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Development of a GIS-based spatial model for the estimation of sustainable biomass potentials in different regions of North West Europe

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Abstract

Within the EU-project BioenNW a GIS-based spatial model for the estimation of the amount and the spatial distribution of different biomass residues, originating e.g. from agriculture, forestry and municipal waste, is being developed using the integrated development environment Eclipse together with the programming language Python and the software ArcGIS. This study presents the model structure and exemplary results for the estimation of residue potentials from cereals and root crops cultivation on arable land in the district Dueren (Germany). Besides to theoretical potentials, so called sustainable potentials are estimated assuming different types of ecological and techno-economic restrictions. The sustainable residue potentials are estimated for the EEA reference grid (1 km) including maps data on land cover, protected areas, soil erodibility and soil organic carbon content together with statistical data on land use and crop yields for the year 2010.

1. Introduction

Estimating the amount and the spatial distribution of biomass resources is crucial for the development of process chains for biomass utilization, especially for questions regarding plant location, plant size and transport distances for raw materials. Spatial analysis can be carried out using Geographic Information Systems (GIS) therewith spatial information on biomass potentials can be calculated as well as collated and displayed. For biomass potential analysis, a spatial model based on a GIS is being developed within work package 2 of the EU-project BioenNW – Delivering Local Bioenergy to North West Europe[2].

1.1 GIS-based approaches for biomass potential analysis

GIS-based approaches are widely used for biomass potential analysis as well as for location and transport distance analysis for biomass resources in different European regions. They permit the inclusion and combination of different types of spatial information, e.g. via maps data, and are therefore suitable for biomass potential and supply analysis taking into account regional conditions, such as land cover or road networks. For example in (Voivontas et al 2001) the spatial distribution of the theoretical, available, technological and exploitable potential of agricultural residues is determined for the island of Crete using a GIS-based approach. In (Beccali et al 2009) the technical and the economic potential for woody residues and energy crops is estimated for Sicily using a GIS-based methodology, including data on land cover, terrain elevation, climate and rain maps, geological, lithological and morphological maps. In (Fischer et al 2010) suitability and yield maps for biofuel feedstock in Europe have been elaborated using climate, topography, soil and land use data. In (Jäppinen/Korpinen 2011) the local availability of forest biomass together with road network properties is evaluated for two case studies in Finland and in (Geijzendorffer et al 2008) a GIS is used in order to account for the spatial distribution of biomass resources in a logistical optimization model for two case studies in the Netherlands.

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[2] http://bioenergy-nw.eu/

1.2 Estimation of sustainable biomass potentials within the project BioenNW

Within the project BioenNW a GIS-based model is being developed in order to estimate and visualize the amount and the spatial distribution of residual biomass fractions, e.g. from agriculture, forestry, and municipal waste, in 5 regions of North West Europe, namely North Rhine-Westphalia (Germany), Île-de-France (France), West Midlands (United Kingdom), Wallonia (Belgium), and South Netherlands (the Netherlands) (cp. Figure 2). Furthermore, the model will be used for the identification of suitable areas for energy crop production. Besides to theoretical potentials in particular sustainable potentials are estimated, considering techno-economic and ecological restrictions, for example in terms of areas and amounts for biomass extraction. The outcomes of the developed GIS-model are supposed to facilitate local Biomass Support Centers (BSCs) which are being installed within the project BioenNW. In this survey, the current status of the model and first results with respect to biomass residues from arable land are presented.

2. Development of a GIS-based model for the estimation of amount and spatial distribution of agricultural residues

The model is being developed using the integrated development environment Eclipse together with the programming language Python and the software ArcGIS. The site-package ArcPy of the software ArcGIS provides access to the geoprocessing tools of the software ArcGIS and therefore allows for the creation of modeling workflows (ESRI 2012). Figure 1 shows an overview of the model for residues from agricultural areas. At first, residue type, model region, restrictions and plant location (optionally) are selected. Then, region-specific maps data is generated from the input maps data and, depending on the selected restrictions, the areas for residue extraction are identified. Together with statistical data, the amount and spatial distribution of the residues is calculated and transport distance calculations are carried out.

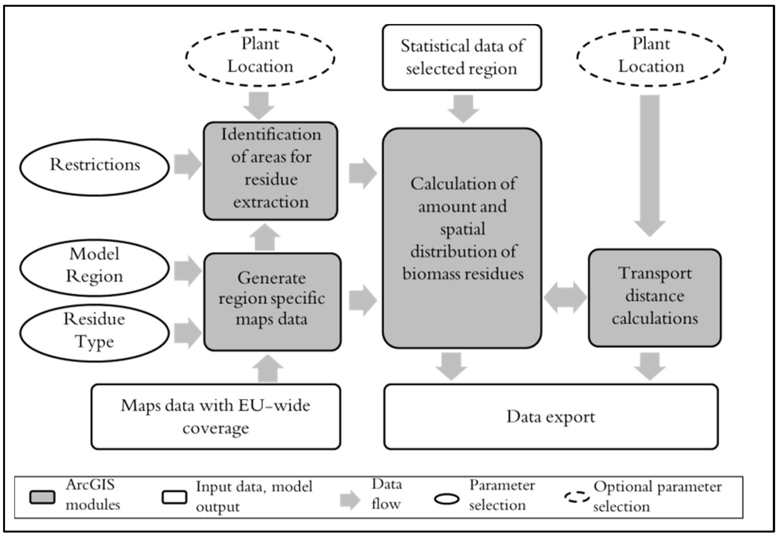

Figure 1: Model-overview for residues from agricultural areas

2.1 Input Data

There are two types of input data to the model (cp. Figure 1): Maps data and statistical data. All maps data used in this survey for the potential estimations are listed in Table 1. The administrative boundaries of the respective model regions are taken from GADM[3]. For residues from arable land, the spatial modeling is based on land cover data together with other areal data, such as data on protected areas (CDDA[4] polygon data) of the EEA (European Environment Agency) and soil data (ESDB-SGDB[5] polygon data, OCTOP[6] raster data) from the European Soil Portal of the EC (European Commission). Data on land cover is taken from the CORINE[7] land cover 2006 (CLC 2006) raster data set of the EEA as well as from the CAPRI[8] Crop Datasets of the EFSA (European Food Safety Authority) which is provided by the European Soil Portal. Besides to EU-wide available maps-data, region-specific statistical data (base year 2010), e.g. cultivation statistics for agricultural crops, is used. Therewith the residue potentials are estimated and displayed for a certain spatial resolution. For the time being the potentials are calculated for each grid cell of the EEA-reference grid[9] (1 km grid and 10 km grid). For plant locations, point data from open street map (OSM[10]) is used. In terms of statistical data, regional databases, such as the German database "Regionaldatenbank Deutschland" (Statistisches Bundesamt 2013) together with other literature, are used (cp. Table 2).

Table 1: Used maps data for the modeling of residues from arable land

Category	**Source**	**Description**	**Type**
Model regions	GADM[3]	Administrative boundaries	Polygon
Protected areas	CDDA[4]	Protected areas according to the International Union for Conservation of Nature (IUCN)	Polygon
Soil data	ESDB-SGDB[5]	Soil erodibility	Polygon
	OCTOP[6]	Soil Organic Carbon Content	Raster 1 km x 1km
Land cover	CORINE[7]	Land cover 2006	Raster 100 m x 100 m
	CAPRI[8]	Crop Datasets of the European Food Safety Authority (EFSA) database	Raster 1 km x 1km
Reference grid	EEA[9]	1 km grid, 10 km grid	Polygon
Plant location	OSM[10]	Location of e.g. Counties, Cities, Towns, Villages	Point

2.2 Model regions and residue types

For each model region of the project BioenNW (cp. Figure 2), different administrative units, i.e. NUTS (Nomenclature of Units for Territorial Statistics) levels, with respective statistical data are considered. The biggest administrative units are the respective NUTS 1 administrative units (cp. Figure 2). The smallest of the considered units represent those NUTS 3 administrative units, where the local BSCs, established within the project BioenNW, are situated. For the time being these are the district Dueren (Germany), the district Yvelines (France), the district Liège (Belgium), the district Zuidoost-Noord-Brabant (Netherlands)

[3] Global Administrative Areas (www.gadm.org)
[4] Common Database on Designated Areas (http://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-5)
[5] European Soil Database – Soil Geographical Database (http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/index.htm)
[6] Organic carbon content in the topsoil (http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/octop_data.html)
[7] Coordination of Information on the Environment (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-clc2006-100-m-version-12-2009)
[8] Common Agricultural Policy Regionalised Impact Modelling System (http://eusoils.jrc.ec.europa.eu/library/Data/EFSA/)
[9] EEA-reference grid (http://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-1)
[10] Open street maps datasets (http://download.geofabrik.de/osm/europe/)

and the district Birmingham (UK). Depending on the statistical data availability, the model can also be applied to other geographical extents and regions within the EU. In this survey the results for the German district Dueren, which is situated within the administrative region Koeln and the respective federal state North Rhine-Westphalia (NRW), are presented (cp. Figure 3). Concerning the residue types, residues from cereals cultivation and from root crops cultivation are considered.

2.3 Restrictions for the use of residues from arable land

For the estimation of residual biomass potentials derived from arable areas, so called theoretical potentials are estimated and reduced due to ecological and/or techno-economic restrictions in order to obtain sustainable potentials.

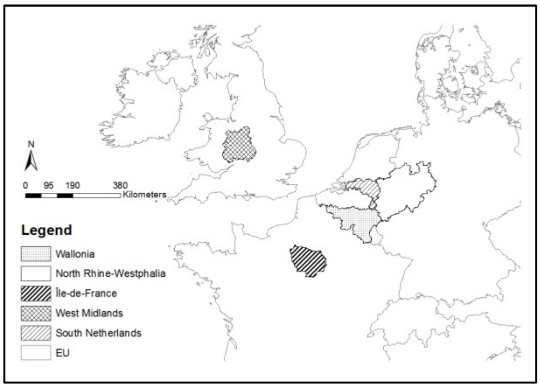

Figure 2: Model regions NW-Europe (NUTS 1)

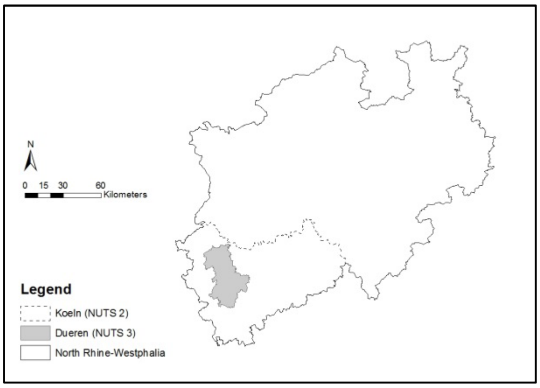

Figure 3: Model regions in Germany: NRW (NUTS 1), Koeln (NUTS 2), Dueren (NUTS 3)

2.3.1 Theoretical biomass potential

The theoretical potential is defined as the total amount of crop residues occurring on arable land, regardless of current usage, harvest losses or ecological restrictions. The theoretical potential of agricultural residues from e.g. cereals cultivation on arable land is estimated using the region-specific total arable area, the percentage of cereals cultivated on arable land, the weighted cereals yield as well as the weighted Residue-to-Product-Ratio (RPR) for cereals.

2.3.2 Sustainable biomass potential

Besides to the theoretical potentials, sustainable potentials are calculated using ecological and/or techno-economic restrictions. In the case of arable areas, ecological restrictions may arise for example due to soil threats, such as soil erosion or low organic carbon content in the topsoil, which may require that residues remain on agricultural areas, or due to the existence of protected areas, which may delimit the available areas for residue extraction. Techno-economic restrictions may arise for example due to harvest losses and/or straw demand for animal husbandry (e.g. in the case of residues from cereals cultivation). In this survey, restrictions refer to limitations of areas for residue extraction as well as to limitations of the amount of extracted residues from arable areas. Currently, different combinations of restrictions are used for the calculation of a *Basis Scenario* with minor restrictions and a *Restrict Scenario* with major restrictions. For the *Restrict Scenario* restrictions include the exclusion of protected areas (IUCN[11]-categories Ia, Ib, II, III, IV according to CDDA), the exclusion of areas with a high risk for soil erosion (erodibility "very strong" according to ESDB-SGDB) as well as the exclusion of areas with low organic carbon content in topsoil (C_{org} in topsoil < 2 % according to OCTOP). For the *Basis Scenario* no areas are excluded for residue extraction. For both scenarios, ecological restrictions (Res^{Ecol}) for the amount of residue extractions are implemented and can be set as a function of C_{org} content in topsoil, taking into account the residue demand for maintaining the C_{org} balance in soils. Currently it is assumed that if C_{org} in topsoil is lower than 6 %, 60 % of the residues are left on the field (Res^{Ecol} = 0.4) and if C_{org} in topsoil is equal or higher than 6 %, 30 % of the residues are left on the field (Res^{Ecol} = 0.7). If no ecological restriction is used, Res^{Ecol} is set to 1 (cp. Equation 1). Furthermore, techno-economic restrictions, e.g. with regard to straw demand for animal husbandry as well as harvest losses of residues, can be included, i.e. respective residue amounts are subtracted from the calculated potentials.

2.4 ArcGIS-modules

The following ArcGIS modules are implemented in Eclipse using the geoprocessing tool reference of ArcGIS together with python scripts.

2.4.1 Generation of region-specific maps data and identification of areas for residue extraction

First of all, from the EU-wide available maps data (cp. Table 1), region-specific maps data is generated for the calculation of areas for residue extraction. Therefore the maps data which is needed for the chosen residue type is converted to a consistent projected coordinate system (ETRS89/LAEA[12]) and the maps data for the chosen model region is clipped from the projected maps data. For the identification of arable areas for residue extraction, the arable areas are selected from the CORINE land cover data (cp. Table 1), i.e. the land cover classes 211 (non-irrigated arable land), 212 (permanently irrigated land), 213 (rice fields), whereby for the north-western European model regions only non-irrigated arable land is relevant. For the *Basis Scenario* no areas are excluded for residue extraction while for the *Restrict Scenario* the respective protected areas, areas with high risk of soil erosion and areas with C_{org} in topsoil < 2 % are excluded (cp. section 2.3.2). If additionally a plant location is selected, the areas for residue extraction are also calculated for a chosen radius around this location.

2.4.2 Calculation of amount and spatial distribution of biomass resources

The identified areas for residue extraction are intersected with the EEA reference grid (1 km) as well as with the maps data on soil erodibility and soil organic carbon content (cp. Table 1). The total arable area for residue extraction per grid cell (A^{Arable_total}) is then calculated for the respective region (r) for each scenario (sc) and is corrected via statistical data for the year 2010. Therefore a region-specific correction share (cs^{Arable}) is calculated through dividing the total arable area of the respective region according to the regional statistics (base year 2010) by the total arable area of the respective region according to CLC 2006. Together with the region-specific share of the respective crop type (S^{Crop}), the arable area for residue extraction for a specific crop type (A^{Arable_Crop}) is obtained (cp. Equation 1).

Equation 1

$$A_{sc,ct,r}^{Arable\_Crop} = A_{sc,r}^{Arable\_total} \cdot cs_r^{Arable} \cdot S_{ct,r}^{Crop} \quad \forall\ sc \in SC,\ \forall\ ct \in CT,\ \forall\ r \in R$$

[11] International Union for Conservation of Nature
[12] European Terrestrial Reference System 1989 (Coordinate Reference System)/Lambert Azimuthal Equal Area (Projection)

A^{Arable_total}	Total arable area per grid cell	(ha)	S^{Crop}	Share crop type	(%)
A^{Arable_Crop}	Arable area per grid cell and crop type	(ha)	cs^{Arable}	Correction share arable area	(-)

SC={Basis; Restrict}, CT={Cereals; Root crops}, R={NRW; Koeln; Dueren}

In order to obtain a better approximation of the spatial distribution of the residues, the CAPRI raster data set (cp. Table 1) which contains data on areas covered with a certain crop and on the respective crop share per grid cell ($sg_{ct}^{Crop\_CAPRI}$) can be used. Therewith the share of a crop type per grid cell (sg_{ct}^{Crop}), resulting from A^{Arable_Crop} (cp. Equation 1), is corrected, if the respective grid area (A^{Grid}) is completely included ($A^{Grid} = 1\ km^2$), if $sg_{ct}^{Crop\_CAPRI} > sg_{ct}^{Crop}$ and if the calculated share of arable land per grid cell is higher than the crop share according to CAPRI ($sg^{Arable} > sg_{ct}^{Crop\_CAPRI}$). Correction means that $sg_{ct}^{Crop\_CAPRI}$ is assumed for the respective grid cells and that the sum of all surpluses is equally subtracted from those grids where no correction is carried out. The subtraction is only carried out if $A^{Grid} = 1\ km^2$ and if $sg^{Arable} > 20\ \%$. Consequently, the spatial correction does not alter the total amount of residues from arable land but the spatial occurrence in the respective region. The inclusion of CAPRI information for the correction of A^{Arable_Crop} results in corrected values for the arable areas for residue extraction per grid cell ($A^{Arable\_Crop\_c}$).

Equation 2

$$R_{sc,ct,oc,r}^{Arable} = A_{sc,ct,r}^{Arable\_Crop\_c} \cdot Y_{ct,r}^{Crop} \cdot RPR_{ct,r} \cdot Res_{oc}^{Ecol}\ \forall\ sc \in SC,\ \forall\ ct \in CT,\ \forall\ oc \in OC,\ \forall\ r \in R$$

R^{Arable}	Residue amount per grid cell	(t)	RPR	Residue-to-Product-Ratio	(-)	Res^{Ecol}	Ecolog. restriction	(-)
Y^{Crop}	Yield crop type	(t/ha)	$A^{Arable\_Crop\_c}$	A^{Arable_Crop} corrected	(ha)	OC={0-20}		

The annual residue amounts from arable areas (R^{Arable}) are calculated for each grid cell, for each scenario (sc) and crop type (ct) and depending on the organic carbon content in topsoil (oc) according to Equation 2.

2.4.3 Transport distance calculations

Based on the estimated amount and spatial distribution of the different biomass residues, the model can be used to estimate the transport distances of the biomass resources to the selected plant location. For transport distance calculations, the grid cell centers of the reference grid (1 km and 10 km) are calculated, the residue amounts of the respective grid cells are assigned to the respective grid cell center and the distance of each grid cell center as potential biomass source to the selected plant location as potential biomass sink is calculated. Currently, the Euclidean distance from each grid cell center of the 1 km grid to the chosen plant location is calculated. With this data, the minimum transport distance of biomass resources for a given plant size can be estimated. Furthermore, distance matrices, containing the distances from each grid cell center to each grid cell center, are generated for the selected region. These matrices can be used as input data for location planning tools taking into account e.g. interim storage and transport routes for biomass processing plants. For reasons of data processing capacity these matrices can only be generated for a limited set of points. As a start, the 10 km EEA reference grid (cp. Table 1) is used and the calculated biomass potentials for the respective 1 km grid cells are aggregated and assigned to the respective grid cell centers of the 10 km grid.

3. Exemplary results for the district Dueren

In this section, the results for the estimation of the amount and the spatial distribution of residues from two crop types, cereals and root crops, cultivated on arable land are presented. In this survey, the district

Dueren in Germany (cp. Figure 3) is chosen as model region and the city of Juelich is chosen as possible plant location. Figure 4 shows the calculated arable areas for sustainable residue extraction in the district Dueren for the *Basis Scenario* and the *Restrict Scenario* and within a 5 km radius around the city of Juelich (*Restrict Scenario*).

3.1 Statistical input data for the district Dueren

Statistical input data for the calculation of residue amounts from cereals and root crops cultivation are shown in Table 2. The arable area and the average agricultural yields for the base year 2010 are derived from regional statistics (Statistisches Bundesamt 2013). The Residue-to-Product-Ratios (RPR) are taken from (Esteban/Carrasco 2011) and from (LWK NRW 2013). Key data for animal husbandry (AH), i.e. animal numbers in terms of livestock units, percentages of animals kept with straw and straw demand for animal husbandry are taken from (Statistisches Bundesamt 2013), from (IT NRW 2011) and from (Kappler 2008). For residues from root crops no use for AH is assumed. According to (Esteban/Carrasco 2011) harvest losses (HL) of straw might account for 10 %. For the time being, competition for straw and root crops residues in terms of an energetic utilization is disregarded.

3.2 Amount and spatial distribution of residues from arable land in the district Dueren

The included grid cells and the respective grid cell centers (1 km and 10 km grid), the straw amounts per grid cell (1 km grid) for the *Basis Scenario* and the *Restrict Scenario* are displayed in Figure 5.

Table 2: Statistical input data for the district Dueren, base year 2010

Category			**Comment**		**Source**
Land use					
Arable land	ha	43,849			
Cereals area	ha	23,747	54 % as per arable land		[1]
Root crops area	ha	12,145	28 % as per arable land		
Cereals					
Weighted cereals yield	t/ha	8.17	Average yield for most common cereals weighted as per cultivation area		[1]
Weighted RPR* min	-	0.8	RPR for wheat, rye, winter barley weighted as		[3], [1]
Weighted RPR max	-	1.4	per cultivation area		[2], [1]
Heating value straw (water free)	MJ/kg	17			[8]
Water content straw	%	14			[8]
Harvest losses straw	%	10			[2]
Root crops					
Weighted root crops yield	t/ha	63.8	Average Yield for potatoes (51.2) and for sugar beet (68.5) weighted as per cultivation area		[1]
Weighted RPR min	-	0.5	RPR for potatoes (0.45) and sugar beet (0.43)		[3]
Weighted RPR max	-	0.6	weighted as per cultivation area		[6]
Heating value stems leaves, collar (water free)	MJ/kg	16			[7]
Water content stems, leaves, collar	%	77.4	Water content of potatoes (65 %) and sugar beet (82 %) residues weighted as per cultivation area		[8]
Animal husbandry (AH)					
Cattle (including dairy cows)	LSU**	11,224	Percentage of animals kept with straw	31 %	[1], [4]
Pigs (including breeding saws)	LSU	583		10 %	

Sheep	LSU	278	100 %	
Solid-hoofed animals***	LSU	1,124	100 %	
Straw demand for AH with straw	t/LSU	2.2		[5]

*Residue-to-Product-Ratio, **Livestock unit, ***Horses, Donkeys, Mules, [1] (Statistisches Bundesamt 2013), [2] (Esteban/Carrasco 2011), [3] (LWK NRW 2013), [4] (IT NRW 2011), [5] (Kappler 2008), [6] (DüV 2006), [7] (Di Blasi et al 1996), [8] (KTBL 2009)

Most of the sustainable straw potential can be found in the eastern part of the district Dueren (cp. Figure 5). The residue amounts of each grid cell are summed up in order to obtain the total amount for the respective region or for a chosen radius around the selected plant location. Table 3 shows the calculated sustainable residue potentials from cereals and root crops cultivation in the district Dueren and within a 5 km radius around the city of Juelich (RPR max, *Basis Scenario* and *Restrict Scenario*). Compared to the *Basis Scenario*, residue amounts are around 34 – 42 % lower for the *Restrict Scenario*. From the residue amounts (t/a) the respective annual energy potentials (TJ/a) are calculated (cp. Table 3) using the average water content together with the water-free heating value for the respective crop type (cp. Table 2). While in the district Dueren the amount of residues from root crops cultivation is higher than the amount of residues from cereals cultivation, the contrary is the case for the energy potential. This goes mainly back to the considerably higher water content of residues from root crops cultivation compared to cereals straw. Additionally, first transport distance approximations are carried out. If for example a 10 MW bioenergy plant should be provided with straw (approx. 20,000 t straw/a) from the district Dueren, a radius of approximately 12 km around the city of Juelich would be needed for residue collection (*Scenario Restrict*, RPR max, no consideration of straw demand for AH, no consideration of HL).

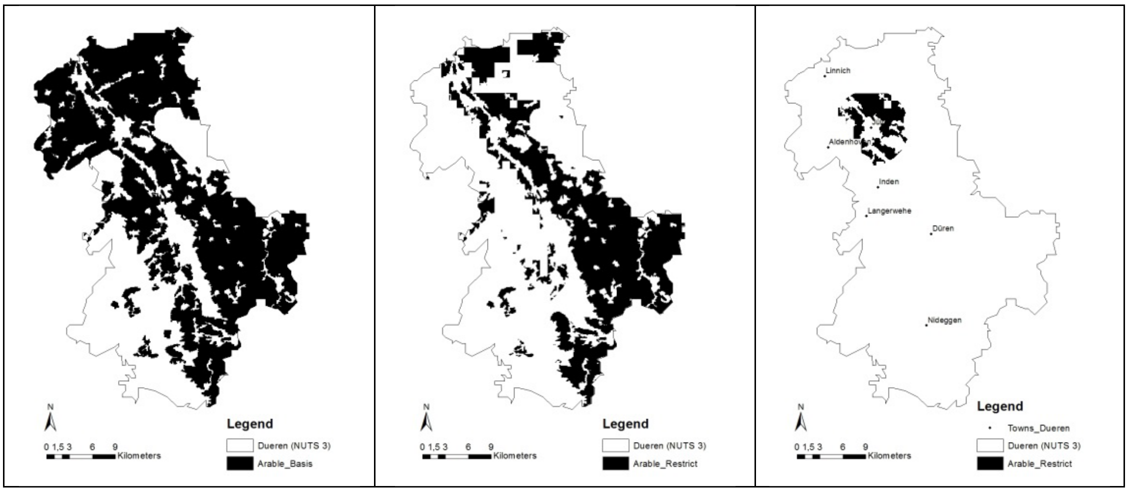

Figure 4: Arable areas for residue extraction in the district Dueren, *Basis Scenario* (left), *Restrict Scenario* (middle), and within a 5 km radius around the city of Juelich, *Restrict Scenario* (right)

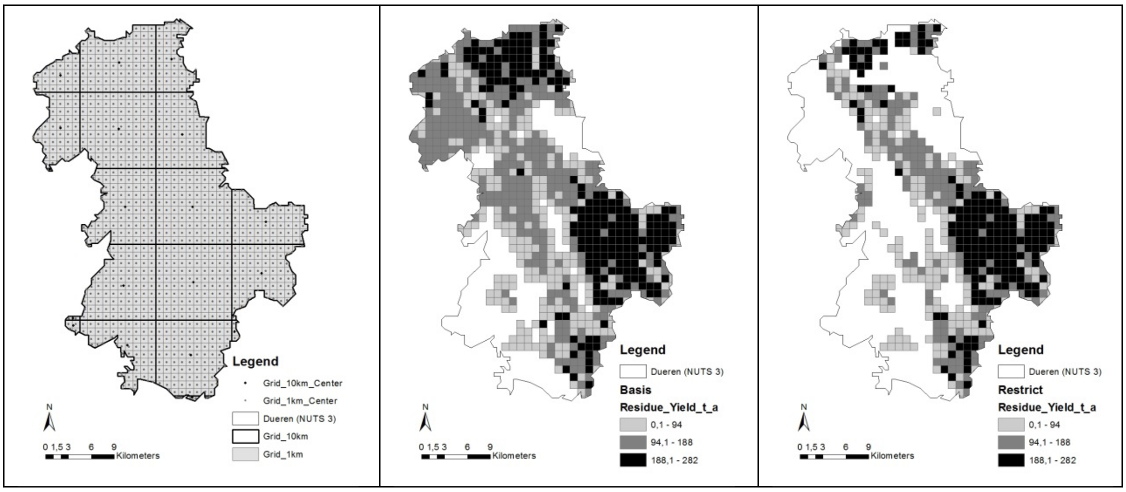

Figure 5: EEA reference grid (1 km, 10 km) with grid cell centers (left), straw amount per grid cell (1 km grid) in the district Dueren *Basis Scenario* (middle), *Restrict Scenario* (right), RPR max, no consideration of straw demand for AH, no consideration of HL

Table 3: Calculated sustainable residue potential and corresponding energy potential in the district Dueren and within a 5 km radius around the city of Juelich, RPR max, *Basis Scenario* and *Restrict Scenario*

			Basis Scenario		**Restrict Scenario**	
Straw demand for AH considered			yes	no	yes	no
Residues from cereals (straw)						
District Dueren	Residues	t/a	93,681	104,401	58,650	69,387
	Energy	TJ/a	1,338	1,491	837	991
City of Juelich (5 km radius)	Residues	t/a	nc	11,421	nc	7,155
	Energy	TJ/a	nc	163	nc	102
Residues from root crops						
District Dueren	Residues	t/a	na	180,803	na	106,844
	Energy	TJ/a	na	312	na	185
City of Juelich (5 km radius)	Residues	t/a	na	18,023	na	10,481
	Energy	TJ/a	na	31	na	18

AH = Animal Husbandry; na = not applicable; nc = not calculated; RPR = Residue-to-Product-Ratio

4. Summary and Outlook

In this paper, the structure and exemplary results of a GIS-based spatial model for the estimation of sustainable biomass potentials in different European regions is presented. For potential estimations, a variety of spatial data on regional conditions is included. The rather fine spatial resolution of 1 km grid cells which is used for the modeling of residues from arable areas particularly permits the support of regional stakeholders when it comes to questions of regional availability of biomass resources and transport distances for biomass conversion plants. In order to enable a preferably wide range of application, other biomass types, e.g. residues from other agricultural areas, residues from forest areas, residues from cattle breeding (slurry, manure), organic residues from municipal waste, energy crops, will be included into the model, considering appropriate ecological and/or techno-economic restrictions. At the same time the module for transport distance calculations will be further developed, i.e. the road distances instead of Euclidean distances will be calculated and applied to first use cases, considering e.g. different plant locations, plant sizes and feedstock.

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