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German Renewable Energy Policies and Their Implications for Local Land Use – Maize for Biogas From 2008 - 2018 in Brandenburg

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Abstract: This study investigates the spatiotemporal dynamics of maize cultivation for biogas production in Brandenburg, Germany, from 2008 to 2018, employing a spatially explicit multicriteria analysis. By combining plot-level land-use data from the Integrated Administration and Control System (IACS) with biogas pnt information, we analyze the likelihood of maize cultivation for biogas at the plot level and find that maize for biogas accounts for over 5% of the total arable land in Brandenburg. We identify patterns of high concentration, particularly in the northwest of the region. The analysis also reveals a steady increase in maize cultivation, aligning with regulatory changes in the Renewable Energy Sources Act (EEG). These findings offer valuable insights into the spatial patterns and drivers of biogas maize production, providing a basis for future environmental and economic research. The study highlights the need for plot-level information to evaluate the effects of renewable energy policies on local land use.

Keywords: Maizification, Biogas, Maize, Multicriteria Analysis, AHP, Land-Use

1 Introduction

Renewable energy has become a central pillar in global climate protection strategies (Demirbas, Demirbas, 2007), with profound implications for environmental sustainability and economic development (Adanma, Ogunbiyi, 2024; Grundmann, Klauss, 2014). Among renewable energy sources, biogas production holds particular promise in the agricultural sector as it both offers farmers the opportunity to dispose of manure surpluses and is an additional source of revenue (Amon et al., 2007; Lüker-Jans et al., 2017). In Germany, biogas has grown rapidly (Quitzow at al., 2026; Torrijos, 2016), supported by policies like the Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG: BMJ, 2014). However, this growth has sparked significant debate as it is associated with significant changes in agricultural land use towards crops for energy production and particularly maize. While biogas production offers economic opportunities, its reliance on maize has raised pressing questions about its impact on landscapes, biodiversity, and soil degradation (e.g. Pedroli et al., 2013; Sauerbrei et al., 2014; Häußermann et al., 2020; Lupp et al., 2014; Huth et al., 2019). Moreover, the focus on energy crops has escalated competition with food production, driving up farmland prices and reducing land availability for other uses (Grundmann, Klauss, 2014; Gutzler et al., 2015). This competition may have led to indirect land-use change, where land dedicated to energy crops in Germany contributes to deforestation and agricultural expansion in other regions (Gawel, Ludwig, 2011; Britz, Delzeit, 2013). These consequences make biogas production an issue that both matters - due to its environmental and economic impacts - and is controversial, given the polarized views on its sustainability. However, little is known about the rates and patterns of changes in maize production on a plot-level and there is no data nor method available to assess the likelihood of maize production for biogas.

Therefore, this paper addresses the questions: how can the likelihood of plots being cultivated for biogas production with a focus on maize be assessed and what are the spatial and temporal dynamics of patterns that may be associated with renewable energy policies? Assessing these spatial and temporal dynamics on a plot-level is essential for further evaluating the local impacts of bioenergy policies and balancing energy needs with sustainable agricultural practices.

While the benefits and challenges of maize production for biogas have been critically discussed, up to now, there has been substantial uncertainty concerning the information on the quantity and location of plots that are used for biogas energy crop production. Some initial studies have analysed the expansion of energy crops using a multi-criteria analysis, but those are based on aggregated district level (Gutzler et al., 2015) or the state-wide level data (MUGV, 2010). These studies do not assess field-level information on maize production nor do they use such data. Comprehensive plot-based information on agricultural land use is available from the Integrated Administration and Control System (IACS) that offers annual data on agricultural land use as of May 31 of each year. While in 2015, a new category - “biogas silage maize” - was introduced in IACS, the data remains unreliable due to its non-mandatory nature. The missing information on the likelihood of plots being used for biogas maize production leads to critical gaps in understanding the localized effects of renewable energy policies on agricultural practices and environmental outcomes.

This study makes three key contributions: first, it develops a multi-criteria approach to estimate the likelihood of plots being used for biogas maize production, providing the first field-level analysis of its kind as a basis for similar analysis. Second, it examines the spatial and temporal dynamics and spatial clusters of maize cultivation for biogas in Brandenburg from 2008 to 2018, offering valuable insights for future studies on driving factors and environmental and economic impacts of maize production for biogas production, such as soil erosion, biodiversity loss or land price changes. Finally, it summarizes the biogas relevant EEG reforms and explores potential temporal alignments with changes in biogas maize production in Brandenburg, offering initial insights on likely associations between policy-induced land-use changes and thereby contributing to the body of literature on policy impact evaluation.

The remainder of this paper is organized as follows. Section 2 provides background information on the study area of Brandenburg and the relevant biogas strategies and policies. Section 3 details the data and methodology, including the multi-criteria approach used to analyse field-level information. Section 4 presents and discusses the results, focusing on spatial and temporal trends in biogas maize cultivation and identifying clusters and discusses the implications of these findings, particularly in relation to EEG policy reforms and environmental sustainability. It is followed by a discussion section including a critical reflection. Finally, Section 6 concludes the study with avenues for future research.

2 Background: The Current State of Biogas, Relevant Strategies and Policies in Brandenburg

2.1 The Current State of Biogas

We selected the state of Brandenburg for this study because it holds large shares of agricultural land (45% the total area), is one of the German states with highest increase rates of investments in renewable energy, and is expected to become an energy exporter, as proposed by the State's Energy Strategy 2030 (MWEn, 2012; MWEn, 2018). Located in the north-east of Germany, Brandenburg is the fifth largest German state by area with 29,640 km². Most of Brandenburg's agricultural land is arable (75%). Brandenburg comprises 14 districts plus four free district cities, and it surrounds the German capital, Berlin (see Figure 1).

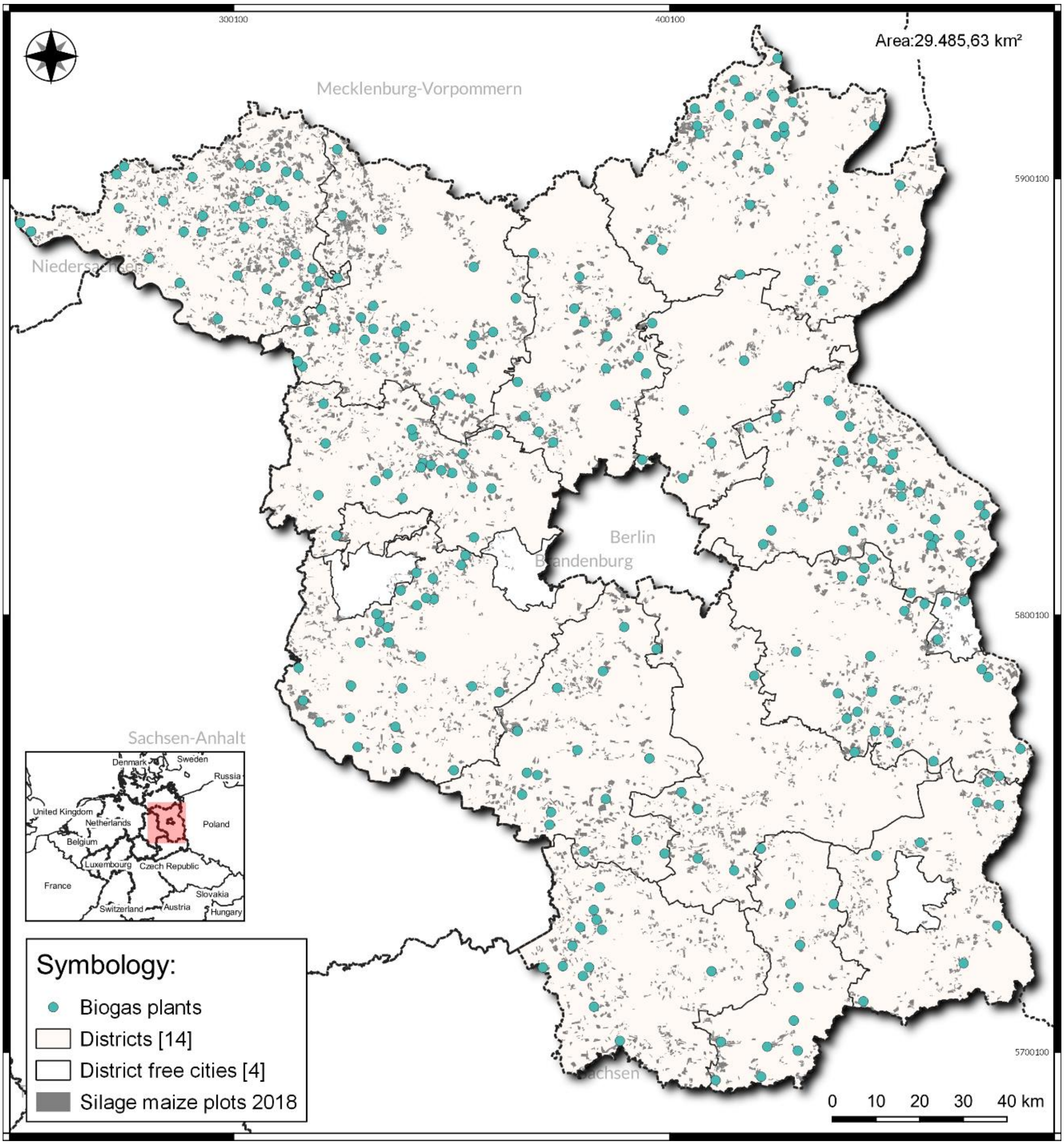

Figure 1. Biogas plants and maize plots for biogas in Brandenburg, Germany, in 2018

Data source: Silage maize plots (MLUK 2020); biogas plants (LfU, 2019)

In Brandenburg, soil quality is low on average since almost two-thirds of the land consists of sandy and sandy loamy soil (Gutzler et al., 2015). The climate is characterised as warm and humid but the area has a comparably dry continental climate according to the Köppen classification (climate-data, 2019). The average annual rainfall in Brandenburg is 591 mm with June being the wettest month and October the driest month (weather-and-climate, 2019). This largely determines the type of crops that can be cultivated in the federal state: rye is the most cultivated crop in terms of area, accounting for 38% of the area under cereal cultivation, as it is best suited to poor quality soils and long dry periods (MIL, 2012; Scott, Emery, 2016). As of

2011/2012, silage maize is the second most cultivated crop in terms of area in Brandenburg with 164,400 hectares (MIL, 2012).

Agricultural practice in the federal state is dominated by large farm enterprises. As of 2020 the average farm size in Brandenburg is just under 247 ha (Statistik Berlin Brandenburg, 2021), which is almost four times the German average farm size of 63 ha (BMEL, 2022). This is partly rooted in the history of the German Democratic Republic (Wolz, 2013), but is also due to the unfavourable climate and soil conditions of the state (Venghaus, Acosta, 2018). After the reunification of Germany in 1990, EU funding programs also gained influence on the agricultural structure in Brandenburg. Therefore, the geographical conditions and farm structures may have positively influenced the state's energy policy program, which turned Brandenburg into an important region for agri-ecological and agri-energy ventures in Europe (Venghaus, Acosta, 2018).

The development of the number and capacity of biogas plants in Brandenburg is illustrated in Figure 2. From 156 biogas plants and an installed electric power of 98 MW in 2008, numbers increased by nearly threefold in 2014 to 442 biogas plants and 261 MW. After then, the increase in the number of plants and electricity capacity has slowed down. The amount of electricity produced consequently increased tremendously and has continued to grow since 2014. In 2016, biogas supplied over 8.2% of the gross electricity consumption in Brandenburg, thus accounting for over 47% of the biomass electricity production of the federal state (AEE, 2018).

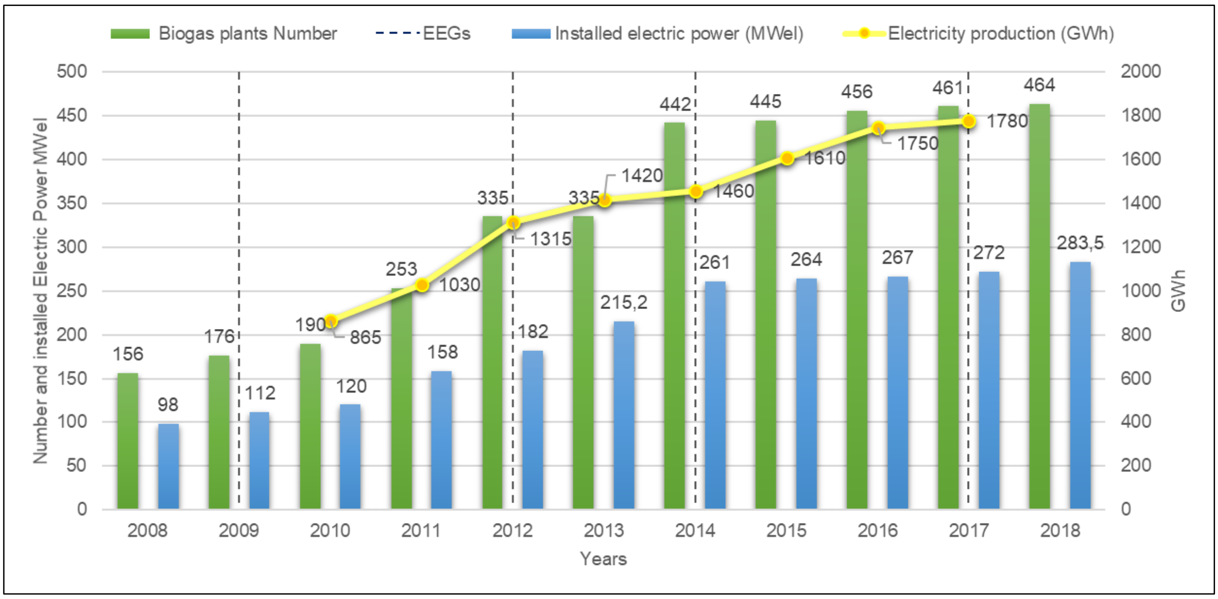

Figure 2. Development of the number of biogas plants, their installed electric power (MWel) and the electricity produced in Brandenburg (GWh), and EEG Reforms from 2008 to 2018

Data sources: AEE (2018), DBFZ (2017), BNetzA (2019)

2.2 Biogas Strategies and Policies

Several strategies and their implementations have directly or indirectly addressed the investment in biogas across different scales, from local to regional (for example, EU Renewable Energy Directive) and/or specific technological aspects (Gas Network Access Ordinance) (MUGV, 2010). Strategies focusing explicitly on the state of Brandenburg are the “Biomass Strategy of Brandenburg” (2010) and the “2030 Energy Strategy of the State of Brandenburg” (MWEn, 2012 and 2018). These strategies highlight the importance and future role of biogas production in Brandenburg for increasing energy independence and contributing to rural development. According to the Energy Strategy (MWEn, 2018), renewable energies should account for 40 % of final energy consumption by 2030. in the federal state of Brandenburg.

Besides these strategies, the EEG played a major role in promoting biogas technology in Brandenburg because of its feed-in tariffs of up to 20 years for biogas. Between its implementation in 2000 and the end of our study time frame in 2018, the EEG was updated five times (in 2004, 2009, 2012, 2014, and 2017) to address efficiency measures, technology improvements, and new steps towards flexibilization of biogas plants and direct marketing of electricity (BMWi, 2016; Torrijos, 2016) (Table 1).

Table 1. Evolution and main aims of the Renewable Energy Sources Act (EEG)

Phase	Year	Main aim	Effects on biogas production
Feed-in tariff	2000	Start EEG	Steady increase in energy maize from the year 2008 to 2012 was expected to be observed, followed by a stabilization in maize cropped area for energy purposes after 2012.
	2004	Energy crop bonus	
	2009	Strong growth energy production	
	2012	Maize silage CAP	
Cut off & Tenders	2014	Subsidies cut for biogas plants	Decrease in medium-size and large-size biogas plants installation
	2017	Controlled capacity expansion	Decrease in small biogas plants installation

Source: adapted from Balussou (2018)

However, in contrast to other renewable energy sources, biomass production costs have not been declining, making it increasingly expensive in relative terms (Appunn, 2016). The implementation of the feed-in tariff is based on scientific studies and enables certain biomass and technology types to be used profitably (Couture, Gagnon, 2010; Fell, 2009; Klein et al., 2008; Lupp et al., 2014). The level of the tariff depends on the type of biomass used and the biogas plant's capacity. With the EEG amendments in 2009, the financial support for large plants decreased while that for smaller plants increased. The intention was to further increase the production of renewable energy and biomass, and to strengthen rural areas (Lupp et al., 2014; Torrijos, 2016). In 2012, the eligible biogas plant types were expanded to promote the use of manure (BMU, 2012), biomass from sustainable cultivation, bark and wood residues as well as biomass with "environmental benefits", such as landscape maintenance material (Lupp et al., 2014). In 2014 and 2017, the EEG underwent more fundamental adjustments. The first amendment made important changes in order to reduce the feed-in tariffs for new plants, to establish an annual biomass plant construction limit of 100 MegaWatt (MW), and to limit the fixed payment to 50% of the power that the biomass plants provide. Meanwhile, the rest was left to be adapted according to market requirements (Appunn, 2016; BMEL, 2015; DBFZ, 2016). As a result, there was a significant drop in the construction of new biogas plants (see Table 1). In the EEG's 2017 amendment, the intention was to make biogas more competitive, moving from fixed prices to auctions (BMWi, 2017). Theoretically, this would extend the possibility to invest in the biogas production development. Moreover, it was stated that operational biomass plants could extend their feed-in tariff for an additional 10 years with guaranteed feed-in tariffs in order to participate in auctions for follow-up financing (Appunn, 2016; MLUK, 2016). However, the distribution of financial benefits from the EEG feed-in tariffs has raised equity issues, as larger farms tend to capture most of the subsidies, leaving smaller farms at a disadvantage (Appel et al., 2016). Additionally, increasing investment in agricultural land for renewable energy projects has created competition for farmland, suggesting an increase in land prices (Brendel, 2011; Myrna et al., 2019) and new market power constellations which need to be further empirically studied (Balmann et al. 2021).

3 Materials and Methods

3.1 Data

We use three main datasets for this study: 1) data from the Integrated Administration and Control System (IACS, "Integriertes Verwaltungs- und Kontrollsystem", InVeKoS) to extract data on agricultural land use per farm; 2) livestock data per farm (IACS); 3) and a dataset on biogas plants provided by the "Agentur für Erneuerbare Energien" (AEE).

IACS and livestock data were made available from the Ministerium für Landwirtschaft, Umwelt und Klima (MLUK) for the whole agricultural area of Brandenburg for the period between 2005 and 2018. The IACS contains plot-level data on land use in May of each year (BMJV, 2019; Europäischer Rat, 2009). It provides data for all agricultural areas for which CAP direct payments are received, likely representing all the agricultural land of the state. In this study, we selected plots that were used for maize in at least one year between 2005 and 2018, based on the following IACS codes referring to potential maize plots for biogas production: silage maize (411 for 2005-2018) since it is mostly used for biogas, maize for biogas (172 for 2015-2018) and maize with wild boar hunting area (and good agricultural and ecological conditions) (176 (177), for 2012-2014). We did not consider corn maize and Corn Cob Mix (CCM) (171), sugar maize (174), and mixes with other crops (175) since these types are mainly use for "Feeding" or for human consumption. The IACS contains livestock data per farm and therefore allowed us to assign the number of cattle, swine, sheep, and poultry per farm on a yearly basis from 2005 to 2018. This data is needed to better assess the interactions between the different types of silage maize utilisation within a farm.

In addition to the IACS data, we use datasets derived from the Statistisches Jahrbuch Brandenburg for the criteria calculation such as silage maize yield (tonnes/ha) and data on biogas plants. The latter yearly data about active biogas plants for the period from 2005 to 2018, was derived from datasets from the "Energie- und Klimaschutzatlas Brandenburg" (EKS, 2016) and the "Biogas Kataster" (LfU, 2019). We selected those plants that were categorised as biogas plant and biomethane plant and the 8 plants that had no classification. Plants that are not used for biogas (e.g. natural gas, landfill gas, etc.) were excluded from the analysis. Overall, we selected on average 84% of the total number of plants for each year for analysis in this study. The final number of biogas plants selected in this study was verified by comparing it to the number of plants published in AEE (2018). The plants were allocated in space at their exact locations. Where multiple biogas plants were located on the same farm, they were counted as one plant with aggregated capacity.

3.2 Methods

We developed and applied a spatially explicit multi-criteria approach (Kumar et al., 2017; Malczewski, 2006) for assessing the likelihood that plots were being used for biogas maize production. In order to determine the likelihood of biogas production of each maize plot, we adapted the multicriteria land suitability approach from Tenerelli et al. (2007). We chose the frequently used Analytical Hierarchical Process (AHP) method (Saaty, 1980) to determine the importance of each criteria for the model. This method is known to solve complex problems through a mathematical process known as hierarchy superposition that helps to reduce the problem's complexity (Malczewski, Rinner, 2015). It relies on quantitative data, expert opinions, and the provision of relative weights of the criteria, which can then be subject to an evaluation of their consistency (Castro et al., 2016). The details are explained in the following sections.

3.2.1 Choice of Criteria

To identify the likelihood that maize was being used for biogas production, we selected the following four criteria: the distance to and capacity of biogas plants (Catchment area, CA), the permanency of maize use on a plot (persistency), the number of livestock in terms of heads on a farm (livestock), and the area in hectare of the farm (farm size) (see Figure 3).

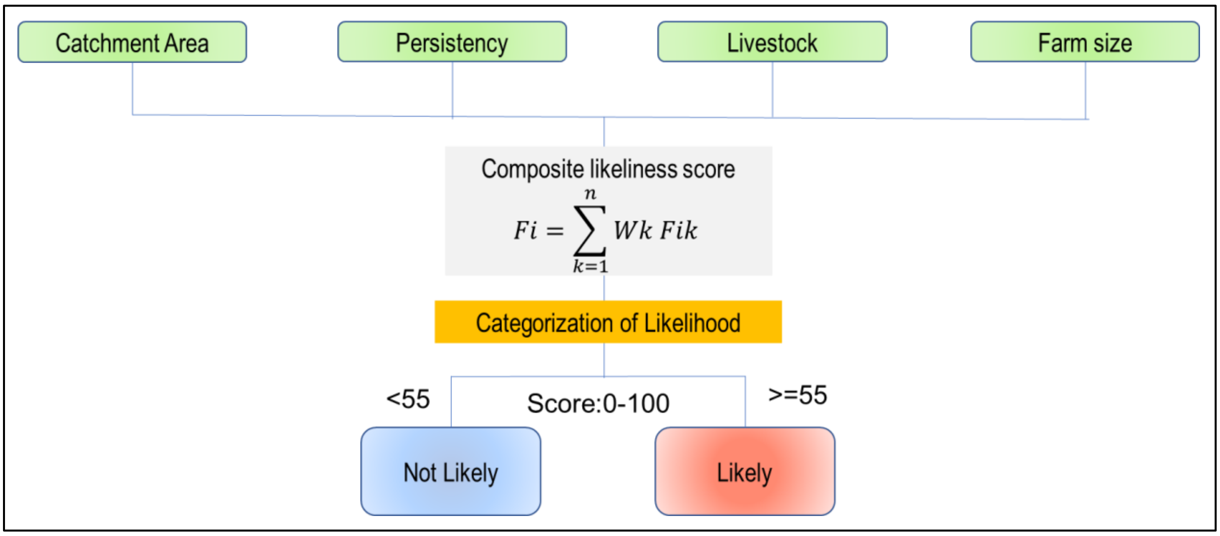

Figure 3. Identification of likelihood of maize for biogas production

Fi = Composite likeliness score; k = Criteria; Wk = Weight of a criteria; Fik =Score of a criteria
Source: authors

In the following, we explain for each one of the four criteria the reasoning for choice of criteria, the respective data processing, and the assignment of the score index from 0 to 100, following Tenerelli et al. (2007).

1. Catchment area (CA): we select this criterion because the distance to and the power capacity of a biogas plant determines the likelihood that maize is being used for biogas to a large degree. This assumption is based on location theory (Thünen, 1966; Weber, 1929) which explains local land-use decisions based upon differences in transportation costs of inputs and outputs (Delzeit and Kellner, 2013). Thus, the site of a biogas plant can be expected to be in close proximity to its substrates in order to minimize feedstock transportation costs. Maize is not always grown specifically for a particular use (e.g. grain maize), but the final use is only decided depending on the annual weather conditions and the achievable yield and price level (MIL, 2012). Therefore, we expand existing studies that use a static radius derived from biogas plants (Delzeit, Kellner, 2013; Epp et al., 2008) and calculate a dynamic radius for each biogas plant, per year. This allows us to include the feedstock availability expressed as the silage maize yield (tonnes/ha). If the silage maize yield is high, the radius will be small while, in comparison to years with lower yields, the necessary substrate will most likely be harvested in the wider surroundings, therefore leading to a larger radius.

   To better reflect the continuous increase in the likelihood that maize is being used for biogas the closer it is located to a biogas plant, we applied an inverse quartic distance.

   To assess the catchment area of the biogas plants, we calculate the dynamic radius of each biogas plant according to the capacity, then derive raster layers covering the whole study area for each year and finally, we intersect these raster layers with silage maize plots and calculate a plot-specific catchment area value for each year.

First, the capacity of each biogas plant as maize silage quantity (in tonnes) is calculated:

$$Q_{ij} = \frac{(W_{ij}hK)}{S}(tonnes)\{K = 0.60; j < 2012; K = 0.57; j \geq 2012 \quad (1)$$

where Q_{ij} represents the maize silage quantity (tonnes) of the ith-biogas plants of the jth-year; W_{ij} (kW) is the power capacity of the ith-biogas plants of the jth-year; h is the operation hours per year (hours), K is the maize energy proportion used in biogas plants in Germany (in %), and S is the conversion factor of maize amount to electricity. We assume h = 8.000 (following Bidart et al. (2014)), K = 0.60 (before 2012) and K = 0.57 after 2012 because of the changes due to the "Maisdeckel" in 2012 (DBFZ, 2015, 2012), and S = estimated as 367.80 kWhel-t , based on harvest and energy content (LELF, 2016), and considering the energy conversion efficiency of 38% kWhel combined heat and power of a biogas plant (FNR, 2019).

Next, the radius r can be calculated by:

$$Q_{ij} = \left(\pi r_{ij}^2\right)100\varepsilon_j Y_j(tonnes) \quad (2)$$

$$r_{ij} = \sqrt{\frac{Q_{ij}}{100}\pi\varepsilon_j Y_j} * \tau(km) \quad (3)$$

With Q = maize silage quantity (tonnes), ε_j = yearly substrate availability in Brandenburg calculated as the proportion between the maize silage and total Brandenburg area (in %) and Y_j= yearly maize silage yield (tonnes/ha). The yearly values of ε and Y were based on existing literature (AfSBB, see Appendix Table A1). Further, is the tortuosity factor that represents the relationship between the actual transport distance and the direct distance (Overend, 1982; Sultana, Kumar, 2014; Walla, Schneeberger, 2008). Sultana and Kumar (2014) estimate the tortuosity factor to be 1.27. In order to adjust Y_j from hectares to square kilometres, we multiplied the tortuosity factor by 100. We receive a dataset with the biogas plant capacity (kW) and specifically for each year.

We then calculated the catchment area radius to derive a raster layer with the sum of the values of the different catchment areas (between 0-1) for each raster cell of 90 metre resolution.

$$Z_j = \sum_{i=1}^{n} \left(1 - \left(\frac{d_{iz}}{r_{ij}}\right)^2\right)^2, for\ d_z < r_{ij} \quad (4)$$

where Z is the (x,y) location (within Brandenburg State); d_{iz} represents the distance between i and z; and r_{ij} is the radius of ith-biogas plant of the jth-year. i= 1,…,n are the biogas plants. We only consider those plants where d_{iz} is lower than r_{ij}. In result, we receive a raster layer with the summed values of catchment area for a grid cell for each year with values ranging between 0 and 1. In some cases, values exceeding 1 could occur, such as when two radii overlap. Since these values are not relevant at this stage, any value over 1 was set to 1. Plots assigned a value of 0 are located outside the catchment area of any biogas plant.

In the final step, the raster layers were polygonised and reclassified using regular intervals between 0 and 100 due to hardware capabilities (i.e. 0-0.025=0; >0.025-

0.0725=5; >0.0725-0.125=10). The raster layers were then intersected with the identified silage maize plots. In case a plot intersected with one or more classes, the proportion of each intersection was calculated and then summed (Appendix FigureA1).

2. Persistency of Maize: the continuous cultivation of maize on a plot suggests that it is being used for biogas production. It is known that the farmers practise crop rotation in producing energy, however, to cope with the increasing demand for maize in Brandenburg (Appel et al., 2016), biogas farmers have reoriented their production and are maintaining maize for more than one year (EEA, 2007; Herrmann, 2013).

   We calculate the persistency of maize cultivations of 3 years for each maize plot on a yearly basis between 2005 and 2018. To account for changes in plots in terms of agricultural land use, we calculate the proportional area of the last 3 years (see Figure 4 with an example).

   We first calculate:

$$\sigma_{mj} = \sum_{u=1}^{n=3} \frac{A\}\, rsub\, \{m\, j-u\}}{A_{mj}} \tag{5}$$

   Where σ_{mj} represents the cumulative area proportion of maize for the previous 3 years for a mth-plot of a jth-year; A_{mj} is the area of the mth-plot used as maize of the jth-year; and u is a unit to identify the 3 previous years. We receive the persistency information for each plot and year in metres units. Next, the persistency score index is calculated:

$$P_{mj} = 100 * (1 - e^{-\sigma_{mj}}) \tag{6}$$

   P_{mj} is the persistency score of the mth-maize plot of the jth-year. Figure 4 shows an example for plot that changes over time.

Figure 4. Persistency of a maize plot that changes in land use over time

411 = silage maize, 311 = rapeseed, 121 = winter rye, $\boldsymbol{P_{mj} = 77,67}$
(with 2008-2005 = 1, 2008-2006 = 0, 2008-2007 = 0,5)
Source: authors

We assumed an exponential relationship for the score because we expect that recent years of maize cultivation are more indicative of biogas production than earlier years, with the most recent year being the most critical. For example, if a plot was cultivated in 2008 with maize over the previous 3 years, it will receive a score of approximately 95. If in 2006-2007 the plot was cultivated with rye, the score will still be at 86. Finally, we adjusted the formula to receive a persistency score between 0 and 100 for each maize plot and year.

3. Livestock: we considered livestock farming a positive factor influencing the likelihood of maize being used for biogas production, as manure constitutes around 43% of the biogas input substrate (DBFZ, 2015). Biogas plants that utilise manure as input are typically located near livestock or dairy farms (Delzeit and Kellner, 2013). Our focus was on swine and cattle, as they are the major contributors to manure substrate, accounting for approximately 82% of the total manure substrate (DBFZ, 2015). However, since cattle not only provide manure as a substrate but also consume maize silage, we assigned a negative factor adjusted according to their type and age.

   To calculate the indicator, we used the number of heads of cattle and swine per farm. If a farm has no swine or cattle, the livestock score index is equal 0. With respect to swine, we calculate a binary value of 0 (= no swine) and 100 (= existence of swine on the farm). If a farm has cattle, we calculate:

$$L_{fj} = 100 - \left(\frac{(C_{fj} * \varphi_j)}{A_{fj}} * 100\right); \quad (7)$$

   Where f_j represents a farm of the jth-year; L_{fj} is the livestock score index of the fth-farm of the jth-year; A_{fj} is the total area of the fth-farm of the jth-year; C_{fj} indicates the number of cattle of the fth-farm of the jth-year; and φ is the maize silage consumption factor of the jth-year.

   To calculate how much silage maize area in ha is consumed by cattle yearly (φj, see (h)) we use an average consumption area factor per cattle type) multiplied by the distribution (δ) per jth-year in Brandenburg. As our dataset does not classify the cattle type of a farm, we used a cattle distribution according to the available district level data (Appendix Tables A1, A2 and A3):

$$\varphi j = \sum_{c=1}^{n=5} \frac{(\gamma * \delta j)}{n} \quad (8)$$

   If the consumption area by cattle is higher than the total area of a farm, we assume a score of 0 and that the farm purchases fodder from outside.

4. Farm Size: we assumed a positive relationship between farm size and biogas plant size because larger farms have a greater propensity to cultivate maize for biogas (Venghaus, Acosta, 2018). For example, Brendel (2011) establishes that for a biogas plant of 1,000 kW around 550 ha of energy crops are needed, while 200 ha is needed to operate a plant of 150 kW. Likewise, Venghaus, Acosta (2018) conclude that biogas farms in Brandenburg are substantially larger than non-biogas farms, with an average farm size of 1,564 ha. The commonly cited reasons are that operating a biogas plant requires a certain farm size to provide enough substrate for biogas production, as well as sufficient financial resources to enable the financing of the investment.

   To assess the farm size indicator, we relied on the farm sizes classes of Venghaus, Acosta (2018) and specified the farm size score$_{fj}$ according to A_j, i.e. the area in ha of the fth-farm of the jth-year into 5 classes as follows:

$> 1{,}550$ ha = 100
$> 1{,}250 \leq 1{,}550ha$ = 75
$> 600 \leq 1{,}250ha$ = 50
$>350 \leq 600ha \ = \ 25$
$\leq 350ha \ = \ 0$

3.2.2 Calculation of Likelihood Scores Using the Analytical Hierarchical Process

To determine the likelihood score, we calculated the weights of each criteria according to pairwise comparisons of the criteria using the Analytical Hierarchical Process (AHP), a well-established method in multi-criteria decision analyses (Malczewski, 2006; Malczewski, Rinner, 2015). First, we applied pairwise comparisons among the criteria with a ratio scale from 1 to 9, i. e. Saaty's scale (Saaty, 1980). 1 means an equal importance between two elements (or neutral value), 3 a moderate, 5 a strong, 7 a very strong and 9 an extremely higher importance of one element compared to another one. The aim is to obtain the main eigenvector of each pairwise comparisons matrix, that synthesises the numerical judgements at each level of the network (Saaty, 1980). Secondly, we checked the level of consistency of the pairwise comparisons with a pairwise comparisons matrix, using the Saaty scale consistency formula:

$$CI = \left[\frac{\lambda max - n}{n-1}\right] \quad (9)$$

$$RC = \frac{CI}{RI} < 0.1(10\%) \quad (10)$$

Where CI is the consistency index, λmax the highest eigenvalue in the comparison matrix (associated with the principal eigenvector), n is the dimension of the comparison matrix, RI is the random index of consistency, which depends on the number of criteria (4 criteria is equal to 0.9), and RC is the ratio of consistency. If RC is larger than 0.1, the weighting is discarded and must be redone (Saaty, 1980).

To assign the weights, we follow earlier studies that also use literature for the weighting process (Treves et al., 2020; Castro et al., 2016). We combine the literature-based information with our own expertise and provide the detailed reasoning for the choice of weights in the following: the CA criteria is expected to be the most important one, because biogas plants are highly dependent on energy crops in their immediate vicinity (Epp et al., 2008; Mitiku Teferra, Wubu, 2018). Persistency is assumed to have the least influence due to existing crop rotation practices. Livestock and farm size are assigned the same importance: the former refers to the complementarity of the biogas and livestock production, indicating at least a medium-term relation (Appel et al., 2016; Venghaus, Acosta, 2018), while the latter refers to a direct relation between size and biogas production in Brandenburg (Venghaus, Acosta, 2018). Afterwards, the pairwise comparisons were applied, and its levels of consistency were checked being approved with a 99.98% of consistency. We received the following final weights: CA: 52.7%; Persistency: 4%; Livestock: 21.7%; Farm Size: 21.7% (Table 2). Finally, the likelihood score was computed and classified into "Unlikely" (0-55) and "Likely" (55-100) using an iterative approach to identify an adequate threshold (see Appendix Figure A2).

Table 2. Values for the four criteria in the AHP step

Factors	CA	Persistency	Livestock	Farm size	Final weights
CA	1.00	9.00	3.00	3.00	52.7
Persistency	0.11	1.00	0.14	0.14	4.00
Livestock	0.33	7.00	1.00	1.00	21.7
Farm size	0.33	7.00	1.00	1.00	21.7

Source: own estimations based on expert knowledge and literature

We created a multicriteria model workflow to automate the process of data pre-processing and data analysis in the R environment and ArcGIS. The scripts and more details on the calculation are made available via GitHub (Biogas_silage_maize, 2020).

We then calculated the annual change rate of maize for biogas and for total maize for the study period. For example, the change rate of maize for biogas for the year 2018 (LSb2018) is calculated as:

$$LSb2018 = \frac{LSb2018 - LSb2017}{LSb2017} * 100 \quad (11)$$

To complement the visual assessment of patterns of likelihood of maize for biogas, we calculate the local indicator of spatial association using Anselin local Moran's I (LISA; Anselin, 1995). The indicator quantifies the spatial associations for a variable of a plot and its neighbours and returns high-high, high-low, low-high and low-low clusters. High-high clusters are those, where maize plots with high values of likelihood of utilisation for biogas are surrounded by neighbouring maize plots with high values of likelihood utilisation for biogas. This allows us to not only identify single plots but also local hotspots where maize for biogas is present. We report only the significant clusters ($p<0.05$) using a randomization procedure based on 499 permutations.

To quantitatively verify and validate our approach we relied on literature analysis whenever possible (see Chapter 3.3.1) and compared our plot-based outcomes for the likelihood of biogas silage maize with the results of earlier studies. Moreover, we compared the plots that were reported as maize for biogas in IACS with our likelihood class for the year of 2018.

4 Results

In the following we present and discuss the results of first, the identified likelihood of maize for biogas over time, and second, the identified spatial clusters.

4.1 Likelihood of Maize Used for Biogas in Brandenburg From 2008-2018

Our results show that the area of maize production likely used for biogas in proportion to the total arable area increased from 3.1% to 7.1% from 2008 to 2018. Total maize area increased significantly from 2008 to 2011, then the area remained relatively stable for 4 years. Between 2016 and 2018 we again identify an increase but not so strong as at the beginning of the time analysis. Regarding maize for biogas we identify an increase from 2008 to 2010 and two peaks in 2015, and in 2018 (see Figure 5). In contrast, 2009, 2014 and 2017 showed lower values which can be mainly attributed to higher yields in these specific years (see Appendix Table A2). Maize for biogas pattern has increased, reaching its peak in the last year of analysis at 72,000 ha.

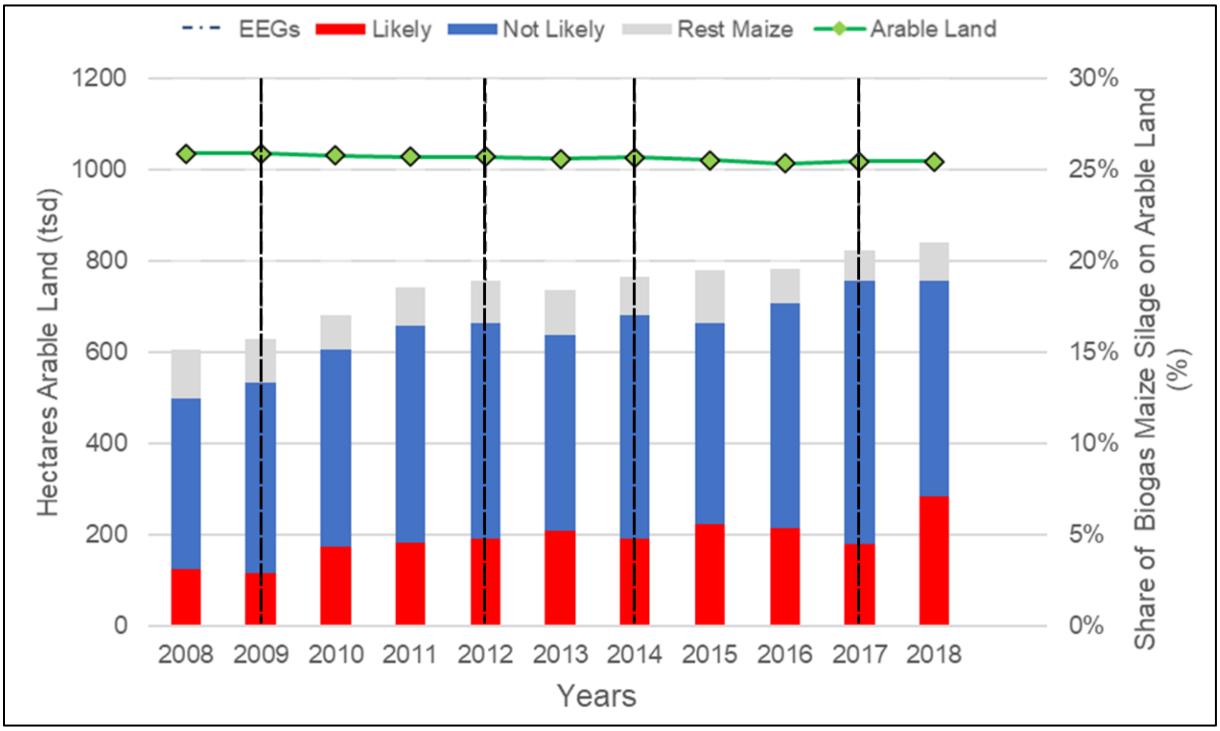

Figure 5. Development in the likelihood of maize for biogas from 2008-2018

Source: own calculations and AfSBB (2019)

The accuracy evaluation of our study reveals that the identified values of maize for biogas are within the reasonable range of the studies used for validation. MUGV (2010) indicates that approximately 28% of the maize was being used for biogas production, which is very close to the 28.6% that we identified in this study. AEE (2013) stated that in 2011 51,000 ha were used for biogas, which is only slightly more than the 47,420 ha found in this study. On the other side, LELF (2019) estimated that around 95,000 to 100,000 ha were used for biogas production, which is more than the approximately 72,000 ha that we identified for 2018. In principle, the areas identified in the IACS data as code 172 (maize for biogas and maize (biogas)) could also provide a potential validity check. However, certain challenges remain: the information of this code is based on a mandatory reporting by the farmers, is not checked for correctness and is only available for selected years (2015-2018). Moreover, there seems to be a bias in the data in several regards since we find a spatial distribution that does not coincide with the locations of the biogas plants and that the average size of the plots with the code 172 is substantially smaller than the average size of all plots. It suggests that there are either plots that are wrongly classified as maize for biogas or that there are biogas plants missing in the dataset. Nonetheless, to identify a threshold value for a binary classification, we compared the plots with the code 172 with the derived likelihood score and iteratively identified 55% as a threshold since a large percentage of the maize area of the plots seem to classified as maize for biogas (see Appendix Figure A2). However, we are well aware of the uncertainties involved in this procedure. Our multi-criteria analysis with the selected choice of criteria and weighting is based on a literature analysis and our own expertise and seems to reflect the key criteria in farmers' decision-making process quite well. However, a more comprehensive validation remains to be done in future studies due to missing data in this study, e.g. with interviews or surveys with farmers.

Regarding possible associations with the EEG amendments, Table 3 shows the annual change rate of maize for biogas and total maize. It seems that there might be an association between new EEG amendments and observed changes in land use one or more years later. The change rate of 2010 increased substantially after the implementation of the 2009 EEG amendment, for example.

Table 3. Amendments in the EEG and respective changes in the land used for maize for biogas and total maize from 2008-2018

Years EEG amendments in bold	Maize for biogas* (Tsd. ha)	Annual change rate maize for biogas* (%)	Total maize (Tsd. ha)**	Annual change rate maize** (%)	Maize silage yield** (tonnes/ha)
2008	32.50	-	132.0	-	31.59
2009	29.91	-7.97	143.8	8.94	33.11
2010	44.73	49.57	154.2	7.23	28.57
2011	47.42	6.02	165.4	7.26	38.75
2012	49.56	4.49	164.7	-0.42	36.26
2013	53.27	7.49	163.7	-0.61	30.68
2014	49.01	-7.99	175.4	7.15	36.94
2015	57.08	16.47	179.3	2.22	28.98
2016	54.53	-4.48	179.7	0.22	32.41
2017	46.24	-15.20	192.4	7.07	38.54
2018	72.53	56.86	199.1	3.48	21.42

Data source: *own calculations, **Statistischer Bericht (AfSBB), Statistisches Jahrbuch Brandenburg (2009-2019)

The demand for biogas maize area is closely linked to the observed yields, i.e. for years with high yield the demand decreases and in years with low yields the demand for land increases. The lower annual change rate of maize for biogas in 2011 compared to 2010, for example, may be associated with the fact that 2011 had the highest yield in our analysis period and at the same time, a large number of biogas plants installed, which demanded a large amount of maize for biogas. Figure 6 shows the estimated quantities of maize silage produced in total and for biogas. After the increase following the EEG amendment in 2009, the amount of biogas maize silage stabilised over the subsequent years, although the total amount of maize silage was subject to strong fluctuations.

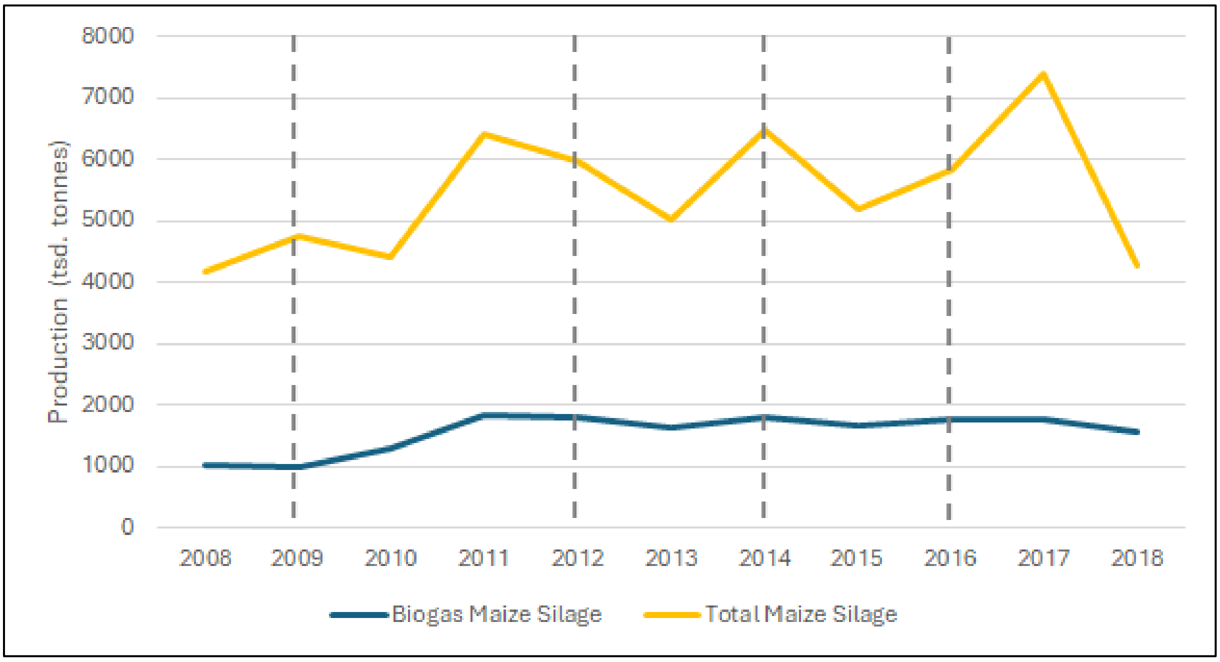

Figure 6. Quantities of maize silage produced in total and for biogas in 2008-2018

Data source: own calculations and AfSBB (2019)

4.2 Spatial Clusters of Maize Plots for Biogas Production in Brandenburg

Our results over the investigated time period of 2008 to 2018 reveal a distinct spatial pattern and clustering of areas where maize plots for biogas production dominate in Brandenburg. The identified statistically significant hotspots of maize for biogas calculated by the LISA analysis for the accumulated "likely" values from 2008 to 2018 are represented in Figure 7. The largest agglomeration is located in the northwest, specifically in Prignitz district. Other pronounced clusters are identified in the Märkisch-Oderland, Oder-Spree, Ostprignitz-Ruppin, Teltow-Fläming and Potsdam-Mittelmark districts. The remaining hotspots are spread across the state according to the biogas plant locations. Likewise, in certain districts such as Uckermark, Elbe-Elster, and Oberspreewald-Lausitz, the clusters of high maize likelihood are located close to the border of the federal state, which may indicate that many biogas plants also rely on maize produced in neighbouring federal states. On the other hand, the south-east districts show almost no hotspots, likely due to the presence of the Spreewald reserve. Concerning the spatial distribution, we see that the pattern is most likely driven by the spatial patterns of the catchment criteria, which is derived from the location and power capacity of the existing biogas plants. With a weight of 52%, the CA substantially influences the multicriteria analysis. In general, in the clusters of the northwest and the central-east of the state, we find medium-sized biogas plants. The comparison of soil quality, using the Muencheberg Soil Quality (M-SQR) classification (Mueller et al., 2007), shows that more than 14% of the dominant plots area could be considered to be located in high-quality soil, and almost 75% in moderate-quality soil (Mueller et al., 2007).

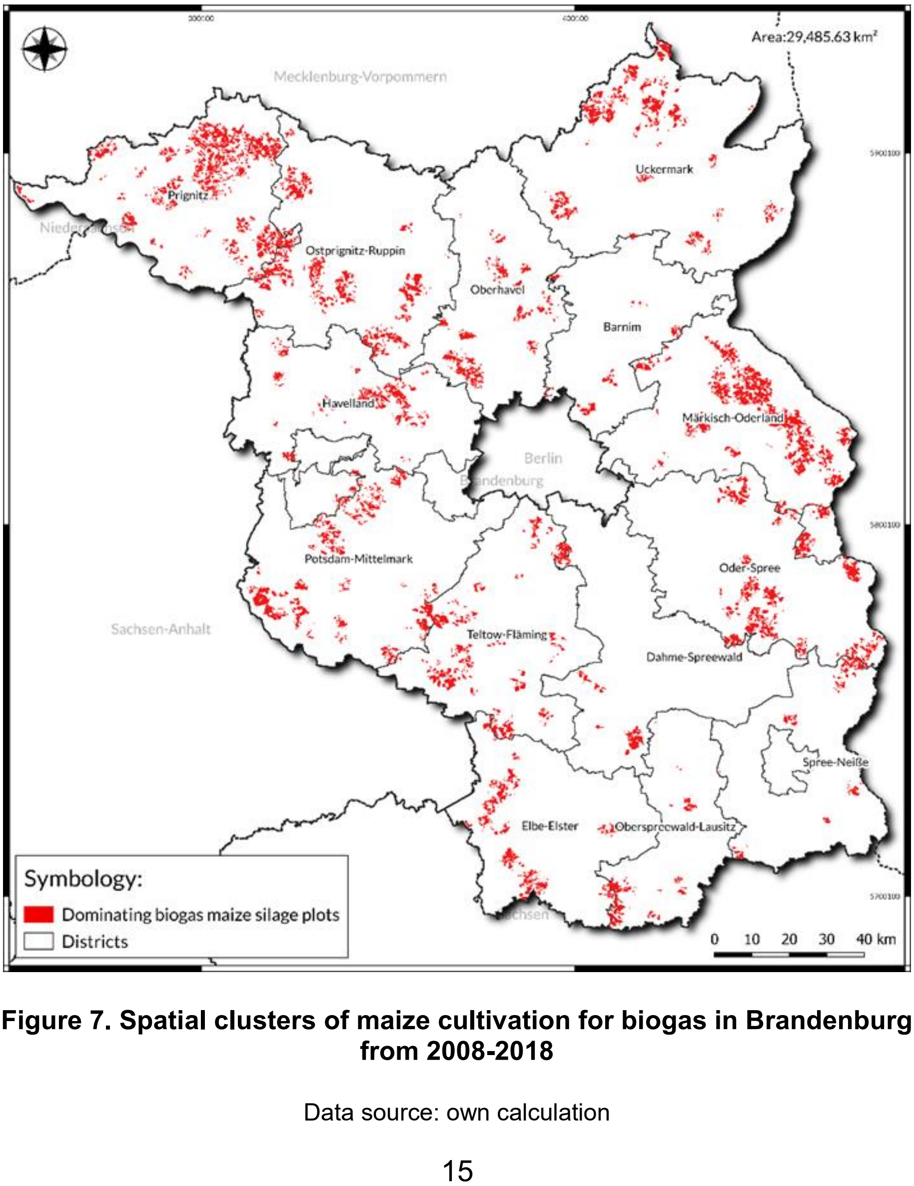

Figure 7. Spatial clusters of maize cultivation for biogas in Brandenburg from 2008-2018

Data source: own calculation

5 Discussion

Our results show that between 2008 and 2018 the total maize area that was most likely used for biogas increased steadily, while the proportion of maize for biogas to total maize barely changed over the years, which indicates that the intra-land-use competition for maize is not very high. This can be explained by the fact that both cows (especially intensive cattle and dairy cows) and biogas production rely on maize which causes higher competition for maize in regions with high livestock density (Delzeit and Kellner, 2013; Delzeit et al., 2012), while at the same time the energy of the maize used as feed in cattle farming is not completely lost for the biogas plant, as it can be used in the form of manure.

From the spatial analysis, we see a concentration and clustering of maize for biogas in four districts. This suggests that these districts concentrated their maize cultivation on biogas production. These districts are not evenly distributed across the territories, but are concentrated in the north-east (Prignitz, Ostprignitz-Ruppin), in the south-east (Märkisch-Oderland, Oder-Spree), and west (Potsdam-Mittelmark). The spatial patterns reveal very distinct characteristics of maize cultivated for biogas across the area independent of administrative boundaries. The plot-based analysis adds important insights in comparison to an aggregated level of a district as done in an earlier study (Gutzler et al., 2015). It allows for the identification of an increase in maize area because of the spatially explicit analysis of land use on a detailed level. An agglomeration of several plots that were cultivated for several years primarily with maize for biogas can be understood as "hotspots" where biogas production led to huge increase in maize production. When the results are analysed at a district level, they indicate a high concentration of maize plots for biogas production in districts like Uckermark and Märkisch-Oderland. The LISA results (see Figure 7) show, however, that this land use is concentrated in certain locations of those districts – a phenomenon that also occurs in other districts. The reason for the presence of maize hotspots for biogas could be that especially successful enterprises with greater purchasing power on the land market invested further in biogas (Appel et al., 2016). Another factor is that these clusters may be determined by spatial conditions such as protected areas which dominate large shares of Brandenburg, size of plots or soil conditions as shown above.

Plot-based information is essential for evaluating the effects of renewable energy policies on local land. The identification of hotspots of maize for biogas is potentially useful for future identification of subordinate local effects on the environment. Moreover, the identification of specific plots and hotspot clusters provides important assets to understand the effect of biogas production on farmland prices such as in studies by Bartoli et al. (2016).

Our results suggest that the EEG 2009 had an effect on the increase in maize for biogas. Beginning in 2012, the increasing trend of maize cultivation for biogas began to slow down. This may be attributed to the fact that there is a time delay before the effects of an amendment become visible in the actual investments due to the duration for planning and approval of a new plant. However, farmers knew beforehand about the aim of the EEG 2012 (BMU, 2012) and presumably waited for the final design of the EEG 2012 before deciding on potential further investments.

After the implementation of the EEG in 2009, we see an increase in the area used for the production of maize for biogas. From 2012 onwards, the intended effect of the 2012 EEG amendment to mitigate the increase in area of biogas maize may be seen in the relatively stable production of maize silage for biogas. In contrast, the total amount of maize silage produced is subject to fluctuations. This suggests that farms prioritise ensuring a continuous supply of maize for their biogas plants (Schulze Steinmann, Holm-Müller, 2010; UBA, 2013): To manage potential yield fluctuations, the remaining maize silage appears to serve as a buffer. Depending on the importance of this buffer function for the farms, they are likely to increase their total maize silage production to secure a stable supply for their biogas plants during years with lower yields. Thus, the incentives of the guaranteed feed-in tariffs of the EEG could be responsible for the further increase of the total area for maize cultivation while keeping the land used for maize silage production for biogas rather stable after 2012. This means that the EEG amendment of 2012 may have had the expected effect of decreasing maize cultivation for biogas but may have increased the cultivation of maize for other purposes (see Table 3) in 2014. Maize silage prices were excluded as it is predominantly produced on-farm or regionally, with no global market influence. Additionally, Brandenburg's climate limits maize production, rendering world market prices irrelevant locally.

The identified developments in local land use following the EEG amendments in 2009, 2012, 2014, and 2017 reveal the importance of European and national policies on the local land-use decisions of farmers. For example, even though the EEG 2012 may have stopped the increase in area used for biogas maize, clusters were already established and they did not substantially decrease in size after 2012.

There are several limitations of our study. One limitation of this study is that there is no comprehensive validation data available to test the presented approach. To circumvent this drawback, our selection of criteria and weighting was based on a thorough literature analysis and our expertise, aiming to capture the complexity of farmers' decision-making processes as accurately as possible. We also compared our findings to existing data, i.e. average values for some criteria, as far as possible. The comparison of the IACS data of biogas maize revealed a good fit (see Appendix Figure A2), however, a further analysis could certainly improve the validity of the threshold approach compared to the continuous values of likeliness. Secondly, developing a transparent, quantitative multicriteria approach that can be applied at a plot-level every year for larger areas requires the simplification of complex matters and depends heavily on the availability of data. For example, given the available data sources there are difficulties in determining the type, substrate and power of each biogas plant. Moreover, while we prioritized the most significant factors to ensure a clear and manageable framework, there is scope for refinement and expansion. For example, assumptions such as the three-year horizon used in the persistence criterion or the specific weightings could be further refined, as adjustments to these parameters are likely to yield slightly different outcomes. A more comprehensive validation of these assumptions, such as through interviews or surveys with farmers, remains a task for future studies due to the limited availability of data in the present study. Additionally, integrating criteria like farm typologies likely to produce biogas maize or incorporating insights on social network production and social institutions (Bock und Polach et al., 2015; Venghaus, Acosta, 2018) could enhance the framework. Finally, this study focuses on Brandenburg's conditions, but accounting for interactions with neighbouring federal states - either as maize suppliers or locations for biogas plants - could provide a broader perspective. These considerations highlight the balance between simplicity and comprehensiveness in our approach, while offering pathways for future studies.

6 Conclusions

Using a multicriteria approach, this study has identified the likelihood that maize was used for biogas production in the timeframe 2008-2018 in Brandenburg. We introduced a method for identifying the likelihood that maize plots are used for biogas production by integrating four criteria that determine if a plot with maize has been cultivated for biogas production within a year. We applied this model for the state of Brandenburg in Germany and found distinct temporal and spatial dynamics. First, within the period studied, we identified a tendency towards increased spatial clustering in the north-west of Brandenburg (Prignitz and Märkisch-Oderland). Second, our results show a temporal alignment of EEG amendments and the likelihood that maize was being used for biogas production. However, we were not able to test whether this causal link actually exists. Also, the competition of energy versus food production is noticeable since the overall share of arable land used in Brandenburg for maize production increased. We, therefore, conclude that the use of agricultural land for biogas production in Brandenburg is important to consider. Although maize for biogas has likely accounted for just over 5% of total arable land on average since 2013, its cultivation can represent a much higher proportion in certain regions, forming significant hotspots of spatially concentrated maize production. In these hotspots, there could be increased negative impacts of maize cultivation (Bunzel et al., 2014), including a decline in soil fertility, a reduction in biodiversity on agricultural land (Pedroli et al., 2013; Sauerbrei et al., 2014), increased nitrogen use in agriculture with subsequent nitrogen leaching (Häußermann et al., 2020; Lupp et al., 2014). Moreover, we discussed indications that the incentives of the guaranteed feed-in tariffs are partially responsible for the increase in maize cultivation for other uses, in particular due to the influence of biogas production on the intensification of livestock farming. Biogas plants, especially in combination with the manure bonus, offer incentives for cattle farming without grazing, as manure collection is not possible in pasture-based systems. In order to use the manure for biogas production, cattle must be kept in stables, which provides additional incentives for a shorter grazing period or year-round stabling. This reduction in pasture use leads to a higher proportion of maize silage in the feed ration. In addition, farms need a buffer stock to ensure a constant supply of maize for biogas plants even in years with lower crop yields.

This paper presents a method for identifying the spatiotemporal dynamics but can only approximate the reality and comprehensive sensitivity and validation analysis remains to be undertaken with additional data. However, this paper explores the potential of the IACS data in combination with the data on biogas plants, linking energy production with the respective land use. IACS is the most complete and reliable agricultural dataset, combining high levels of detail on space, time, and content - therefore, being a crucial pillar for future policy modelling and an important source for research in agricultural landscapes (Burchfield et al. 2024; Tóth, Kučas, 2016; Lakes et al., 2020; Leonhardt et al., 2022). The presented method of processing plot-level data on the likelihood of maize for biogas is transferable to other European study areas where similar datasets are available (particularly the IACS data). Such derived plot-level information is essential to further identifying subordinate local effects of renewable energy policies. Future studies may focus at a plot-level on aspects such as environmental effects (soil erosion, water pollution), land price change, the effect of climate change on maize silage yield (Peichl et al., 2019), or the institutional context of maize for biogas (Bock und Polach et al., 2015). Relating our findings to an in-depth analysis of the decision-making behaviour of farmers who invest in the bioenergy market (Reise et al., 2011), developing scenarios for future developments and possible trade-offs (Schmid et al., 2017), and validating the methodological assumptions with expert interviews may be a next step in the future.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability

The scripts "Biogas_silage_maize" that support this study are openly available for reproducibility and further development in github at https:// github.com/vergoraf/Biogas_silage_maize.git (last access 17.2.2025). The data of the biogas plants is now openly available from the Energieagentur Brandenburg (former Energieatlas Brandenburg) via the following link: https://energieportal-brandenburg.de/cms/inhalte/unser-portal/datenservice/daten-der-energieerzeugungsanlagen (last access 17.2.2025). The script available in github is based on a former version of a biogas_list.xls that integrated the formerly available datasets from the Energieatlas (EKS) and the Landesamt für Umwelt (LfU). Restrictions apply to the availability of the IACS and livestock data per farm. Data using the farm level identifier are available upon request from the MLEUV (Ministerium für Land- und Ernährungswirtschaft, Umwelt und Verbraucherschutz, former MLUK).

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Appendix

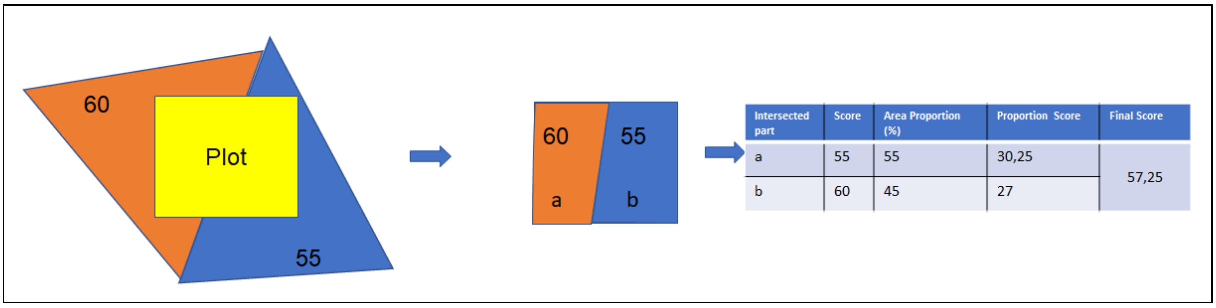

Figure A1. Example for catchment area score calculation when a maize plot is located within 2 or more catchment areas

Source: authors

Table A1. Substrate availability and average yield values of silage maize in Brandenburg

Year	Availability of silage maize (0-1 proportion) * (A)	Average yield of silage maize in tonnes/ha* (Y)
2008	0.04	31.59
2009	0.05	33.11
2010	0.05	28.57
2011	0.06	38.75
2012	0.06	36.26
2013	0.06	30.68
2014	0.06	36.94
2015	0.06	28.98
2016	0.06	32.41
2017	0.07	38.54
2018	0.07	21.42

Data source: *AfSBB (2019)

Table A2. Example of calculating the consumption factor for the year 2008

Cattle cow type	Consumption area silage maize (ha/yr)	Cattle cow distribution prop. Brandenburg 2008	Maize silage consumption factor (ha/yr) normalized values
Calves	0***	0.157	0
Fattening animals	0.2**	0.13	0.03
Heifers	0.05**	0.276	0.01
Dairy milk	0.32*	0.28	0.09
Other cows	0***	0.16	0
Total	-	1	0.13

Source: *LELF (2016); **calculated on Thüringen Landesanstalt für Landwirtschaft (2009, 2011), ***and own calculations

Table A3. Final consumption factor per year*

Year	Consumption factor (cow/ha)
2008	0.131
2009	0.122
2010	0.122
2011	0.122
2012	0.124
2013	0.125
2014	0.126
2015	0.124
2016	0.121
2017	0.130
2018	0.124

*This factor underestimates the role of dairy cows and overestimates the rest, however, due to the data limitations (we only have the total number of cows) this is the best approximation.
Source: own calculations

Validation and sensitivity analysis

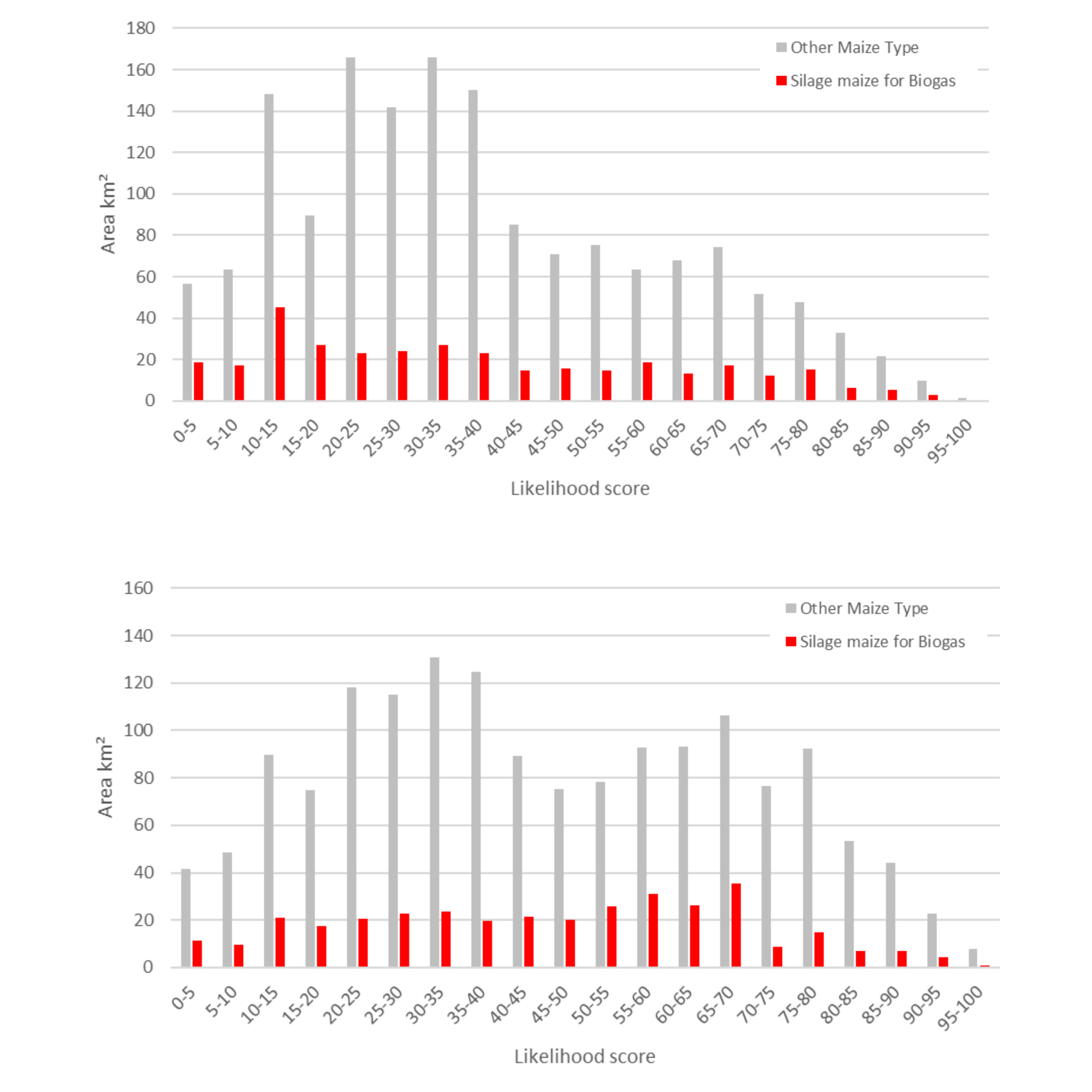

Figure A2. Comparison of plots classified as maize for biogas (in area) and the calculated likelihood score for 2017 and 2018

Source: own calculations