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Narrow Row Spacing and Cover Crops to Suppress Weeds and Improve Sulla (*Hedysarum coronarium* L.) Biomass Production

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Abstract: Sulla (*Hedysarum coronarium* L.) is a new candidate crop for biofuel production. A field trial was conducted in 2018–2020 in Pyrgos, Greece, and repeated in 2019–2021 to evaluate different row spacings and cover crops for weed management in sulla in a two-factor randomized complete block design (RCBD) with four replications. Four row spacings, namely 76-cm, 51-cm, 38-cm, and 19-cm, were assigned to the main plots. Three cover crops, namely farro wheat (*Triticum turgidum* subsp. *dicoccum* (Schrank ex Schübler) Thell.), common vetch (*Vicia sativa* L.), white mustard (*Sinapis alba* L.), and an untreated control, were assigned to the subplots. In the first year of sulla growth, weed biomass, sulla stem, and total dry matter yield (DMY) were affected by growing cycles (p-value ≤ 0.05). The 19- and 38-cm row spacings resulted in the lowest weed biomass and the highest stem and total sulla DMY in the first year of sulla growth. White mustard was the most weed-suppressive cover crop in both years and growing cycles followed by farro heat. The highest stem DMY was observed in subplots with white mustard in both years. The combination of 38 cm row spacing and white mustard as a cover crop resulted in the highest cumulative two-year sulla DMY (18.9 t ha^{-1}). Further case studies are needed to evaluate more cultural practices for weed management in sulla and other major biomass crops under different soil and climatic conditions.

Keywords: white mustard; farro wheat; common vetch; *Avena sterilis* L.; *Sinapis arvensis* L.; stem DMY; early flowering; early seed set

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1. Introduction

Sulla (*Hedysarum coronarium* L.) is a short-lived perennial legume native to the Mediterranean region grown as a biennial cool-season forage crop that regrows in the fall [1–3]; the forage is suitable for pasture, hay and, silage production [4]. Sulla is also important for honey production and can be grown as a cover crop in arable fields and orchards [5,6].

However, this species is also a promising feedstock for biofuel production [7]. There is evidence that sulla biomass yields can reach about 14 and 17 t ha^{-1} dry matter [8]. Sulla biomass is also suitable for bioethanol production because the stems are rich in total soluble sugars, celluloses, and hemicelluloses [9]. Alberti and Mennella et al. [10] and Zanoli et al. [11] refer to sulla biomass as a lignocellulosic feedstock suitable for bioethanol production. Amato et al. [8] reported that the theoretical ethanol yield (TEY) of sulla in the first and second year of the crop's growing cycle was 1850 and 2884 L ha^{-1} in, respectively, with the stems contributing up to 75% of the TEY of the whole plant. The same authors also reported that sulla is a potential feedstock for biomethane production, as the predicted biomethane production (pBMP) of sulla reached 2107 and 2654 m^3 CH_4 ha^{-1} in the first and second year of the crop's growing cycle, respectively. Stems contributed to 40 and 60% of the total pBMP in the first and second year of sulla growth, respectively. Selvaggi et al. [12] also found high biogas and biomethane production for sulla, and revenues significantly exceeded bioenergy production costs. Moreover, Chinnici et al. [13] and Chinnici et al. [14]

considered sulla as a species whose biomass can be used in fermentation processes for bioenergy production in Mediterranean soil and climatic conditions. In another recent study, Pappalardo et al. [15] reported that 34,485 kNm^3 of biomethane can be produced annually from sulla biomass in Southern Italy.

In general, sulla is considered a low-input crop that adapts well to marginal lands and drought-prone areas. Once the stand is well established, sulla can produce large amounts of biomass during its two-year growing cycle with plants being more productive in the second year of growth [4]. To improve sulla biomass production, weed management should be considered an essential agronomic practice. As with many important bioenergy feedstocks, weed competition at early growth stages can lead to establishment failure and significantly reduce biomass yields [16]. However, weed control can be difficult because there are no herbicides registered for these novel crops. Therefore, weed management should rely on the use of non-chemical cultural practices [16].

One of the non-chemical cultural practices that can be used to suppress weeds is to reduce crop row spacing. Narrow row spacing accelerates the formation of a dense crop canopy that shades the soil in the spaces between the rows. The amount of light reaching the soil surface is reduced and fewer weed seeds can germinate, resulting in less weed emergence [17]. There are numerous studies highlighting the potential of narrow row spacing for weed suppression in major field crops [18–21]. However, there are no studies that have examined the role of narrow row spacing in reducing weed pressure and improving sulla biomass production.

The use of cover crops is another agronomic practice for weed management [22]. Cover crops are grown early in the season and can be mechanically terminated before the cash crop is established [17]. Cover crop residues can then be incorporated into the upper soil layers to suppress or delay weed emergence in the main crop [17,23]. This is mainly attributed to the potential allelopathic effects of the residues on weed seeds, which limit weed seed germination [24]. A wide variety of cereals, legumes, and crucifers can be used as winter cover crops [22,25]. To date, there is only one study in the literature in which cereals and crucifers as cover crops suppressed weed emergence in the sulla crop [26].

Thus, the objective of the current study was first to evaluate different row spacings cover crop species for weed suppression in the first and second year of the sulla growing cycle. In addition, the effects of row spacing and cover crop species on sulla stem and whole plant biomass were examined in each year of sulla growth. The effects of row spacing and cover crop species on sulla two-year stem and whole plant biomass were also investigated.

2. Materials and Methods

2.1. Site Description

A field trial was conducted in the prefecture of Pyrgos, Elis, Greece from August 2018 to May 2021. The experimental site was located 4 km outside the town of Pyrgos (37.685° N, 21.471° E). Oat (*Avena sativa* L.) was the previous crop since 2015. The soil type was sandy loam (SL) and the soil texture (0–30 cm) was: 57.1% sand, 27.3% silt, and 15.6% clay with a pH of 7.5 and an organic matter content of 1.4%. Sulla was the studied crop (cv. *Bellante*, Agrositos S.A., Nea Moudania, Greece). As for the climatic conditions, the monthly average temperature was typical for the western Peloponnese, and the highest precipitation heights occurred in November and December 2019 (Table 1).

2.2. Experimental Setup

Given that sulla is a crop with a two-year growing cycle, the field trial was conducted over two growing cycles in order to replicate it over time. Specifically, the crop was grown from December 2018 to May 2020 and (in different plots at the same site) from December 2019 to May 2021. Hereafter, the first growing season is referred to as "2018–2020" and the second growing season is referred to as "2019–2021".

Table 1. Monthly average temperature (°C) and precipitation height (mm) in the experimental area for both sulla growing cycles (2018–2020 and 2019–2021).

Month	Average Temperature (°C)				Total Precipitation (mm)			
	2018	2019	2020	2021	2018	2019	2020	2021
January	-	9.5	10.4	10.0	-	180.8	122.8	81.4
February	-	9.0	12.2	11.3	-	95.5	39.2	55.9
March	-	13.7	14.0	13.6	-	60.6	53.4	66.7
April	-	16.3	16.0	15.8	-	85.8	8.0	21.1
May	-	18.4	21.2	19.5	-	15.6	5.2	16.1
June	-	25.7	23.2	-	-	0.8	3.8	-
July	-	27.1	27.5	-	-	5.4	4.4	-
August	27.9	28.4	28.1	-	5.2	0.0	0.6	-
September	24.7	25.0	24.6	-	39.8	79.9	61.8	-
October	20.8	21.4	21.0	-	17.0	84.8	94.3	-
November	16.6	17.7	17.3	-	168.8	399.0	202.2	-
December	11.7	13.3	13.6	-	106.0	312.2	171.7	-

In each growing cycle, the experiment was performed in a two-factorial (split plot) randomized complete block design (RCBD) with four replicates (blocks). Four sulla row spacings, namely 76-, 51-, 38-, and 19-cm, were assigned to the main plots. Four cover crop treatments were assigned to the subplots. Specifically, farro wheat [*Triticum turgidum* L. subsp. *dicoccum* (Schrank ex Schübler) Thell.; cv. Kaploutzas, Organic Farm Kiziridis, Kilkis, Greece], common vetch (*Vicia sativa* L.; cv. Evinos, Agroland S.A., Karditsa, Greece), and white mustard (*Sinapis alba* L.; cv. Iris, Vandinter Semo B.V., Scheemda Groningen, The Netherlands) were the cover crops studied. An untreated control with no cover crop was also included. As four subplots were established four times in each main plot, this resulted in a total of 128 subplots in the entire experimental area. The size of the subplots was 18 m^2 (3 m long and 6 m wide), the size of the main plot was 288 m^2 (12 m long and 24 m wide), and the total size of the experimental area was 1152 m^2 (12 m long and 96 m wide). Borders of 0.5 m were maintained between adjacent subplots whereas borders between main plots were 1.0 m. All borders were kept weed free by hand hoeing at two-week intervals.

Cover crops were established in late August and terminated in early December. Before cover crop sowing, the soil was first deeply ploughed (at a depth of 30 cm) and then tilled with a rotary hoe (at a depth of 20 cm) in early August. The soil was disked again and fertilizer (Nutriphos®, Hellagrolip S.A., Athens, Greece) was incorporated to provide cover crops with 80 kg N ha^{-1} and 100 kg P_2O_5 ha^{-1} (plus 65 kg SO_3 ha^{-1}). A shallow harrow pass (at 10 cm depth) was also performed to further break up the soil clods and ensure that a firm seedbed was prepared. Cover crops were sown on 21 August 2018, and 18 August 2019, prior to the 2018–2020 and 2019–2020 sulla growing cycles, respectively, using a '*SJ Expert*' hand seeder (Sepeba Ebra, Saint-Martin-du-Fouilloux, France). Seeding rates were 120, 80, and 40 kg seed ha^{-1} for farro wheat, common vetch, and white mustard, respectively. Row spacing was 19 cm for all cover crops to ensure that a dense canopy formed quickly and maximum biomass production was achieved. Sowing depth was 0.5 cm. To further improve germination and growth of the cover crops, the field was irrigated with sprinklers twice per week in August and September. No fungal infections or pest infestations were observed in any of the three cover crops.

Cover crop termination by flail mowing was performed on 3 December 2018, and 1 December 2019, using a medium-type flail mower with hydraulic motion control, a capacity of 35 HP, and a mowing width of 150 cm (OMA SGK /S 150, Panagrotiki S.A., Lamia, Greece). The cover crop residues were then disked into the soil, followed by another harrow pass to prepare the seedbed immediately prior to sulla sowing. In 2018, the final harrow pass and sulla sowing were performed the day after cover crop termination (4 December 2018). However, this was not possible in 2019 due to heavy rainfall between 2 and 5 December 2019. Therefore, the last harrow pass and sulla sowing were carried out on 13 December 2019. Sowing rate was 30 kg ha^{-1} of dehulled viable seed and sowing depth was 1 cm. The four row spacings of 76, 51, 38, and 19 cm resulted in 8, 12, 16, and 32 rows in each subplot, respectively. At the sulla stem elongation growth stage (BBCH: 30–39), deltamethrin (Decis 25 EC, Bayer Hellas S.A., Athens, Greece) was applied at an application rate of 12.5 g a.i. ha^{-1} at two-week intervals to control *Myzus persicae* (Sulzer, 1776) infestation. The insecticide was applied in both years of the two growing cycles using a Gloria® 410 T pressure sprayer (Gloria Haus & Gartengeraete GMBH, Witten, Germany) calibrated to deliver 500 L ha^{-1} of spray solution at a constant pressure of 400 kPa through a brass hollow-cone nozzle (2 mm diameter; 80° spray angle). After the first year of each growing cycle, summer annual weeds (mainly *Chenopodium album* L., *Amaranthus retroflexus* L., and *Datura stramonium* L.) present in the field were removed by hand, as the study focused on the management of winter weeds in sulla.

2.3. Data Collection

Biomass production of cover crops was assessed the day before termination. Cover crop samples were manually harvested at three sampling points determined by a wooden 1 m^2 quadrat in each subplot. Samples were then oven dried at 60 °C for 48 h (DHG–9025, Knowledge Research S.A., Athens, Greece) to measure the dry biomass of each species using a digital balance '*KF–H2*' (Zenith S.A., Athens, Greece).

Sulla emergence occurred on 9 December 2018, and 19 December 2019, and the plants began to develop their rosettes about 1 month after sowing. The first weed biomass evaluation was conducted on 11 February 2019, and 24 February 2020, for the 2018–2020 and 2019–2021 growing cycles, respectively. At these dates, the plants were in the final stage of rosette growth (BBCH: 29) and about to begin stem elongation. These evaluations occurring around 70–80 days after sowing have been chosen also in one of the view studies where weed pressure has been estimated in sulla [26], and other legumes with perennial growing cycle [27–29]. The predominant weeds in the first year of crop growth were *Avena sterilis* L. and broadleaved species, with *Fumaria officinalis* L., *Papaver rhoeas* L., *Gallium aparine* L., and *Veronica hederifolia* L. being the most common. Weed biomass was reassessed on 18 April 2019 and 27 April 2020, when sulla plants were in the early flowering stage and 50% of flowers were open (BBCH: 65). Final weed biomass evaluations were conducted on 9 May 2019 and 15 May 2020 at the early seed set growth stage when approximately 30% of the loments were green (BBCH: 73). Hereafter, the first, second, and third weed biomass evaluations are referred to as 'Eval 1', 'Eval 2', and 'Eval 3', respectively.

In the second year of sulla growth, regrowth occurred on 17 October 2019, and 11 October 2020, for the 2018–2020 and 2019–2021 growing cycles, respectively. Sulla plants reached the final stage of rosette growth (BBCH: 29) on 30 November 2019, and 21 November 2020, and early flowering (BBCH: 65) on April 2020 and 22 March 2021, and early seed set (BBCH: 73) on 23 April 2020 and 11 April 2021. Weed biomass was assessed on each of the above dates, resulting in three evaluations (Eval 1, Eval 2, and Eval 3). The composition of the weed flora did not change between 2018–2020 and 2019–2021. In particular, *Sinapis arvensis* L. dominated the field in the second year of both growing seasons, and other broadleaf weeds such as *Capsella bursa–pastoris* (L.) Medik., *Anthemis cotula* L., *Lamium amplexicaule* L. and *Stellaria media* (L.) Vill. were also present.

The same procedures were used to evaluate weed biomass in both years and growing cycles. Three metallic 0.5 m^2 quadrats were permanently placed in each subplot and marked with 1 m-high wooden stakes in areas of uniform weed flora and away from subplot edges. One quadrat was used per evaluation. Weeds were harvested by hand at a height of 2–3 cm and placed in numbered plastic bags. Weed samples were then classified by species, oven dried at 60 °C for 48 h, and weighed.

Sulla biomass was evaluated at the growth stages of early flowering (Eval 1) and early seed set (Eval 2). There is recent evidence that sulla stem biomass at these two growth stages is a suitable feedstock for bioethanol production [8]. No evaluations have been conducted at the late bud stage because of lower stem biomass compared to the above growth stages [8]. Moreover, in view of the results of Amato et al. [8], no evaluation was made at the time of seed set. These authors reported that the low content of total soluble sugar and the high content of lignin (up to 100 g kg^{-1}) in the stems make this late growth stage unsuitable for harvesting sulla grown for bioethanol production. Sulla was harvested manually at a height of 6 cm immediately after weed harvest in each subplot from three sampling sites determined by a wooden 1 m^2 quadrat. Sulla samples were then separated into stems and leaves (and inflorescences/loments, if present). Both fractions were oven dried at 60 °C for 48 h and weighed to determine the dry matter yield (DMY) of each fraction. Two-year stem and total (whole plant) DMY were also calculated for 2018–2020 and 2019–2021. Prior to air-drying, main stem length was also measured for five randomly selected plants per quadrat in each subplot to determine plant height.

2.4. Statistical Analysis

Cover crop biomass was first analyzed using a two-way analysis of variance (ANOVA) in which year of cover crop establishment (2018 or 2019) and cover crop species were considered fixed effects and replicates were considered random effects. Cover crop biomass was again analyzed using the one-way ANOVA procedure to compare biomass production among species in each year. Weed biomass and sulla parameters were first subjected to three-way ANOVA. Growing cycles, row spacing, and cover crop species were the fixed factors, whereas block effects were considered random. If growing cycle effects were significant, the data were reanalyzed separately for each growing cycle. When growing season effects were not significant, data were pooled across growing cycles. In each of the above cases, data were reanalyzed by two-way ANOVAs (row spacing by cover crop). All ANOVAs were conducted at a significance level of $a = 0.05$, and means were compared using Fischer's least significant difference (LSD) test. Statgraphics Centurion XVI (Statgraphics Technologies, Inc., P.O. Box 134, The Plains, VA, USA) was the statistical package used for all data analyses.

3. Results

3.1. Cover Crop Biomass

Cover crop biomass production was influenced by years (p-value ≤ 0.01) and cover crop species (Table S1). Cover crop biomass was significantly higher in 2019 than in 2018 (Figure 1a). In 2018, white mustard produced 23 and 42% more biomass compared to farro wheat and common vetch, respectively. Farro wheat was significantly more productive than common vetch in both 2018 and 2019. In 2019, white mustard remained the most productive species with biomass production of 3782.2 kg ha^{-1} (Figure 1b).

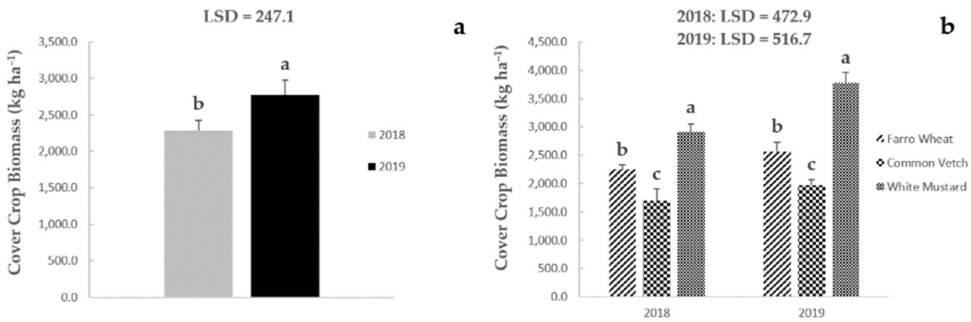

Figure 1. Cover crop biomass production (kg ha^{-1}) in 2018 and 2019 before the 2018–2020 and 2019–2021 sulla growing cycles, respectively, averaged (**a**) across all species and (**b**) per species. Different lowercase letters indicate significant differences. Vertical bars indicate standard errors.

3.2. Weed Biomass

3.2.1. First Year of Sulla Growing Cycle

For all three evaluations in the first year of sulla growth, *A. sterilis* biomass, broadleaved weed biomass, and total weed biomass were higher in 2018–2020 than in 2019–2021 (Figure 2a).

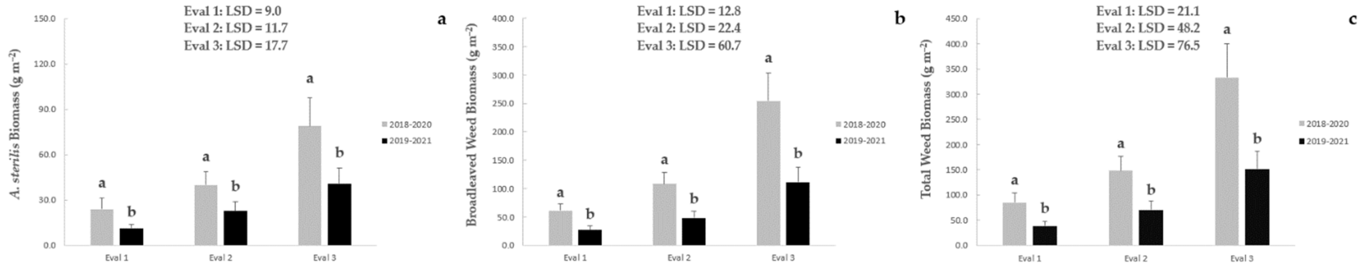

Figure 2. (**a**) Biomass of *A. sterilis* (g m^{-2}). (**b**) Biomass of broadleaved weeds (g m^{-2}). (**c**) Total weed biomass (g m^{-2}). Data are for the first year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Different lowercase letters indicate significant differences. Vertical bars indicate standard errors.

Growing cycles, row spacing, and cover crop species influenced *A. sterilis* biomass, broadleaved weed biomass, and total weed biomass in all evaluations. Significant interactions between growing and cover crops were observed for *A. sterilis* biomass in Eval 2 and Eval 3, broadleaved weed biomass in all evaluations, and total weed biomass in Eval 1 and Eval 3 (Table S2). Growing cycle effects on the above weed parameters were significant in all evaluations (p-value $\leq$ 0.05). Therefore, data were reanalyzed for each growing cycle (Table 2).

Table 2. The effects of sulla row spacing and cover crops on *A. sterilis* biomass, broadleaved weed biomass, and total weed biomass in the first year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were analyzed separately for each growing cycle.

Factors	**DF** [1]	**Two-Way ANOVA (RS × CC) for 2018–2020**								
		A. sterilis			**Broadleaf Weeds**			**Total Weeds**		
		Eval 1	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**
RS	3	0.0024	0.0042	0.0021	0.0003	0.0004	0.0002	0.0004	0.0005	0.0003
Error (a)	9									
RS × CC	3	0.8685	0.4713	0.5870	0.9378	0.6915	0.8514	0.9576	0.7493	0.8904
CC	9	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Error (b)	36									
Total	63									
Factors	**DF**	**Two-Way ANOVA (RS × CC) for 2019–2021**								
		A. sterilis			**Broadleaf Weeds**			**Total Weeds**		
		Eval 1	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**
RS	3	0.2023	0.7915	0.2840	0.1813	0.0364	0.1069	0.1911	0.0687	0.1336
Error (a)	9									
RS × CC	3	0.9501	0.5193	0.8770	0.6228	0.1672	0.5592	0.7583	0.2546	0.6572
CC	9	0.0000	0.0002	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000
Error (b)	36									
Total	63									

[1] Abbreviations: DF; Degrees of Freedom, GC; Growing Cycle, RS; Row Spacing, CC; Cover Crop, Error (a); RS × Block, Error (b); Block × CC(RS), Eval; Evaluation.

In the 2018–2020 sulla growing cycle, row spacing affected *A. sterilis* biomass at Eval 1, Eval 2, and Eval 3 (p-value $\leq$ 0.01). The same was found for broadleaved weed biomass and total weed biomass in all evaluations (p-value ≤ 0.001). In 2019–2021, row spacing had no significant effect on the weed parameters studied (p-value ≤ 0.05). In contrast, the effects of cover crop species on biomass of *A. sterilis* and broadleaved weeds were significant and the same was observed for total weed biomass (p-value ≤ 0.001). This observation was the same for Eval 1, Eval 2, and Eval 3 in both growing cycles.

For 2018–2020, the narrowest row spacing (19-cm) suppressed *A. sterilis* biomass by nearly 50% compared to the widest row spacing (76-cm) in Eval 1, Eval 2, and Eval 3. No significant differences were observed between 19-cm and 38-cm. Broadleaved weed biomass was lowest with 19-cm row spacing in all measurements. Moreover, 38-cm row spacing reduced broadleaved weed biomass compared to 76-cm in Eval 1 and Eval 2 (Table 3).

The narrowest row spacing (19-cm) reduced total weed biomass by 46, 48, and 52% compared to 76-cm in Eval 1, Eval 2, and Eval 3, respectively. Aboveground weed biomass increased by 40% at sulla early seed set (Eval 3) at 38-cm row spacing than at 19-cm. The row spacing of 38 cm significantly suppressed total weed biomass compared to 76-cm in Eval 1, Eval 2, and Eval 3. White mustard and farro wheat cover crops significantly reduced *A. sterilis* biomass, broadleaved weed biomass, and total weed biomass compared to common vetch and the untreated control in all evaluations. Weed biomass was not significantly different between white mustard and farro wheat subplots. Common vetch did not differ from the untreated control (Table 3).

In 2019–2021, row spacing did not affect *A. sterilis* biomass in any of the evaluations. Broadleaved weed biomass was reduced by up to 42% in Eval 2 with 19-cm row spacing compared to 51-cm. In general, weed pressure was lower in all main plots, and no differences were observed in Eval 1. In Eval 2, 38- and 19-cm resulted in 32 and 37% lower weed biomass than 51-cm. No differences were observed between 51- and 76-cm. Similar results were obtained in Eval 3.

Table 3. The effects of sulla row spacing and cover crops on *A. sterilis* biomass (g m^{-2}), broadleaved weed biomass (g m^{-2}), and total weed biomass (g m^{-2}) in the first year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were analyzed separately for each growing cycle.

Factors	**Two-Way ANOVA (RS × CC) for 2018–2020**								
	***A. sterilis* (g m^{-2})**			**Broadleaf Weeds (g m^{-2})**			**Total Weeds (g m^{-2})**		
	Eval 1	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**
RS [1]									
76-cm	31.8 a [2] (6.6)	51.3 a (11.2)	103.7 a (24.9)	75.9 a (14.4)	139.9 a (25.5)	310.1 a (50.0)	107.7 a (22.8)	191.2 a (36.1)	413.8 a (64.1)
51-cm	28.6 a (4.3)	44.9 ab (6.7)	87.7 ab (16.1)	71.4 ab (10.2)	119.9 ab (23.7)	299.5 a (46.6)	100.0 ab (17.5)	164.8 ab (20.5)	387.2 ab (62.5)
38-cm	20.5 b (4.4)	37.3 bc (7.4)	71.7 bc (18.3)	61.8 b (11.4)	111.4 b (21.7)	259.6 a (48.0)	82.3 b (17.2)	148.6 b (28.5)	331.4 b (65.2)
19-cm	14.9 b (4.5)	25.9 c (6.0)	51.9 c (9.0)	35.7 c (5.5)	73.8 c (12.3)	147.9 b (34.8)	50.3 c (9.4)	99.6 c (25.9)	199.8 c (59.0)
$LSD_{0.05}$	7.4	11.5	21.0	13.1	20.9	52.3	19.1	29.7	68.0
CC									
Untreated	37.0 a (6.9)	60.2 a (12.9)	117.8 a (26.6)	78.6 a (13.6)	138.2 a (20.2)	328.1 a (57.7)	115.6 a (24.2)	198.4 a (31.9)	446.0 a (83.8)
Farro Wheat	17.5 b (4.6)	28.7 b (8.3)	54.6 b (16.0)	47.9 b (10.2)	94.7 b (19.1)	198.9 b (56.9)	65.4 b (15.6)	123.7 b (31.2)	253.5 b (72.6)
Common Vetch	29.9 a (4.7)	50.3 a (8.0)	101.9 a (18.6)	85.1 a (11.3)	155.1 a (18.5)	356.2 a (48.3)	115.0 a (17.3)	205.5 a (26.1)	458.1 a (66.0)
White Mustard	11.4 b (3.5)	19.9 b (5.7)	40.8 b (10.9)	32.9 c (8.5)	57.0 c (16.5)	133.8 b (36.5)	44.3 b (12.7)	76.9 c (21.8)	174.6 b (48.3)
$LSD_{0.05}$	11.3	12.8	28.2	17.0	29.8	73.1	27.8	40.8	99.7

Table 3. *Cont.*

Factors	Two-Way ANOVA (RS × CC) for 2019–2021								
	A. sterilis (g m^{-2})			Broadleaf Weeds (g m^{-2})			Total Weeds (g m^{-2})		
	Eval 1	Eval 2	Eval 3	Eval 1	Eval 2	Eval 3	Eval 1	Eval 2	Eval 3
RS									
76-cm	13.0 a (3.7)	21.3 a (5.6)	44.4 a (12.0)	29.1 ab (6.5)	55.6 ab (13.4)	121.6 ab (32.8)	42.1 a (11.4)	77.0 ab (18.9)	166.0 ab (34.1)
51-cm	12.6 a (2.1)	25.4 a (5.4)	47.1 a (9.0)	31.2 a (4.8)	76.7 a (19.5)	131.3 a (22.0)	43.8 a (7.4)	102.2 a (25.0)	178.4 a (32.5)
38-cm	10.6 a (2.8)	21.6 a (5.4)	38.4 a (11.0)	25.3 ab (7.0)	48.4 b (14.6)	105.8 ab (30.0)	35.9 a (9.8)	70.0 b (18.1)	144.2 ab (35.4)
19-cm	8.9 a (2.2)	22.3 a (8.5)	32.3 a (8.6)	21.9 b (5.3)	44.7 b (11.8)	85.9 b (21.1)	30.8 a (7.5)	64.9 b (16.4)	118.9 b (29.0)
$LSD_{0.05}$	4.5	10.3	16.7	9.2	21.8	38.4	12.5	28.8	53.7
CC									
Untreated	16.4 a (3.8)	31.6 a (8.3)	56.4 a (13.0)	37.4 a (8.2)	70.8 ab (8.3)	156.6 a (24.9)	53.9 a (12.0)	102.4 a (21.7)	212.9 a (43.8)
Farro Wheat	10.8 b (2.7)	19.9 b (5.8)	39.0 b (10.5)	25.8 b (6.9)	52.7 b (5.8)	106.3 a (28.7)	36.4 b (9.6)	70.6 b (19.3)	145.3 b (32.6)
Common Vetch	13.7 ab (3.0)	29.3 ab (8.0)	50.2 ab (11.4)	32.8 ab (6.8)	79.9 a (8.0)	137.4 ab (27.8)	46.5 ab (9.8)	109.3 a (26.8)	187.8 ab (36.0)
White Mustard	4.2 c (1.3)	9.9 c (3.3)	17.2 c (5.6)	11.5 c (3.5)	22.0 c (3.3)	44.3 b (7.6)	15.7 c (4.8)	31.8 c (8.6)	61.6 c (18.3)
$LSD_{0.05}$	4.1	9.8	13.5	8.5	24.6	35.8	12.5	30.9	48.6

[1] Abbreviations: GC; Growing Cycle, RS; Row Spacing, CC; Cover CropEval; Evaluation. [2] Different lowercase letters between the same column highlight significant differences.

White mustard suppressed *A. sterilis* biomass by 62, 70, and 75%, respectively, compared to farro wheat, common vetch, and the untreated control in Eval 1. Similar were the results in Eval 2 and Eval 3. White mustard also reduced broadleaved weed biomass by 56–59% compared to farro wheat. The biomass of broadleaved weeds decreased in farro wheat subplots compared to common vetch and the untreated subplots. Total weed biomass was similar in subplots with farro wheat and common vetch as cover crops in Eval 1. In Eval 2, farro wheat resulted in 36% lower weed biomass than common vetch. Furthermore, white mustard reduced weed biomass by 55–58, 67–71, and 69–72% compared to farro wheat, common vetch, and the untreated control, respectively.

3.2.2. Second Year of Sulla Growing Cycle

In the second year of sulla growth, row spacing, and cover crop species influenced *S. arvensis* biomass and total weed biomass in all evaluations. In Eval 1, 19-cm row spacing reduced *S. arvensis* biomass by 35, 48, and 53% compared to 38-, 51-, and 76-cm, respectively. In Eval 2, 19- and 38-cm row spacings resulted in the lowest *S. arvensis* biomass. The narrowest row spacing (19-cm) reduced total weed biomass by 47% and 52% compared to 51- and 76-cm in Eval 1. In Eval 2 and Eval 3, 19-cm again resulted in the lowest weed biomass. In Eval 3, 38-cm row spacing reduced weed biomass by 26% compared to 76-cm.

White mustard was the cover crop that most suppressed *S. arvensis*, reducing the biomass of this species by 54–57 and 63–65%, respectively, compared to farro wheat and common vetch. Farro wheat also significantly reduced the biomass of *S. arvensis* compared to common vetch, although common vetch did not differ from untreated. Total weed biomass was lowest in the white mustard subplots in all evaluations. In both Eval 1 and Eval 3, farro wheat resulted in lower weed biomass than common vetch and the untreated control. In addition, common vetch had similar weed biomass values to the untreated control in Eval 1, Eval 2, and Eval 3 (Table 4).

Table 4. The effects of sulla row spacing and cover crops on *S. arvensis* biomass (g m^{-2}) and total weed biomass (g m^{-2}) in the second year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were pooled across growing cycles.

Factors	DF [1]	Two-Way ANOVA (RS × CC)					
		S. arvensis			Total Weeds		
		Eval 1	Eval 2	Eval 3	Eval 1	Eval 2	Eval 3
RS	3	0.0041	0.0060	0.0052	0.0069	0.0159	0.0084
Error (a)	9						
RS × CC	3	0.8808	0.9215	0.9182	0.9825	0.9966	0.9871
CC	9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Error (b)	36						
Total	63						
Factors		**Two-Way ANOVA (RS × CC)**					
		***S. arvensis* (g m^{-2})**			**Total Weeds (g m^{-2})**		
		Eval 1	**Eval 2**	**Eval 3**	**Eval 1**	**Eval 2**	**Eval 3**
RS							
76-cm		130.6 a [2] (23.8)	209.2 a (40.3)	295.4 a (50.4)	147.6 a (33.8)	245.7 a (67.9)	331.9 a (67.8)
51-cm		116.9 ab (22.0)	192.3 a (34.4)	254.7 ab (43.2)	132.3 ab (29.6)	225.3 a (53.1)	287.7 ab (62.1)
38-cm		94.0 b (13.2)	157.6 b (20.6)	221.4 b (30.7)	105.5 bc (16.8)	182.4 ab (30.6)	246.2 bc (42.3)
19-cm		61.8 c (13.0)	101.7 c (20.2)	149.4 c (34.8)	71.0 c (17.4)	121.3 b (29.4)	169.0 c (39.7)
$LSD_{0.05}$		31.7	11.5	64.7	38.3	71.9	81.4
CC							
Untreated		119.6 ab (20.6)	202.0 ab (32.1)	274.8 ab (44.1)	138.9 ab (29.8)	242.3 a (58.0)	315.8 ab (68.6)
Farro Wheat		104.3 b (22.4)	168.9 b (33.8)	240.8 b (48.7)	115.0 b (27.2)	191.9 a (47.2)	263.5 b (62.3)
Common Vetch		130.7 a (16.7)	211.8 a (30.1)	299.8 a (34.6)	148.3 a (24.9)	249.6 a (49.6)	337.6 a (52.6)
White Mustard		48.7 c (12.3)	78.1 c (19.4)	105.8 c (29.0)	54.4 c (15.6)	90.2 b (26.2)	117.9 c (36.2)
$LSD_{0.05}$		23.9	38.1	54.1	31.8	60.0	73.4

[1] Abbreviations: DF; Degrees of Freedom, RS; Row Spacing, CC; Cover Crop, Error (a); RS × Block, Error (b); Block × CC(RS), Eval; Evaluation. [2] Different lowercase letters between the same column highlight significant differences.

3.3. Sulla Biomass

3.3.1. First Year of Sulla Growing Cycle

In the first year of sulla growth, sulla plant height, stem DMY and total DMY were higher in 2019–2021 than in 2018–2020 in both Eval 1 and Eval 2 (Figure 3a–c).

In the first year of sulla growth, plant height was influenced by growing cycles (p value $\leq$ 0.001) in Eval 1 and Eval 2, row spacing in Eval 1 (p-value $\leq$ 0.05) and Eval 2 (p-value $\leq$ 0.001), and cover crop species in both assessments (p-value $\leq$ 0.001). Stem and whole plant DMY were influenced by row spacing in Eval 1 (p-value $\leq$ 0.05) and Eval 2 (p-value $\leq$ 0.05). Cover crop species also had a large effect on all sulla parameters in both evaluations (p-value $\leq$ 0.001). Significant row spacing by cover crop interactions were found for plant height (Eval 2), stem DMY (Eval 1 and Eval 2), and total DMY (Eval 1 and Eval 2; Table S3). Given that the effects of growing cycle on the parameters studied were significant, the data were reanalyzed for each growing cycle (Table 4). Row spacing influenced plant height, stem biomass, and whole plant biomass in Eval 2 (p-value $\leq$ 0.05) in 2018–2020. In 2019–2021, row spacing factor influenced stem and total DMY in Eval 1

(p-value ≤ 0.001). In Eval 2, row spacing influenced plant height, stem, and total DMY (p-value ≤ 0.001). In addition, cover crop species influenced all parameters in both growing cycles and evaluations (Table 5).

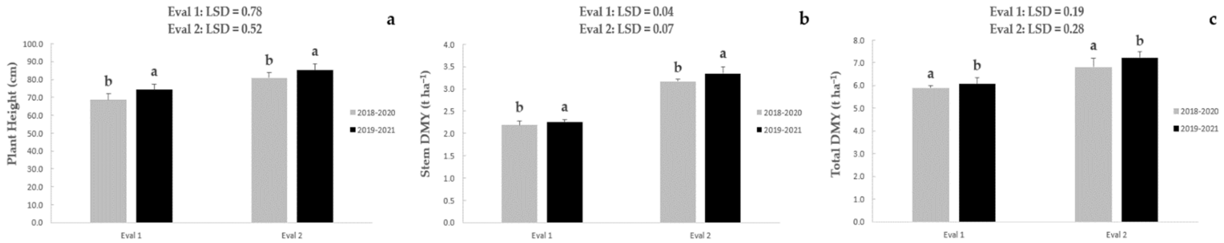

Figure 3. Sulla (**a**) plant height (cm), (**b**) stem DMY (t ha^{-1}), and (**c**) total DMY (t ha^{-1}). Different lowercase letters indicate significant differences. Vertical bars indicate standard errors. DMY; Dry Matter Yield.

Table 5. The effects of sulla row spacing and cover crops on sulla plant height, stem DMY, and total DMY in the first year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were analyzed separately for each growing cycle.

Factors	**DF** [1]	**Two-Way ANOVA (RS × CC) for 2018–2020**					
		Plant Height		**Stem DMY**		**Total DMY**	
		Eval 1	**Eval 2**	**Eval 1**	**Eval 2**	**Eval 1**	**Eval 2**
RS	3	0.0768	0.0134	0.0600	0.0004	0.0613	0.0029
Error (a)	9						
RS × CC	3	0.7487	0.5777	0.2070	0.0203	0.5981	0.2899
CC	9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Error (b)	36						
Total	63						
Factors	**DF**	**Two-Way ANOVA (RS × CC) for 2019–2021**					
		Plant Height		**Stem DMY**		**Total DMY**	
		Eval 1	**Eval 2**	**Eval 1**	**Eval 2**	**Eval 1**	**Eval 2**
RS	3	0.4525	0.0001	0.0025	0.0002	0.0036	0.0003
Error (a)	9						
RS × CC	3	0.4818	0.7319	0.0409	0.1407	0.0704	0.1851
CC	9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Error (b)	36						
Total	63						

[1] Abbreviations: DF; Degrees of Freedom, RS; Row Spacing, CC; Cover Crop, Error (a); RS × Block, Error (b); Block × CC(RS), DMY; Dry Matter Yield, Eval; Evaluation.

In 2018–2020, 38- and 19-cm row spacing further improved plant height and stem DMY compared to 51- and 76-cm (Eval 1). In Eval 2, the row spacing of 38 cm resulted in 5%, 9%, and 11% higher stem DMY than 19-, 51-, and 76-cm, respectively. Total sulla DMY was higher at 19- and 38-cm row spacing than at to 51- and 76-cm in Eval 1. In Eval 2, 38-cm row spacing increased total DMY 19-cm (Table 6).

Plant height in both Eval 1 and Eval 2 was highest in the subplots with white mustard as a cover crop; intermediate values occurred in farro wheat subplots. The lowest plant height was observed in the subplots with common vetch and the untreated subplots. In Eval 1, stem DMY was higher in the subplots with white mustard than in common vetch and the untreated subplots. Furthermore, white mustard and farro wheat significantly increased sulla stem DMY in Eval 2 compared to common vetch and the untreated control. Total DMY was higher in the subplots with white mustard and farro wheat subplots than in common vetch and the untreated subplots (Eval 1 and Eval 2).

Table 6. The effects of sulla row spacing and cover crops on sulla plant height (cm), stem DMY (t ha^{-1}), and total DMY (t ha^{-1}) in the first year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were analyzed separately for each growing cycle.

Factors	Two-Way ANOVA (RS × CC) for 2018–2020					
	Plant Height (cm)		Stem DMY (t ha^{-1})		Total DMY (t ha^{-1})	
	Eval 1	Eval 2	Eval 1	Eval 2	Eval 1	Eval 2
RS [1]						
76-cm	65.4 b [2] (2.8)	85.1 c (3.4)	2.129 b (0.044)	3.027 c (0.062)	5.722 b (0.119)	6.540 c (0.135)
51-cm	66.8 ab (3.4)	90.4 bc (3.4)	2.168 ab (0.039)	3.068 c (0.055)	5.858 ab (0.105)	6.713 bc (0.120)
38-cm	71.4 a (4.3)	98.9 a (3.8)	2.223 a (0.049)	3.371 a (0.074)	6.021 a (0.133)	7.129 a (0.156)
19-cm	70.7 ab (2.9)	94.2 ab (2.8)	2.220 a (0.043)	3.203 b (0.072)	5.946 a (0.114)	6.869 b (0.132)
$LSD_{0.05}$	5.5	7.4	0.08	0.12	0.22	0.25
CC						
Untreated	60.6 c (3.1)	79.2 c (3.5)	2.055 d (0.048)	2.929 d (0.079)	5.532 c (0.128)	6.237 d (0.145)
Farro wheat	72.1 b (3.4)	97.5 b (3.8)	2.259 b (0.037)	3.245 b (0.053)	6.067 a (0.099)	7.054 b (0.115)
Common Vetch	64.1 c (3.3)	83.9 c (3.1)	2.117 c (0.057)	3.023 c (0.080)	5.725 b (0.153)	6.536 c (0.176)
White Mustard	77.8 a (3.5)	108.8 a (3.1)	2.321 a (0.034)	3.474 a (0.051)	6.224 a (0.091)	7.423 a (0.109)
$LSD_{0.05}$	5.0	6.8	0.06	0.09	0.16	0.19
Factors	**Two-Way ANOVA (RS × CC) for 2019–2021**					
	Plant Height (cm)		**Stem DMY (t ha^{-1})**		**Total DMY (t ha^{-1})**	
	Eval 1	**Eval 2**	**Eval 1**	**Eval 2**	**Eval 1**	**Eval 2**
RS						
76-cm	72.8 a (2.7)	84.9 c (3.6)	2.141 b (0.079)	3.122 c (0.120)	5.804 b (0.214)	6.761 c (0.262)
51-cm	74.6 a (3.5)	90.7 b (3.6)	2.252 a (0.038)	3.361 b (0.056)	6.102 a (0.102)	7.257 b (0.121)
38-cm	76.6 a (3.3)	98.6 a (4.0)	2.311 a (0.034)	3.563 a (0.052)	6.224 a (0.093)	7.639 a (0.111)
19-cm	73.4 a (2.7)	93.1 b (3.0)	2.292 a (0.046)	3.338 b (0.066)	6.123 a (0.095)	7.245 b (0.144)
LSD	5.3	3.6	0.07	0.12	0.20	0.26
CC						
Untreated	67.4 c (3.4)	78.4 c (3.6)	2.126 b (0.054)	3.113 c (0.078)	5.761 b (0.145)	6.757 b (0.170)
Farro wheat	76.3 b (3.1)	97.0 b (4.0)	2.387 a (0.030)	3.496 b (0.045)	6.298 a (0.082)	7.542 a (0.098)
Common Vetch	70.0 c (2.7)	84.4 c (3.2)	2.159 b (0.083)	3.118 c (0.129)	5.805 b (0.224)	6.780 b (0.274)
White Mustard	83.7 a (3.0)	107.7 a (3.3)	2.424 a (0.029)	3.656 a (0.045)	6.427 a (0.078)	7.827 a (0.095)
$LSD_{0.05}$	4.7	7.9	0.09	0.15	0.27	0.32

[1] Abbreviations: RS; Row Spacing, CC; Cover Crop, DMY; Dry Matter Yield, Eval; Evaluation. [2] Different lowercase letters between the same column highlight significant differences.

In 2019–2021, plant height was not affected by row spacing in Eval 1. Stem and total DMY increased at 38-, 19-, and 51-cm row spacing than at 76-cm. In Eval 2, the row spacing of 38 cm resulted in the highest plant height, whereas 76-cm resulted in the lowest plant height. Reducing sulla row spacing from 51 cm to 38 cm increased stem dry matter production by 6%, and similar were the differences between these two row spacings in terms of whole plant DMY. The narrowest row spacing (19-cm) was characterized by lower stem and whole plant biomass yields than 38-cm. In comparison to 76-cm row spacing, 38-cm row spacing improved stem and total biomass production by 14 and 12%, respectively.

Sulla plants were taller in the farro wheat subplots than in common vetch and the untreated subplots. The greatest plant heights were obtained with white mustard as a cover crop. In Eval 1, white mustard and farro wheat resulted in higher stem and total DMY than common vetch and the untreated control. In Eval 2, white mustard improved stem biomass by about 15% compared to common vetch and the untreated control. Total DMY was 11 and 12% higher in farro wheat subplots than in common vetch and the untreated subplots, respectively. Moreover, white mustard had no significant differences with farro wheat.

3.3.2. Second Year of Sulla Growing Cycle

In the second year of sulla growth, growing cycles did not affect plant height, stem, or total DMY of sulla in any evaluation (Table S4). Therefore, data for the 2018–2020 and 2019–2021 growing cycles were combined (Table 7).

Row spacing and cover crops influenced plant height and stem DMY in both evaluations (p-value $\leq$ 0.001). Total sulla biomass yield was influenced by row spacing in Eval 1 (p-value $\leq$ 0.01) and Eval 2 (p-value $\leq$ 0.05). Cover crop species also influenced total DMY in Eval 1 (p-value $\leq$ 0.001) and Eval 2 (p-value $\leq$ 0.01). No significant row spacing by cover crop interactions were found for any of these sulla parameters.

The row spacing of 38 cm resulted in the greatest sulla height, whereas the lowest values corresponded to 76-cm. The row spacing of 51 and 19 cm also improved plant height compared to 76-cm. These observations were identical in Eval 1 and Eval 2. The narrowest row spacing (19-cm) resulted in higher stem DMY compared to 51- and 76-cm, but lower stem DMY compared to 38-cm. Total DMY also increased at 19-cm row spacing compared to 76-cm; the highest DMY was obtained at 38-cm. As with stem DMY in Eval 2, row spacings differed significantly in descending order: 38-cm > 19-cm > 51-cm > 76-cm. In addition, 38-cm row spacing resulted in about 10% higher total DMY than 19-, 51-, and 76-cm.

In contrast, two-year stem and total sulla DMY did not differ between 2018–2020 and 2019–2021 in Eval 2 (p-value $\geq$ 0.05). Row spacing and cover crop species influenced both parameters in Eval 1 and Eval 2 (p-value $\leq$ 0.05). Significant row spacing by cover crop interactions were observed for cumulative stem DMY in Eval 1 (p-value $\leq$ 0.05) and for total DMY in Eval 2 (p-value $\leq$ 0.01; Table S5). Therefore, Eval 1 data were reanalyzed for each growing cycle, whereas Eval 2 data were averaged across growing cycles (Table 8).

Table 7. The effects of sulla row spacing and cover crops on sulla plant height (cm), stem DMY (t ha^{-1}), and total DMY (t ha^{-1}) in the second year of sulla growth in the 2018–2020 and 2019–2021 growing cycles. Data were pooled across growing cycles.

Factors	DF [1]	Two-Way ANOVA (RS × CC)					
		Plant Height		Stem DMY		Total DMY	
		Eval 1	Eval 2	Eval 1	Eval 2	Eval 1	Eval 2
RS	3	0.0001	0.0000	0.0006	0.0000	0.0010	0.0374
Error (a)	9						
RS × CC	3	0.9415	0.9696	0.1576	0.1702	0.2392	0.9696
CC	9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0051
Error (b)	36						
Total	63						

Table 7. *Cont.*

Factors	Two-Way ANOVA (RS × CC)					
	Plant Height (cm)		Stem DMY (t ha^{-1})		Total DMY (t ha^{-1})	
	Eval 1	Eval 2	Eval 1	Eval 2	Eval 1	Eval 2
RS						
76-cm	92.8 c [2] (4.0)	100.1 c (4.8)	4.095 c (0.083)	5.418 d (0.223)	7.673 c (0.171)	8.809 b (0.225)
51-cm	99.6 b (4.8)	108.6 b (5.7)	4.183 c (0.076)	5.808 c (0.132)	7.965 bc (0.177)	8.979 b (0.389)
38-cm	108.5 a (5.8)	118.9 a (7.0)	4.545 a (0.101)	6.357 a (0.155)	8.378 a (0.175)	9.708 a (0.241)
19-cm	103.5 b (3.2)	113.2 b (3.9)	4.362 b (0.084)	6.085 b (0.141)	7.977 b (0.192)	8.853 b (0.195)
$LSD_{0.05}$	4.3	4.8	0.16	0.25	0.28	0.37
CC						
Untreated	83.6 c (4.1)	88.4 c (4.6)	3.899 c (0.091)	5.362 c (0.139)	7.194 d (0.216)	8.167 d (0.233)
Farro wheat	108.6 b (4.9)	120.2 b (6.0)	4.461 b (0.077)	6.300 b (0.136)	8.269 b (0.143)	9.532 b (0.176)
Common Vetch	90.5 c (4.0)	96.3 c (4.3)	4.100 c (0.105)	5.493 c (0.265)	7.588 c (0.205)	8.685 c (0.239)
White Mustard	121.9 a (4.7)	136.4 a (6.5)	4.724 a (0.069)	6.693 a (0.108)	8.672 a (0.138)	9.966 a (0.382)
$LSD_{0.05}$	8.2	8.9	0.12	0.26	0.25	0.33

[1] Abbreviations: DF; Degrees of Freedom, RS; Row Spacing, CC; Cover Crop, Error (a); RS × Block, Error (b); Block × CC(RS), DMY; Dry Matter Yield, Eval; Evaluation. [2] Different lowercase letters between the same column highlight significant differences.

White mustard marginally improved plant height and stem DMY compared to farro wheat, whereas farro wheat significantly increased plant height compared to common vetch and the untreated control (Eval 1 and Eval 2). In Eval 1, whole plant DMY differed among all cover crops in descending order: white mustard > farro wheat > common vetch > untreated. In Eval 2, total DMY reached nearly 10 t ha^{-1} in the white mustard subplots and was 5%, 13%, and 19% higher than in farro wheat, common vetch, and the untreated subplots, respectively.

3.3.3. Cumulative Two-Year Biomass

In the first evaluation of sulla biomass, cumulative two-year, stem, and total sulla DMY were higher in 2019–2021 than in 2018–2020 (Figure 4a,b).

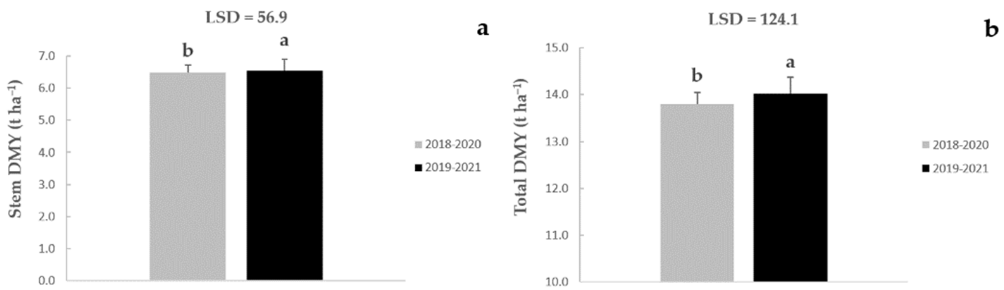

Figure 4. Sulla cumulative two-year (**a**) stem DMY (t ha^{-1}) and (**b**) total DMY (t ha^{-1}). Data refer to the first evaluation of sulla DMY (Eval 1). Different lowercase letters indicate significant differences. Vertical bars indicate standard errors. DMY; Dry Matter Yield.

Table 8. The effects of sulla row spacing and cover crops on sulla cumulative two-year stem DMY and total DMY in the 2018–2020 and 2019–2021 growing cycles. Data of Eval 1 were analyzed separately for each growing cycle. Data of Eval 2 were pooled over growing cycles.

Factors	DF [1]	Two-Way ANOVA (RS × CC) for 2018–2020—Eval 1	
		Stem DMY	Total DMY
RS	3	0.0030	0.0072
Error (a)	9		
RS × CC	3	0.4027	0.3710
CC	9	0.0000	0.0000
Error (b)	36		
Total	63		
Factors	**DF**	**Two-Way ANOVA (RS × CC) for 2019–2021—Eval 1**	
		Stem DMY	**Total DMY**
RS	3	0.0001	0.0005
Error (a)	9		
RS × CC	3	0.1416	0.4470
CC	9	0.0000	0.0000
Error (b)	36		
Total	63		
Factors	**DF**	**Two-Way ANOVA (RS × CC) Pooled over GC—Eval 2**	
		Stem DMY	**Total DMY**
RS	3	0.0000	0.0053
Error (a)	9		
RS × CC	3	0.0714	0.0251
CC	9	0.0000	0.0000
Error (b)	36		
Total	63		

[1] Abbreviations: DF; Degrees of Freedom, RS; Row Spacing, CC; Cover Crop, Error (a); RS × Block, Error (b); Block × CC(RS), Eval; Evaluation, GC; Growing Cycles, DMY; Dry Matter Yield.

Row spacing affected both cumulative stem and total DMY in 2018–2020 (p-value ≤ 0.01) and 2019–2021 (p-value ≤ 0.001). Cover crop effects on both parameters were significant in both growing cycles (p-value ≤ 0.001). In Eval 2, row spacing influenced two-year stem (p-value ≤ 0.001) and total DMY (p-value ≤ 0.01). Cover crops also influenced both parameters (p-value ≤ 0.001).

In Eval 1 of 2018–2020, 38- and 19-cm row spacings yielded the highest cumulative stem and total DMY. Two-year stem and total DMY were lower at 51-cm row spacing than at 38-cm. There was a tendency for higher stem and total DMY at 19-cm row spacing than at 51-cm row spacing, but these differences were not significant. The same was true for the comparison between 51-cm and 76-cm. In addition, the narrowest row spacing (19-cm) improved both two-year stem and whole plant DMY compared to 76-cm.

White mustard increased stem DMY by 4%, 12%, and 14% compared to farro wheat, common vetch, and the untreated control, respectively. Farro wheat also improved the two-year stem DMY compared to common vetch and the untreated. As for the cumulative total DMY, cover crops followed the descending order: white mustard > farro wheat > common vetch > untreated (Table 9).

In Eval 1 in 2019–2021, the row spacing of 38 cm resulted in the highest values of two-year stem and sulla whole plant biomass. The narrowest row spacing of 19 cm increased both the two-year stem and whole plant DMY compared to the row spacing of 51 cm. In addition, both the cumulative stem and whole plant biomass production increased by reducing row spacing from 76 cm to 51 cm. In addition, white mustard increased two-year stem DMY by 6%, 12%, and 15% compared to farro wheat, common vetch, and the untreated control, respectively. Farro wheat improved stem DMY by 8% and 11% compared to common vetch and untreated control, respectively.

In Eval 2, cumulative stem DMY exceeded 10 t ha^{-1} at 38-cm row spacing. The next highest value corresponded to 19-cm. Stem biomass increased by reducing row spacing from 51 to 19 cm. The row spacing of 51 cm also improved two-year stem biomass compared to 76-cm. Similar results were obtained for two-year whole-plant DMY, except that there was no not a significant difference between 19- and 51-cm. Among cover crops, white mustard increased cumulative stem and total DMY compared to farro wheat. Farro wheat resulted in 12% and 9% higher stem and total DMY, respectively, compared to common vetch. Common vetch increased stem and total DMY compared to the untreated control.

Table 9. The effects of sulla row spacing and cover crops on sulla cumulative two-year stem DMY (t ha^{-1}) and total DMY (t ha^{-1}) in the 2018–2020 and 2019–2021 growing cycles. Data of Eval 1 were analyzed separately for each growing cycle. Data of Eval 2 were pooled over growing cycles.

Factors	2-Way ANOVA (RS × CC) for 2018–2020—Eval 1	
	Stem DMY (t ha^{-1})	Total DMY (t ha^{-1})
RS [1]		
76-cm	6.228 c [2] (0.044)	13.365 c (0.275)
51-cm	6.348 bc (0.039)	13.562 bc (0.243)
38-cm	6.775 a (0.049)	14.378 a (0.320)
19-cm	6.579 ab (0.043)	13.908 ab (0.267)
$LSD_{0.05}$	0.24	0.51
CC		
Control	5.957 d (0.048)	12.753 d (0.296)
Farro Wheat	6.718 b (0.037)	14.305 b (0.234)
Common Vetch	6.214 c (0.057)	13.292 c (0.355)
White Mustard	7.041 a (0.034)	14.862 a (0.218)
$LSD_{0.05}$	0.18	0.38
Factors	**2-Way ANOVA (RS × CC) for 2019–2021—Eval 1**	
	Stem DMY (t ha^{-1})	**Total DMY (t ha^{-1})**
RS		
76-cm	6.233 d (0.079)	13.506 c (0.376)
51-cm	6.438 c (0.038)	13.788 c (0.317)
38-cm	6.859 a (0.034)	14.664 a (0.217)
19-cm	6.657 b (0.046)	14.116 b (0.332)
$LSD_{0.05}$	0.17	0.38
CC		
Control	6.022 d (0.054)	12.927 d (0.397)
Farro Wheat	6.789 b (0.030)	14.599 b (0.159)
Common Vetch	6.266 c (0.082)	13.415 c (0.402)
White Mustard	7.115 a (0.029)	15.132 a (0.219)
$LSD_{0.05}$	0.19	0.51

Table 9. *Cont.*

Factors	2-Way ANOVA (RS × CC) Pooled over GC—Eval 2	
	Stem DMY (t ha^{-1})	**Total DMY (t ha^{-1})**
RS		
76-cm	8.493 d (0.220)	15.460 c (0.383)
51-cm	9.023 c (0.134)	15.961 b (0.443)
38-cm	10.004 a (0.156)	17.088 a (0.314)
19-cm	9.355 b (0.142)	15.909 b (0.224)
$LSD_{0.05}$	0.29	0.46
CC		
Control	8.384 c (0.139)	14.664 d (0.370)
Farro Wheat	9.671 b (0.143)	16.829 b (0.258)
Common Vetch	8.561 c (0.265)	15.334 c (0.235)
White Mustard	10.258 a (0.107)	17.591 a (0.410)
$LSD_{0.05}$	0.32	0.53

[1] Abbreviations: RS; Row Spacing, CC; Cover Crop, Eval; Evaluation, GC; Growing Cycles, DMY; Dry Matter Yield. [2] Different lowercase letters between the same column highlight significant differences.

In addition, a significant row spacing by cover crop interaction was observed for two-year whole plant DMY in Eval 2 (p-value ≤ 0.05; Table 8). Over two years of sulla growth, the combinations of 38-cm row spacing with farro wheat and white mustard cover crops resulted in the production of 17.8 and 18.9 t ha^{-1} of dry matter. Sulla two-year total biomass yield exceeded 17.5 t ha^{-1} in the subplots with 76-cm row spacing and white mustard as a cover crop. DMY tended to be higher in the subplots with 51-cm row spacing and farro wheat as a cover crop than in the subplots with 19-cm row spacing and farro wheat, 38-cm row spacing and common vetch, and 51-cm with white mustard. Intermediate sulla two-year DMY (15.1–15.8 t ha^{-1}) was observed for the other combinations of row spacing and cover crop treatments, in the following descending order: 51-cm with common vetch > 38-cm with the untreated > 19-cm with common vetch. The lowest two-year biomass was in the combinations of 76-cm row spacing with the untreated control and common vetch (Figure 5).

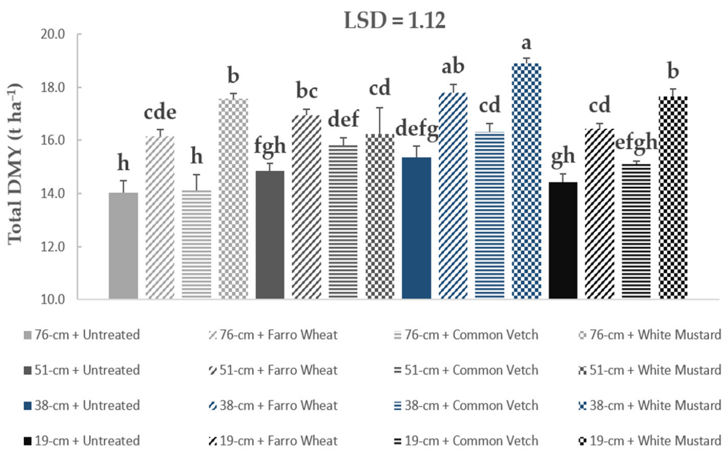

Figure 5. Sulla cumulative two-year total DMY (t ha^{-1}). Data refer to the significant row spacing by cover crop interaction observed in the second evaluation of sulla DMY (Eval 2). Different lowercase letters indicate significant differences. Vertical bars indicate standard errors. DMY; Dry Matter Yield.

4. Discussion

Cover crop biomass increased in 2019 compared to 2018, which can be attributed to weather conditions. Specifically, rainfall heights in September, October, and November 2019 were 67.8, 40.1, and 230.2 mm higher than in 2018, respectively. Therefore, higher rainfall during cover crop growth in the second growing season (2019) improved cover crop biomass accumulation. These results are consistent with recent studies that also report similar differences in cover crop biomass, which they attribute to differences in precipitation heights that occurred over the years [30–32]. White mustard produced the greatest amounts of biomass, which is consistent with previous studies highlighting this species as a rigorous cover crop with high biomass production [33,34]. Common vetch was the least productive cover crop because it grew more slowly than the other species, resulting in strong competition from early emerging winter annual weeds that reduced its productivity. Farro wheat was the next most productive cover crop after white mustard, indicating that this species is a promising cover crop with good biomass potential, as also shown by other studies in the Mediterranean region [35].

Another observation was that in the first year of sulla growth, weed biomass was lower in the 2019–2021 growing cycle than in the 2018–2020 growing cycle. This may be attributed to the rainfalls between 2 and 5 December 2019, shortly after cover crop termination and before the start of the 2019–2021 growing cycle. These rainfalls delayed the final seedbed preparation by 1 week, and some weed seedlings emerged in the meantime, creating a false seedbed [36]. Subsequently, the emerged weed seedlings were controlled by the last shallow harrow pass before sulla sowing. Therefore, weed emergence was lower during the first year of sulla growth in the 2019–2021 growing cycle. These results suggest that preparing a false seedbed could be another cultural practice for effective non-chemical weed management as in previous field trials under similar soil and climatic conditions [37,38]. In the above studies, eliminating weeds before sowing by preparing a false seedbed resulted in significantly lower weed competition and higher yields compared to conventional practices.

This was also observed in the current study in relation to sulla stem and whole plant DMY. More specifically, both these two parameters increased significantly in the 2019–2021 growing cycle than in 2018–2020, which can be attributed to weather conditions. First, higher rainfall during cover crop growth prior to the start of the 2019–2021 growing cycle resulted in greater cover crop biomass production. Thus, higher amounts of residue were incorporated into the soil to suppress weed emergence. These results suggest that interannual variability in weather and especially rainfall height during cover crop growth exerts a strong influence on cover crop and weed biomass, as observed in other recent studies focused on cover crops [39]. This, along with the false seedbed established prior to 2019–2021 due to rainfall before final seedbed preparation, resulted in less weed pressure on the crop and sulla was able to produce significantly more biomass compared to 2018–2020.

Weed biomass decreased with decreasing sulla row spacing, as the canopy closed faster in the main plots with the row spacings of 38 and 19 cm row spacing than in the main plots with the wider row spacings of 51 and 76 cm (visual observations). Our results are consistent with the results of several studies conducted on major field crops in the last two decades, which are summarized in recent literature reviews [18–21]. In addition, the results of the current study suggest that narrow row spacing facilitates weed suppression in sulla through the rapid development of a dense crop canopy that suppresses weed growth. The observations at the weed species level indicating greater suppression of *A. sterilis* and *S. arvensis* by using narrow row spacing are consistent with the recommendations of Bajwa et al. [40] and the findings of McCollough and Melander [41].

In addition, narrow row spacing improved the cumulative two-year stem and total DMY. This could be due to the significant reduction in weed biomass caused by the reduction in sulla row spacing. In any case, the higher biomass yields at the narrow row spacings of 38 and 19 cm are consistent with studies in sweet sorghum [*Sorghum bicolor* (L.) Moench.], kenaf (*Hibiscus cannabinus* L.), switchgrass (*Panicum virgatum* L.), and sunn hemp

(*Crotalaria juncea* L.) [42–45]. However, it should be noted that although the row spacing of 19 cm resulted in the lowest weed biomass, it did not contribute more to sulla DMY than the row spacing of 38 cm, which could be due to the potential intraspecific competition between sulla plants with the row spacing of 19 cm. This is supported by research showing that intraspecific competition can be a major obstacle to higher yields in crops grown with very narrow row spacing [46,47].

Thus, further case studies are needed to evaluate the role of row spacing on weed management in a broad range of bioenergy feedstocks, including sulla. In general, our results suggest that changes in row spacing aimed at increasing plant density should be considered in the development of weed management strategies for bioenergy crops for which herbicides are not yet approved [16]. Given the experience from major field crops [48–53], manipulation of row spacing along with the use of other non-chemical practices should be further explored to maximize weed suppression and achieve higher biomass yields. This is also supported by our recent results at sulla showing that the combination of narrow row spacing and white mustard as a cover crop resulted in a two-year cumulative whole plant DMY of nearly 19 t ha^{-1}.

White mustard was the species that provided the highest level of weed suppression in most weed biomass assessments. The ability of white mustard and species belonging to the botanical family Brassicaceae can be explained by their high allelopathic potential, which is due to the high content of allelochemicals called glucosinolates in the plant tissue [54]. Glucosinolate molecules are hydrolyzed by an enzyme, namely myrosinase, to a variety of biologically active products, with isothiocyanates having the highest allelopathic potential [55]. This process occurs when plant tissue is disturbed by mowing, grazing, frost, tillage, or root death [56]. Therefore, in the present study, it is very possible that the incorporation of mowed residues of white mustard plants resulted in the release of toxic allelochemicals into the upper soil layers, which impaired weed seed germination and consequently reduced weed emergence.

There is a similar explanation for the suppression of weed biomass in farro wheat subplots. Cereal straw contains allelochemicals, mainly phenolic compounds, that can reduce weed seed germination when incorporated into the soil after terminating a cereal cover crop [57]. In contrast, common vetch did not provide adequate weed control compared to the cover crops mentioned above. Legume cover crops do not usually produce such large amounts of biomass and they are characterized by lower allelopathic potential than cereals and crucifers [58]. In fact, legume cover crops are preferable for improving soil conditions by enriching the soil with nitrogen and increasing the productivity of the main crop [25].

Regarding sulla biomass, white mustard resulted in the highest stem and total plant DMY, followed by farro wheat. Our results agree with the recent findings of Kanatas et al. [34] who obtained greater weed control and consequently higher yields in white mustard plots compared to untreated plots. In addition, Dhima et al. [59] reported that winter cereal cover crops can reduce weed emergence in the following main crop and improve its productivity. In another study, Campiglia et al. [60] found that cruciferous and cereal cover crops suppressed weeds more than legume cover crops, resulting in the highest crop yields. In any case, cover crops are reported to improve weed management at establishment and increase productivity of bioenergy crops. For example, Aluko et al. [61] observed that sweet potato [*Ipomoea batatas* (L.) Lam.] and egusi melon (*Citrullus lanatus* (Thunb.) Matsum. and Nakai.) reduced weed biomass and increased kenaf biomass yield. In addition, Sadeghpour et al. [62] reported significantly lower weed biomass and higher biomass production for switchgrass by using oat as a cover crop.

However, it should always be kept in mind that establishing, maintaining, and terminating cover crops can increase production costs. Therefore, an economic evaluation of this practice is needed to demonstrate that revenues significantly exceed the cost of bioenergy production. It should also be noted that further studies should follow so as to confirm the key findings of the present study and generate more research on the role of weed management not only in achieving higher biomass yields in sulla, but also in a broader range of important bioenergy crops.

5. Conclusions

In most evaluations, 19- and 38-cm row spacing resulted in significantly lower weed biomass compared to 51- and 76-cm. White mustard was the cover crop that produced the greatest amounts of biomass, followed by farro heat. White mustard also showed the strongest potential for weed suppression in both years and growing seasons, which may be due to the allelopathic potential of this cover crop. In the first year of sulla growth, a false seedbed established before the start of the second growing season due to weather conditions reduced weed pressure on sulla compared to the first growing cycle. The row spacing of 38 cm resulted in the highest stem and total DMY whereas 19-cm did not further improve sulla biomass production. Stem and total DMY were highest in plots with white mustard as a cover crop. The above results were observed in both years and growing cycles. The combination of 38 cm row spacing and white mustard as a cover crop resulted in the highest cumulative two-year sulla DMY (18.9 t ha^{-1}). Further case studies are needed to evaluate more cultural practices for weed management in sulla and other major biomass crops under different soil and climatic conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15197425/s1, Table S1: The effects of years and cover crop species on cover crop biomass and the effects of cover crop species on cover crop biomass in each year.; Table S2: The effects of sulla growing cycle, row spacing, and cover crop species on *A. sterilis* biomass, broadleaved weed biomass, and total weed biomass in the first year of sulla growth.; Table S3: The effects of sulla growing cycle, row spacing, and cover crop species on *S. arvensis* biomass and total weed biomass in the second year of sulla growth.; Table S4: The effects of sulla growing cycle, row spacing, and cover crop species on sulla plant height, stem DMY, and total DMY in the first year of sulla growth.; Table S5: The effects of sulla growing cycle, row spacing, and cover crop species on sulla plant height, stem DMY, and total DMY in the second year of sulla growth.; Table S6: The effects of sulla growing cycle, row spacing and cover crop species on sulla cumulative two-year stem DMY and total DMY.

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