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Converting an Established *Sida hermaphrodita* Field into Arable Farming

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Abstract: The long-term performance of perennial energy crops and their elimination is important for long-term planning and use of agricultural land. In this study, the elimination of a six-year-old *Sida hermaphrodita* (hereafter referred to as *Sida*) stock for agricultural reclamation was investigated over three years. Crop rotation using maize, winter wheat, and sugar beet, a catch crop, as well as mechanical–chemical treatments were employed according to agricultural practices. After soil grubbing at the beginning of the experiment and prior to further treatments, on half of the former *Sida* planting area, visible *Sida* roots were manually removed in addition to determining their potential effect on total resprouting. Prior to each crop harvest, resprouted *Sida* plants were counted. At harvest, by the end of the first year, 476 versus 390 resprouted *Sida* plants were found in the investigated areas of 315 m^2 each, where preceding manual root removal either took place or not, respectively. This accounted for 76% and 62% of the initial *Sida* planted. In the second year, the overall number of resprouted *Sida* declined significantly, accounting for 15 and 11 plants (i.e., 2.4% and 1.8% of initially planted), and in the third year, only two and four residual plants (i.e., 0.3% and 0.6%) were found, representing an almost 100% *Sida* elimination rate. We conclude that additional root removal did not result in a significant difference in *Sida* regrowth compared to the mechanical–chemical treatments only. No impediments to harvesting and no loss of yield in any crops were observed due to resprouted *Sida* in the existing field crops. No *Sida* plants were found outside the initial field, indicating a low dispersion potential and invasiveness. The results show that successful recultivation of an established *Sida* stock is possible through common agricultural practices and that resprouting *Sida* plants did not negatively affect the subsequent crops.

Keywords: Virginia fanpetals; Virginia mallow; *Ripariosida hermaphrodita*; energy plants; bioenergy; crop rotation; herbicide; crop yield; neophyte; invasive non-native species

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1. Introduction

The use of biomass for sustainable energy production has always played a crucial role. The growing awareness of the dramatic effects of climate change has brought the use of biomass back into the focus of energy use. In this context, many plants, such as grasses, perennial shrubs, and fast-growing trees, have been studied for their suitability for energy production. Among them are some species non-native to Europe, such as *Sida hermaphrodita* (L.) Rusby, also known as Virginia fanpetals or Virginia mallow, is recently also synonymous with *Ripariosida hermaphrodita* (L.) Weakley & D.B.Poind [1] (in the following referred to as *Sida*), a perennial mallow species originating from Northern America.

Sida was originally introduced in the former USSR in the 1930s as a forage plant before being further cultivated in Poland in the 1950s [2]. There, *Sida* has been grown primarily as an energy crop in recent decades because its biomass, which dies off and dries out over the winter, is well suited as a solid fuel for combustion [3]. Recent studies on

Sida showed that *Sida* biomass is very suitable as a solid fuel, with the advantage of good processability (harvesting, pelleting, briquetting), good combustion properties, a high ash melting temperature, and an overall good comprehensive life cycle assessment [4,5]. In an earlier study, the use of *Sida* biomass for biogas production was also investigated, but the energy yield is clearly inferior to that of its use as a solid fuel, considering the dry biomass [6]. Furthermore, it has been shown that regular harvesting of fresh *Sida* biomass at the vegetative stage to be used as a biogas feedstock reduces emergence in subsequent years [7]. This is probably due to the fact that the plants cut in summer cannot transport sufficient assimilates back into the root system to have adequate energy for full resprouting in the following year. *Sida* biomass is increasingly being discussed and investigated as a promising feedstock for biorefinery applications and as a supplier of lignocellulose [8–10]. Further, *Sida* appears to be a potential feedstock supplier for the pulp and paper industry and a suitable alternative to wood [11].

Depending on soil conditions, planting density, and fertilizer applications, reported *Sida* biomass yields from established stands account for up to 20 t/ha, but also yields of up to 28 t/ha have been observed [2,12–15]. In addition, it has been shown that *Sida* can also grow well on marginal, sandy substrates, particularly when ameliorated with organic fertilizers [16,17]. In particular, organic fertilizers such as digestate placed in the root zone, inspired by the Controlled Uptake Long Term Ammonium Nutrition (CULTAN) procedure [18], resulted in successful emergence and good biomass production in pure sand [19]. The sustainable cultivation of biomass on non-productive and non-arable, especially marginal lands, is of growing importance also with regard to social–ecological aspects [20]. This makes the development and use of set-aside land for biomass production or the redevelopment and amelioration of abandoned land important. Many studies have successfully demonstrated the cultivation of *Sida* on contaminated soils and even sewage sludge, allowing a dual use of this crop for biomass production for energy applications on the one hand and stabilization of such soils and affected areas on the other [21–25].

In addition to the potential high yields, another advantage of *Sida* is the fact that the above-ground biomass, i.e., the lignified stalks or stems, dies off and dries over the winter. Unlike wood chips or wood sawdust, for example, this fact reduces the need for subsequent drying of the biomass to a minimum or makes additional drying even unnecessary. Accordingly, this reduces further energy input, resulting in a net energy yield increase. *Sida* biomass can be harvested in spring with conventional maize choppers before resprouting and subsequently processed for pellet and/or briquette production, as pellets were found to have the best combustion properties [4]. Cultivation of *Sida* by direct seeding employing conventional seeders is not recommended due to poor seed germination. Further, *Sida* seedlings are sensitive to weed competition and excessive drought, so care must be taken to ensure good soil preparation and, if necessary, additional irrigation in the first year. Thus, young *Sida* plants or root cuttings are recommended to allow for a successful plant establishment [26]. As shown in a recent study on the establishment of *Sida*, the use of a biodegradable mulch film resulted in significantly greater plant growth compared to the control without film [27]. This could be primarily attributed to the effective weed suppression by the mulch film, among other plant growth-supporting factors. After the successful establishment and rapid growth of the *Sida* plants under favorable conditions, a dense stand occurs from the second year onwards. At this stage, the *Sida* stand may not require further weed-control measures, since the dense foliage suppresses competing plants.

Among the outlined advantages of *Sida*, however, knowledge about the removal of perennial biomass plants after their productive life phase and its possible impact on subsequent crops is important for planning and acceptance by the farmer. In the case of *Miscanthus* (*Miscanthus x giganteus*), another important perennial biomass and bioenergy crop belonging to the Poaceae family, a combination of the broad-spectrum herbicide glyphosate application and tillage in spring contributed to a significant reduction in biomass growth [28]. Nevertheless, in accordance with the cited study, several treatments appear to be necessary to eliminate a mature *Miscanthus* stand. Another study on herbicide efficiency and application timing to eliminate an existing *Miscanthus* stand showed that glyphosate, in particular, led to 100% elimination if the herbicide was applied during the active growth phase in June or July [29]. Nevertheless, the use of chemical herbicides such as glyphosate is of concern; therefore, alternatives should be found for the eradication of perennial biomass crops under ecological and sustainable criteria. As a recent study demonstrated, a perennial *Miscanthus* stand could be eradicated by a combination of tillage and grass herbicides from maize cultivation and subsequent cultivation of maize and winter wheat [30].

Comparable studies and information on the eradication of existing *Sida* stocks do not yet exist. However, these are important in order to promote the acceptance and cultivation of this biomass plant. As a non-native plant species in Europe, *Sida* is largely unexplored in terms of its invasiveness, eradication, and recultivation potential on agricultural land. However, the extent to which elimination and recultivation of an existing *Sida* stand are possible without affecting subsequent crops is of crucial importance to the practitioner and farmer.

Thus, in this study, we monitored and investigated the reclamation of a six-year-old, successfully established *Sida* stock using common mechanical–chemical agricultural practices over a total of three consecutive years. The aims of this study were to investigate the following: (1) how far an elimination of the established *Sida* field is possible by means of the applied conventional mechanical–chemical agricultural practices; (2) if resprouted *Sida* plants impede the productivity of subsequent crops used in this study, i.e., maize, winter wheat, and sugar beet; (3) if resprouted *Sida* plants hinder harvesting of the following crops; and (4) if *Sida* shows an invasive nature in the agricultural area of investigation.

2. Materials and Methods

2.1. Experimental Field and Background Information

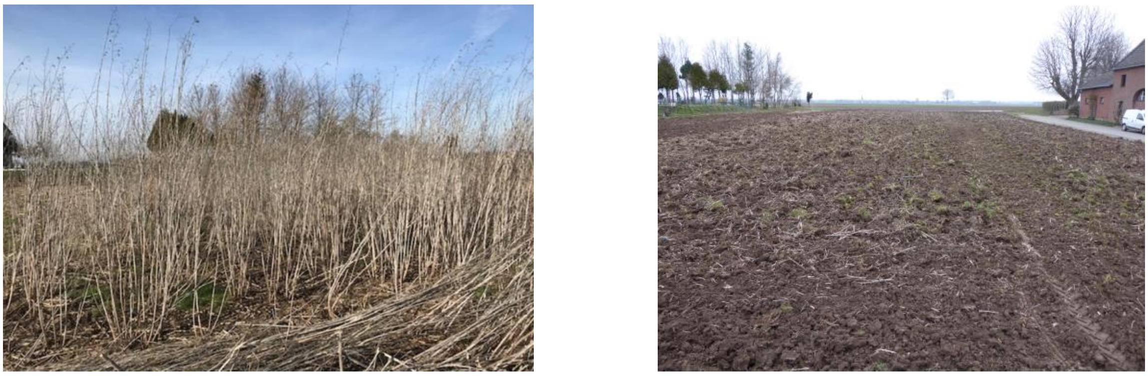
The experimental field used for this study served as a *Sida* field trial from 2015 to 2021. The area of investigation was initially established by planting two *Sida* root cuttings per square meter. Detailed information about the field and the earlier study on *Sida* biomass use as a solid energy carrier for combustion have been published previously [4]. Briefly, the field was located in Titz Sevenich, Germany (100 m a.s.l., 50°58′13.0″ N 6°23′31.0″ E). The soil was composed of 5.6% sand, 79.0% silt, and 15.4% clay, classified as a clayey silt with pH 7.0 and a humus content of approx. 2.3%. The soil value (in German, "Bodenwertzahl", used as an indicator for soil quality and profitability) of the field of experimentation accounts for 90 and is, therefore, of very high quality [31,32]. Except for a single nitrochalk application in March 2016 (equaling 27 kg N/ha) to promote initial *Sida* growth, no fertilizers were applied to the *Sida* field trial until its termination in 2021. While in the earlier study, only part of the entire field was used for yield investigations at three different *Sida* planting densities, this study considered the remaining *Sida* field of approx. 1100 m^2 with a planting density of two plants per square meter for recultivation.

2.2. Final Sida Harvest and Experimental Field Preparation

In February 2021, the established *Sida* stand was terminated, and recultivation of the field was initiated to return the field to common agricultural use. It was decided to meet the increasing demand for locally produced cash crops.

Prior to first soil treatments, a final *Sida* biomass harvest was conducted on 19 February 2021. For this purpose, three biological replicates, i.e., entire individual plants, were taken completely by cutting the shoots directly above the soil surface. The number of shoots was counted, and the fresh and dry biomass was determined for each replicate plant. The final biomass determination was considered necessary to compare the *Sida* yield after six years of standing with yield values from the previous years, as presented earlier [4].

Subsequently, all remaining *Sida* plants were cut by operating a conventional flail mower. The soil was then cultivated over the entire area with a grubber to expose the *Sida* roots and bring them to the surface, followed by a molding cutter treatment. Details of all measures applied are listed in Table A1, provided in the Appendix A. Visual impressions of the *Sida* at final harvest and the field after grubber treatment are provided in Figure 1.

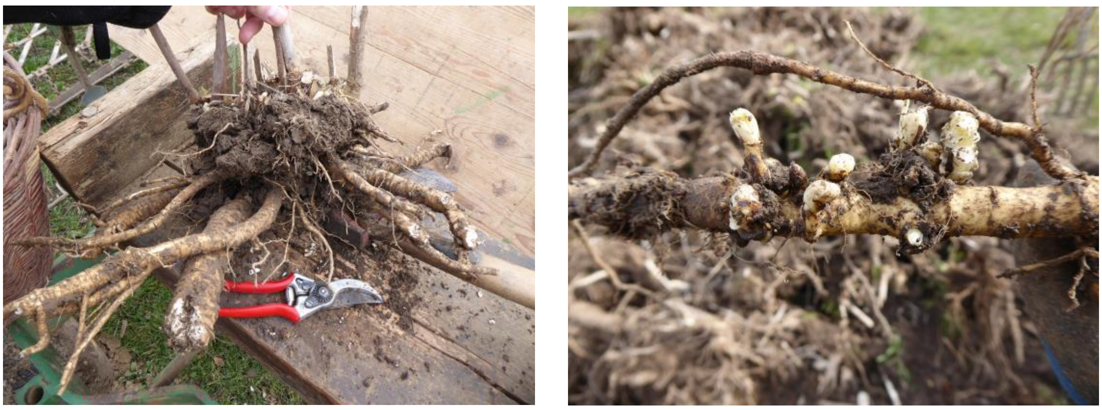


(**a**) (**b**)

Figure 1. *Sida* field in 2021 (**a**) at harvest and (**b**) after grubber and molding cutter treatment.

The entire field where, initially, two *Sida* plants per square meter were planted was divided into two areas, A and B, each approx. 550 m^2 in size. Three plots within area A (namely A1, A2, A3) and B (namely B1, B2, B3), each 5.25 × 20 m (=105 m^2 each) in size, were implemented to facilitate the counting and statistical analysis of the resprouted *Sida* plants. For technical reasons, complete randomization of the plots within the field had to be omitted. These reasons include work organization and practical agricultural workflows. Due to the use of heavy agricultural equipment, regular soil cultivation, and chemical measures, as well as harvesting the crops, it was not possible to establish small, randomized, and clearly defined subplots in the field in the long term. However, results from plots A and B were not significantly different, and a randomization would not have changed the outcome of this study.

In all of area A, before any further mechanical and chemical measures were taken (Table A1), all clearly visible and vital *Sida* roots lying on the soil surface were removed by hand. This amounted to a total of approx. 400 kg of *Sida* root cuttings, equaling approx. 0.7 kg roots/m^2 (≈7 t fresh root biomass per ha). Visual impressions of the removed *Sida* rootstocks and roots are provided in Figure 2.



(**a**) (**b**)

Figure 2. *Sida* roots at time of root collection on 23 March 2021: (**a**) mature *Sida* root stock; (**b**) resprouting *Sida* root.

In area B, no *Sida* roots were manually removed prior to any further treatments, as listed in detail in Table A1. The purpose of this step was to investigate whether excessive removal of exposed *Sida* roots influenced the number of resprouting *Sida* plants compared to a purely mechanical–chemical treatment following common conventional agricultural practice. Subsequently, the entire field was treated with a rotary tiller in two different depths, first at 6 cm depth and second at 10 cm depth, with opposite directions of travel. The objective of this was to shred the *Sida* roots and stimulate resprouting in order to achieve sufficient *Sida* leaf area for a herbicide application before the first field crop maize was sown. All further mechanical and chemical agricultural measures throughout the three-year study period are listed in Table A1 and were carried out in both areas A and B. No additional or specially adapted work steps were carried out from the time of seedbed preparation for maize sowing in 2021. All work steps carried out were in accordance with common agricultural practices for all crops.

2.3. Data Collection on Sida Resprouting and Applied Crop Rotation

To determine the number of resprouted *Sida* plants in the plots in areas A and B and in the entire surrounding field, regular monitoring walks were carried out in the field, and all resprouted *Sida* plants within the plots in areas A and B were recorded. The decisive factor was the number of *Sida* plants counted at each crop harvest. The year and each planted crop for the respective year were as follows:

2021: maize (*Zea mays* L., SUCORN DS1710C, SAATEN-UNION GmbH, Isernhagen, Germany), using 9 grains m^2 (90,000 grains per ha) with a row spacing of 75 cm; 2022: winter wheat (*Triticum aestivum*, RGT REFORM Winterweizen, Getreidefonds Z-Saatgut e. V. (GFZS), Bonn, Germany), using 310 grains per m^2 with a spacing of 12.5 cm per row; 2023: sugar beet (*Beta vulgaris* subsp. *vulgaris*, Altissima-Gruppe, BTS 6975 N, Betaseed GmbH, Frankfurt am Main, Germany), using approx. 11 seeds m^2 (105,000 seeds per ha) with a spacing of 50 cm per row. In addition, a catch crop mixture (DSV TerraLife® Beta-Sola, Deutsche Saatveredelung AG, Lippstadt, Germany) was used during the months of September 2022 until January 2023 (Table A1).

To assess whether the six-year-old *Sida* stand could have adverse effects on yields of succeeding crops, harvest results of the respective crops from the former *Sida* field trial and the surrounding fields grown under the same environmental conditions were recorded. These values were used for estimation and comparison with official statistical yield data from the region, provided by "Landesbetrieb, Information und Technik Nordrhein-Westfalen, Statistisches Landesamt" (Statistical Office of the Federal State North Rhine-Westphalia), Düsseldorf, Germany (www.landesdatenbank.nrw.de/ldbnrw/online, accessed on 13 December 2023, search keyword "*Feldfrüchte*", search result: "Erntebericht: Hektarerträge nach ausgewählten Fruchtarten (12)—kreisfreie Städte und Kreise—Jahr; Düren").

2.4. Data Processing and Image Design

Microsoft Excel 2019 (Redmond, WA, USA) was used to analyze the data. Independent samples *t*-tests were applied to evaluate the variances between regrown *Sida* plants in areas A and B, as well as to assess the statistical significance of differences in crop yield averages in the local area ("Düren region") and those obtained from the field of investigation.

3. Results

3.1. Yield Evaluation and Plant Parameters at Final Sida Harvest

The final *Sida* yield estimation in 2021, six years after the *Sida* plantation took place in 2015, accounted for 11.2 (±0.2) t/ha dry mass (DM), with a mean number of 19 (±1.4) shoots per plant and a mean height of 287 (±17.0) cm of the longest shoots.

3.2. Development of Sida and Its Response to the Applied Measures

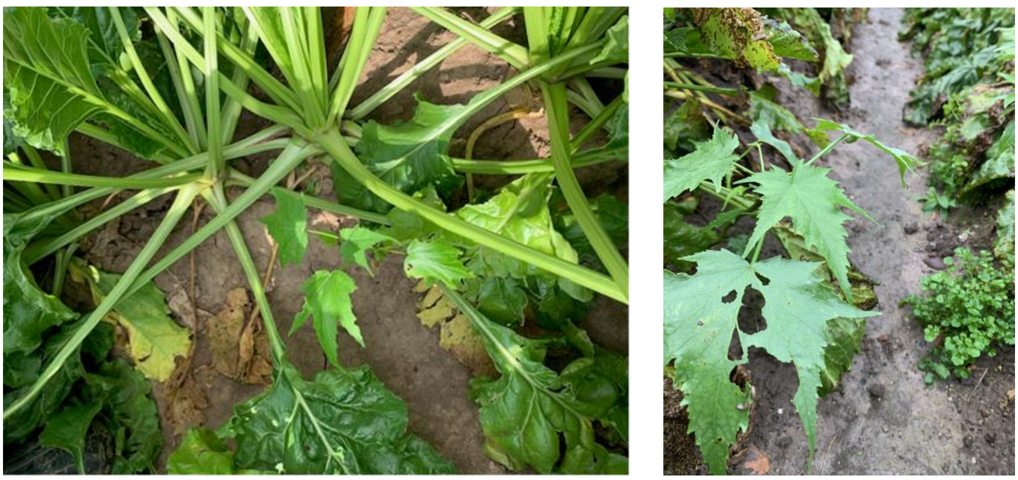
At harvest, by the end of the first year in 2021, a total of 476 resprouted *Sida* plants were found in the plots of area A, where manual root removal took place prior to the mechanical–chemical treatments, versus 390 plants in the plots of area B, where only mechanical–chemical treatments were employed. These numbers accounted for approx. 75% and 62% of the initial *Sida* planted when considering an initial planting density of two plants per square meter (Table 1). Differences in counted *Sida* plants among the two areas

A and B were not statistically different ($p > 0.6$) throughout the study period by means of a two-sided *t*-test, comparing the mean values of the counted *Sida* plants per year from plots A1–A3 with those from plots B1–B3.

Table 1. Number of total counted resprouted *Sida* plants in the plots of investigation (A1–3: preceding manual root removal; B1–3: no additional root removal). Final counting was conducted at time of crop harvest for maize (2021), winter wheat (2022), and sugar beet (2023). No significant differences ($p > 0.6$) in the number of resprouted *Sida* plants among the investigated areas and years were detected by means of an independent samples *t*-test.

	Counted *Sida* at Harvest		
Area/Plot	**2021**	**2022**	**2023**
A1	218	4	0
A2	92	9	2
A3	166	2	0
Sum	476	15	2
Mean/m^2	≈1.5 plants/m^2	≈0.05 plants/m^2	≈0.006 plants/m^2
% of initially planted	75.56%	2.38%	0.32%
B1	174	10	0
B2	43	0	4
B3	173	1	0
Sum	390	11	4
Mean/m^2	≈1.2 plants/m^2	≈0.03 plants/m^2	≈0.01 plants/m^2
% of initially planted	61.90%	1.75%	0.63%

Repeated disruption of growth by the applied mechanical–chemical treatments, in conjunction with strong resource competition from the planted crops, allowed for an almost complete elimination of *Sida* already by the second year of this study in 2022, accounting for 15 and 11 remaining *Sida* plants in the plots of areas A and B, respectively. This equals approx. 2.4% and 1.8% of the plants that were initially planted when considering an initial planting density of two plants per square meter (Table 1). In 2023, only two and four residual plants, i.e., approx. 0.3% and 0.6% of initially planted plants, were found in the plots of areas A and B, respectively, implying an elimination rate for *Sida* of almost 100% (Table 1). These plants originated in approximately equal parts from roots and seeds and were found in the ruts or headlands only. A visual impression of resprouted *Sida* plants in sugar beet in 2023 is given in Figure 3.



(**a**) (**b**)

Figure 3. Resprouted *Sida* plant between the sugar beets on (**a**) 20 July 2023 and (**b**) 19 October 2023. All resprouted *Sida* plants along the entire field were found only in the ruts.

3.3. Mutual effects of Sida, the Applied Crop Rotation and Crop Yield

All crops grown in rotation, i.e., maize, winter wheat, and sugar beet, were not inhibited in their growth by the partially resprouted *Sida* plants. Cash crop yields from the recultivated *Sida* field did not differ from yields of the same crops in each respective year from surrounding fields and accounted for approximately 70.2 t fresh mass/ha for maize (2021), harvested as whole plant silage to be used as a feedstock for biogas production at 32% dry matter content, 11.5 t/ha for winter wheat (2022), and 91.9 t/ha for sugar beet (2023), respectively, as shown in Table 2. These values are 7.8% higher for maize and 19.8% higher for winter wheat than the comparable values from the Düren region (for further details, see Section 2.3 and www.landesdatenbank.nrw.de/ldbnrw/online (accessed on 13 December 2023). Table 2 presents the yield data from the former *Sida* trial field and from adjacent fields in direct proximity characterized by the same soil value of 90, as well as the official cash crop yield values for the Düren region provided by the State Office for Information and Technology North Rhine-Westphalia—State Statistical Office, Düsseldorf, Germany. As shown in Table 2, these values amount to 65.1 t/ha for maize in 2021 and 9.6 t/ha for winter wheat in 2022, respectively. Reliable data for sugar beet from 2023 were not yet available from the State Statistical Office when the manuscript was submitted and are not expected to be available until April 2024. Nevertheless, the sugar beet yield of 91.9 t/ha from the former *Sida* field in 2023 is 17% higher than the four-year (2019–2022) average value of 78.5 t/ha from the Düren region (Table 2).

Table 2. Cash crop yield values from the former *Sida* trial field and surrounding fields and average values from the Düren region. Data from the Düren region were obtained from "Landesdatenbank NRW, Landesbetrieb Information und Technik Nordrhein-Westfalen—Statistisches Landesamt" (https://www.landesdatenbank.nrw.de, accessed on 13 December 2023), search keyword "Feldfrüchte", result: Code 41241-01d, content: "Erntebericht: Hektarerträge nach ausgewählten Fruchtarten (12)—kreisfreie Städte und Kreise—Jahr". Values are given in t/ha (metric ton, equal to 1000 kg, i.e., one megagram). SD: standard deviation, $n = 4$. n.a.: data not available.

	Former *Sida* Trial Field and Adjacent Fields (t/ha)				**Four-Year Mean Value ± SD (t/ha)**	**Former *Sida* Trial Field (t/ha)**
Cash Crop	**2019**	**2020**	**2021**	**2022**		**2023**
Maize	59.2	n.a.	70.2	52.0	60.5 ± 7.5	-
Winter wheat	10.3	11.1	9.8	11.5	10.7 ± 0.7	-
Sugar beet	92.9	90.8	96.3	86.0	91.5 ±3.7	91.9
	Reference Values of Düren Region (t/ha)				**Mean Value of Four Years ± SD (t/ha)**	**Reference Values of Düren Region (t/ha)**
	2019	**2020**	**2021**	**2022**		**2023**
Maize	50.7	48.9 *	65.1	46.7	54.2 ± 7.9	n.a.
Winter wheat	8.7	8.6	8.0	9.6	8.7 ± 0.6	n.a.
Sugar beet	76.6	72.2	84.9	80.2	78.5 ± 4.6	n.a.

* In 2020, the *Sida* experimental field was still used for the *Sida* study. Maize was also not grown on the adjacent fields in this year. Accordingly, no yield data for maize are available for 2020 for the former *Sida* trial field and the adjacent fields. Therefore, for a comparison with the yield values from the former *Sida* trial field, the value for maize from the Düren region in 2020 was not included in the statistical calculations. n.a.: data not available.

When comparing the average yield values from 2019 to 2022 from the former *Sida* field and from fields in the immediate vicinity of the *Sida* trial field, the yields for winter wheat and sugar beet were significantly higher at 10.7 (±0.67) t/ha ($p = 0.009$) and 91.5 (±3.73) t/ha ($p = 0.01$) compared to the yield data from the same period from the Düren region, which correspond to 8.7 (±0.56) t/ha and 78.5 (±4.64) t/ha, respectively. The average maize yield of 60.5 (±7.48) t/ha from the fields around the former *Sida* trial field was approx. 12% higher than the four-year average value of 54.2 (±7.92) t/ha from the Düren region but was not significant (p = 0.46).

4. Discussion

4.1. General Remarks

Perennial biomass/energy crops play an important role in energy security and the overall energy mix and could contribute to agro-biodiversity and overall landscape aesthetics, stimulating landscape heterogeneity and providing additional ecosystem services [20]. However, a sensitive balance between cash crop production to maintain food/feed security and perennial crop production for energy and feedstock should be considered. Advantages for soil health, organic carbon sequestration, resilience, and biodiversity were found in numerous perennial energy crops [33–35], making such plants a promising tool for maintaining agricultural sustainability. Irrespective of these advantages, knowledge about the possible reintegration into crop rotation is crucial for the acceptance of perennial energy crops such as *Sida*. Among local demands, the additional motivation to return an established *Sida* field to crop production can be a decline in yield as a result of drought, pests and plant diseases, dominant weed pressure, or age of the crop. As documented, *Sida* yield increased in the first 4–5 years [3,12]. While it was stated that *Sida* could remain productive for 20 years [36], only one study so far documented the *Sida* yield over a period of thirteen successive years, showing a rapid and rather constant decrease from year six onwards due to adverse biological and abiotic circumstances [3]. However, the reported findings might have been site-specific. It is, therefore, of importance to anticipate possible eventualities before establishing a perennial *Sida* stand and to better assess possible consequences for the subsequent crops. The presented results of this study can be useful in the decision-making process, providing information on the behavior of *Sida* in crop rotation and agricultural practice.

4.2. Final Sida Harvest and Biomass Yield

Established, full-grown *Sida* plants have assimilated reserves in their large root systems so that resprouting of the plants from their roots is possible. The biomass yield obtained at the final harvest of the *Sida* plants was slightly lower when compared with the earlier reported values from this *Sida* stock in 2017 (12.2 t/ha DM) and 2018 (13.9 t/ha DM), i.e., two and three years after planting [4]. This yield decline might be due to manifold reasons and could be associated with a lack of water due to hot and dry summer seasons in the previous two years, a potential depletion of soil nutrients over time, and a simultaneous increase in resource competition by weeds. Considering flood plains and riverine areas as the natural habitat of *Sida* [37], drought was found to severely affect *Sida* growth and biomass allocation, particularly in young plants still missing a deep-reaching root system [38,39]. This may become crucial for commercial *Sida* biomass production in terms of climate change, which is apparent by more frequent heat waves and estimated drought events.

With regard to the available literature, the further yield development on the *Sida* field of investigation would have been speculative. It remains unknown whether the *Sida* stand would have remained productive or whether the yield would have decreased successively, as demonstrated earlier [3,36]. As stated by Kwiatkowski et al., among drought, severe detrimental factors influencing *Sida* growth and yield over time were associated with a shortened growing season due to late spring frosts and *Sclerotinia* stem rot infections caused by the fungus *Sclerotinia sclerotiorum* [3]. Whether an early termination of a perennial *Sida* stand, characterized by an excessive biomass decline due to biotic or abiotic factors, makes sense can only be decided on a situational basis and according to local needs. However, the high establishment efforts could also justify waiting for further development and possible recovery of the *Sida* stock.

4.3. Effects of Mechanical–Chemical Treatments

The almost complete elimination of *Sida* was achieved by a total of 15 mechanical soil treatments in combination with a total of five herbicide applications in the studied areas during the period of investigation. These treatments were part of the conventional agricultural cultivation measures and were carried out independently of the earlier *Sida* plantation. All mechanical operations carried out from the seedbed preparation of maize onwards were standard measures for the cultivation of maize, wheat, catch crops, and sugar beets. Over the three-year duration of this study, these treatments were subdivided into nine mechanical and one chemical treatments in 2021, three mechanical and one chemical treatments in 2022, and three mechanical and three chemical treatments in 2023 (Table A1).

From an agronomic point of view, other options would have been available for the eradication of *Sida*, such as the use of broad-spectrum herbicides, e.g., glyphosate, or other crop rotations with more intensive mechanical–chemical treatments necessary. Accordingly, we assume that the approach followed in this study was rather conservative in nature and that *Sida* can be eliminated even faster and more thoroughly by harsher treatments. However, the agricultural measures applied in our study led to the elimination of the existing *Sida* stand to a very large extent, allowing for a successful recultivation of the investigated area for cash crop production. Interestingly, all residual *Sida* plants found grew only in the ruts or headlands and not in the closed beet stand. Ruts are obviously predestined for *Sida* resprouting because there was less competition for light, nutrients, etc., from the beets, and also, the effect of the soil herbicide was reduced due to various passes of machinery.

Among all the following field operations and measures applied, mechanical tillage and herbicide applications are considered the primary reasons for the successful repression of the *Sida* plants during the years of investigation. This was particularly pronounced for the used herbicides Goltix Titan, Metafol, and Betasana as applied to the *Sida* field in the third year of investigation, 2023, containing the active compounds Metamitron (4-Amino-3-methyl-6-phenyl-1,2,4-triazine-5-on), and Phenmedipham (Methyl-3-(3-methylcarbaniloyloxy)carbanilate), respectively.

Overall, the available literature on herbicides in the context of *Sida* is very limited. Field studies on the herbicide sensitivity of *Sida* demonstrated that a large number of commonly used herbicides were not or only poorly tolerated [40]. However, the cited study was conducted on young *Sida* plants 4–5 weeks after emergence or earlier only. The herbicides Metamitron, Phenmedipham, and their mixtures, as also applied in our study in the third year, induced medium damage in the postemergence period. A similar field study with variation in the herbicides used, including Metamitron, was conducted in Poland, using juvenile *Sida* plants at the 1–2 and 3–4 leaf stages [41]. The cited study concluded that the most important factor, apart from the herbicide active compound, was the developmental stage of *Sida* at the time of herbicide application. With regard to the existing literature, it can, therefore, be said that juvenile, underdeveloped *Sida* plants, in particular, react sensitively to herbicides.

The used herbicide Metamitron in the cited studies is a standard for the control of annual eudicotyledonous weeds, primarily in sugar beet production. It acts through both the roots and the leaves. In the pre-emergence application, the effect is mainly achieved via the roots of the plants. In postemergence, the effect is additionally exerted via the leaves, which causes the plant to die off more quickly. Metamitron causes the inhibition of photosynthesis, which in turn results in less nutrients stored and electrons being transported within the plant, finally resulting in plant death [42]. Even though Metamitron application on young *Sida* plants induced only medium damage in the cited studies above, it can be assumed that Metamitron, as a soil-active herbicide applied among others in the third year of the presented study, resulted in a further elimination of the mature but weakened *Sida* plants.

In a non-agricultural context, a previous study tested the sensitivity of *Sida* to the herbicide glyphosate as an endangered non-target macrophyte in Canada [43]. The authors reported that the growth of the main shoot was toxicologically sensitive to glyphosate and recommended that the main shoot length should be considered for assessing *Sida* responses to herbicides applied via foliar spray. Since in the cited study, only four-week-old *Sida* plants were used, a direct comparison with our six-year-old, mature *Sida* plants regarding their herbicide sensitivity and ability to resprout from the densely developed root system is not appropriate.

4.4. Soil Quality Determines Crop Yield Rather than Residual Sida Effects

In the entire Düren region where this study was executed, a strong local soil heterogeneity can be observed, ranging from soil values as low as 20 to up to 90 (https://grundsteuer-geodaten.nrw.de/, accessed on 4 December 2023). On average, the soil value accounts for 70 in the entire Düren region [44]. The arable land of the former *Sida* trial field, as well as the adjacent fields from which the cash crop yield data were collected, has a soil quality of 90. The observed differences in yield values for the respective crops from the former *Sida* field could, therefore, be attributed to this very high soil value. Consequently, the higher yields obtained for each cash crop when compared with the statistical average values for the larger region of Düren can be attributed to the local soil differences and the very high soil value on the former *Sida* field and its adjacent fields.

The obtained yield values demonstrate that neither the crop yield nor the crop harvest was negatively influenced by the resprouted *Sida* plants in the respective years. However, influences of locally varying precipitation, soil moisture, and dryness, as well as fertilization, were not taken into account in the given yield values. Due to the large amount of underlying data for the Düren region, these eventualities can possibly be averaged out.

In 2021, the resprouted *Sida* plants were harvested together with the maize and subsequently used for ensilaging as feedstock for biogas production. It can be assumed that silage maize or other fast- and tall-growing plants are ideal as a subsequent crop for the reclamation of an existing *Sida* stand. Maize is characterized by fast and tall growth that interferes with resprouting and growth of *Sida*. In addition, resprouted *Sida* plants do not interfere with harvest or product, as the total biomass is used as silage for feed or biogas substrate. This assumption corresponds with earlier findings on the reintegration of *Miscanthus* fields into crop rotation, indicating that maize cultivation suppressed *Miscanthus* regrowth most successfully [45]. Also here, maize was particularly efficient in *Miscanthus* suppression due to a combination of both crop management (harrowing before sowing) and crop competition due to greater plant height, making maize also a suitable crop for cultivation following a perennial *Miscanthus* stock.

4.5. Observations on Sida Invasiveness at Agricultural Field Conditions

Due to our observations on the spreading and invasiveness of *Sida* in the field of experimentation, this plant could be considered to be of low ecological risk. A report on environmental risk analyses of non-native biomass crops in the Netherlands from 2015 classified *Sida* as a plant with "likely ecological risk to the categories dispersion potential and invasiveness and colonization of high value conservation habitats" but also a "deficient data risk classification to the categories adverse impacts on native species and alteration of ecosystem functions" [46]. As stated in the cited report, this is mainly due to deficient data for most risk assessment categories.

However, it should be noted that the term "invasive" needs to be differentiated more clearly between arable land and near-natural ecosystems where invasive species may outcompete species of the native natural vegetation. In this study, conclusions could only be drawn from the arable land of investigation. In such field studies on arable land, the term "perennial plant species of high economic relevance" might further be considered instead.

The results of this study could contribute to a better assessment of *Sida* invasiveness and its ecological risk at the agricultural level. However, it should be noted that *Sida* is a wild plant species. It is generally known from wild plants that seeds present in the soil can remain vital for long periods and could germinate even after many years. According to the presented findings, it can be assumed that *Sida* plants germinating from seeds have no chance for a thorough establishment under conventional agricultural field cultivation. In future years, the observation of the possible resprouting of remaining *Sida* roots in the field will be continued.

5. Conclusions

The measures employed in this study achieved a successful elimination and reclamation of a six-year-old, fully established *Sida* stand for conventional crop production. Nevertheless, the results shown are a result of the treatments applied in this study. To what extent a different crop rotation or other mechanical–chemical measures can also successfully eradicate *Sida* remains unclear at this point and needs further research. However, it can be assumed that regular soil cultivation and crop rotation will lead to a relevant repression of *Sida* plants within the general framework of conventional agricultural practice. Resprouted *Sida* plants neither impeded the productivity of subsequent crops used in this study, i.e., maize, winter wheat, and sugar beet, nor did they hinder the harvesting of the crops. Overall, *Sida* did not show an invasive nature in the agricultural area of investigation throughout the study period of three consecutive years. Knowledge and information on the behavior of perennial, neophytic biomass plants such as *Sida* and their eradication are important for biomass producers, decision-makers, and ecologists. Such information is important for the practical management of biomass plant species and should, therefore, be carried out in parallel with yield studies in the future. More research is needed to show that purely mechanical measures in the context of, e.g., organic farming can also successfully repress *Sida* so that farmland can again be used to grow conventional crops without the risk of crop losses due to excessive competition from remaining *Sida* plants.

Author Contributions: N.D.J.: conceptualization of the study, methodology employed, software application, data validation, formal data analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision, and project administration. B.O.: methodology employed, software application, data validation, formal data analysis, investigation, data curation, writing—review and editing, and visualization. M.G.: methodology employed, software application, data validation, formal data analysis, investigation, data curation, writing—review and editing, and visualization. T.K.: conceptualization of the study, methodology employed, data validation, investigation, resources, data curation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Overview of the timeline and applied treatments during the recultivation of the established, 6-year-old *Sida* stand under agricultural conditions. Active compounds are provided for the herbicides only.

Year of Investigation/Timeline/Treatments					
2021		2022		2023	
Time	**Treatment**	**Time**	**Treatment**	**Time**	**Treatment**
20.02.2021	*Sida* plants chopped by flail mulcher	02.03.2022	Fertilization (SSA with 170 kg/ha = 36 kg N/ha and 40 kg S/ha).	07.01.2023	Catch crop mulched
25.02.2021	Total area treated with grubber to 15 cm depth	16.03.2022	Fertilization (AHL with 193 kg/ha = 58 kg N/ha	09.01.2023	Total area plowed
26.02.2021	Surface processed with molding cutter to 15 cm depth	28.03.2022	Herbicide application: Broadway [1] (160 g/ha), active compounds: 68.3 g/kg Pyroxsulam (B; 2); 22.8 g/kg Florasulam (B; 2); 68.3 g/kg Cloquintocet-mexyl [3]; 0.7 L/ha CCC: 720 g/L Chlormequatchlorid [2]*	15.04.2023	Fertilizer application: AHL 369 kg/ha = 111 kg N/ha
22.03.2021	Soil cultivation on the whole field by means of grubber	16.04.2022	Fertilization AHL with 98 kg/ha = 29 kg N/ha	17.04.2023	Tillage seedbed combination
23.03.2021	Manual roots removal from entire area A, ca. 400 kg root pieces (approx. 0.7 kg roots/m^2)	20.04.2022	Plant protection: 1 L/ha Ampera [1]; 0.15 L/ha Moddus [2]*; micronutrients (Ca, S, Si).	18.04.2023	Tillage power harrow plus roller; Sugar beets (BTS6975) sowing, approx. 11 seeds m^2 (105,000 seeds per ha) with a spacing of 50 cm/row
24.03.2021	Milling of the whole field (A and B) in two different depths. 1.: 6 cm depth, and 2.: 10 cm depth in opposite direction of travel	09.05.2022	Leaf fertilization: 30 L/ha Neco (+Si)	11.05.2023	Herbicide application (L/ha): 1.4 L Goltix Titan (active compound: 525 g/L Metamitron (45.1 w.-%), 40 g/L Quinmerac (3.4 w.-%)); 0.9 L Metafol SC (696 g/L Metamitron); 0.45 L Oblix (500 g/L Ethofumesat); 0.3 L Kantor (additive); 1.4 L Betasana SC (160 g/L Phenmedipham) *

Table A1. *Cont.*

Year of Investigation/Timeline/Treatments					
2021		2022		2023	
Time	**Treatment**	**Time**	**Treatment**	**Time**	**Treatment**
08.05.2021	Fertilizer application (450 kg/ha KAS = 120 kg N/ha)	13.05.2022	Plant protection: 0.65 L Gigant [1] 0.4 L Camane [1]; 0.05 L Moddus [2]*	17.05.2023	Herbicide application (L/ha): 0.9 L Goltix Titan (525 g/L Metamitron (45.1 w.-%), 40 g/L Quinmerac (3.4 w.-%)); 0.9 l Metafol SC (696 g/L Metamitron); 0.4 l Oblix (500 g/L Ethofumesat); 0.3 L Kantor (additive); 1.3 L Betasana SC (160 g/L Phenmedipham); 30 g Debut (500 g/L Triflusulfuron-Methyl: Sulfonylharnstoff) + FHS 0.15 L Venzar (500 g/L Lenacil) *
10.05.2021	Total area treated with grubber to 15 cm depth	21.05.2022	Fertilization (AHL 143 kg/ha = 43 kg N/ha)	19.05.2023	Insecticide application against aphids: 300 g Pirimor *
11.05.2021	Seedbed preparation using a power harrow	25.05.2022	Fungicide treatment: 1.3 L Sirena [1]*	27.05.2023	Herbicide application (L/ha, only on the edges on 3 m): 2 L Targa Gold (46.3 g/L Quizalofop-P); 0.6 L Spectrum (720 g/L Dimethenamid-P, 64 w.-%) *
14.05.2021	Sowing maize: variety: "Sucorn"; 9 plants per m^2, 75 cm row distance, including application of sub-foot fertilizer (18 kg N/ha + 25 kg P_2O_5/ha)	19.07.2022	Winter wheat harvest (approx. 11.5 t/ha) and straw collection	30.05.2023	Herbicide application (L/ha): 1.5 L Metafol SC (696 g/L Metamitron); 0.55 L Oblix (500 g/L Ethofumesat); 0.3 L Kantor (additive); 1.5 L Betasana SC (160 g/L Phenmedipham); 23 g Debut (500 g/L Triflusulfuron-Methyl: Sulfonylharnstoff) + FHS; 0.3 L Venzar (500 g/L Lenacil) *
07.06.2021	Herbicide application: 1.1 L MaisTer + 1.1 L Aspect *, active compounds: 30.0 g/L Foramsulfuron (as Na-salt 31.5 g/L); 9.77 g/L Thiencarbazone (as Methylester 10 g/L); 0.85 g/L Iodosulfuron (as Methylester-Na 1 g/L); 15 g/L Cyprosulfamide (Safener); 333 g/L Terbuthylazin; 200 g/L Flufenacet)	27.07.2022	Tillage on total area with grubber to 10 cm depth	14.06.2023	Foliar fertilizer application: 1 L Wuxal-Boron; 0.2 L silicon; 0.4 L CaB Top

Table A1. *Cont.*

Year of Investigation/Timeline/Treatments					
2021		**2022**		**2023**	
Time	**Treatment**	**Time**	**Treatment**	**Time**	**Treatment**
15.10.2021	Maize harvest as whole plant silage (approx. 70.2 t FM/ha at 32% DM)	09.08.2022	Digestate application and incorporation 9.9 t/ha = 60 kg N/ha	14.07.2023	Fungicide application (L/ha): 1 L Amistar Gold [1]; 1.9 L CUS [1]*; + 9 L Folistim N-fertilizer
20.10.2021	Maize stubbles were mulched, crushing also the *Sida* plants that survived the maize chopper	07.09.2022	Tillage with grubber on total area to 15 cm depth	07.08.2023	Fungicide application (L/ha): 0.92 L Diadem [1]; 1.9 L CUS [1]*; 9 L Folistim N-fertilizer
21.10.2021	Grubber treatment on total area at 30 cm depth	07.09.2022	Sowing catch crop (DSV TerraLife® BetaSola catch crop mixture, Deutsche Saatveredelung AG, Lippstadt, Germany, 30 kg/ha, using a power harrow combi)	28.08.2023	Fungicide application (L/ha): 1 L Domark + 0.91 L Grifon
23.10.2021	Sowing winter wheat: RGT Reform, 310 grains/m^2, using a power harrow combination			18.09.2023	Fungicide application (L/ha): 0.4 L SCORE
				28.11.2023	Sugar beet harvest (approx. 91.9 t/ha)

* in 250 L water/ha; KAS = "Kalkammonsalpeter": calcium ammonium nitrate; FM = fresh mass; DM = dry mass; SSA = "Schwefelsaures-Ammoniak": Sulfuric acid ammonia; AHL = "Ammoniumnitrat-Harnstoff-Lösung": Ammonium nitrate urea solution; FHS = formulation adjuvant. [1] Fungicide; [2] Growth regulator; [3] Safener.

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