Biomass production and energy balance of *Miscanthus* over a period of 11 years: A case study in a large-scale farm in Poland

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Abstract

Giant miscanthus (*Miscanthus × giganteus* Greef and Deuter) and Amur silver grass (*Miscanthus sacchariflorus* Maxim./Hack) are rhizomatous grasses with a C4 photosynthetic pathway that are widely cultivated as energy crops. For those species to be successfully used in bioenergy generation, their yields have to be maintained at a high level in the long term. The biomass yield (fresh and dry matter [DM] yield) and energy efficiency (energy inputs, energy output, energy gain, and energy efficiency ratio) of giant miscanthus and Amur silver grass were compared in a field experiment conducted in 2007–2017 in North-Eastern Poland. Both species were characterized by high above-ground biomass yields, and the productive performance of *M. × giganteus* was higher in comparison with *M. sacchariflorus* (15.5 vs. 9.3 Mg DM ha−1 year−1 averaged for 1–11 years of growth). In the first year of the experiment, the energy inputs associated with the production of *M. × giganteus* and *M. sacchariflorus* were determined at 70.5 and 71.5 GJ/ha, respectively, and rhizomes accounted for around 78%–79% of total energy inputs. In the remaining years of cultivation, the total energy inputs associated with the production of both perennial rhizomatous grasses reached 13.6–15.7 (M. × giganteus) and 16.9–17.5 GJ ha−1 year−1 (M. sacchariflorus). Beginning from the second year of cultivation, mineral fertilizers were the predominant energy inputs in the production of *M. × giganteus* (78%–86%) and *M. sacchariflorus* (80%–82%). In years 2–11, the energy gain of *M. × giganteus* reached 50 (year 2) and 264–350 GJ ha−1 year−1 (years 3–11), and its energy efficiency ratio was determined at 4.7 (year 2) and 18.6–23.3 (years 3–11). The energy gain and the energy efficiency ratio of *M. sacchariflorus* biomass in the corresponding periods were determined at 87–234 GJ ha−1 year−1 and 6.1–14.3, respectively. Both grasses are significant and environmentally compatible sources of bioenergy, and they can be regarded as potential energy crops for Central-Eastern Europe.

Keywords

Amur silver grass, biomass, energy efficiency ratio, energy gain, energy inputs, energy output, giant miscanthus
1 | INTRODUCTION

In recent years, growing concerns about energy security and energy self-sufficiency have prompted many countries to diversify their energy sources and place greater emphasis on renewables. These concerns have engaged a growing demand for energy, price fluctuations in fuel prices, and the harming environmental impact of fossil fuels (Khanna, Dhungana, & Clifton-Brown, 2008; Turley, 2008). In the European Union (EU), approximately 45%–73% of renewable energy is generated from biomass (Stolarski, Niksa, Krzyzaniak, Tworkowski, & Szczerbinski, 2017). Biomass for energy generation is obtained mainly from forests, wood processing plants, roadside and urban habitats, organic waste, and agricultural production. Sustainable production of agricultural biomass, mainly perennial and industrial crops, is likely to play a key role in a bio-based economy (Bentsen & Felby, 2012). Perennial energy crops include: (a) fast-growing trees and shrubs (willow, poplar, etc.), (b) perennial plants that yield semi-woody biomass (Virginia mallow, willow, sunflower, etc.), and (c) grasses that yield straw biomass (giant miscanthus, Amur silver grass, prairie cordgrass, etc.; Amaducci et al., 2017; Laurent, Pelzer, Loyce, & Makowsky, 2015; Stolarski et al., 2015,2019; Stolarski, Śnieg, Krzyzaniak, Tworkowski, & Szczerbinski, 2018; Stolarski, Śnieg, Krzyzaniak, Tworkowski, Szczerbinski, et al., 2018). Biomass can be more effectively converted into energy by pyrolysis and fermentation rather than direct incineration. Biogas production also plays a very important role in bioenergy generation (Oslaj, Mursec, & Vindis, 2010). In Europe, maize biomass is most commonly used for biogas production due to its high methane yields, optimized agronomic practices and harvest logistics, relatively easy preservation, and storage (as silage; Barbosa, Nabel, & Jablonowski, 2014). However, strong dependence on a single substrate in biogas generation can have adverse environmental impacts (Herrmann, 2013; Svoboda et al., 2013; Vogel, Deumlish, & Kaupenjohann, 2016). For this reason, new crop species with a more ecologically sustainable profile have to be identified to diversify the raw material base for the biogas sector (Kiesel, Wagner, & Lewandowski, 2017) and to increase biodiversity in agricultural production (Jankowski, Dubis, Budzyński, Bórawski, & Bulkowska, 2016). The biomass yield of the candidate crops should be comparable to or higher than that of maize (Jankowski et al., 2016). Perennial rhizomatous grasses of the genus Miscanthus with a C4 photosynthetic pathway meet these criteria (Clifton-Brown et al., 2017; Dubis et al., 2017; Lewandowski et al., 2016; Meehan, Finnan, & Mc Donnell, 2013; van der Weijde et al., 2016; Zamora, Wyatt, Apostol, & Tschirner, 2013). These crops are characterized by high biomass yields (Borkowska & Molas, 2013; Christou, Papavassiliou, Alexopoulos, & Chatziathanassiou, 1998; Heaton, Voigt, & Long, 2004; Lewandowski & Kicherer, 1997; Meehan et al., 2013; Schwarz, Greef, & Schnug, 1995), they can be grown under less favorable soil and climatic conditions (Gelfand et al., 2013; Sang & Zhu, 2011), and have low agricultural requirements (Anderson et al., 2011; Beringer, Lucht, & Schaphoff, 2011; Godin et al., 2013; Larsen, Jørgensen, Kjeldsen, & Lærke, 2014; Meehan et al., 2013). Perennial rhizomatous grasses are environmentally friendly, and they do not compete with food crops (Lewandowski et al., 2016; McCalmont et al., 2017; Tilman et al., 2009; Valentine et al., 2012). Giant miscanthus (Miscanthus × giganteus), a tall C4 perennial rhizomatous grass from Asia (Greef & Deuter, 1993), is the most popular energy crop of the genus Miscanthus in Europe. The area under giant miscanthus is estimated at 20,000 ha in the EU and 500 ha in Poland (Lewandowski et al., 2016). Its popularity is relatively low due to high production costs which decrease the crop’s profitability and competitiveness relative to fossil fuels. There are several reasons for the above: (a) the absence of sufficiently effective production technologies; (b) high costs of establishing a plantation; (c) small biomass market; and (d) farmers’ reluctance to dedicate arable land to perennial crops (Lewandowski et al., 2016). Amur silver grass is less suitable for bioenergy generation than giant miscanthus due to lower biomass yield per unit area. However, Amur silver grass is more resistant to unfavorable weather and environmental conditions (frost, salinity, etc.), and it is better suited for cultivation on low-quality soils (degraded and marginal land; Lewandowski et al., 2016; van der Weijde et al., 2016).

The energy efficiency of agricultural crops should be optimized in an era of growing demand for energy, including renewable energy (Stolarski et al., 2019). The biomass yield of energy crops should be maximized, and raw material inputs and energy inputs should be decreased to achieve the above goal (Roszkowski, 2013). According to research, the energy yield of perennial grasses of the genus Miscanthus exceeds that of willow, cannabis, and oilseed rape (Hastings et al., 2009; Heaton, Long, Voigt, Jones, & Clifton-Brown, 2004; Heaton, Voigt, et al., 2004; Stampfl, Clifton-Brown, & Jones, 2007).

The aim of this study was to determine the biomass yield and the energy efficiency of giant miscanthus (M. × giganteus Greef and Deuter) and Amur silver grass (Miscanthus sacchariflorus Maxim./Hack) grown in a large-area farm in northeastern (NE) Poland over a period of 11 years.

2 | MATERIALS AND METHODS

2.1 | Field experiment

A field experiment was carried out in 2007–2017 in the Agricultural Experiment Station in Balcyny (53°35′46.4″N, 19°51′19.5″E, elevation 137 m) in NE Poland. The station comprises around 2000 ha of agricultural land, and it is a part of the University of Warmia and Mazury in Olsztyn. The experimental variables were two species of perennial rhizomatous grasses
as sources of lignocellulosic biomass: (a) giant miscanthus (*M. × giganteus* Greef and Deuter) and (b) Amur silver grass (*M. sacchariflorus* Maxim./Hack). The applied farming operations, mineral fertilization rates, rate of crop protection agents, and the timing of farming operations (Table 1) were adapted to the specific requirements of the analyzed plant species. The experimental field had an area of 5 ha (200 m × 250 m). The experiment had completely randomized design with three replications. The experimental field was situated at a distance of around 800 m from the center of the station. The experiment was established on Haplic Luvisol originating from boulder clay (IUSS Working Group WRB, 2006).

### 2.2 | Biomass processing experiment

The crops were harvested in growth stages that were most conducive to ensiling to effectively preserve lignocellulosic biomass during long-term storage (the end of the September). Amur silver grass was harvested in the flowering stage, and giant miscanthus was harvested after the lower leaves had dried (up to one third of stem length; Table 1). Fresh matter yield (FMY) was determined by weighing the harvested biomass immediately after harvest. Dry matter (DM) content was estimated by drying a subsample of 1 kg at 105°C in a ventilated oven (FD 53 Binder GmbH, Germany) until constant weight.

### 2.3 | Energy output analysis

The unit energy value (higher heating value [HHV]) of biomass was determined by adiabatic combustion in a calorimeter (IKA C 2000, USA) with the use of a dynamic method. The lower heating value (LHV) of biomass was expressed in terms of moisture content determined at harvest (Kopetz, Jossart, Ragossnig, & Metschina, 2007). The energy value of biomass was determined as the product of LHV (MJ/kg) and FMY (Mg/ha).

### 2.4 | Energy inputs analysis

The energy inputs associated with the production of the analyzed crops were determined based on direct measurements of diesel oil consumption, labor, and the field capacity of farming machines and equipment (Table 2). Energy inputs were divided into categories based on the respective energy fluxes (labor, energy carriers, farming machines and equipment, and materials). The energy inputs associated with labor, operation of tractors and machines, consumption of diesel oil, and production materials (rhizomes, pesticides, and fertilizers) were determined based on literature data and are summarized in Table 3. To estimate fuel consumption, each farming operation was started with a full fuel tank, which was refilled at the end of the operation. The energy efficiency of crop production was determined based on the energy gain and the energy efficiency ratio (Jankowski, Budzyński, & Kijewski, 2015).

### 2.5 | Statistical analysis

Biomass yield, HHV, LHV, and the energy value of biomass yield (energy output) were analyzed by repeated measures ANOVA, where *Miscanthus* species was the fixed factor and 11 years of production was the repeated factor. Treatment means were compared based on the least significant difference in Tukey’s test. All analyses were performed in the Statistica 13.3 program (TIBCO Software Inc., 2017). The *F*-values of ANOVA are presented in Table 4.

### 3 | RESULTS

#### 3.1 | Weather conditions

The field experiment was conducted in NE Poland which is a temperate transitional zone between the oceanic climate in the west and the continental climate in the east. The continental climate...
| Farming operations          | Parameters of self-propelled machines | Parameters of accompanying machines | Service life (hr) | Weight (kg) | Performance of self-propelled machines and accompanying machines (ha/hr)b | Fuel consumption (L/hr)b |
|-----------------------------|---------------------------------------|-------------------------------------|------------------|-------------|--------------------------------------------------------------------------|--------------------------|
| Skimming (5–8 cm)           | 136 kW                                | 7 (number of furrows)               | 12,000           | 2,000       | 9,285 2,600                                                              | 4.0 32.5                 |
| Fall plowing (18–22 cm)     | 136 kW                                | 7 (number of furrows)               | 12,000           | 2,000       | 9,285 3,360                                                              | 2.4 60.0                 |
| Tillage-cultivation unit    | 246 kW                                | 4 m (working width)                 | 12,000           | 2,000       | 13,003 2,150                                                             | 4.4 32.9                 |
| Disking                     | 114 kW                                | 6 m (working width)                 | 9,000            | 1,600       | 5,635 3,100                                                              | 3.1 23.6                 |
| Planting                    | 53 kW                                 | 4 (number of rows)                  | 9,000            | 800         | 5,635 420                                                                | 0.7 8.2                  |
| Mineral fertilization       | 114 kW                                | 30 m (working width)                | 9,000            | 1,200       | 5,635 300                                                                | 15.8 16.8                |
| Weed protection             | 53 kW                                 | 20 m (working width)                | 9,000            | 1,050       | 3,550 1,350                                                              | 7.0 5.7                  |
| Harrowing                   | 53 kW                                 | 7.5 (working width)                 | 9,000            | 1,800       | 3,550 647                                                                | 3.0 10.0                 |
| Weeding between rows        | 53 kW                                 | 2.7 (working width)                 | 9,000            | 800         | 5,635 438                                                                | 1.0 8.7                  |
| Harvest                     | 232 kW/3.0 m (working width)          | —                                   | 3,000            | —           | 3,500 —                                                                  | 1.0–2.0b 22.5–37.5b      |
| Biomass transport           | 97 kW                                 | 12 Mg (carrying capacity)           | 9,000            | 1,600       | 5,200 3,900                                                              | —                        |
| Loading                     | 55 kW /2,500 kg (load capacity)       | —                                   | 4,800            | —           | 4,922 —                                                                  | —                        |

aAverage of 11 years.

bDifferences result from variations in biomass yield.
climate is characterized by hot and dry summers and very cold winters. Precipitation occurs mostly in winter. The temperate oceanic climate has warm summers and mild winter, with precipitation occurring throughout the growing season. Poland is located in the transitional zone with warm summers, cold winters, and year-round precipitation (Schneider, Laizé, Acreman, & Flörke, 2013). Average daily temperatures and rainfall patterns in the studied site are presented in Table 5. During the experiment, precipitation levels ranged from 454 to 940 mm, with a long-term average (1981–2015) of approximately 588 mm. The last 2 years of the experiment (years 10 and 11) were characterized by very high rainfall (750–940 mm, i.e., 128%–160% of the long-term average). In 4 years (2009, 2010, 2012, and 2013), the average annual temperature was similar to or slightly below (by 0.1–1.1°C) the long-term average (1981–2015). In the remaining years of the experiment, the average annual temperature was significantly above (by 0.6–1.3°C) the long-term average (Table 5).

3.2 | Energy inputs

In the first year of the study (plantation establishment), the consumption of energy associated with the production of giant miscanthus and Amur silver grass biomass reached 70.5 and 71.5 GJ/ha, respectively, and rhizomes accounted for 78%–79% of total energy inputs. In the remaining years of the experiment, the energy demand of both species of perennial rhizomatous grasses was determined at 13.6–15.7 (giant miscanthus) and 16.9–17.5 GI ha⁻¹ year⁻¹ (Amur silver grass). Beginning from the second year of cultivation, mineral fertilizers were the predominant energy inputs in the cultivation of giant miscanthus (78%–86%) and Amur silver grass (80%–82%; Table 6). The annual energy inputs associated with the production of both species of perennial rhizomatous grasses reached 20.0 (giant miscanthus) and 22.2 GJ ha⁻¹ year⁻¹ (Amur silver grass; Table 7). The production technology of Amur silver grass was more energy-intensive (by 11% on average) in comparison with giant miscanthus (Table 7) due to higher fertilizer requirements in the Polish climate (Table 1).

3.3 | Biomass yield

In NE Poland, both species of perennial rhizomatous grasses achieve average yields in the third year of cultivation (Figure 1). In the first 2 years of the experiment, the FMY of Amur silver grass was 1.35–6.20 Mg/ha higher (31%–62%) in comparison with giant miscanthus. Beginning from the third year of the study, giant miscanthus exceeded Amur silver grass by 1.7– to 3.7-fold in terms of FMY (55.1 Mg/ha). The FMY of giant miscanthus peaked in year 5 (55.1 Mg/ha). Between years 6 and 9, the FMY of giant miscanthus decreased to 41.0 Mg/ha (by 1% per year), and a repeated increase to 48.6 and 53.3 Mg/ha (by 19% and 30% relative to year 9) was observed in years 10 and 11 (Figure 1). The increase in the FMY of giant miscanthus in the last 2 years of the experiment (Figure 1) was attributed to highly favorable weather conditions, including abundant precipitation (26%–60% higher than the long-term average) and high average daily temperatures (0.6–1.3°C higher than the long-term average; Table 5). In NE Poland, the FMY of Amur silver grass was exceptionally low, marking a 32% and 54% decrease from the preceding years (2010 and 2014, respectively; Figure 1). In 2011, the FMY of Amur silver grass decreased in response to a water deficit in May–June (rainfall equivalent to 73% of the long-term average), which slowed down early plant development (Table 5). In 2015, a water
deficit in April–June and August was accompanied by high average daily temperatures in August (Table 5), which led to premature drying of Amur silver grass plants. The biomass of Amur silver grass was characterized by higher DM content (by 27–175 g/kg) than giant miscanthus (Figure 2). The DM content of giant miscanthus biomass increased by approximately 16 g kg\(^{-1}\) year\(^{-1}\) between years 1 and 6, and it decreased gradually (by approx. 13 g kg\(^{-1}\) year\(^{-1}\)) between years 7 and 11. DM accumulation in the harvested biomass of Amur silver grass was not influenced by the plantation’s age. The average DM content of Amur silver grass biomass was 470 g/kg (Figure 2). Above-average values of DM concentration in harvested biomass were noted in 2007, 2008 (1 and 2 year old plants), and 2015 (drought caused premature plant drying; Figure 2; Table 5).

In NE Poland, the dry matter yield (DMY) of Amur silver grass exceeded that of giant miscanthus only in the first 2 years of growth (Figure 3). In the remaining years of the experiment (years 3–11), the DMY of giant miscanthus was 8.25 Mg ha\(^{-1}\) year\(^{-1}\) (by 82%) higher on average in comparison with Amur silver grass. In 2007–2012, the DMY of giant miscanthus exceeded that of Amur silver grass by 6.2 Mg ha\(^{-1}\) year\(^{-1}\) on average. The DMY of giant miscanthus continued to increase until year 5 (20.5 Mg/ha), and it decreased by 0.97 Mg ha\(^{-1}\) year\(^{-1}\) between years 6 and 8. In years 9 and 10, the analyzed parameter increased to 19.0 and 20.0 Mg/ha (Figure 3), respectively, due to very high precipitation and above-average temperatures (Table 5). The DMY of Amur silver grass continued to increase throughout the experiment and was highest at 14.4 Mg/ha in year 11 (Figure

**Table 5** Weather conditions during the experiment (2007–2017) versus the long-term average (1981–2015) in the Agricultural Experiment Station in Bałcyny, Poland (53°35′46.4″N, 19°51′19.5″E)

| Month       | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 1981–2015 |
|-------------|------|------|------|------|------|------|------|------|------|------|------|-----------|
| **January** | 10   | 31   | 16   | 13   | 30   | 88   | 35   | 44   | 29   | 29   | 16   | 32        |
| **February**| 15   | 34   | 15   | 14   | 21   | 25   | 21   | 11   | 9    | 51   | 41   | 22        |
| **March**   | 28   | 47   | 68   | 24   | 9    | 21   | 14   | 56   | 46   | 21   | 53   | 30        |
| **April**   | 27   | 34   | 4    | 9    | 34   | 34   | 23   | 26   | 23   | 33   | 52   | 30        |
| **May**     | 80   | 48   | 90   | 108  | 42   | 34   | 46   | 35   | 25   | 51   | 41   | 22        |
| **June**    | 177  | 47   | 82   | 88   | 172  | 112  | 164  | 20   | 71   | 139  | 106  | 85        |
| **July**    | 53   | 29   | 30   | 46   | 15   | 34   | 57   | 80   | 78   | 54   | 43   |           |
| **August**  | 61   | 28   | 133  | 74   | 56   | 107  | 45   | 72   | 43   | 66   | 110  | 72        |
| **September**| 65   | 17   | 16   | 45   | 39   | 41   | 69   | 31   | 51   | 17   | 211  | 55        |
| **October** | 49   | 105  | 59   | 11   | 30   | 58   | 15   | 21   | 21   | 96   | 160  | 48        |
| **November**| 50   | 41   | 41   | 110  | 10   | 49   | 23   | 81   | 78   | 49   | 45   |           |
| **December**| 25   | 29   | 30   | 39   | 46   | 15   | 34   | 57   | 80   | 78   | 54   | 43        |
| **∑**       | 667  | 563  | 578  | 633  | 570  | 628  | 515  | 492  | 750  | 940  | 588  |           |
| **Mean daily temperature (°C)** | 2.5  | 0.7  | −3.9 | −8.8 | −1.5 | −1.9 | −4.4 | −3.3 | 0.6  | −4.0 | −3.3 | −2.4     |
| **January** | −2.1 | 2.5  | −1.5 | −2.7 | −6.6 | −7.2 | −0.8 | 2.0  | 0.5  | 2.7  | −1.0 | −1.8     |
| **February**| 5.3  | 2.9  | 1.9  | 1.9  | 2.0  | 3.4  | −4.0 | 5.4  | 4.6  | 3.5  | 5.0  | 1.9      |
| **March**   | 7.3  | 7.8  | 9.7  | 7.9  | 9.7  | 8.4  | 6.3  | 9.5  | 7.2  | 8.8  | 6.7  | 7.8      |
| **April**   | 13.5 | 12.3 | 12.1 | 12.0 | 13.5 | 13.8 | 15.0 | 13.1 | 12.1 | 14.8 | 13.0 | 13.3     |
| **May**     | 17.5 | 16.6 | 14.7 | 15.7 | 17.5 | 15.2 | 17.4 | 14.8 | 15.7 | 18.0 | 16.7 | 15.9     |
| **June**    | 17.5 | 18.3 | 18.9 | 20.8 | 18.0 | 19.0 | 17.9 | 21.0 | 18.0 | 18.5 | 17.2 | 18.3     |
| **July**    | 18.3 | 17.8 | 18.5 | 19.4 | 18.0 | 17.9 | 18.1 | 18.0 | 21.3 | 17.5 | 18.7 | 17.9     |
| **August**  | 12.6 | 11.9 | 14.7 | 12.2 | 14.6 | 14.0 | 11.5 | 14.5 | 14.2 | 14.7 | 13.5 | 13.1     |
| **September**| 7.4  | 8.7  | 5.9  | 5.3  | 8.7  | 8.0  | 9.3  | 9.6  | 6.6  | 6.9  | 9.4  | 8.2      |
| **October** | 1.0  | 4.0  | 5.2  | 4.4  | 3.1  | 4.9  | 4.9  | 4.4  | 5.1  | 2.5  | 4.3  | 3.0      |
| **November**| 0.5  | −0.1 | −1.7 | −6.9 | 2.4  | −3.4 | 2.3  | −0.5 | 3.8  | 1.0  | 1.9  | −0.7     |
| **December**| 8.4  | 8.6  | 7.9  | 6.8  | 8.3  | 7.7  | 7.8  | 9.0  | 9.1  | 8.7  | 8.5  | 7.9      |
3. The only exceptions were years 5 (2011) and 9 (2015), when the DMY of Amur silver grass decreased by 40%–49% (Figure 3) relative to the preceding years (2010 and 2014, respectively) due to drought in the early (2011) and final (2015) stages of plant growth (Table 5).

3.4 | Energy output

Between years 1 and 5, the HHV of plant biomass was 1%–2% higher in giant miscanthus than in Amur silver grass (Figure 4). In successive years of the experiment, (year ≥6), the HHV of Amur silver grass was around 1% higher in comparison with giant miscanthus. In both species of perennial rhizomatous grasses, this parameter peaked in year 1 (18.2–18.5 MJ/kg), after which, it continued to decrease until years 7 (giant miscanthus) and 8 (Amur silver grass; by approx. 0.12–0.19 MJ kg⁻¹ year⁻¹ on average). In years 7(8)–11, the HHV was stabilized at 17.4–17.6 (Amur silver grass) and 17.2–17.5 MJ/kg (giant miscanthus; Figure 4).

Amur silver grass was characterized by higher LHV than giant miscanthus throughout the entire experiment (Figure 5). This difference was particularly pronounced (up to 32%–49%) in the first and second year of the study. In the remaining years (year ≥3), the LHV of Amur silver grass was 19% higher on average in comparison with giant miscanthus (Figure 5).

In NE Poland, the energy value of giant miscanthus biomass (energy output) was lowest in the first and second year of the experiment (28 and 63 GJ/ha, respectively; Figure 6). Beginning from year 3, the energy output of giant miscanthus biomass ranged from 295–365 (years 3–5) to 279–348 GJ ha⁻¹ year⁻¹ (years 6–11). The average energy output of Amur silver grass (2007–2017) was around 40% lower (108 GJ ha⁻¹ year⁻¹) in comparison with giant miscanthus. The only exceptions were years 1 and 2 when the analyzed parameter was 1.7-fold and 2.4-fold higher, respectively, in Amur silver grass than in giant miscanthus. The energy output of Amur silver grass increased with the plantation’s age (from 49 GJ/ha in year 1 to 252 GJ/ha in year 11; Figure 6). The energy output of Amur silver grass decreased by approximately 41%–42% in 2011 and 2015 (Figure 6) when unfavorable weather conditions led to a drop in biomass yields (FMY and DMY, Figures 1 and 3). The energy output of giant miscanthus continued to increase until year 5 (365 GJ/ha), and a clear decrease of approximately 18.2 GJ ha⁻¹ year⁻¹ on average was noted between years 6 and 9 (Figure 6). In years 10 and 11, the value of energy accumulated in giant miscanthus biomass increased to 328–348 GJ/ha (Figure 6) as a result of rapid biomass growth (FMY and DMY, Figures 1 and 3) in response to highly favorable weather conditions (Table 5). The total energy output of both species of perennial rhizomatous grasses per year of cultivation was determined at 163.2 (Amur silver grass) and 271.6 GJ ha⁻¹ year⁻¹ (giant miscanthus; Table 7).

3.5 | Energy efficiency ratio

The performance of giant miscanthus and Amur silver grass was analyzed based on the energy gain/net energy yield (calculated as the difference between energy output and energy

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**Table 6** Energy inputs associated with the production of perennial rhizomatous grasses by energy fluxes (2007–2017)

| Specification          | Giant miscanthus | Amur silver grass |
|------------------------|------------------|------------------|
|                        | Year 1ᵃ          | Years 2–11ᵇ      | Year 1ᵃ          | Years 2–11ᵇ      |
| **MJ ha⁻¹ year⁻¹**     | **%**            | **MJ ha⁻¹ year⁻¹** | **%**            | **MJ ha⁻¹ year⁻¹** |
| Labor                  | 375              | 0.5              | 54               | 119              | 0.4–0.8          |
| Tractors and machines  | 676              | 1.0              | 264              | 673              | 1.9–4.3          |
| Fuel                   | 3,590            | 5.1              | 1,079            | 2,736            | 8.0–17.4         |
| **Total, including:**  | **65,855**       | **12,165**       | **12,165**       | **12,165**       | **100.0**        |
| Rhizomes               | 56,000           | 0                | 11,640           | 11,640           | 85.8–77.6        |
| Fertilizers            | 9,330            | 11.640           | 85.8–77.6        | 13.1             | 79.9–82.4        |
| Herbicides             | 525              | 525              | 525              | 525              | 3.9–3.5          |
| **Total**              | **70,497**       | **13,562**       | **15,693**       | **100.0**        |                   |

ᵃ2007. ᵇ2008–2017. ᶜDifferences result from variations in biomass yield during the experiment and the energy inputs associated with biomass harvest and transport.

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In Table 6, the energy inputs associated with the production of perennial rhizomatous grasses by energy fluxes (2007–2017) are provided. The data include labor, fuel, and materials, with specific values and ranges for each category in both species. The table highlights the differences in energy inputs and the impact of variations in biomass yield on energy efficiency.
TABLE 7  Energy efficiency analysis of perennial rhizomatous grasses (2007–2017)

| Years | Giant miscanthus | Amur silver grass |
|-------|-----------------|------------------|
|       | Energy inputs (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy output (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy gain (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy efficiency ratio | Energy inputs (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy output (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy gain (GJ ha\(^{-1}\) year\(^{-1}\)) | Energy efficiency ratio |
| 2007  | 70.5            | 28               | −42              | 0.4          | 71.5            | 49               | −22              | 0.7          |
| 2008  | 13.6            | 63               | 50               | 4.7          | 16.9            | 152              | 135             | 9.0          |
| 2009  | 15.0            | 295              | 280              | 19.7         | 17.5            | 175              | 157             | 10.0         |
| 2010  | 15.0            | 335              | 320              | 22.3         | 17.5            | 176              | 159             | 10.1         |
| 2011  | 15.7            | 365              | 350              | 23.3         | 16.9            | 104              | 87              | 6.1          |
| 2012  | 15.0            | 348              | 333              | 23.2         | 16.9            | 157              | 140             | 9.3          |
| 2013  | 15.0            | 279              | 264              | 18.6         | 17.5            | 172              | 154             | 9.8          |
| 2014  | 15.0            | 305              | 290              | 20.3         | 17.5            | 223              | 206             | 12.8         |
| 2015  | 15.0            | 293              | 278              | 19.5         | 16.9            | 115              | 98              | 6.8          |
| 2016  | 15.0            | 328              | 313              | 21.9         | 17.5            | 219              | 201             | 12.5         |
| 2017  | 15.7            | 348              | 333              | 22.2         | 17.6            | 252              | 234             | 14.3         |
| ∑     | 220.4           | 2,988            | 2,767            | 13.6         | 244.1           | 1795             | 1551            | 7.4          |
| Per 1 year of production | 20.0 | 271.6 | 251.5 |

FIGURE 1  Fresh matter yield of giant miscanthus and Amur silver grass during the growing seasons of 2007–2017

FIGURE 2  Dry matter content of giant miscanthus and Amur silver grass during the growing seasons of 2007–2017

FIGURE 3  Dry matter yield (Mg ha\(^{-1}\) year\(^{-1}\) DM) of giant miscanthus and Amur silver grass during the growing seasons of 2007–2017

The analyzed energy efficiency ratios were noted in year 1 for Amur silver grass and in years 1 and 2 for giant miscanthus. The analyzed energy efficiency ratio was calculated as the ratio of energy output to energy input per hectare.
indicators improved in both species of perennial rhizomatous grasses from the establishment year onward (Table 7). The improvement in energy balance was particularly pronounced in the production of giant miscanthus biomass where energy gain increased from −42 (year 1) to 50 (year 2) and 307 GJ ha⁻¹ year⁻¹ (annual average for years 3–11). The energy efficiency ratio increased from 0.4 to 18.6–23.3 between year 1 and the successive years of growth. In the production of giant miscanthus, the net energy yield peaked in year 5 (350 GJ/ha), and the energy efficiency ratio was highest in years 5 and 6 (23.2–23.3). In successive years of the study (years 6–11), energy gain decreased by 16% and the energy efficiency ratio of giant miscanthus decreased by 12%. In the production of Amur silver grass, energy gain was determined at 87–234 GJ ha⁻¹ year⁻¹ and the energy efficiency ratio ranged from 6.1 to 14.3 in years 2–11. Both parameters peaked in year 11. The average energy gain and energy efficiency ratio of giant miscanthus biomass were determined at 251.5 GJ ha⁻¹ year⁻¹ and 13.6, respectively, during the 11-year experiment (2007–2017). Energy gain was 44% lower and the energy efficiency ratio was 46% lower in Amur silver grass (Table 7) than in giant miscanthus.

4 | DISCUSSION

4.1 | Energy inputs

The demand for energy continues to grow in countries with high levels of economic development. Energy consumption increases in response to population growth and higher energy consumption per capita (Chmielewski, 1998). Economic growth and agricultural intensification also increase energy consumption in the farming sector. The world’s heavy dependence on fossil fuels has prompted the search for alternative energy sources (Escobar et al., 2009). In Europe, agricultural biomass is the main renewable resource for energy generation (Stolarski, Śnieg, Krzyżaniak, Tworkowski, & Szczukowski, 2018; Stolarski, Śnieg, Krzyżaniak, Tworkowski, Szczukowski, et al., 2018). In the future, lignocellulosic biomass will be the main substrate for biorefineries (bioproducts, biofuels, bioenergy; Stolarski et al., 2015). Perennial rizomatous grasses of the genus *Miscanthus* are valuable sources of lignocellulosic biomass which can replace fossil fuels in bioenergy generation and reduce greenhouse gas emissions (Cadoux, Riche, Yates, & Machet, 2012). Even the most efficient biomass production technologies require considerable energy inputs, including labor, farming machines, fuel, and production materials (seeds/seedlings, fertilizers, pesticides; Jankowski et al., 2016). In the present experiment, the amount of energy invested in the production of C4 perennial rizomatous grasses (giant miscanthus and Amur silver grass) was highest in the year of plantation establishment due to soil tillage and rhizome planting operations (Angelini, Ceccarini, Nasi, & Bonari, 2009; Mantineo, D’Agosta, Copani, Patanè, & Cosentino, 2009). Energy inputs associated with plantation establishment and cultivation of giant miscanthus and Amur silver grass range from 17 to 34 GJ/ha in the first year of biomass production.
The yield of C4 perennial rhizomatous grasses in dedicated biomass cropping systems is two or three times higher in comparison with C3 grasses (Heaton et al., 2010; Heaton, Long, et al., 2004; Heaton, Voigt, et al., 2004; Somerville, 2007; Zhu, Long, & Ort, 2008). Perennial rhizomatous grasses with the highest yield potential include *M. × giganteus* and *M. sacchariflorus*. Their lignocellulosic biomass can be converted to biofuels and energy (Jankowski et al., 2016). The high yield potential of perennial rhizomatous grasses can be attributed to their rapid growth and high photosynthetic efficiency. Perennial plants also utilize soil nutrients more effectively, which decreases the demand for fertilizers and related management operations (Dohleman, Heaton, Arundale, & Long, 2012; Himken, Lammel, Neukirchen, Czypionka-Krause, & Olfs, 1997; Lewandowski & Schmidt, 2006; Zhu et al., 2008).

In the favorable climate of Southern Europe, which is characterized by high annual incident solar radiation and high average temperatures, the biomass yield of giant miscanthus can reach 30–50 Mg DM ha$^{-1}$ year$^{-1}$ (Angeli et al., 2009). Similar yields have been reported in the USA (Arundale, Dohleman, Voigt, & Long, 2014). In Central-Eastern Europe (Poland) where insolation and temperatures are lower, the DMY of giant miscanthus biomass (after reaching full productive potential) is determined at 16–29 Mg ha$^{-1}$ year$^{-1}$ (Borkowska & Molas, 2013; Dubis et al., 2017; Jankowski et al., 2016; Kołodziej, Antonkiewicz, & Sugier, 2016; Figure 3). Similar biomass yields have been noted in Western Europe, including Germany (Clifton-Brown et al., 2001; Gauger, Graeff-Hönninger, Lewandowski, & Claupin, 2012; Himken et al., 1997; Knörzer, Hartung, Piepho, & Lewandowski, 2013), Belgium (Godin et al., 2013), and France (Lesur-Dumoulin, Lorin, Bazot, Jeuffroy, & Loyce, 2016). In Scandinavian countries (Northern Europe), the yield potential of giant miscanthus is estimated at 10–20 Mg DM ha$^{-1}$ year$^{-1}$ (Jørgensen, 1997). Amur silver grass has an extensive root system and produces a high number of tillers; therefore, it is more resistant to environmental stressors and adapts better to less favorable habitats than giant miscanthus (Szcuzkowski, Kościk, Kowalczyzk-Juśko, & Tworkowski, 2006). However, Amur silver grass is more sensitive to drought than giant miscanthus (Gauder et al., 2012). The biomass yield of Amur silver grass reached 10.7 Mg DM ha$^{-1}$ year$^{-1}$ in south-west Germany, and ranged from 6.2 to 15.3 Mg DM/ha in NE and south-eastern Poland (Borkowska & Molas, 2013; Jankowski et al., 2016; Stolarski, Śnieg, Krzyżaniak, Tworkowski, & Szcuzkowski, 2018). In this study (NE Poland), the DMY of Amur silver grass was determined at 9.26 Mg DM/ha, and it was equivalent to 60% DMY of giant miscanthus (average for 11 years).

In perennial rhizomatous grasses, biomass yields and biomass quality are determined by soil, weather conditions, agricultural inputs, harvest date, and the plantation’s age (Clifton-Brown, Stampfl, & Jones, 2004; Himken et al., 1997; Khanna et al., 2008). When harvested in autumn, giant miscanthus and Amur silver grass are characterized by higher yields of biomass with lower DM content. Delayed harvest (in winter or spring) decreases both parameters in the analyzed perennial rhizomatous grasses (Heaton et al., 2010). Biomass harvested in winter and early spring is a valuable substrate for heat generation, whereas biomass harvested in autumn is better suited for conversion into biogas (Hodgson et al., 2011; Le Ngoc, Rémond, Dheilly, & Chabbert, 2010; Lewandowski & Heinz, 2003). Crops with stable yields directly improve the security of biomass supplies for energy generation, which is an important consideration (Borzęcka-Walker, Faber, & Borek, 2008; Roncucci, Nasso, & Tozzini C, Bonari E, Ragaglini G, 2015). Giant miscanthus is generally characterized by two yield phases:
a mature phase between the 3rd and the 8th year of growth (average yield of 29.4 Mg DM ha⁻¹ year⁻¹) and a reduced yield phase between the 9th and 12th year of growth (average yield of 20.4 Mg DM ha⁻¹ year⁻¹; Angelini et al., 2009).

In the present experiment, giant miscanthus yields continued to increase until year 5 (20.5 Mg DM ha⁻¹ year⁻¹), and a decrease in biomass yield was noted between years 6 and 9 (20.1–16.9 Mg DM ha⁻¹ year⁻¹). In the current study, giant miscanthus yields continued to increase for a longer than average (3 years) period, which could result from relatively lower (by 30%) planting density of rhizomes (Angelini et al., 2009, Table 1). Biomass yields are influenced by the amount and distribution of rainfall, which suggests that water availability is a key yield-building factor in this grass species (Gauder et al., 2012). High precipitation levels (Gauder et al., 2012) and soils capable of accumulating water (Arundale, Dohleman, Heaton, et al., 2014; Larsen, Jaiswal, Bentzen, Wang, & Long, 2016; Miguez, Maughan, Bollero, & Long, 2012; Wang et al., 2015) minimize variations in biomass yield. In this study, abundant precipitation in years 10 and 11 (2016 and 2017) contributed to an increase in the biomass yield of giant miscanthus (19.0–20.0 Mg DM ha⁻¹ year⁻¹). In the production of Amur silver grass, the first 3 years are a yield-building period. Biomass yields are stabilized in years 4–6 (12 Mg DM/ha) and begin to decrease past the seventh year (≤10 Mg DM/ha; Gauder et al., 2012). In this study (NE Poland), the biomass yield of Amur silver grass continued to increase until year 11 (14.4 Mg DM ha⁻¹ year⁻¹). The only exceptions were years with low precipitation in May–June and/or August. The high sensitivity of Amur silver grass to water deficit was confirmed by Gauder et al. (2012), in whose study, biomass yields were reduced from 12 to 8 Mg DM ha⁻¹ year⁻¹ when precipitation levels decreased from 543 to 262 mm across two consecutive years.

According to the literature, giant miscanthus achieves high and stable yields in the third year of growth (Clifton-Brown et al., 2001), but in our experiment, yields were stabilized only in years 5 and 6 (Arundale, Dohleman, Voigt, et al., 2014; Borkowska & Molas, 2013; Larsen et al., 2014). In turn, the biomass yields of Amur silver grass are highest in years 9–11 (Gauder et al., 2012). In this study (NE Poland), giant miscanthus produced the highest biomass yield in year 5, and Amur silver grass in year 11.

### 4.3 Energy output

Energy crops are specifically grown for use as a fuel; therefore, their DMY and energy accumulation have to be maximized per area unit (Stolarski et al., 2019). In Europe, the highest energy yields are derived in farms dedicated to the production of C4 energy crops, mainly maize and giant miscanthus (Boehmel, Lewandowski, & Clauepin, 2008; Jankowski et al., 2016; Muylle et al., 2015). The energy yield of giant miscanthus biomass was determined at 380 GJ ha⁻¹ year⁻¹ in Belgium (Muylle et al., 2015) and at 230–324 GJ ha⁻¹ year⁻¹ in Germany (Boehmel et al., 2008; Iqbal, Gauder, Clauepin, Graaff-Hönninger, & Lewandowski, 2015). In central Italy, the energy yield of giant miscanthus grown in a large-area farm over a period of 4–12 years reached 479 GJ/ha on average (Angelini et al., 2009). The energy output of giant miscanthus grown for more than 4 years in NE Poland ranged from 298–333 (Dubis et al., 2017) to 441–492 GJ ha⁻¹ year⁻¹ (Jankowski et al., 2016). On average, the biomass of Amur silver grass accumulates 42% less energy than giant miscanthus biomass (Jankowski et al., 2016). In the presented 11 year experiment, the average energy output of the evaluated species of perennial rhizomatous grasses was determined at 271.6 (giant miscanthus) and 163.2 GJ ha⁻¹ year⁻¹ (Amur silver grass). The energy output of giant miscanthus biomass peaked in year 5 (365 GJ/ha), and it continued to decrease by 2.83 GJ ha⁻¹ year⁻¹ in successive years of the experiment (years 6–11). The energy output of Amur silver grass was highest in year 11 (252 GJ ha⁻¹ year⁻¹).

### 4.4 Energy efficiency ratio

Plant species characterized by high biomass yields and a positive energy balance are best suited for energy generation. The energy efficiency of biomass is determined by the amount of energy invested in biomass production and the energy gain of biomass (Yuan, Tiller, Al-Ahmad, Stewart, & Stewart, 2008). In Western (Germany, Belgium) and Southern Europe (Italy), agricultural crops, in particular thermophilic C4 grasses, require less energy to produce high yields. In these regions of Europe, the energy efficiency ratio of giant miscanthus biomass is very high (up to 32–45; Boehmel et al., 2008; Muylle et al., 2015). In the colder climate of Central-Eastern Europe (Poland), the energy efficiency ratio of giant miscanthus and Amur silver grass is considerably lower at 22–25 and 7–15, respectively (Budzynski, Szemplinski, Parzonka, & Salek, 2014; Jankowski et al., 2016; Tworkowski, Szczukowski, Stolarski, Krzyzaniak, & Graban, 2014). In this study, the average energy efficiency ratio of giant miscanthus biomass was 13.6 (0.4 to 18.6–23.3 between the first year and successive years of growth). This parameter was highest (23.2–23.3) in years 5 and 6. The average energy efficiency of Amur silver grass was 46% lower in comparison with giant miscanthus (0.7 to 6.1–14.3 between the first year and successive years of growth). Amur silver grass biomass was characterized by the highest energy efficiency ratio in year 11.

### 5 Conclusion

The share of energy from renewable sources in gross final energy consumption has to be increased in the EU Member
States, which contributes to the growing popularity of agricultural biomass. In order to meet the renewable energy target, the area under cultivation of perennial high-yielding energy crops has to be steadily increased. In contrast, biomass from dedicated energy crop plantations could promote the rapid development of a new sector of agricultural production—the agroenergy sector.

When biomass is used for energy purposes, the yield potential of energy crops and the energy efficiency of the production process (cultivation technology) are important considerations. Our 11 year field experiment with grasses of the genus *Miscanthus* (giant miscanthus and Amur silver grass), performed in NE Poland with the use of techniques and methods applied on large-scale farms, revealed that in the group of non-energy crops whose biomass can be used as substrate or cosubstrate in agricultural biogas plants, giant miscanthus is characterized by the highest and most stable yields (15.5 Mg DM/ha). The yield potential of Amur silver grass was 40% lower. The DMY of giant miscanthus continued to increase until year 5 (20.5 Mg/ha). The DMY of Amur silver grass continued to increase until year 11 when it reached the maximum value of 14.4 Mg/ha.

In the year of plantation establishment, the consumption of energy associated with the production of giant miscanthus and Amur silver grass biomass was 70.5 and 71.5 GJ/ha, respectively, and rhizomes accounted for approximately 78%–79% of total energy inputs. In the remaining years of the experiment, the energy demand of both species of perennial rhizomatous grasses was determined at 13.6–15.7 (giant miscanthus) and 16.9–17.5 GJ ha$^{-1}$ year$^{-1}$ (Amur silver grass), and mineral fertilizers were the predominant energy inputs (78%–86%).

In NE Poland, the average (11 years) energy output of both species of perennial rhizomatous grasses reached 271.6 (giant miscanthus) and 163.2 GJ ha$^{-1}$ year$^{-1}$ (Amur silver grass). The energy output of giant miscanthus biomass peaked in year 5 (365 GJ/ha). The energy output of Amur silver grass was highest in year 11 (252 GJ ha$^{-1}$ year$^{-1}$). The average energy efficiency ratio of giant miscanthus biomass was 13.6 (0.4 to 18.6–23.3 between the first year and the following years of growth). The average energy efficiency of Amur silver grass was 46% lower in comparison with giant miscanthus.

Giant miscanthus is characterized by higher biomass yields and higher energy efficiency of biomass production. However, Amur silver grass is more tolerant of frost and soil salinity, and in the future, it can become an important energy crop, particularly in regions with lower quality soils and more severe winters (including Eastern and Northern Europe).

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