

Article

# Potential Bioenergy Production from *Miscanthus* × *giganteus* in Brandenburg: Producing Bioenergy and Fostering Other Ecosystem Services while Ensuring Food Self-Sufficiency in the Berlin-Brandenburg Region

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**Abstract:** Miscanthus  $\times$  giganteus (hereafter Miscanthus) is a perennial crop characterized by its high biomass production, low nutrient requirements, its ability for soil restoration, and its cultivation potential on marginal land. The development of the bioenergy sector in the state of Brandenburg (Germany), with maize as the dominant crop, has recently drawn attention to its negative environmental impacts, competition with food production, and uncertainties regarding its further development toward the state's bioenergy targets. This study aimed to estimate the potential bioenergy production in Brandenburg by cultivating Miscanthus only on marginal land, thereby avoiding competition with food production in the Berlin-Brandenburg city-region (i.e., foodshed), after using the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) model. We estimated that by 2030, the Berlin-Brandenburg foodshed would require around 1.13 million hectares to achieve 100% food self-sufficiency under the business as usual (BAU) scenario, and hence there would be around 390,000 ha land left for bioenergy production. Our results suggest that the region would require about 569,000 ha of land of maize to generate 58 PJ-the bioenergy target of the state of Brandenburg for 2030—which is almost 179,000 ha more than the available area for bioenergy production. However, under Miscanthus plantation, the required area would be reduced by 2.5 times to 232,000 ha. Therefore, Miscanthus could enable Brandenburg to meet its bioenergy target by 2030, while at the same time avoiding the trade-offs with food production, and also providing a potential for soil organic carbon (SOC) sequestration of around 255,200 t C yr-1, leading to an improvement in the soil fertility and other ecosystem services (e.g., biodiversity), compared with bioenergy generated from maize.

**Keywords:** land competition; food-energy nexus; perennial crops; renewable energy; sustainable development; climate change; ecosystem services; land-use change; land-use conflicts; foodshed; energyshed

# 1. Introduction

Bioenergy is widely regarded as a major source of renewable energy with numerous benefits including Greenhouse Gas (GHG) reduction and climate change mitigation [1,2] To address the climate change challenge, an ideal approach would be to replace fossil fuels with renewable energy sources combined with a rapid improvement in energy efficiency [3,4] Bioenergy was intended to mitigate climate change through lowering GHG emissions, nonetheless, many biofuels nowadays emit as much



or even more GHGs than fossil fuels or lead to only small savings, considering their whole lifecycle and taking into account the negative impacts of indirect land-use changes [5].

Several factors are impeding bioenergy's sustainability development pathways. The most controversial issue is the trade-off between the cultivation of bioenergy crops and food production (i.e., competition for land) [6–8]. In recent years, many fertile agricultural lands have been converted to bioenergy crops, mainly maize, rapeseed, and sugar beet [9,10].

The most common biofuel in Germany is biogas [11]. Maize as a bioenergy crop has been responsible for 70% biogas production input [12,13] Maize is usually planted as a monocrop and its cultivation is characterized by high nutrition requirements (i.e., fertilizers and/or good soil fertility properties) [14]. Biodiversity in maize monoculture farms is very low, and they are often called "grass deserts" [15]. Monoculture does not permit the reproduction of other species since only one species is planted and weeds are controlled by using pre- and post-emergence herbicides [16]. In this regard, the environmental effects of maize as a bioenergy crop is still a controversial topic [17]. Intensification in maize monoculture is recognized to result in soil erosion, groundwater contamination, and biodiversity loss, impacting all organisms that live in agricultural habitats [18]. In Germany, in almost all regions under intense agricultural practices, high nitrate contamination of groundwater can be expected [19]. N fertilizers contribute to various environmental issues such as contamination of groundwater and air pollution. Furthermore, nitrous oxide gas (N<sub>2</sub>O) emissions, also considered as GHG, contribute to climate change [20,21] In this line, the 2030 Biodiversity Strategy of the European Union (EU) [22] includes specific goals to restore, for example, damaged ecosystems to reduce risks from chemical pesticides, or mitigating the decline in farmland birds and insects.

Maize and other edible common energy crops such as wheat, sugarcane, and rapeseed are considered as the feedstock for the first generation (1G) of biofuels [23]. The problem regarding the use of these crops for bioenergy production is, first, they are either food or feed crops that directly generate negative effects on food security [24,25]. Such crops that could be part of the food cycle are being severely processed to be burnt as a fuel. Secondly, their production is competing with food production as they also require arable land [26,27]. While bioenergy production is attracting great attention as a renewable source of energy, the world's population is rapidly increasing and consequently the demand for food is increasing [28]. According to the Food and Agriculture Organization of the United Nations (FAO), to feed the growing population by 2050, agricultural production will need to increase by 60% [29]. This raises the question of how to feed the world, which has become a major problem in facing bioenergy development in a regional decision-making context.

To alleviate these negative impacts on the environment and the competition with food production, one of the solutions suggested by many researchers is the use of marginal land for bioenergy cropping [30–32]. Thus, the fertile arable land could still be used for food production. Whereas 1G energy crops, the second generation of biofuels (2G), come from non-edible biomass plant species that contain lignocellulosic compounds [33], *Miscanthus*, black locust, switchgrass, and canary grass are common 2G bioenergy crops [34,35]. The other common alternative pathway towards the sustainability of the biofuels is to consider a shift to 2G bioenergy crops [36,37].

*Miscanthus* is a perennial C4 rhizomatous grass native to Southeast Asia, and with lignified stems similar to bamboo [33,38–40]. It has specific features such as large root systems and a dormant ability, resulting in higher stress resistance, higher survival rates, lower growth restrictions, and improved yield [41]. *Miscanthus*, as an energy crop with relatively low maintenance requirements and a high dry matter yield and energy content, may play a major role in the sustainable development of biofuels [42,43]. Furthermore, and more importantly, *Miscanthus* can enhance soil organic carbon (SOC) accumulation, which improves soil fertility and, consequently, crop yields [44] and, on the other hand, contributes to mitigating CO<sub>2</sub> emissions to the atmosphere from the soil [45]. Under unfertilized *Miscanthus*, N<sub>2</sub>O emissions might be five times lower than annual crops, and up to 100 times lower than conventional pastures. In *Miscanthus* plantations, nitrogen (N) fertilizers are not usually required unless the soil is very poor. Herbicides are only needed for the establishment years, after that, due

to its canopy closure, weed suppression happens naturally by shading [46]. Pesticides are also only required in the establishment period when the shoots are young and fragile, in most cases after the establishment period, pesticides can be avoided [38]. Due to these environmental benefits, it has been suggested to include this crop as a greening measure of the EU's common agricultural policy (CAP) [47].

Because *Miscanthus* can be planted on marginal land, competition for land with food production can be avoided or significantly reduced [48]. Therefore, in order to evaluate the possibility of achieving the bioenergy goal of Brandenburg for 2030 and at the same time avoiding competition for land with food production, a backcasting methodology has been applied in the region for the first time.

Thus, the aim of this study is fourfold:

- 1) Estimate the area required to meet Brandenburg's bioenergy target for 2030 (58 PJ) by using silage maize and *Miscanthus* (backcasting process).
- 2) Estimate the bioenergy potential production from maize and *Miscanthus* by using only the available area for bioenergy without occupying the estimated land for achieving 100% of food self-sufficiency in the Berlin-Brandenburg foodshed (forecasting process).
- 3) Select the most suitable pathway by comparing the results from the backcasting and forecasting.
- 4) Identify and, in some cases roughly measure, other ecosystem services beyond provisioning services that may be positively affected after *Miscanthus* plantation in degraded lands.

# 2. Materials and Methods

# 2.1. Study Case: Brandenburg

a) Geography and pedoclimatic conditions

Brandenburg is located in the northeast of Germany (Figure 1), has a population of 2.5 million people, and covers an area of 29,478 km<sup>2</sup>. It is the fifth-largest German state by area and the tenth most populated. However, it is considered a populated area with very low density, as there are only 85 inhabitants per square kilometer. Brandenburg encircles Berlin—the national capital and city-state—and together they form the Berlin-Brandenburg Metropolitan Area, Germany's third-largest metropolitan area, and a metropolitan city-region (i.e., foodshed). Brandenburg is formed by 14 districts plus 4 free district cities (Figure 1).



**Figure 1.** Location of Germany (green) and Brandenburg (yellow) (**left**). Districts forming of the Berlin-Brandenburg metropolitan city-region or foodshed (**right**).

The agricultural land accounts for 45% of Brandenburg's area, of which 75% is arable land. Nearly two-thirds of this is formed by sandy- and sandy-loam-texture soils, with a water holding capacity of less than 140 mm [49]. Brandenburg's annual precipitation is 591 mm year<sup>-1</sup>, which is relatively low in comparison to the 750 mm year<sup>-1</sup> average of the country [50]. These two factors, low water holding capacity and low annual rainfall make the agricultural activity difficult since the majority of the crops are rain-fed.

# b) Soil quality categories based on the M-SQR system

To determine the soil quality—or, inversely, the marginality—we applied the Muencheberg Soil Quality Rating (M-SQR) system [51] as a tool to ascertain the marginal land in Brandenburg. The M-SQR is a model developed at the Leibniz Centre for Agricultural Landscape Research (ZALF), which is designed based on 8 basic criteria as well as at least 12 hazard factors addressing features of soil texture, structure, topography, and climate. The scores are conducted using visual soil assessment methods and are supported by monthly climate data. A site manual is also used to offer scores based on indicator levels. Ultimately, the highest quality soil receives 100 and a score of 0 goes to the least favorable soil for agricultural activities. This rating is a long-term soil quality indicator that provides a reasonable estimate of the ability of the soil for delivering specific local crop yields. In detail, it divides the soil quality into 5 classes: 1) of <20 = Very poor, 2) 20-40 = Poor, 3) 40-60 = Moderate, 4) 60-80 = Good, and 5)> 80 = High. The M-SQR scores are limited to the suitability of the soil for crop and grazing. This method mainly focuses on the production of rain-fed crops in temperate zones [51]. Land accounting for an M-SQR < 40 can be considered as marginal land in terms of agricultural land use [32].

To select the marginal land in Berlin and Brandenburg, we applied the M-SQR in Geographic Information System (GIS) and depicted the map of the soil quality of the study area (Figure 2). The map shows the contrast in the soil quality between the different states of Germany, especially in the middle and the south, and Brandenburg, having the least amount of high-quality soil in the country (blue color in Figure 2). Furthermore, nearly half of the arable land (45%) in Brandenburg is considered as poor-quality, which can be classified as marginal land, and only 11% considered as good- or high-quality soil for agriculture (Figure 2B). In Germany, however, only 25% of arable land is considered as marginal land, where more than half the land is regarded as good-quality soil (51% with M-SQR over 60) (Figure 2A).

# 2.2. Calculation of the Potential Energy Production

# a) Potential energy production from maize for biogas

To visualize the spatial distribution of maize for biogas production as an example of the current bioenergy strategy, we created the map of the silage maize for biogas production in Brandenburg. Thereby we used, the Integrated Administration and Control System (IACS) ("Integriertes Verwaltungsund Kontrollsystem," InVeKoS, Brandenburg, Germany) database, to extract data on agricultural land and products. IACS provides spatially specific data at the land parcel level, such as crop type and planted area, providing for the analysis of spatial land-use trends. According to the IACS database (dataset 2018), there are four different maize categories in Brandenburg. In detail this included silage maize for biogas (34,682 ha), maize as fodder (106,418 ha), maize with wild boar hunting (51,324 ha), and maize without silage (19,720 ha).



**Figure 2.** Map of soil quality categories based on the M-SQR index (0–100) for Germany (**A**) and Brandenburg (**B**). Soil quality is divided into five classes: (1) of < 20 = Very poor, (2) 20–40 = Poor, (3) 40–60 = Moderate, (4) 60–80 = Good, and (5)> 80 = High. The proportion of soil quality categories in Germany (**C**) and in Brandenburg (**D**). Maps of own elaboration based on [51].

We estimated the potential electricity generation of silage maize from the database of bioenergy in Germany [12] to be 18,731 kWh for 50 tons of fresh matter of silage maize. Therefore, we estimated that on average, 10,864 kWh electricity can be generated per hectare of arable land in Brandenburg under the cultivation of silage maize, considering its relatively low yield of 29 t FM ha<sup>-1</sup>yr<sup>-1</sup> in the past five years [52]. To estimate the primary energy (i.e., energy contained in raw fuels that has not been subjected to any human engineered conversion process) [53] of silage maize, we considered the conversion factor given by [12] for combined heat and power (CHP), suggesting that 38% of the primary energy is expected to be converted to electricity.

### b) Potential energy production from Miscanthus

There are only a small number of *Miscanthus* fields in Brandenburg. According to the IACS database, there is about 75 ha of *Miscanthus* in the study area. We chose two existing farms to be named here, farm A and farm B, due to data privacy issues, as examples of *Miscanthus* fields since there has been a recent study by [54] on the yield performance of different energy crops in this area, including *Miscanthus*. More importantly, in this area, the soil quality is identified as poor in the M-SQR map, thus making it suitable as a representative of *Miscanthus*' performance in Brandenburg soils

(M-SQR < 40), and the data on yields serve, therefore, to estimate its potential energy production under these poor soils. We estimated the yield of *Miscanthus* based on the average yield over the entire 20 years cultivating the span of the crop. This includes the first 2 years-establishment phase in which there is no harvest available. Then, taking these two years into account, the average yield is calculated based on the mean yield of the third and fourth years, times 18 years of production and divided into the 20 years of the cultivation period (Equation (1)). Furthermore, since the leaves will have fallen by the winter harvest, they will remain on the field and serve as mulch on the soil surface and eventually go back into the soil as organic matter. The stems, therefore, are the only biomass that is usually harvested for bioenergy production.

$$Y_{20}(t DM ha^{-1}yr^{-1}) = \frac{Y_{3-4}}{20} \times 18$$
<sup>(1)</sup>

The average yield of *Miscanthus*  $Y_{20}$  is based on 20 years of productivity.  $Y_{3-4}$  is the average yield of the third and fourth years in tones of dry matter per hectare and year (t DM ha<sup>-1</sup> yr<sup>-1</sup>).

### 2.3. Food Self-Sufficiency Assessment for the Berlin-Brandenburg City Region and Scenarios

This section aims to estimate the potential bioenergy production under different scenarios (forecasting) by using only the available area for bioenergy crops (AAB) (i.e., excluding the area needed to meet 100% self-sufficiency of the Berlin-Brandenburg population). The assessment of the food self-sufficiency has been carried out by using the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) model [55]. We have updated the results found by [55] for the Berlin-Brandenburg foodshed and used them as the starting point of our study. For this study, three scenarios have been selected depending on the consumption pattern and population (Table 1).

|          | 1   |
|----------|---|
| Scenario | Description   |
| BAU_15   | Conventional, current diet, 2015 (Business as Usual/Baseline) |
| BAU_30   | Conventional current diet (population of 2030)                |
| ORG_30   | Organic but regional (population 2030)                        |

Table 1. Description of scenarios.

Briefly, we have estimated the area demand (i.e., area required to feed the population of the foodshed) and, then, after selecting the utilizable agricultural area (UAA) (i.e., the area suitable for agriculture and livestock), the food self-sufficiency is estimated as a percentage. The results show that for all the scenarios, self-sufficiency achieves 100% (Table 2). Therefore, the AAB would be the remaining area for each scenario (Equation (2)):

$$AAB = UAA - A_{demand} \tag{2}$$

where AAB is the available area for planting bioenergy crops (ha), UAA is the total utilizable agricultural area (ha) and  $A_{demand}$  is the area required to feed the population (ha), according to the specific diet and size of population.

**Table 2.** Utilizable agricultural area (UAA), area demand, and the percentage of food self-sufficiency in the three different scenarios. Updated and adapted from [55]

| Scenario | UAA (ha)  | Area Demand (ha) | Food Self-Sufficiency (%) |
|----------|-----------|------------------|---------------------------|
| BAU_15   | 1,522,301 | 1,093,635        | 139                       |
| BAU_30   | 1,522,301 | 1,132,611        | 134                       |
| ORG_30   | 1,522,301 | 1,328,367        | 115                       |

### 2.4. Spatial Analysis

ArcGIS (10.5.1) (ESRI, Redlands, CA, USA) has been used either for the self-sufficiency assessment (more information on this in [55]) and for identifying the current existing maize and Miscanthus fields in Brandenburg, as well as for identifying and measuring the total surface of the soils with the lowest fertility properties.

### 3. Results

### 3.1. Current Bioenergy Production from Maize Plantations in Brandenburg

In Figure 3A, the location of silage maize fields for biogas is shown. After the spatial assessment, we found that 53% of maize for biogas production is being cultivated on fertile land (>40 M-SQR). More specifically, 43% of the maize is planted on moderate-quality soil (M-SQR between 40 and 60), 7% on good-quality soil (M-SQR between 60 and 80), and 3% on high-quality soil (M-SQR > 80). On the contrary, 47% of the silage maize for biogas is located in poor soil (M-SQR < 40) (Figure 3C).



**Figure 3.** Map of "silage maize for biogas" production based on soil quality in Brandenburg (**A**), distribution of "silage maize for biogas" in districts of Brandenburg (**B**), and percentage distribution of "silage maize for biogas" production based on soil quality in Brandenburg (**C**). Map and figures of own elaboration based on data from the IACS database.

Regarding the specific location of the maize plantations in Brandenburg, the districts accounting for the highest UAA of maize for biogas are Prignitz (8424 ha), Ostprignitz-Ruppin (6526 ha), and Märkisch-Oderland (4338 ha) (Figure 3B). Therefore, the districts in the North-West and Central-East of Brandenburg accounted for the highest proportion of maize for biogas plantations, being planted mainly under moderate-quality soil (green color). On the other hand, the district of Märkisch-Oderland presents some cultivation under good quality soils (pink color). Finally, some fields are also located in the area of high-quality soil (blue color), mainly in Teltow-Fläming.

In summary, the spatial assessment shows that more than half of the silage maize cultivation for biogas production occurs on soils of moderate-to-good quality.

### 3.2. Calculation of the Energy Potential and Available Area for Bioenergy (AAB)

### a) Maize for biogas

To estimate the energy potential of silage maize for biogas production in Brandenburg, we assumed the average yield of silage maize as the mean of the yield during the last 5 years (2015–2019), amounting to 29 t ha<sup>-1</sup>yr<sup>-1</sup> (35% dry matter) [52]. To calculate the energy produced per hectare from silage maize in Brandenburg, we applied the conversion factor reported by [56], reporting that 50 t FM (fresh matter) of silage maize is estimated to generate 18,731 kWh electricity. It is assumed that this is 38% of the primary energy that could be converted to electricity in a CHP (combined heat and power) biogas plant. Therefore, we estimate that the primary energy of silage maize for 50 t FM would be around 49,292 kWh. Consequently, 1 ton of FM silage maize would have an energy potential of 986 kWh. Considering the estimated yield of 29 t ha<sup>-1</sup>yr<sup>-1</sup> and the conversion factor (energy generated per hectare), we estimate the primary energy of silage maize to be 28,589 kWh ha<sup>-1</sup>, which could generate 10,863 kWh ha<sup>-1</sup> electricity in Brandenburg (Table 3).

**Table 3.** Estimated dry matter yield, (t  $ha^{-1}yr^{-1}$ ), primary energy, and electricity (kWh  $ha^{-1}$ ) (in GJ  $ha^{-1}$  in brackets) for *Miscanthus* and silage maize in Brandenburg.

| Bioenergy Crop    | Yield (t ha <sup>-1</sup> yr <sup>-1</sup> ) | Primary Energy per<br>Hectare (kWh ha <sup>-1</sup> ) (in<br>GJ ha <sup>-1</sup> in Brackets) | Electricity per Hectare<br>(kWh ha <sup>-1</sup> ) (in GJ ha <sup>-1</sup><br>in Brackets) |
|-------------------|--|---|--|
| <i>Miscanthus</i> | 13.5 DM                                      | 69,363 (250)  | 27,742 (100)   |
| Silage Maize      | 33.0 FM                                      | 28,589 (103)  | 10,864 (39)  |

### b) Miscanthus

On the other hand, we calculated the yield of *Miscanthus* in Brandenburg soil quality by applying Equation (1), obtaining a value of 13.5 t DM ha<sup>-1</sup> yr<sup>-1</sup>, which is 30% lower than the yield reported by [57] for Germany, which estimates a yield of 19 t DM ha<sup>-1</sup> yr<sup>-1</sup>.

According to [58], 1 ton of dry matter of *Miscanthus* biomass produces around 2055 kWh (18.5 GJ) of energy. Therefore, after applying this conversion factor to the estimated average yield of *Miscanthus* in Brandenburg obtained previously, the potential energy per hectare is estimated to be 69,363 kWh ha<sup>-1</sup> (250 GJ ha<sup>-1</sup>) (Table 3).

# 3.3. Assessment of the Required Area for Planting Miscanthus and Maize According to Brandenburg's Bioenergy Goal for 2030 (Backcasting)

To assess the feasibility of achieving Brandenburg's bioenergy goal for 2030 (58 PJ), the backcasting methodology has been applied. In other words, the area required for maize and *Miscanthus* to meet this goal is estimated considering the energy factors for each crop already calculated (Table 4).

**Table 4.** Brandenburg's bioenergy target for 2030 (58 PJ), the area required to meet the goal (ha), and primary energy of *Miscanthus* and maize. Note that only *Miscanthus* is estimated to achieve the goal.

| Crop         | Bioenergy Target (58 PJ) | Area Required to Meet<br>the Goal (ha) | Primary ENERGY per<br>Hectare (kWh ha <sup>-1</sup> ) (in<br>GJ ha <sup>-1</sup> in Brackets) |
|--------------|--------------------------|--|---|
| Miscanthus   | 58                       | 232,000                                | 69,363 (250)  |
| Silage Maize | 58                       | 568,627                                | 28,589 (103)  |

After calculating the potential energy production of each crop based on the crop yield and the energy yield in Brandenburg (Table 3), we estimate that the area required to meet the bioenergy goal would be 568,672 ha for maize and 232,000 ha for *Miscanthus* (Table 4). Thus, these results suggest that

the area required to meet the bioenergy goal of Brandenburg for 2030 under silage maize would be around 2.5 times higher than the estimated area for *Miscanthus*.

# 3.4. Assessment of Potential Bioenergy Production from Miscanthus and Maize Using the Available Area for Bioenergy Production (Forecasting)

After running the MFSS model, the area required for achieving 100% food self-sufficiency was subtracted from the total UAA (Equation (2)) and the remaining agricultural area (i.e., area for agricultural use but not necessary to achieve 100% of food self-sufficiency) can be considered as the AAB and amounts to the highest value (428,666 ha) for the scenario considering conventional diets from regional and non-regional food in 2015 (BAU\_15), followed by the same type of scenario, but in this case considering the projected population for 2030 (BAU\_30) to amount to 389,690 ha (Table 5). However, the differences between these two scenarios were only around 10% for both area and energy produced. In the case of the scenario considering only organic and regional diets in 2030 (ORG\_30), values were around half of that amounted in the BAU\_30, where diets are conventional and food comes from regional and non-regional sources (Table 5).

**Table 5.** Utilizable agricultural area (UAA) (ha), area demand (ha), available area for bioenergy (AAB) (ha), potential energy generation (PJ) for *Miscanthus*, and silage maize in the three scenarios.

| Scenario | UAA (ha)  | Area Demand<br>(ha) | AAB (ha) | Potential Energy<br>Generation<br><i>Miscanthus</i> (PJ) | Potential Energy<br>Generation Silage<br>Maize (PJ) |
|----------|-----------|---------------------|----------|--|---|
| BAU_15   | 1,522,301 | 1,093,635           | 428,666  | 107  | 44.1  |
| BAU_30   | 1,522,301 | 1,132,611           | 389,690  | 97.4   | 40.1  |
| ORG_30   | 1,522,301 | 1,328,367           | 193,934  | 48.5   | 20.0  |

Regarding the differences between the bioenergy potential of maize and *Miscanthus*, in all cases, *Miscanthus* amounted to a higher potential of energy value than maize, in the same proportion as the energy/ha factor for each crop calculated previously (Table 5).

### 3.5. Estimation of Soil Organic Carbon (SOC) Sequestration

*Miscanthus*, as a perennial crop, has positive effects on SOC dynamics, especially after the third year, when it is considered to achieve the commercial yield level. These positive effects are especially visible when shifting from conventional arable crops to *Miscanthus*. In this sense, it has been estimated that up to  $1.1 \text{ t C} \text{ ha}^{-1} \text{ yr}^{-1}$  could be sequestered by substituting conventional arable crops by *Miscanthus* [59]. Considering this C sequestration rate and that all the AAB is converted to be planted with *Miscanthus*, it would be possible to give an estimation on the potential C that could be sequestered in the soils of Brandenburg after planting *Miscanthus*. Importantly, the AAB selected for the study comprises only the area accounting for an M-SQR < 40. The M-SQR system does not consider pastures, since it only qualifies arable land. Therefore, the change in the management would always be from arable to perennial crops. This specification is of high importance, since the conversion of pastures to perennial crops might lead to SOC losses instead of gains.

The highest C sequestration is achieved in those scenarios accounting for the highest AAB. Therefore, the scenarios considering conventional diets in 2015 and 2030 were found to achieve the highest SOC sequestration potential (1.5–1.7 million tones  $CO_2$  per year). However, when shifting to more organic and regional diets, the AAB significantly decreases and so the SOC sequestration potential, to around half of the value achieved for the conventional diets (0.8 million tons  $CO_2$  per year), whereas for the scenario considering organic diets from domestic sources and imports, no SOC sequestration potential is achieved (Table 6).

| Scenario    | Available Area for<br>Bioenergy (AAB) (ha) | Potential SOC<br>Sequestration (t C yr <sup>-1</sup> ) | Potential CO <sub>2</sub><br>Sequestration (t CO <sub>2</sub> yr <sup>-1</sup> ) |
|-------------|--|--|--|
| BAU_15      | 428,666                                    | 471,533  | 1,728,953  |
| BAU_30      | 389,690                                    | 428,659  | 1,571,750  |
| ORG_30      | 193,934                                    | 213,327  | 782,200  |
| Backcasting | 232,000                                    | 255,200  | 935,733  |

Table 6. Potential soil organic carbon (SOC) sequestration of Miscanthus in different scenarios.

Finally, in the backcasting scenario, it was ascertained that if only *Miscanthus* was planted to achieve the goal of 58 PJ, a total of around 0.9 million tons of  $CO_2$  per year would be sequestered into the soils (Table 6).

### 4. Discussion

a) The potential of *Miscanthus* to achieve Brandenburg's bioenergy goals and avoiding competition for land to secure food self-sufficiency for the Berlin-Brandenburg population.

By allocating 74.4% of agricultural land to food production based on the food self-sufficiency baseline scenario (BAU\_30), the state would afford to assign the other 25.6% of its agricultural land for bioenergy crop cultivation. Therefore, by 2030, there would be around 389,690 ha (AAB), which implies that the maximum amount of arable land may be allocated for bioenergy production (Table 5). To reach the 2030 bioenergy goal with maize as the main energy crop, the state would require 568,627 ha of land, while under *Miscanthus*, only 232,000 ha would be needed. Otherwise stated, under the cultivation of *Miscanthus*, Brandenburg would require around 2.5 times less the amount of land in comparison with silage maize. Hence, a transition from maize to *Miscanthus* could spare about 337,000 ha.

Considering the 2030 AAB as 389,690 ha, in the BAU scenario (BAU\_30) of bioenergy production, silage maize as the main energy crop would only be able to provide 40.1 PJ of energy, which is only 69% of the bioenergy target of 2030 (Table 5). On the other hand, substituting *Miscanthus* as the main biomass crop would lead to much higher energy production besides the numerous positive environmental effects that this crop would bring. Because *Miscanthus*' yield is considerably higher than that of maize (almost by 2.5 times) (Table 3), shifting toward a *Miscanthus* plantation could provide nearly twice the 2030 target (117 PJ energy) (Table 5). This means substituting maize with *Miscanthus* as the main energy crop could boost energy production by 245%, which can be relied on marginal land, as opposed to the current system, where almost 52% of biogas-maize cultivation is being planted on fertile land (Figure 3). Therefore, this shift not only could release productive land for food production while achieving food self-sufficiency, but could also produce double the energy of 2030 bioenergy targets.

Therefore, when keeping the same dietary patterns and considering the population growth until 2030, our results suggest that the selected pathway (BAU\_30) would be suitable for achieving Brandenburg's bioenergy potential goal and at the same time avoid competition for land. However, when shifting to organic and regional diets (ORG\_30), the AAB would not be enough to achieve the goal.

#### b) The importance of allocating bioenergy crops in marginal lands

One of the objectives of this study was to demonstrate the importance of spatial land resource allocation in sustainable development. Even though Brandenburg has a considerable amount of arable land, soil fertility is relatively low (45% classified as poor soil) and therefore, it is crucial to assign land for the best possible use. Our results suggest that with silage maize is the main bioenergy crop, the 2030 Brandenburg energy targets would not be reached unless the 568,627 ha land is allocated for bioenergy production (Table 5). However, to achieve 100% of food self-sufficiency by 2030 in the Berlin-Brandenburg region 1,132,611 ha arable land would be required (Table 2). Therefore, considering imposing no further land-use change, the available area for bioenergy production without affecting

regional production to achieve 100% food self-sufficiency would be only around 389,690 ha (Table 5), which is only 68% of the required land for achieving 2030 bioenergy targets under the current silage maize scenario.

According to [60], defining marginal land is complex due to changes in land use and socio-economic impacts. Marginal land may be include a transitional phase of land resources, which is very susceptible to natural processes and different managements. The authors argue that the allocation of resources and the management practices can play an undeniable role in the productivity of land in which mismanagement of productive land may trigger soil degradation and in the long run, result in low productivity of the land, whereas marginal land can be improved and restored to a better quality level in the case of implementing sustainable management practices. Because *Miscanthus* is a perennial crop with a great ability to restore SOC levels, it can be expected that by allocating marginal land to *Miscanthus* production, the SOC depletion may be prevented and, in the long term, soil fertility properties would be improved.

*Miscanthus* is relatively tolerant of several environmental stressors, primarily salinity, drought, and flooding [57,61]. This special resilience encourages the growth of this perennial high yielding grass on marginal land [62]. *Miscanthus* plantation on suitable marginal land is regarded to have enormous potential to boost energy protection and to reduce GHG emissions. However, there is still a range of restrictions to the utilization of this capacity to the full. The major drawback is the confusion regarding the existence of the required marginal land owing to increased demand from other uses, such as land reclamation for food crops or other bioenergy crops [63,64].

Due to the high importance of defining and locating the marginal land in Brandenburg, maps of marginal land were created based on the M-SQR Index (Figure 2). Based on the assessment of [51], marginal land could be considered those soils resulting in an M-SQR level lower than 40. Therefore, according to the results and based on the currently available literature, soils under this value should be allocated for *Miscanthus* production and they should not be allocated for commercial food production.

To alleviate the land competition between food and energy crop production, cultivating bioenergy crops on marginal land should be considered as a suitable land policy. In the current policy scenario, however, 53% of maize as the main energy crop is being cultivated in fertile soil.

### c) The importance of regional food production

Recent concerns about climate change have triggered further justification for local and regional food systems [65,66]. Such issues have included the externalities of long-distance shipping of food and the vulnerability of centralized food production to climate change. Regional and organic food agricultural systems are continuously being considered as a significant step toward a more sustainable future [67]. Increased public awareness in linkages between food, safety, and the environment has driven rapid growth in regional and local food system projects. The associated improvement in the relevant scientific research has come alongside local development [68].

In the beginning of 2020, the COVID-19 has caused a global health and economic crisis, which has also led to an exacerbation in food security and a food crisis in many countries. In fewer than three months, COVID-19 has exposed risks, instabilities, and inequities in global food processes and has brought them to the point of collapse. The COVID-19 pandemic, along with lockdowns, has shown the fragility of the current food system and the dependency on global food supply chains [69]. In these turbulent times, food self-sufficiency can play an essential role since it has direct benefits for the capacity of a country or region to fulfill the nutritional needs of the people independently, despite the external situations [70]. Therefore, the concept of self-sufficiency can bring resilience to the food system and should be prioritized over bioenergy production. For this reason, in this study, the starting point of the calculation of the AAB is the remaining area after calculating the area needed to achieve 100% of food self-sufficiency in the Berlin-Brandenburg region.

# d) Environmental benefits and ecosystem services provided by Miscanthus

*Miscanthus* can be a multifunctional crop that not only offers a great amount of energy but also provides and supports other ecosystem services (ES) (Figure 4). In this section, these will be discussed and estimated values will be given for some of them (underlined ecosystem services in Figure 4). In this study, we specifically estimated the energy and food production (provisioning ES), C sequestration, and  $CO_2$  mitigation potential of *Miscanthus* (regulating ES).

# ES from planting Miscanthus in marginal lands of Brandenburg



**Figure 4.** Scheme of the ES delivered after planting *Miscanthus* for bioenergy in marginal lands in Brandenburg. Underlined ES refers to those that have been specifically estimated in this study, whereas the non-underlined ones are those that have been identified but not estimated because of the lack of enough scientific knowledge or because they were out of the scope of this research.

# 1) Provisioning Services: Energy and Food

According to our results, under *Miscanthus*, each hectare of marginal lands in Brandenburg can generate 250 GJ of energy (Table 3). This would allow the region to allocate more land for food production by up to 100% self-sufficiency (Table 2). Therefore, *Miscanthus* would provide energy, achieving Brandenburg's bioenergy goal (direct provision of ES) and would avoid competition for land with food production (indirect provision of ES).

- 2) Supporting Services
- Soil restoration (soil formation, nutrient cycling, and water cycling)

The low requirements in agrochemical inputs make *Miscanthus* fields more environmentally friendly by reducing the common damage caused by these substances used in conventional farming. For the same reason, *Miscanthus* has been reported to reduce the negative impacts of conventional agricultural activities on groundwater resources (by reducing N runoffs). On the other hand, the relatively high above- and below-ground biomass production has led to high incoming organic C in the soil (leaves on the soil surface and rhizodeposition processes), thus increasing the SOC content and leading to an improvement in the soil quality [71–73].

• Biodiversity

Studies have shown the positive effects of *Miscanthus* on biodiversity. *Miscanthus* can provide structural resources to agricultural landscapes, offer shelter, and improve the temporal variability that is obtained in different seasons by various bird species [74–76]. It increases the number and diversity

of earthworms in arable land, similar to grasslands. Furthermore, [77] showed a considerable increase in bird species diversity in *Miscanthus* fields as well as a greater abundance of mammals, compared with arable lands, which cannot provide as much shelter as in the case of perennial crops allowing the growth of wild vegetation. These authors also assessed the diversity and abundance of invertebrates and revealed that "ground beetles, butterflies, and arboreal invertebrates were more abundant and diverse in the most floristically diverse *Miscanthus* fields" [78].

The spike in maize production in Brandenburg results in a reduction of the habitat area of bird species, such as corn bunting by 28.2% and Skylark by 21.3%. *Miscanthus* cultivation can be a suitable alternative to not only mitigate the loss of biodiversity, but also to foster it by providing shelter for them [49]. This specific characteristic of *Miscanthus* plantations allowing the growth of non-crop plant species could be of critical importance to increase the diversity of insects, birds, and small mammals in Brandenburg.

- 3) Regulating services: climate regulation
- Avoiding CO<sub>2</sub> emissions from fossil fuel combustion

One tone of dry matter biomass through the pyrolysis process can produce 18.5 GJ energy, which is equal to the energy from one tone of coal [58]. However, the significant contrast is that coal releases 500 kg C to the atmosphere while *Miscanthus* only recycles it. According to our results, each hectare of *Miscanthus* in the marginal land of Brandenburg has 250 GJ of energy potential production (Table 3). Therefore, *Miscanthus* could save around 6,750 kg C ha<sup>-1</sup> compared to coal.

• Soil organic carbon (SOC) sequestration

In this study, we calculated the *Miscanthus* potential for SOC accumulation and the associated sequestered CO<sub>2</sub> in soil under the different scenarios selected for the assessment (Table 6). According to [59], an average SOC sequestration rate after planting *Miscanthus* would be around 1.1 t C ha<sup>-1</sup> yr<sup>-1</sup>. Since *Miscanthus* is mowed once a year, the effect on SOC sequestration can be compared to the effect of cover crops that are planted in the inter-row area of some woody crops. In this line, this value is very close to the 0.78 and 1.1 t C ha<sup>-1</sup> yr<sup>-1</sup> found by [79] in a meta-analysis for cover crops/spontaneous plant cover in vineyards and olive orchards, respectively, and the range of the 0.7–2.2 t C ha<sup>-1</sup> yr<sup>-1</sup> estimated by [74] for *Miscanthus* in the UK. An increase of 1.1 t C ha<sup>-1</sup>yr<sup>-1</sup> would imply the sequestration of 4.0 t CO<sub>2</sub> ha<sup>-1</sup>yr<sup>-1</sup>. Considering the cultivation of *Miscanthus* in AAB without affecting food production (389,690 ha) (Table 5), if all this area was planted with *Miscanthus*, the CO<sub>2</sub> sequestration rate would be around 1.6 million t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>.

However, these numbers must be taken carefully, since the organic carbon sequestration in soil is limited and is dependent on the soil texture [80] and the C sequestration rate decreases over time as the SOC content reaches the steady-state (i.e., equilibrium) [79,81]. On the other hand, not all the SOC would be really "sequestered" into the soil, since part of the accumulated SOC would be easily accessible to the microorganisms, thus being rapidly and easily mineralized (i.e., released into the atmosphere as  $CO_2$ ). Although there is a high level of uncertainty, the proportion of this non-protected SOC would range between 20–40% of the total accumulated SOC [82].

Actual levels of SOC in Brandenburg are relatively low and combine with the sandy texture, resulting in a soil poor quality (Figure 2B) (i.e., M-SQR < 40). However, precisely this very low SOC content (i.e., high SOC saturation deficit) leads to a high potential for SOC sequestration [80]. SOC accumulation rate is inversely proportional to the actual SOC content. In other words, the lower the SOC content is, the faster is the accumulation. Therefore, if *Miscanthus* is planted in the poor soils of Brandenburg, a rapid increase in the SOC is expected. However, the SOC saturation limit is expected to be lower due to the lower content of clay [80,83]. Therefore, during the first years after planting *Miscanthus*, the C sequestration rate of  $1.1 \text{ t C ha}^{-1} \text{ yr}^{-1}$  might be reliable. More uncertainty remains over time, as SOC content increases.

#### 4) Other regulating services: Water regulation and pollination

Studies have shown that in comparison to maize fields, N leaching is considerably lower under unfertilized *Miscanthus* [74,84,85]. Leaching can be exacerbated in sandy soils due to low water-holding capacity [86]. In Brandenburg, this is a very common problem where approximately 85% of the lakes are extremely or severely polluted with nutrients, while significant parts of the banks have been damaged in almost all big still water bodies, and around 90% of the existing stocks of grasses have vanished in several lakes [87]. Therefore, *Miscanthus* cultivation instead of maize is expected to alleviate water contamination in the region. Moreover, in terms of water efficiency, if *Miscanthus* was planted instead of maize, one-third of the water could be saved [2]. This is an important issue especially for the next few decades, where climate change is expected to increase water stress in Germany.

*Miscanthus* is not a preferred source of food for most insects and animals, but for many invertebrates and pollinators, its residues left after harvest and canopy closure shade provide nesting, shelter, and breeding sites [88]. The increase in biodiversity, especially the diversity of insects, as a consequence of the increase in the wild vegetation, would improve the pollination activity in the crops placed in the surrounding areas of *Miscanthus* fields.

### 5) Cultural and socio-economic services

According to [89], the attainable gross margins of producing *Miscanthus* for combustion would range from 400 to  $1600 \in ha^{-1}$ , whereas these values would be somewhat higher, around  $1300-2000 \in ha^{-1}$ , in the case of using *Miscanthus* for biogas production. Another key parameter is the labor requirements (e.g., labor peak seasons) of *Miscanthus* compared to other annual crops since it could be expected that farmers will not be dedicated entirely to *Miscanthus* cultivation, but also to other arable crops (cereals or maize). Thus, the labor peaks of the green harvest regime do not coincide with those of the other cereals or intermediate crops. However, some activities of the brown harvest regime overlap with those for other crops, but the only labor peak takes place in March, whereas for the rest of the year, the activity is less intensive. The total labor effort is estimated to be low, as between 4 and 15 h ha<sup>-1</sup> for *Miscanthus* is already established, whereas the highest efforts take place in the establishing year [89]. Therefore, the combination of low peak times in the management of *Miscanthus* and the low labor requirements lead *Miscanthus* to be feasible to be combined with the production of other arable crops.

Furthermore, the facilities to transform *Miscanthus* into energy are also important in terms of quality job creation and population fixation [90,91]. Brandenburg is one of the least densely populated regions in Germany, and under increasing aging that might lead to an increase in land abandonment [92]. The integration of bioenergy crops into the landscape may stimulate the economy of rural areas and thus mitigate the negative impacts of land abandonment [93]. Therefore, to avoid or mitigate this, *Miscanthus* could be of high relevance.

### 6) Limitations of the Study and Future Researches

To examine the sustainability of the current biogas production in Brandenburg on the wider scale of Germany, it is required to have official statistics of the exact amount of each crop, in this case, silage maize, which goes to biogas plants, and the specific locations of these bioenergy farms. However, it must be noted that the total amount of "maize for biogas" planted in Brandenburg is reported as only 34,682 ha, which is expected to be about one-third of the actual area of 110,000 ha, but due to lack of clear official statistics or reports, we only demonstrated and analyzed this amount, which is reported by the official IACS database.

We believe that the application of the backcasting methodology to assess the feasibility of achieving the 2030 bioenergy goal of Brandenburg and integrating it with the food self-sufficiency assessment establishes the first step in the assessment of the regional food–energy nexus and can be the basis for future research focused on some specific issues, like locating potential marginal lands to be planted by *Miscanthus* or the socio-economic impact of these plantations in the region of Brandenburg.

### 5. Conclusions

Our study suggests that in order to produce bioenergy while avoiding competition for land with food production, it is important to move toward the 2G bioenergy crops that can be cultivated on marginal land. In Brandenburg, the agricultural land has been massively affected by the cultivation of maize for biogas production (300% increase in the past 10 years), thereby, the scarce productive land of the region has been under maize monoculture production, which has led to negative environmental repercussions (e.g., biodiversity reduction, soil degradation, or land-use change), which would nullify the potential GHG mitigation of bioenergy production. Thus, a shift from maize to *Miscanthus* as the main bioenergy crop could address almost all the negative environmental externalities caused by maize plantation, due to its perennial character and its low nutrient requirements which allow it to be cultivated on degraded areas.

On the other hand, our findings imply that substituting maize with *Miscanthus* for bioenergy production can ensure food production by releasing productive land for food production and providing a high yield of dry matter, which results in a reduction of land requirements for bioenergy production and, therefore, achieving the 2030 bioenergy goal of Brandenburg would be possible without negatively affecting the food self-sufficiency and in general the resilience of the food system of the Berlin-Brandenburg area.

Today, the world is experiencing a drastic health and economic crisis due to the emergence of COVID-19. This pandemic has shown the fragility of the world's food systems, which is dependent upon international and complex food supply chains. This is another reason to highlight the significance of food self-sufficiency for regions and countries, especially in the events that strike food supply chains. Therefore, now more than ever before, food production should be prioritized over bioenergy production, particularly in regards to the allocation of fertile arable land.

Furthermore, the backcasting methodology applied in this study, which is one of the first studies to apply it in a specific study case in Germany, could be valuable to assess the current bioenergy goals and strategies of the state of Brandenburg. This is also reflected in the light of a city-regional food strategy launched by the Berlin Senate, which puts potentially competing pressure on land resources and consequently incentivizes the transformation of the food supply from Brandenburg by, for example, favoring organic and locally grown potatoes and vegetables for public procurement. On a more general level, we consider these trends and observations as indications of a general shift of paradigm, away from standardized global chain-oriented production to regionally tailored quality production oriented to specific individualized demands, or in other words, the transformation from cost competition to quality competition.

The approach and results of our study underline that for such a transition, integrated governance across sectors is required, particularly at state and regional levels, in order to better link bioenergy strategies with agricultural and food sectoral strategies and overarching environmental, climate and innovation strategies (e.g., climate change, biodiversity, agriculture, food production) and to create clear sustainable pathways to be achieved in 2030. Additionally, we believe that coherence between the different European strategies will be needed (e.g., the CAP, Green Deal, From Farm to Fork Strategy, or the 2030 Biodiversity Strategy).

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