	Breakdown into: piglets under 20kg [15% - 43%] breeding sows over 50kg [4% - 15%] others [47% - 80%]	National Level for EU27	[5]
Total area	km²		NUTS 3	[50]
Animal specific excretion factor	tons per year per animal class	Breakdown into: piglets under 20kg [.8 - 1.9] breeding sows over 50kg [1.9 - 6.7] others [.3 - 1.9]	European Level	[16,51],
Specific share of excretion	%	Breakdown into: Liquid manure [5 %] Slurry [86 %] Solid Dung [8 %]	European Level	[18]
Dry matter content	%	Breakdown into:	European Level	[18]

		Liquid manure [12 %] Slurry [2 %] Solid Dung [23 %]		
Time in stable	%	Breakdown into: Pigs indoor [51.5% - 100%]	NUTS2	[18]
POULTRY				
Total amount of animals		FAO Gridded Livestock of the world	0.00833333 Decimal Degree	[13]
Specific share of animals	heads per km²	Breakdown into: Broilers [16% - 72%] Laying Hens [22% - 83%] Others [0% - 50%]	National Level for EU27	[5]
Total area	km²		NUTS 3	[50]
Animal specific excretion factor	tons per year per animal class	Breakdown into: Broilers [.024 - .027] Laying Hens [.042 - .047] Others [.081 - .086]	European Level	[16,51]
Specific share of excretion	%	Breakdown into:	European Level	[18]

		Liquid manure [97 %] Slurry [3 %]		
Dry matter content	%	Breakdown into: Liquid manure [56 %] Slurry [15 %]	European Level	[18]
Time in stable	%	Breakdown into: Poultry indoor [83% - 100%]	NUTS2	[18]
SEWAGE SLUDGE				
Total population per country	million inhabitants	[38,000 - 83,000,000]	National Level	[7]
Sewage Sludge per capita	kilogram dry matter per capita	[.3 - 32.12]	National Level	[8]
BIOWASTE				
Municipal waste generated per capita	kilogram per capita	[261 - 777]	National Level	[10]
Total country population	million inhabitants	[38,000 - 83,000,000]	National Level	[7]

Organic content	%	[23% - 54%]	European Level	[11]
Separately collected share	%	[0% - 62%]	National Level	[11]
Dry matter content	%	44%	European Level	[12]
PLANT BASED RESIDUES				
Production Area	1,000 ha	Breakdown into: Wheat production [8 - 3201] Rye production [.5 - 570] Barley production [6.9 - 2560] Oats production [1.3 - 517] Grain maize [.1 - 2405] Oilseed rape [1.9 - 1406] Rice [9 - 229] Sugarbeets [.1 - 468] Sunflowers [.3 - 1137]	National Level	[23]
Residue-to-yield ratio	ratio 1:X	Breakdown into: Wheat production [1.25 - 1.68]	National Level	[24]

		Rye production [1.27 - 1.52] Barley production [1.15 - 1.57] Oats production [1.15 - 1.3] Grain maize [1.15 - 1.2] Oilseed rape [1.76 - 1.9] Rice [2.8 - 3.6] Sugarbeets [0.45] Sunflowers [2.7 - 3]		
Specific Yield	t FM per ha	Breakdown into: Wheat production [0.82 - 9.54] Rye production [.9 - 6.12] Barley production [.2 - 7.8] Oats production [.9 - 5.8] Grain maize [4.7 - 12.7] Oilseed rape [1.6 - 4.2] Rice [1.3 - 7.7] Sugarbeets [36 - 95] Sunflowers [1.3 - 3]	National Level	[23]
Dry matter content	%	Breakdown into: Wheat production [85] Rye production [85] Barley production [85] Oats production [85] Grain maize [70]	National Level	[26]

		Oilseed rape [60] Rice [75] Sugarbeets [12.5] Sunflowers [60]		
Sustainable removal rate	%	Breakdown into: Wheat production [40] Rye production [40] Barley production [40] Oats production [40] Grain maize [50] Oilseed rape [50] Rice [50] Sugarbeets [50] Sunflowers [50]	European Level	[26]

9.2 Annex B

*Table 10 Chemical composition used for HTL conversion model **(***Used as representing feedstock for respective feedstock group in calculations)*

Feedstock group	**Feedstock**	**Composition in wt.% (daf)**					**(dry)**	**(ar)**	**MJ/kg**	**Wt.%**			
		C	**H**	**N**	**O**	**S**	**Ash**	**water**	**HHV**	**Lipid**	**Protein**	**Carbo-hydrates**	**Reference**
Animal excretions	Swine manure *	51.49	4.93	2.91	39.52	0.57	13.27	12.7	15.57	18.20	29.90	42.90	[52,53]
	Cattle manure	53.95	6.36	1.14	36.82	0.34	13.67	13.88	14.95				Phylis #1882
	Chicken manure	49.94	7.58	7.38	34.19	0.60	10.58	39.7	10.33				[54]
Municipal wastes	Primary sewage sludge *	52.31	7.54	7.23	30.78	2.00		31.54	9.9	-	41.60	41.10	[28,55]
	Municipal waste	50.37	6.19	0.72	42.65	0.04	4.5						[56]
Lignocellulosics	Wheat straw *	48.46	5.79	1.74	43.64	0.11				5.34	3.48	91.18	[52,57]
	Rice straw	38.91	4.74	1.37	35.31	0.11							[58]
	Miscan-thus	49.28	6.48	0.72	45.06	0.11	2.80	7.30	19.84				Phyllis #1976

9.3 Annex C

Agricultural By-products

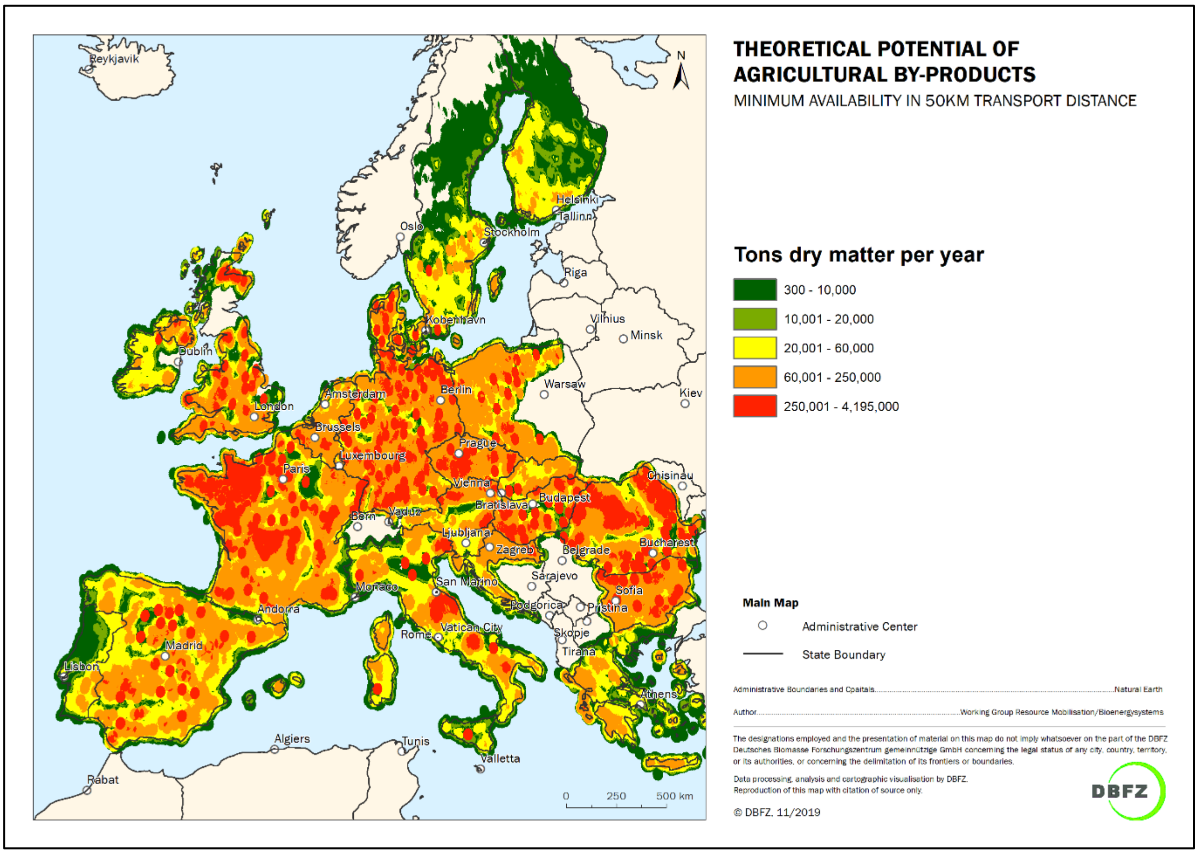

Figure 21 Minimum theoretical biomass potential of agricultural by-products

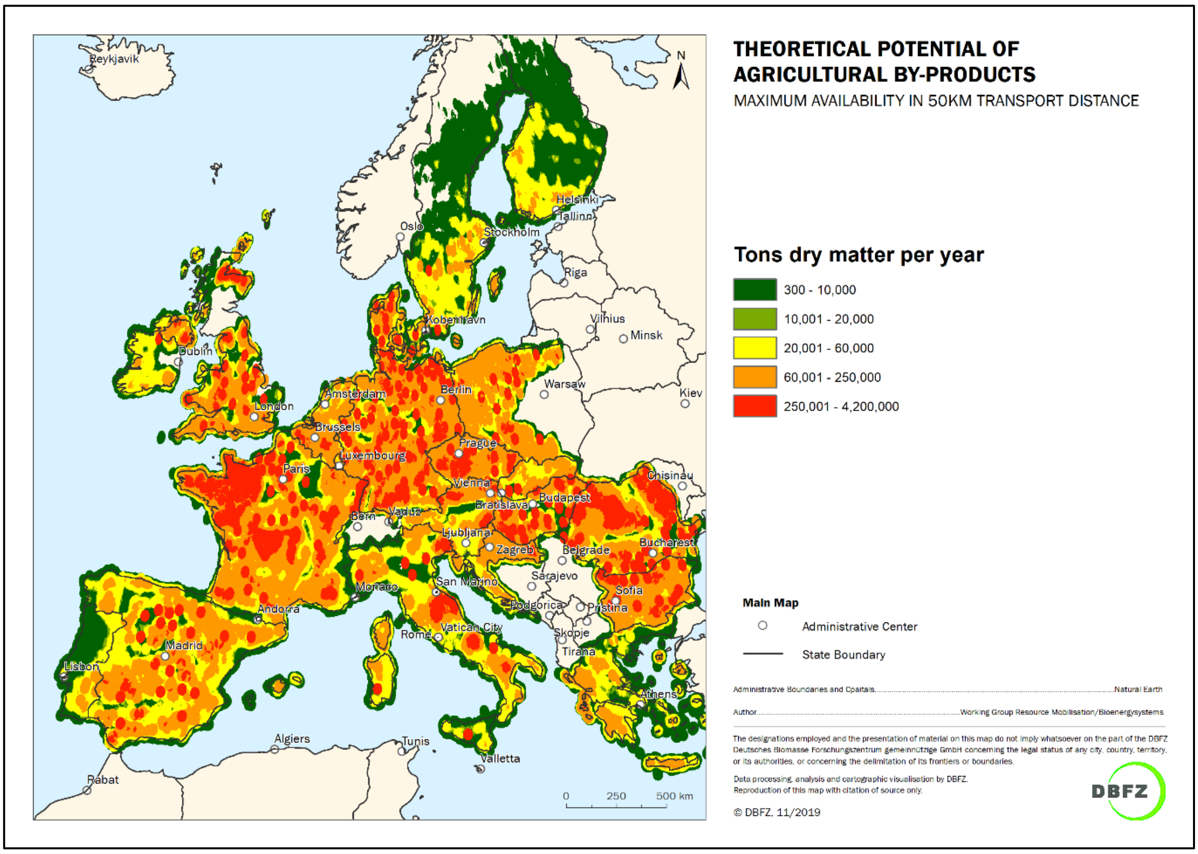

Figure 22 Maximum theoretical biomass potential of agricultural by-products

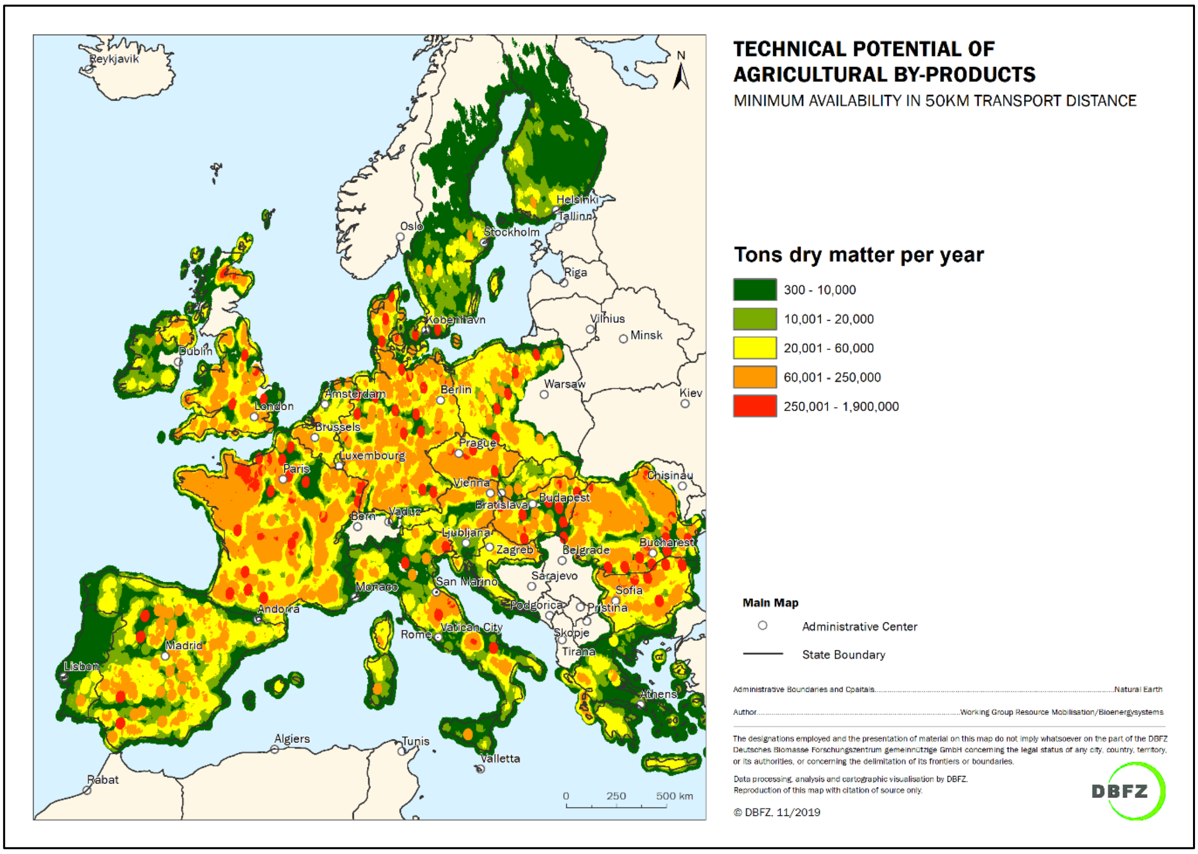

Figure 23 Minimum technical biomass potential of agricultural by-products

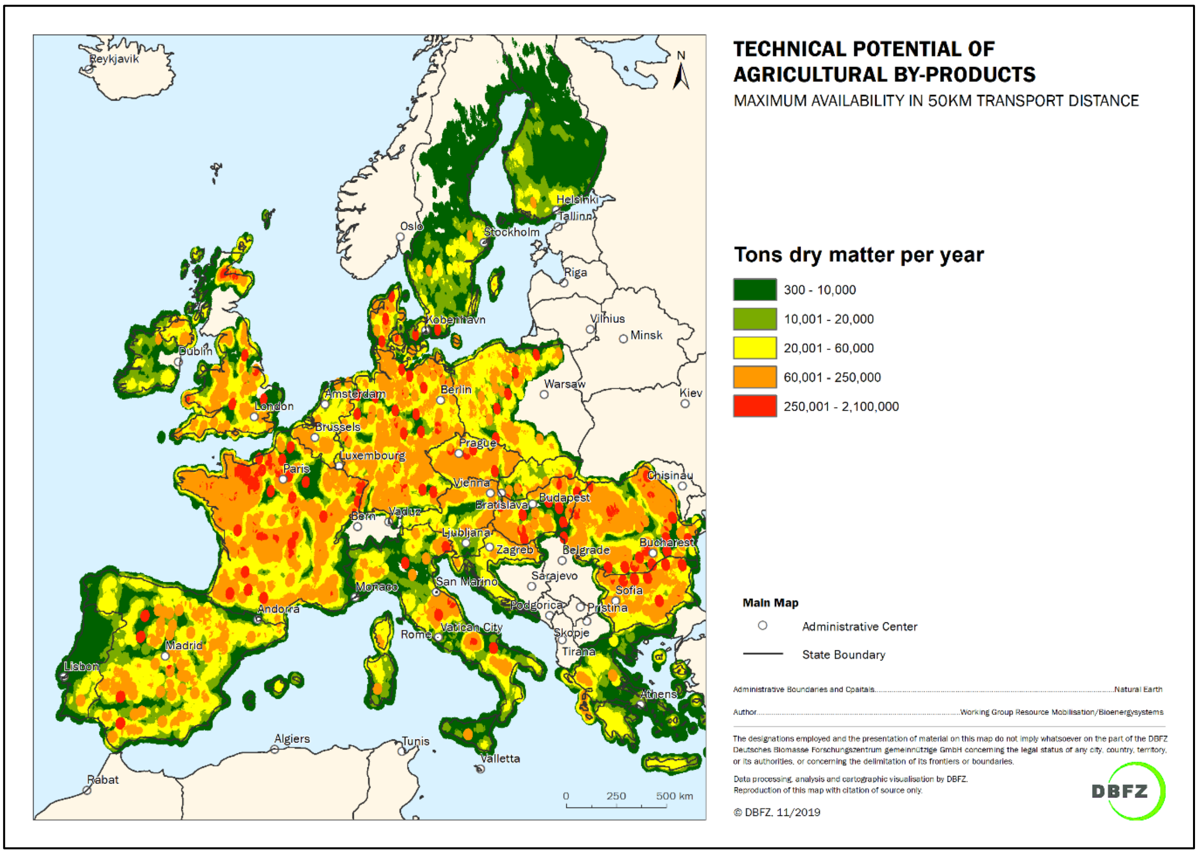

Figure 24 Maximum technical biomass potential of agricultural by-products

Animal Excretions

Cattle

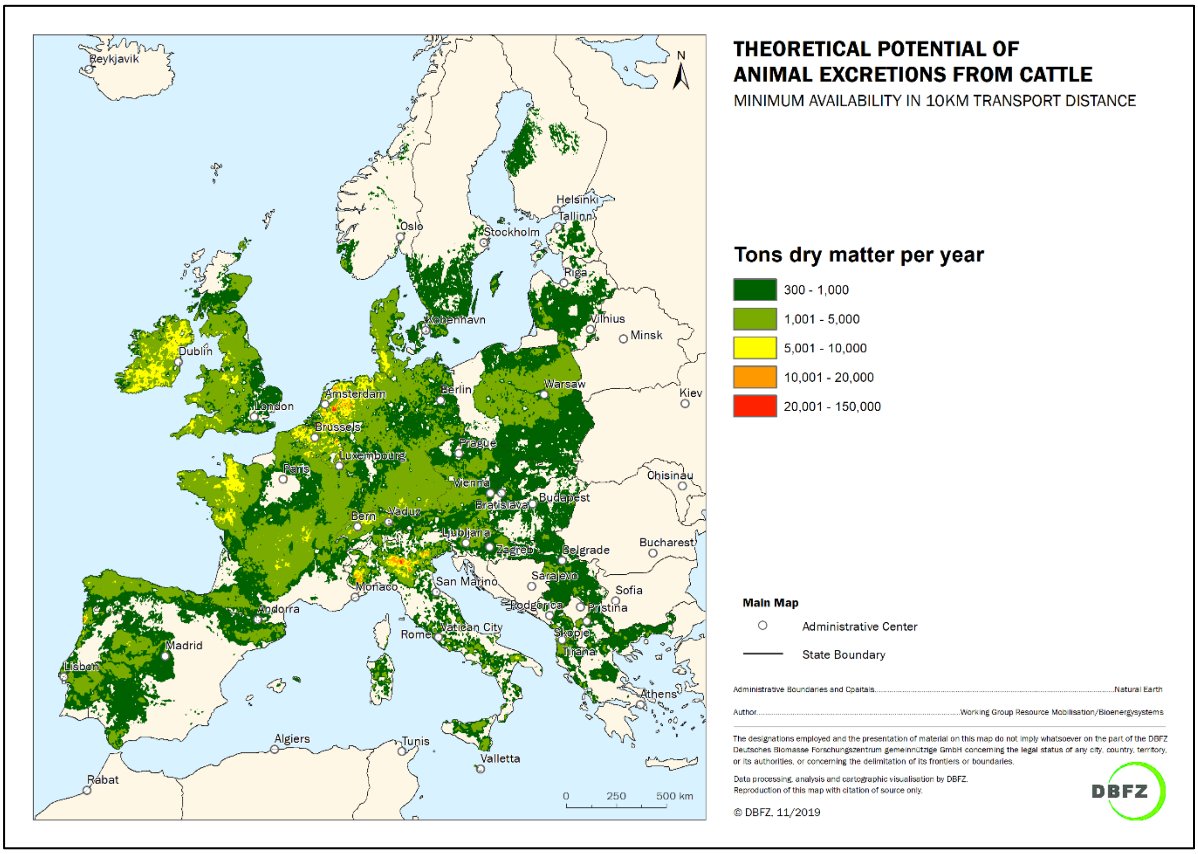

Figure 25 Minimum theoretical biomass potential of cattle excretions

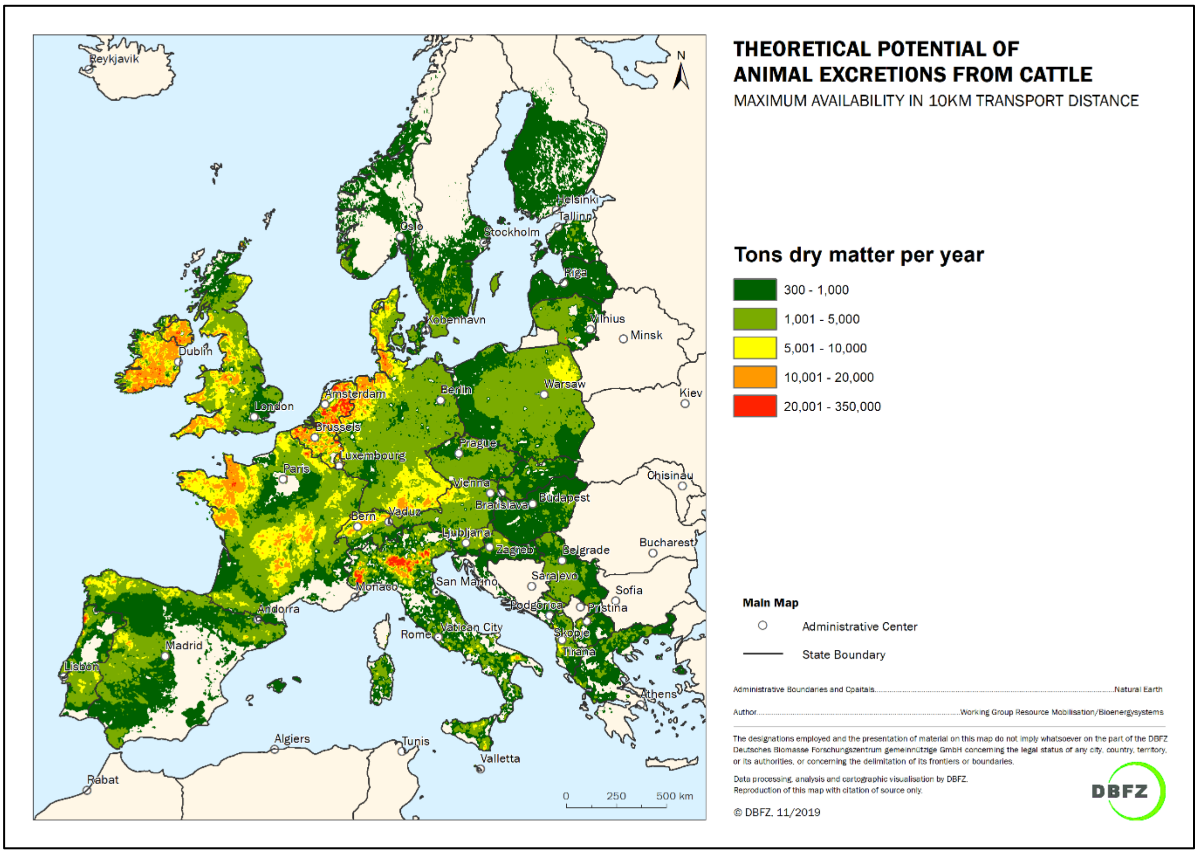

Figure 26 Maximum theoretical biomass potential of cattle excretions

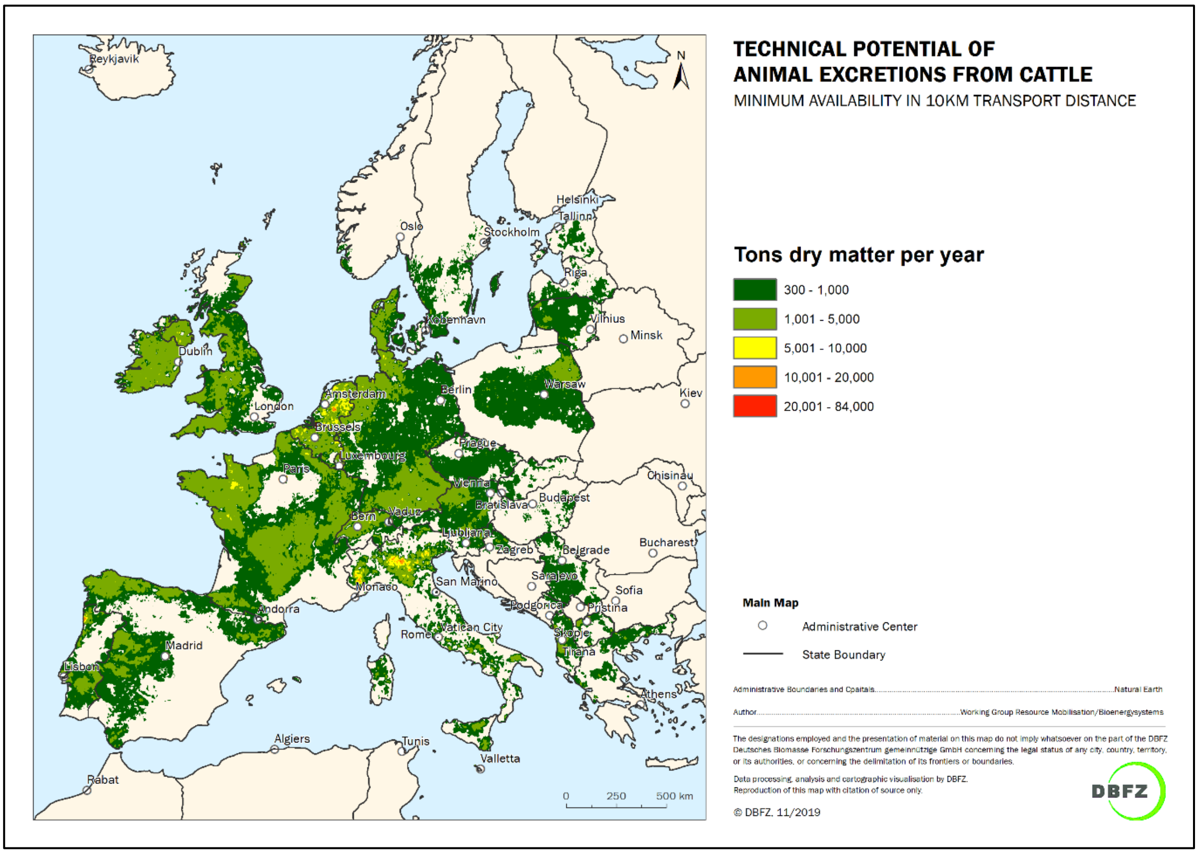

Figure 27 Minimum technical biomass potential of cattle excretions

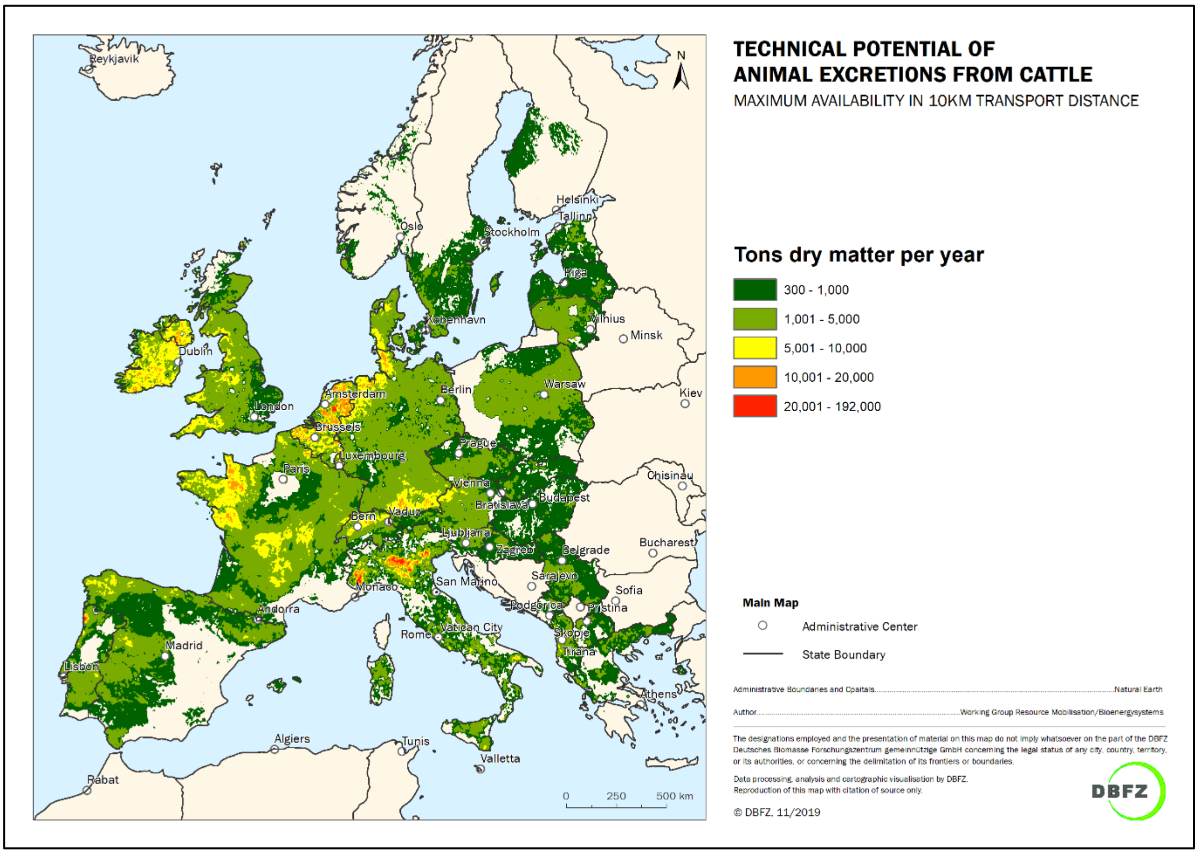

Figure 28 Maximum technical biomass potential of cattle excretions

Pigs

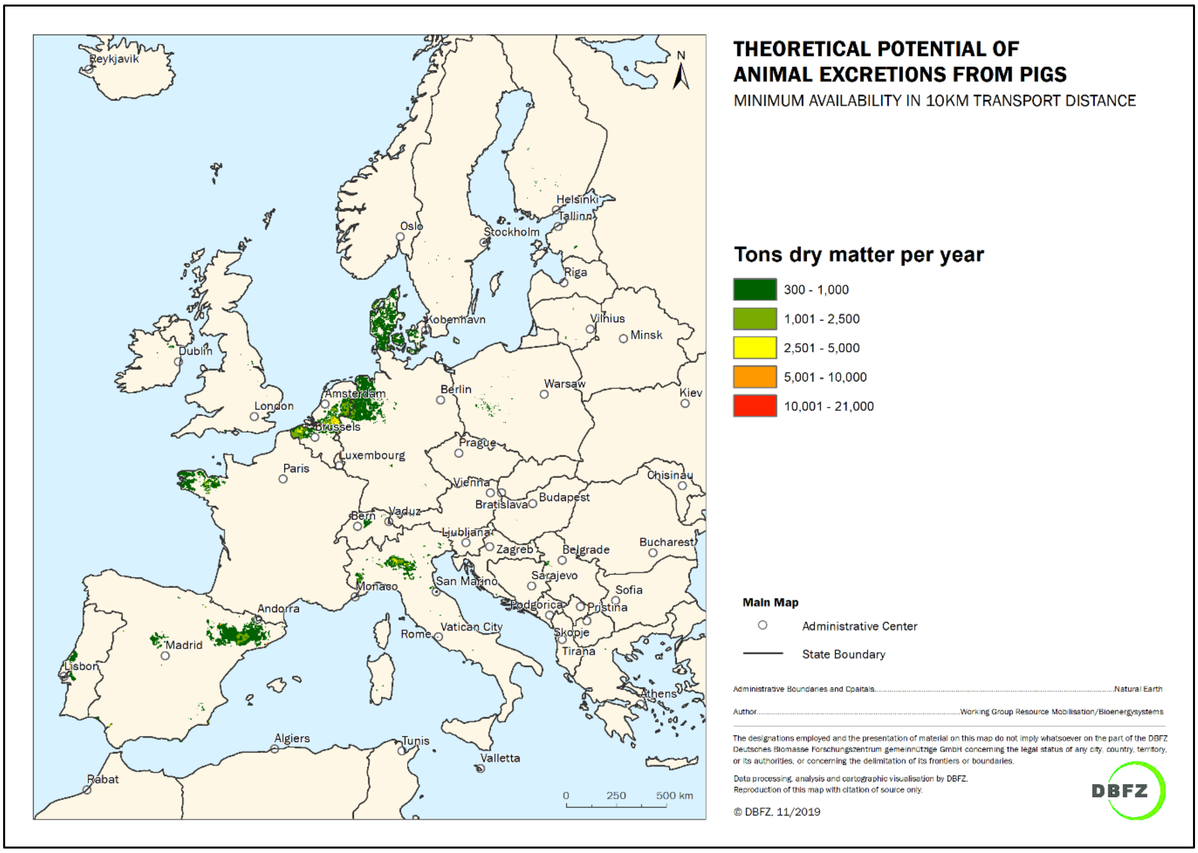

Figure 29 Minimum theoretical biomass potential of pig excretions

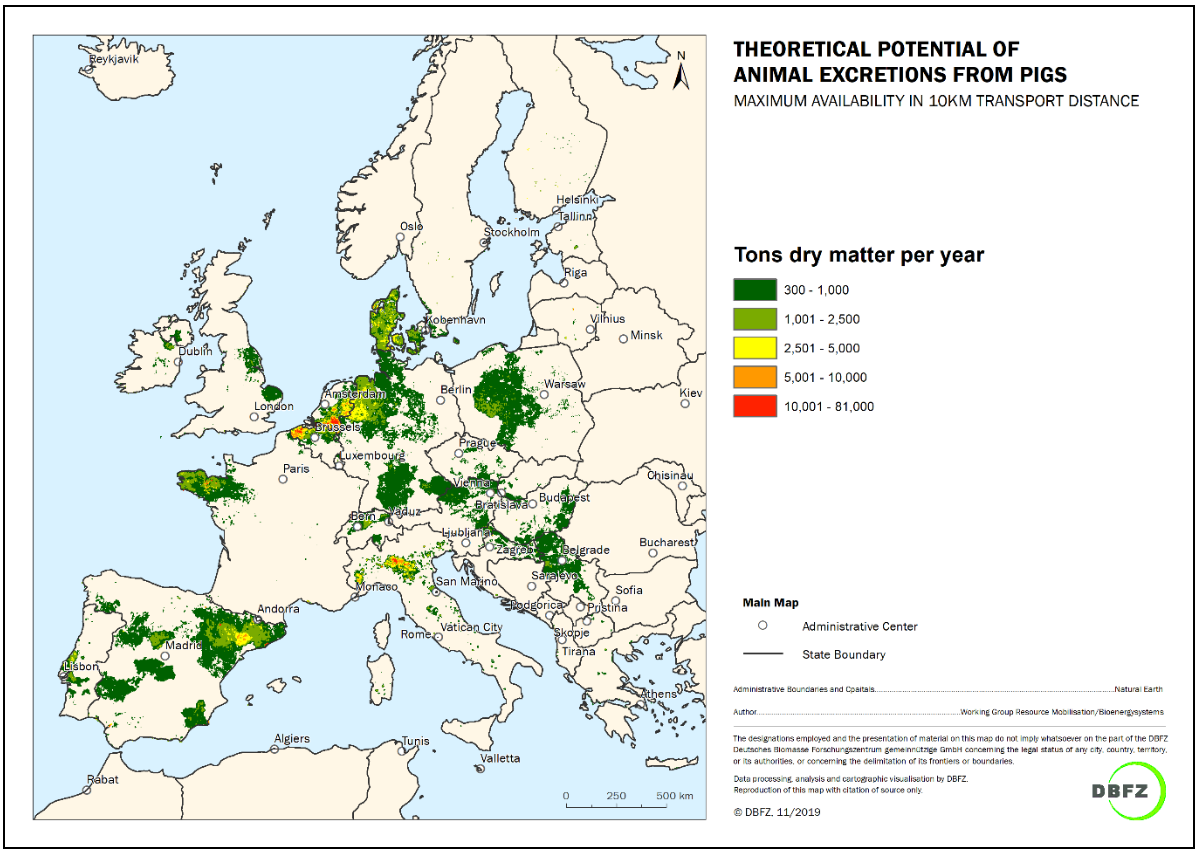

Figure 30 Maximum theoretical biomass potential of pig excretions

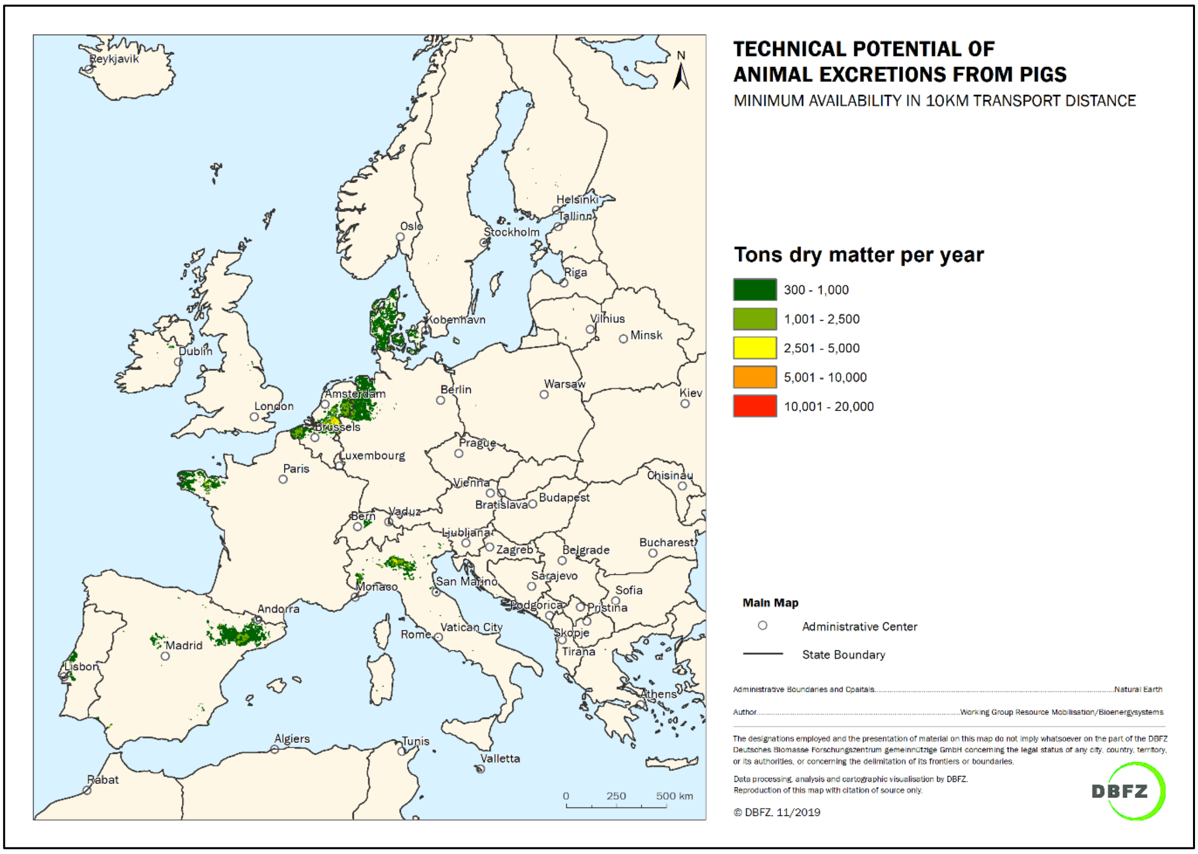

Figure 31 Minimum technical potential of pig excretions

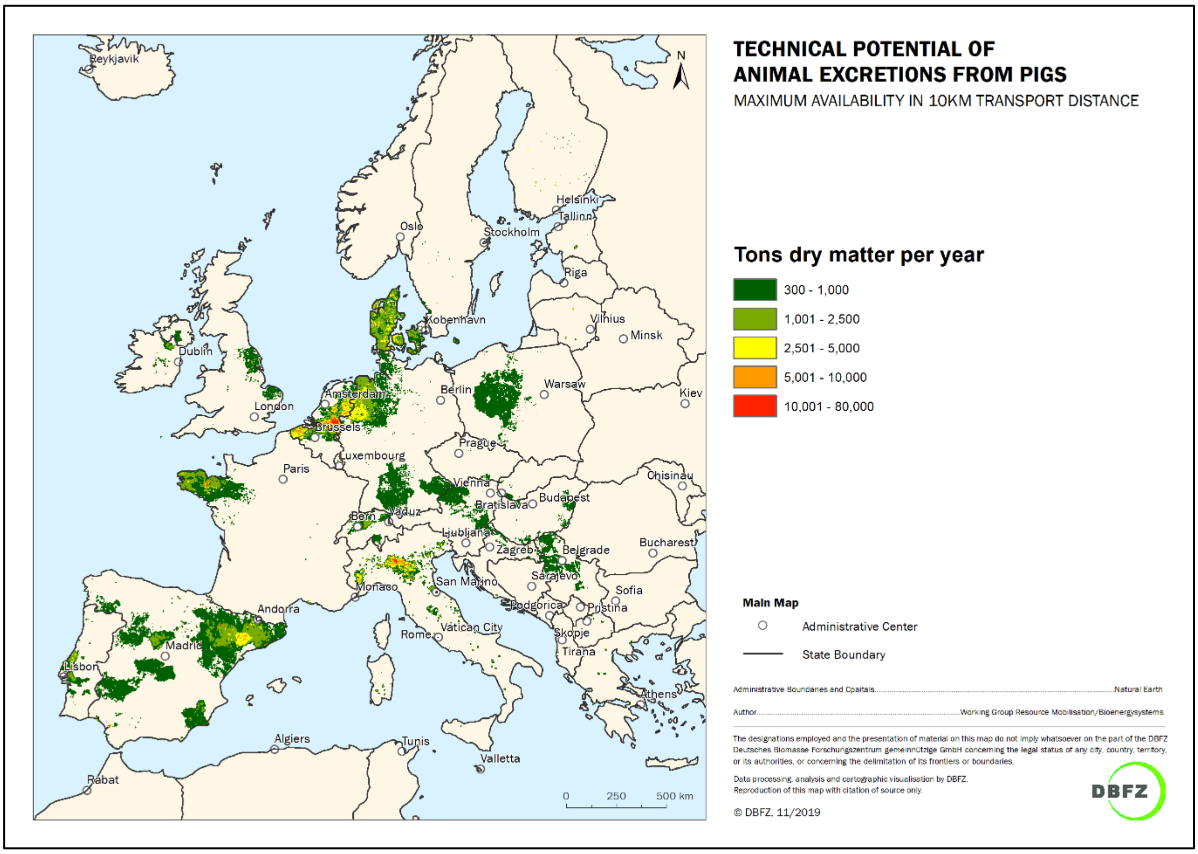

Figure 32 Maximum technical potential of pig excretions

Poultry

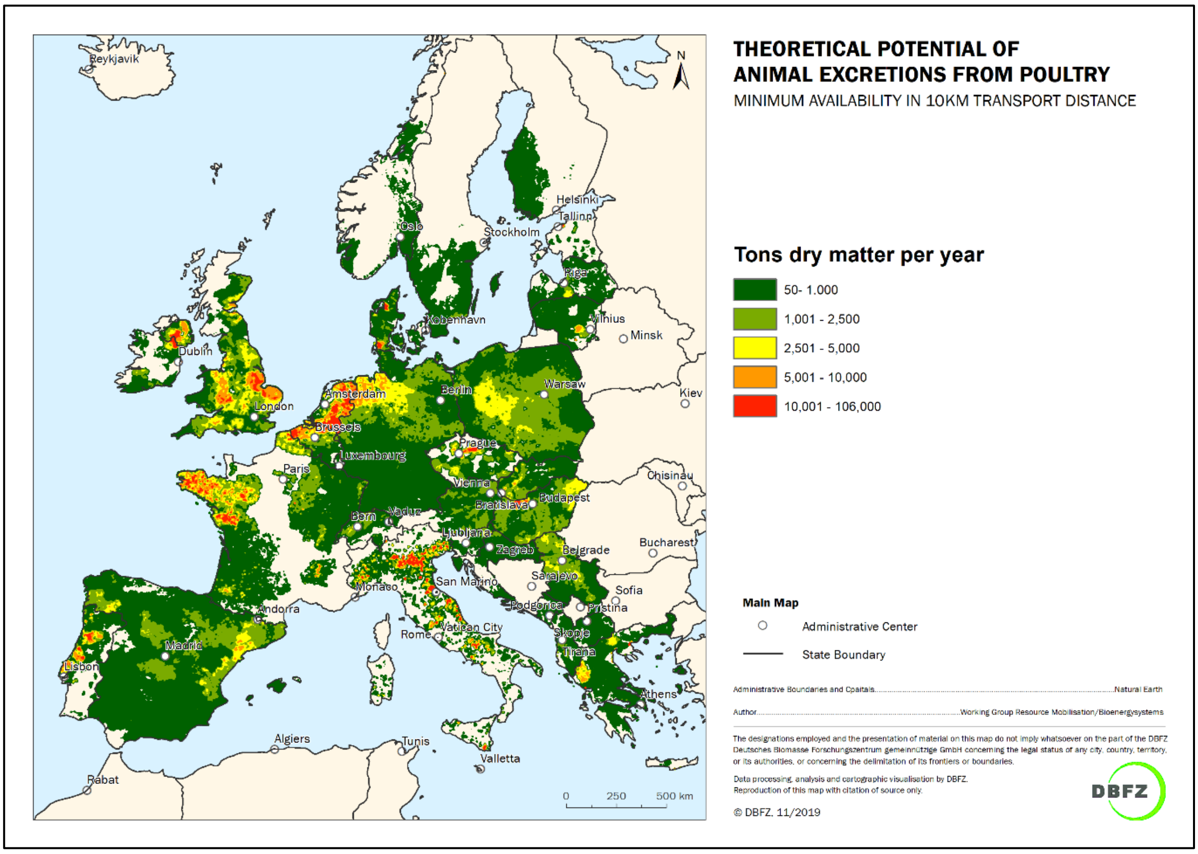

Figure 33 Minimum Theoretical Potential from poultry excretions

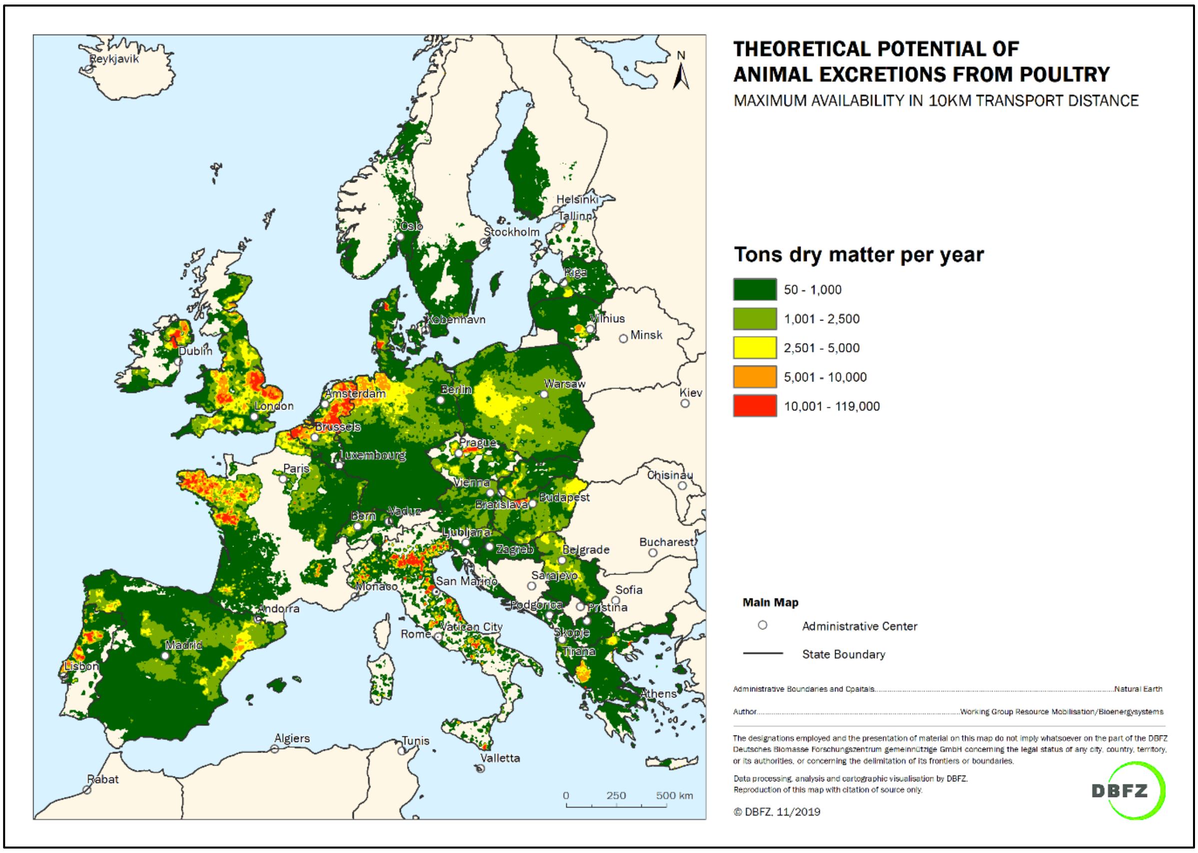

Figure 34 Maximum Theoretical Potential from poultry excretions

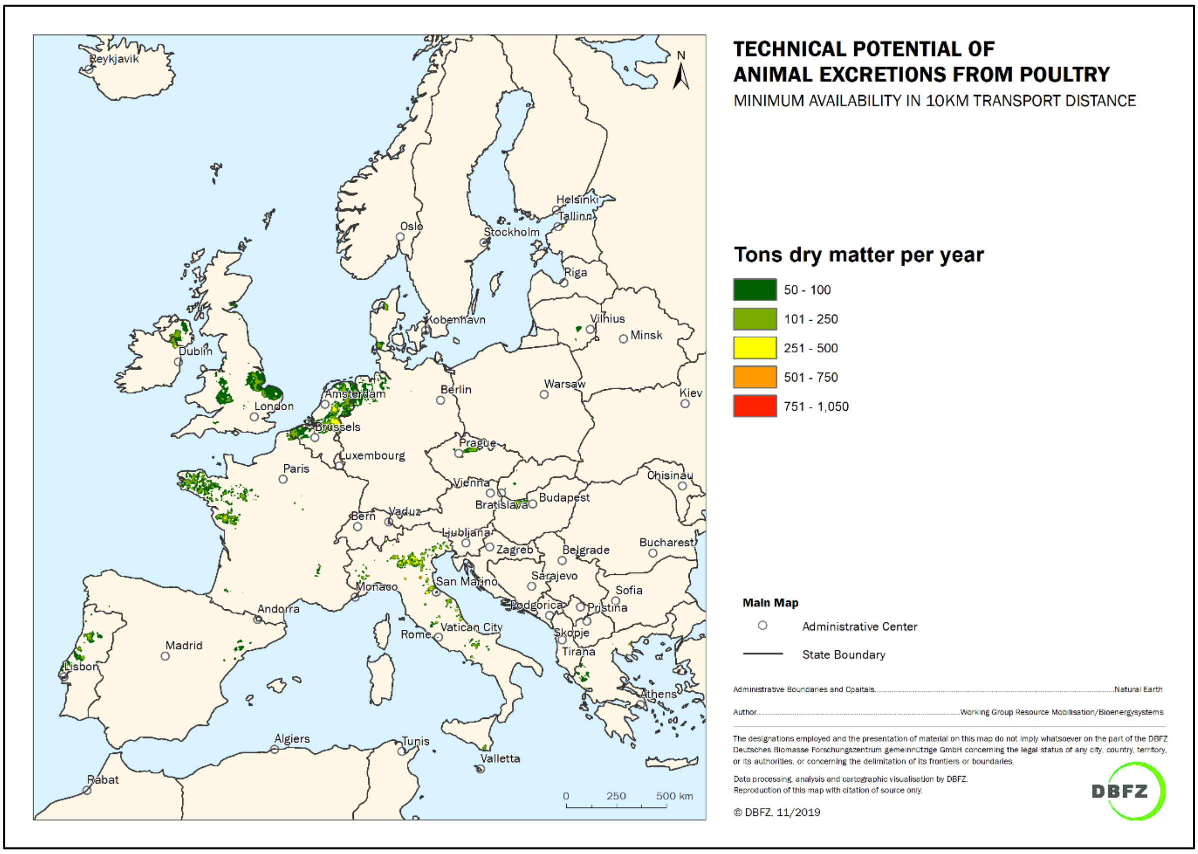

Figure 35 Minimum Technical Potential from poultry excretions

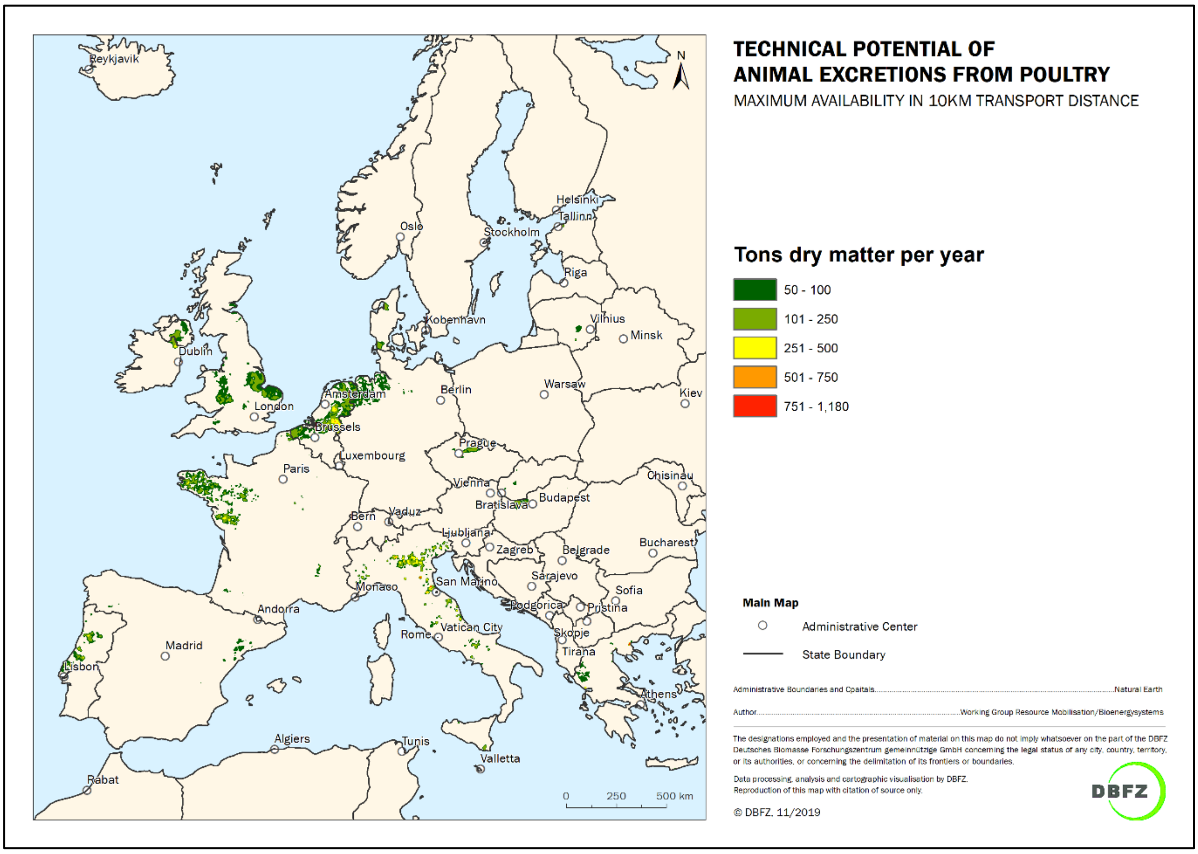

Figure 36 Maximum Technical Potential from poultry excretions

Sewage Sludge

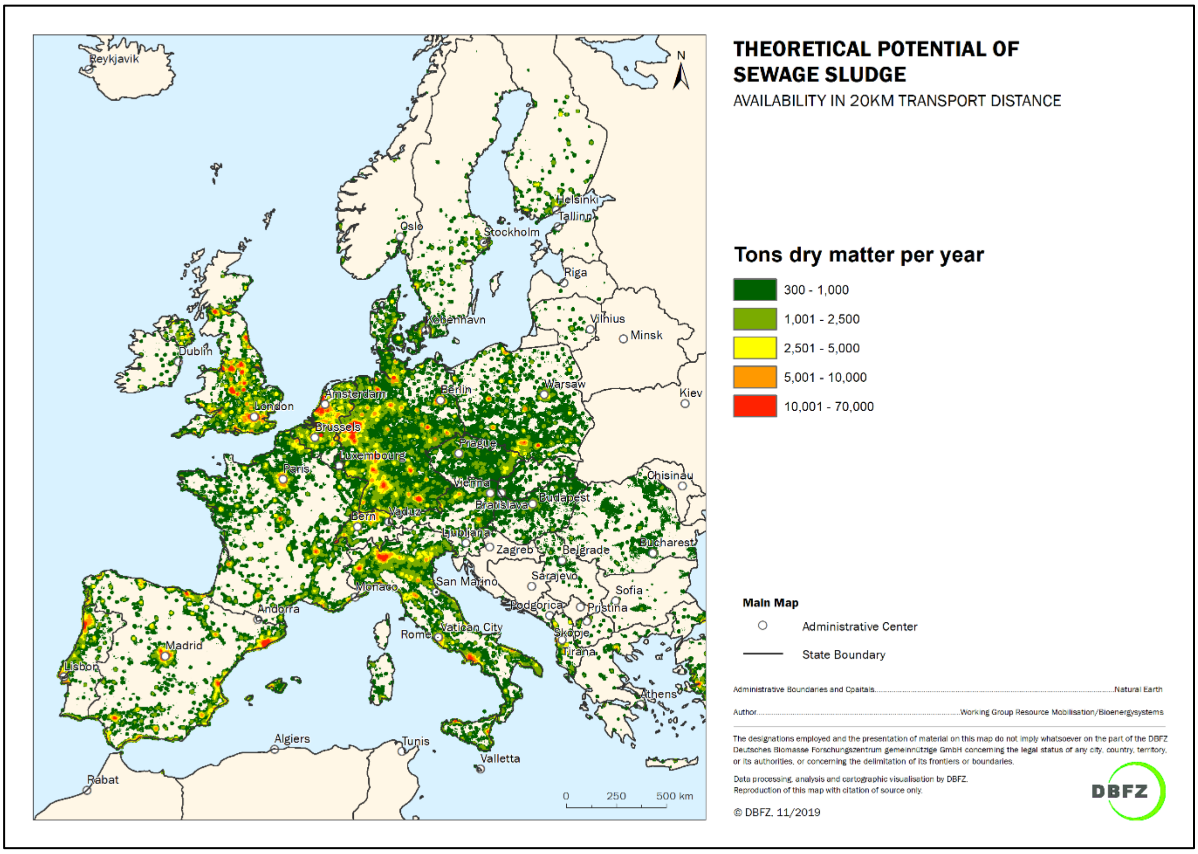

Figure 37 Theoretical potential from sewage sludge

Biowaste

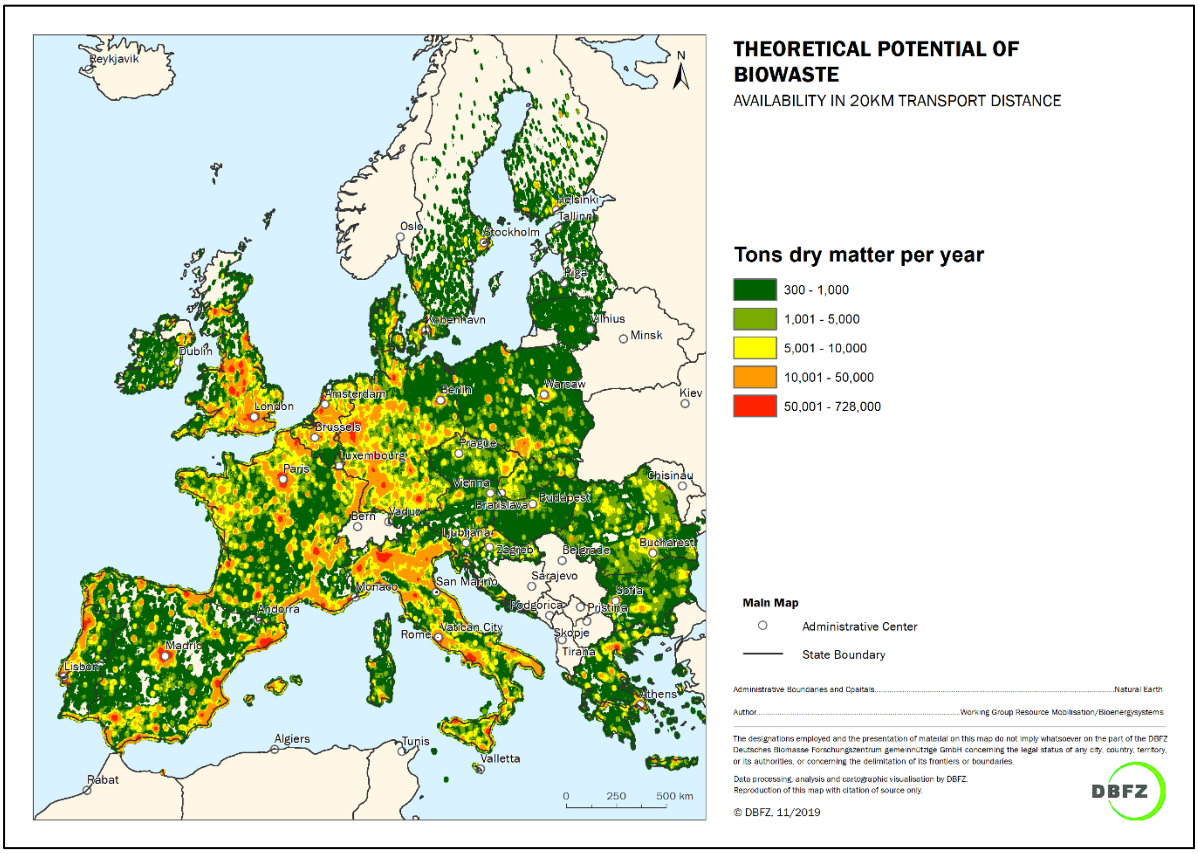

Figure 38 Theoretical potential from biowaste

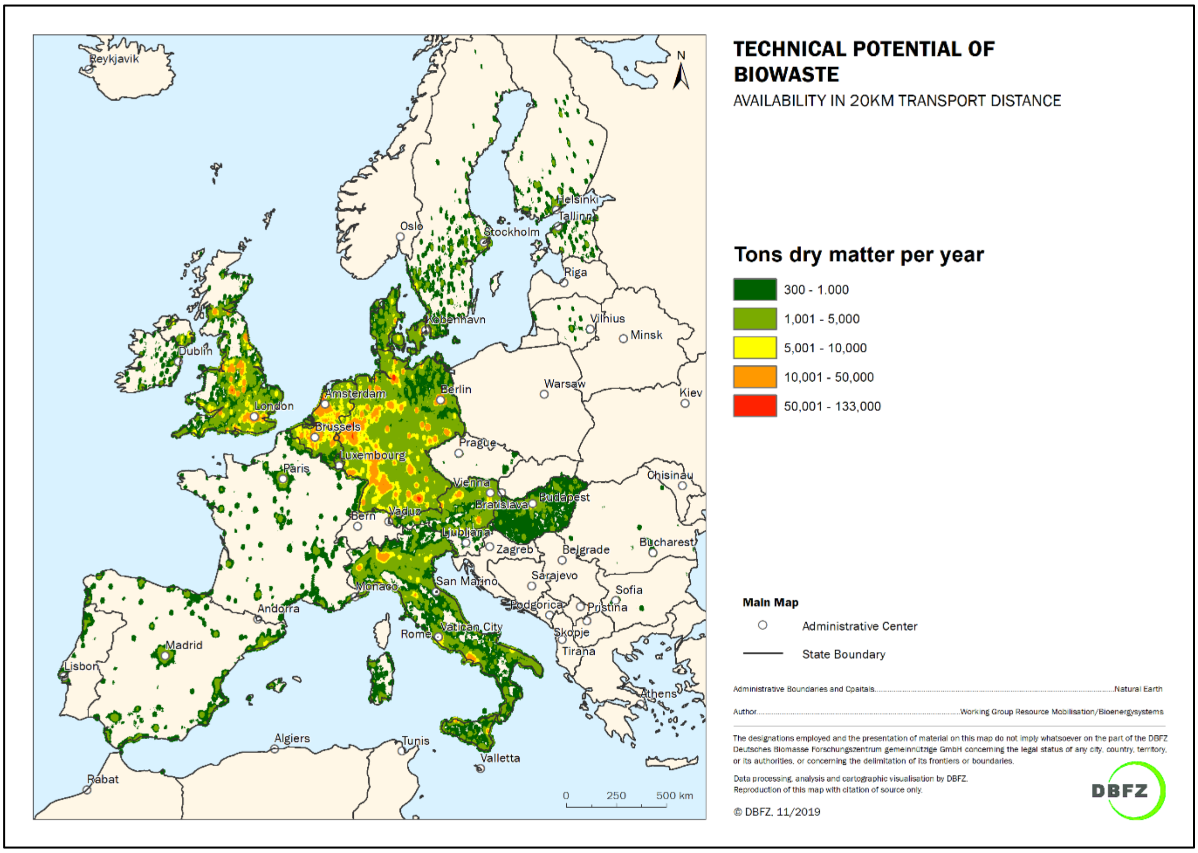

Figure 39 Technical potential from biowaste

HyFlexFuel
Public Report: Report on regional feedstock potentials and preference regions for HTL projects

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