Weed Science

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How repetitive integrated weed management strategies affect weed dynamics in organic crop rotation system

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Research Article

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Abstract

Integrated weed management (IWM) is essential for organic farming cultivation. However, an increased weed presence has been found on a farm that applies crop rotations, certified seed, high seeding rate, and false seedbed. This study aimed to evaluate the effect of false seedbed versus conventional tillage on weed dynamics on the field bean crop (*Vicia faba* L. 'Minor') after 3 yr of application of crop rotation (field bean, sunflower [*Helianthus annuus* L.], and durum wheat [*Triticum durum* L.]) and IWM strategies. The field bean 2024 false seedbed (FB24Fs) yield was 0.9 Mg ha^{-1}, less than half of the field bean 2024 conventional (FB24C) yield (2 Mg ha^{-1}). About 66% of total aboveground biomass (AGBt) was related to wild oat (*Avena fatua* L.) in FB24Fs at harvest. The yield and AGB results at harvest can be explained by the evolution of crop and weed density dynamics. For FB24Fs, the crop plant number (PNc) at germination (G) was 30 m^{-2}, the weed plant number density (PNw) at G was 74% of the total (PNt), with predominance of monocotyledons, PNm (62%). The delay in crop seeding, germination, and environmental and soil differences affected early weed germination and high weed competitiveness. Employing repetitive cultivation strategies, such as false seedbed and late sowing, can lead over time to the selection of a few competitive weeds.

Introduction

Maintaining sustainability in agricultural practices while producing highly nutritious products has been challenging in recent decades. Organic farming is a practical alternative for reducing environmental and climate impact (Jensen et al. 2012). However, weed management is one of the main challenges in organic farming, leading to an increase in weed density, diversity, and evenness (Frenda et al. 2013; Knapp et al. 2023; Marino 2023; Mwangi et al. 2024). Integrating appropriate agronomic practices (Benvenuti et al. 2021) and altering a single approach to holistic integrated weed management (IWM) to achieve sustainability is needed (Riemens et al. 2022). IWM uses all the sciences—physics, chemistry, biology, and ecology—in a holistic/systems-based approach to control weeds (Merfield 2023; Scavo and Mauromicale 2020). Riemens et al. (2022) developed an IWM system based on five "pillars": (1) diverse cropping system; (2) cultivar choice and establishment; (3) field/soil management; (4) direct control; and (5) monitoring and evaluation. Each of the five pillars has a range of management tools associated with it (Merfield 2023). Among the IWM components are minimizing weed seedbank, crop rotations, reducing weed competitiveness, use of certified seeds, and high sowing rates (Haring and Hanson 2022; Riemens et al. 2022). The false seedbed technique could reduce weed emergence and is a more effective and/or lower-cost weed management tool, particularly in cropping systems (Bàrberi 2002; Gruber and Claupein 2009). The primary focus of IWM is preventing weed competition during early crop growth stages (Melander et al. 2017; Walsh et al. 2018). Rotating among spring- and autumn-planted crops could be a valuable weed management tool. Sunflower (*Helianthus annuus* L.), followed by durum wheat (*Triticum durum* Desf.), and legumes (Mazzoncini et al. 2006) is useful to disrupt the establishment of the weed community (Buhler et al. 2000; Knapp et al. 2023). One of the advantages of including legumes in a crop rotation is their capacity to help increase the range of crop species that are cultivated and reduce N fertilizer requirements in cropping systems (Peoples et al. 2001). Legumes deliver multiple agronomic and environmental benefits that can enhance the sustainability of diverse cropping systems (Balázs et al. 2021). One of the important legumes in the Mediterranean region is the field bean (*Vicia faba* L.), which has a greater ability to fix N_2 compared with other grain legumes (Ruisi et al. 2017) and can improve soil physical properties and soil fertility(Karkanis et al. 2018; Ruisi et al. 2017).

Tillage systems affect the composition and density of the weed communities, mainly by modifying the vertical distribution of seeds in the soil (Buhler et al. 2000), affecting weed

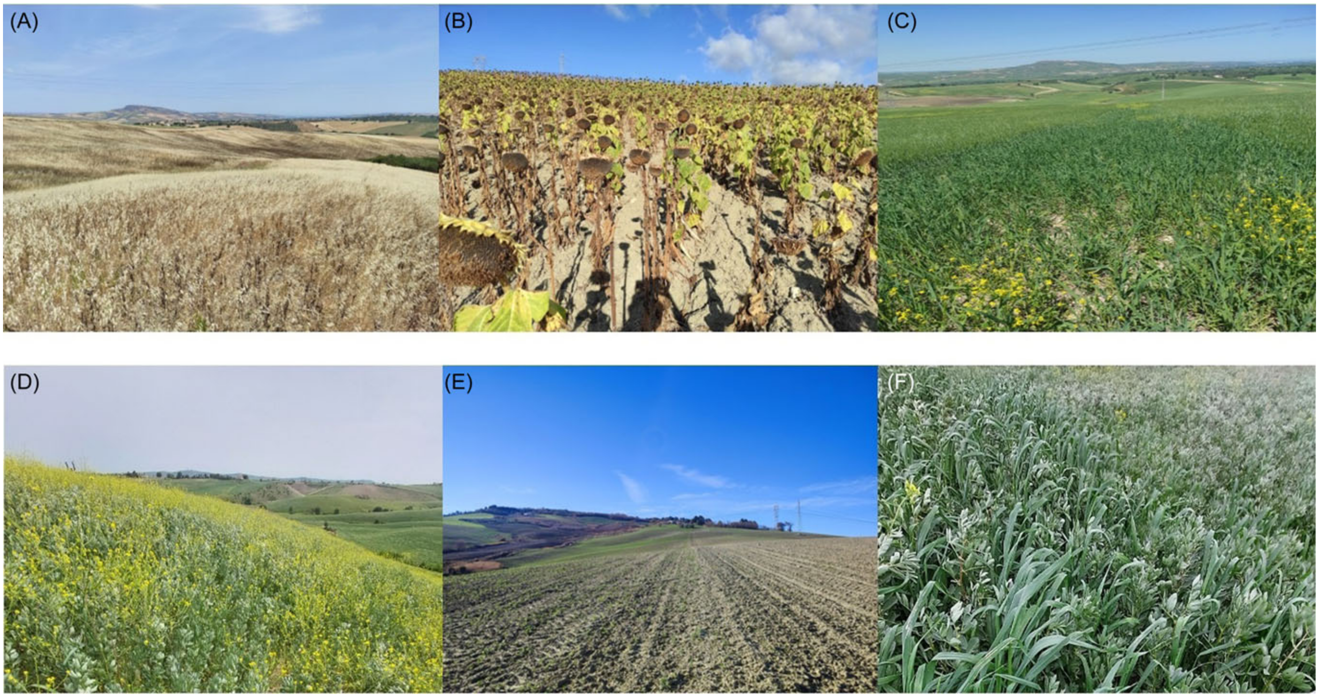

Figure 1. Results of a study in Larino, CB, Italy: (A) Field bean 2021 (FB21); (B) sunflower 2022 (SF22); (C) durum wheat 2023 (DW23); (D) field bean 2024 conventional (FB24C); (E) field bean field 2024 (FB24); and (F) field bean 2024 false seedbed (FB24Fs).

emergence, management, and seed production (Buhler et al. 2000). Moreover, tillage may increase germination of some seeds by mechanisms such as exposure of buried seed to light, aeration of soil, increased soil temperature, soil–seed contact and removal of plant canopy, and release of soil-bound volatile inhibitors (Mwangi et al. 2024). The combined effects of crop rotation and tillage on weed flora deserve special attention despite contrasting results (Omami et al. 1999).

False seedbed preparation is one of the most important techniques for reducing weed populations in organic farming; it consists of one or more seedbed preparations, followed by late sowing (Benvenuti et al. 2021; Gruber and Claupein 2009). False seedbeds are efficient and inexpensive to implement for any crop (Merfield 2023). For the false seedbeds, the machinery must be able to achieve 100% weed removal with a preference to kill weeds using a very shallow re-tillage, ideally less than 2 to 5 cm (Merfield 2023), for example, a rotary cultivator (rotating vertically) and rotary harrow (rotating horizontally) (Benvenuti et al. 2021). This technique often follows a delayed planting date and high seeding rate to ensure the seedbank in the surface layer of soil is depleted and subsequent weed emergence is reduced (Bond and Grundy 2001; Pratchler 2019).

The false seedbed technique is a method providing weed seedbank depletion. Important environmental parameters that influence weed seed germination and seedling emergence can affect the efficacy of false seedbed as a weed management practice. Further research is needed to understand the parameters that influence weed emergence in order to optimize eco-friendly management practices such as false seedbeds in different soil and climatic conditions. To the best of our knowledge, no study reported the same methods of IWM that we applied on legume–cereal–oilseed crops to reduce weed abundance. However, we found one report (Gruber and Claupein 2009) concerning tillage management practices and crop rotation of biennial grass–clover mixture to reduce weed infestation in organic farming. Therefore, there is a need to develop effective and sustainable IWM programs (Chauhan 2020). We applied IWM strategies such as high seeding rates, certified seed, tillage preparation, and false seedbed on field bean in 2021 (FB21), sunflower in 2022 (SF22), and durum wheat in 2023 (DW23) crop rotation in an organic farming system.

We investigated yield, crop plant number, and crop and weed aboveground biomass in a 3-yr crop rotation (FB21, SF22, and DW23), then analyzed weed dynamics in field bean 2024 (FB24) with two different tillage preparation techniques and sowing dates (FB24C and FB24Fs). This study aimed to evaluate the effect of false seedbed versus conventional tillage on weed dynamic during the crop cycle on the field bean crop after 3 yr of application of a crop rotation system and IWM strategies in an organic farming system.

Materials and Methods

Study Area and IWM Strategies

This study was conducted during the 2021 to 2024 growing seasons in an approximately 14-ha open-field farm at Larino, CB, Italy (41.840225°N, 14.910936°E; 492,605.50 E, 4,632,040.67 N: UTM-WGS84 zone 33 N Italy). This organic farm, certified in 2016, is located near the eastern coast of Italy, in the lower reaches of the Biferno River. The following crop rotation was adopted: field bean (2020 to 2021) (FB21); sunflower (2022) (SF22); durum wheat (2022 to 2023) (DW23); and field bean (2023 to 2024) (FB24). On FB21, SF22, and DW23, crop traits and weed composition were monitored. For FB24, the effect of false seedbed (FB24Fs) versus conventional tillage (FB24C) and sowing date on crop traits and weed abundance and dominance (impact) were evaluated (Figure 1).

The IWM strategies were applied to control the soil weed seedbank and to increase the crop's competitive capacity (Scavo and Mauromicale 2020). Field bean, durum wheat, and sunflower crops were included in the crop rotation strategies. An earlier

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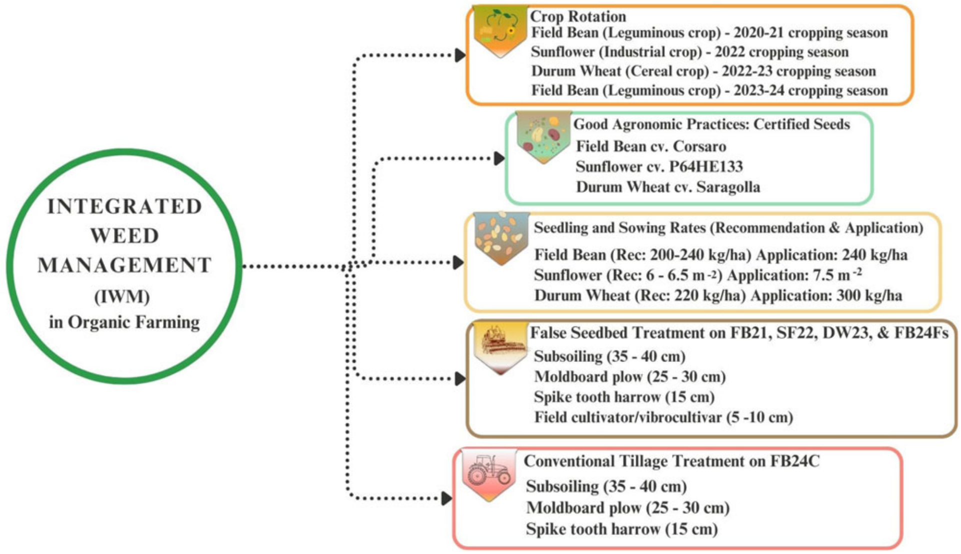

Figure 2. Flowchart for application of integrated weed management (IWM) strategies in organic farming.

Table 1. Agronomic integrated weed management (IWM) application in 4-yr crop rotation in Larino, CB, Italy.

Crop	Abbr.	Date		Certified seeds	Tillage operation
		Sowing	Harvest		
Field bean	FB21	December 6, 2020	June 11, 2021	'Corsaro' Seed: 240 kg ha^{-1}	1 subsoiling, 1 moldboard plowing, 2 spike tooth harrowing, 2 field cultivator/ vibrocultivator
Sunflower	SF22	May 5, 2022	August 22, 2022	P64HE133 ('Pioneer') Seed: 7.5 m^{-2}	1 subsoiling, 1 moldboard plowing, 2 spike tooth harrowing, 2 field cultivator/vibrocultivar
Durum wheat	DW23	December 13, 2023	July 23, 2023	'Saragolla' Seed: 300 kg ha^{-1}	1 subsoiling, 1 moldboard plowing, 2 spike tooth harrowing, 2 field cultivator/vibrocultivar
Field bean Conventional Field bean False seedbed	FB24C FB24Fs	December 4, 2023 December 11, 2023	June 9, 2024 June 10, 2024	'Corsaro' Seed: 240 kg ha^{-1}	C:1 subsoiling, 1 moldboard plowing, 2 spike tooth harrowing. Fs:1subsoiling, 1 moldboard plowing, 2 spike tooth harrowing, 2 field cultivator vibrocultivator

seedbed preparation followed by mechanical weed control was adopted. Furthermore, certified seeds with a high pureness rate and high crop density were used. The IWM strategies and agronomic practices are reported in Figure 2 and Table 1.

The sowing, tillage operation, cultivar information, and harvest dates of the 3-yr crop rotation, FB24C, and FB24Fs are reported in Table 1. For FB24, subsoiling was applied on September 2 and moldboard plowing on September 25. For FB24C, two-spike tooth harrowing was used on November 13 and 30. For FB24Fs, two-spike tooth harrowing was applied on October 20 and November 5. Field cultivator/vibrocultivator for false seedbed was applied on November 23 and December 7. Agronomic practices and tillage intensity practiced by the farmers followed the traditional practices of the area.

Weather Data and Soil Characteristics

Weather data were collected from a weather station located within 1 km of the experimental sites and reported in Figure 3. The total rainfall and average temperature for the FB21, SF22, DW23, and FB24 were 851.3 mm and 12.9 C; 208.3 mm and 35.0 C; 560 mm and 14.7 C; 374.5 mm and 14.8 C, respectively. The minimum temperature during the growing period was recorded in February (−2.5 C) for FB21, May (10.6 C) for SF22, February (−0.6 C) for DW23, and January (0.6 C) for FB24. The maximum temperature was recorded in June (36.2 C), July (36.6 C), June (35.3 C), and June (39.7 C) for FB21, SF22, DW23, and FB24, respectively.

Ten soil samplings (0 to 30 cm) of the experimental field were collected on February 21, 2024. The mean soil characteristics (FB24C; FB24Fs) of the experimental field are reported in Table 2. The soil texture is clay with slight alkalinity pH 7.78 (FB24C) and pH 7.63 (FB24Fs); low values of total N%, 0.24% for FB24C and 0.14% for FB24Fs; low available P 1.596 mg kg^{-1} (FB24C) and 0.316 mg kg^{-1} (FB24Fs); moderate soil organic matter, 1.67% for FB24C and 1.44% for FB24Fs; and moderate organic C of 9.71 g kg^{-1}in FB24C and 8.40 g kg^{-1} in FB24Fs.

Data Collection

Field Measurements

A stratified random sampling (StrRS) strategy was adopted in the field for all crops across 4 yr (Zhao et al. 2016). StrRS utilizes

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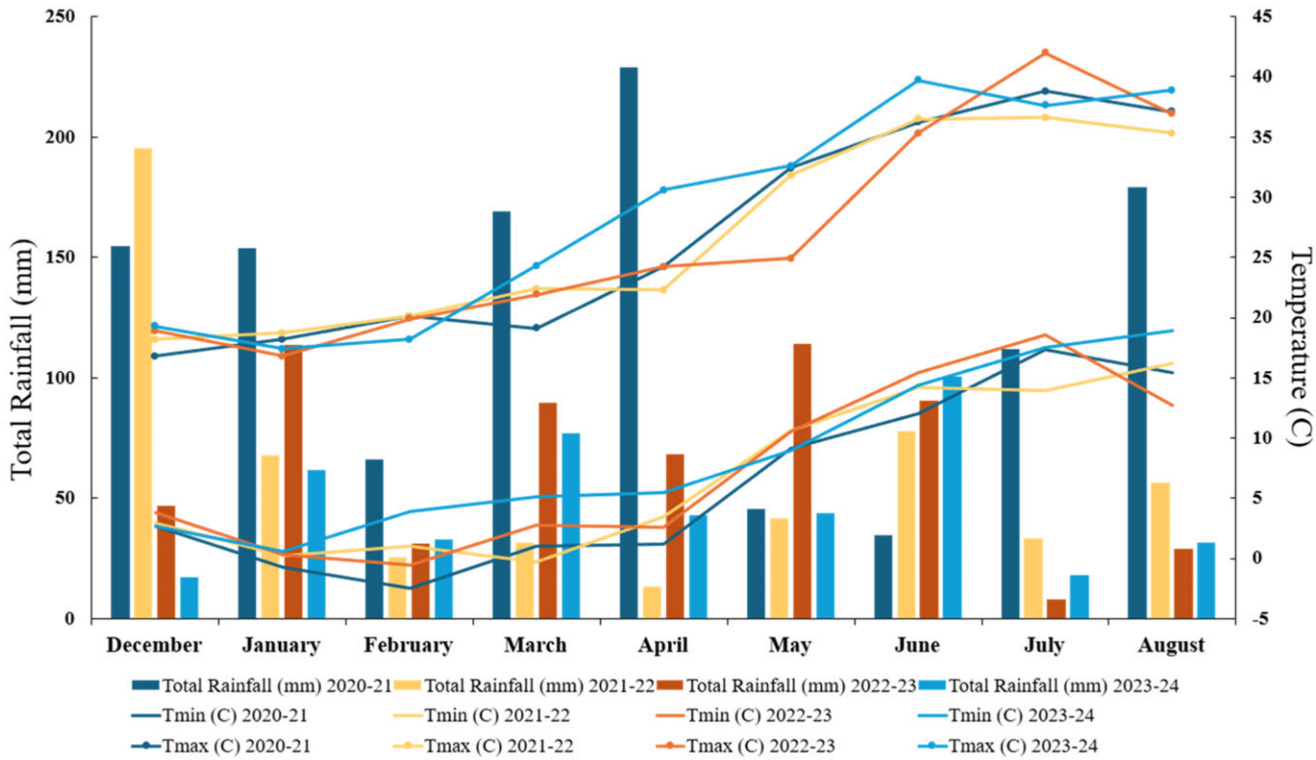

Figure 3. Monthly total rainfall (mm), minimum and maximum temperature (C), during 4-yr cropping seasons (2020–2024) in Larino, CB, Italy.

Table 2. Soil characteristics at the field study site in Larino, CB, Italy: soil properties, field bean 2024 conventional (FB24C) and field bean 2024 false seedbed (FB24Fs) and soil analysis methods.

	Area		
Soil properties	FB24C	FB24Fs	Methods
Sand (0.02 mm)	17.75%	24.24%	Hydrometer
Silt (0.002–0.02 mm)	29.68%	23.38%	
Clay (<0.002 mm)	51.60%	52.39%	
Soil texture	Clay	Clay	
pH (H_2O)	7.78	7.63	H_2O
Total N	0.24%	0.14%	Kjeldahl
Available P (mg kg^{-1})	1.596	0.316	Olsen
Organic matter	1.67%	1.44%	Walkley-Black
Organic C (g kg^{-1})	9.71	8.40	

known information about the population elements to separate the sample units into nonoverlapping groups, or strata, from which they are then randomly selected. It is a method by which some observations are drawn from a population in order to make inferences about the population as a whole (Glasgow 2005). Stratification may produce a gain in precision for estimates of characteristics of the whole population. It will be beneficial whenever a heterogeneous population can be divided into relatively homogeneous strata and may be used to address differences in sampling problems across different parts of populations. For example, different sampling methods might be required or desired for different strata. Estimates of population parameters may be desired for certain subpopulations within the general population. This approach is especially useful if one or more strata are relatively rare in the population (Glasgow 2005) In this case, an oversampling of this strata can be used to estimate population parameters for these strata. Moreover, in StrRS, proportional and optimal allocations of the samples into strata improve the sampling precision. Georeferenced data were collected on a 1-m^2 surface for each sampling.

In crop rotation growing seasons (2020 to 2023), a total of 21 samplings for FB21, 20 samplings for SF22, and 33 samplings for DW23 were collected before harvest. Moreover, crop yield; crop plant number (PN); crop aboveground biomass (AGBc), and weed aboveground biomass (AGBw) were evaluated, and weed species were also analyzed.

A total of 20 samplings for FB24C and 20 samplings for FB24Fs were collected before harvest for crop and weed trait analyses. Moreover, in FB24, the number of plants and weeds was evaluated from the end of January to the middle of May for C treatment (53, 79, 108, 134, and 163 d after sowing [DAS]) and for Fs treatment (46, 72, 101, 127, and 156 DAS), using 12 georeferenced samplings for each treatment and stage with a total of 120 randomized 1-m^2 field samplings of each.

The FB24 data were collected at different phenological stages according to the BBCH (Meier 2018) growth stage scale from the germination (G), leaf development (LD), flowering (FL), development of fruit (FR), and ripening (RI) stages. Subsequently, weed species were identified and grouped into monocotyledon (m) and dicotyledon (d). On June 9 and 10, 2024, the whole field of field beans (FB24) was mechanically harvested, and the yield was determined at 13% moisture content. Whole crop traits were determined after oven-drying plant material at 65 C until reaching constant weight. Plant and weed height were measured using a ruler. The leaf area surface (LAS) of plants and weeds were measured using a leaf area meter (L1-3100C, Lincoln, NE, USA).

Table 3. The mean value of the crop yield (yield), crop plant number (PN), crop aboveground biomass (AGBc), and weed aboveground biomass (AGBw) in FB21, SF22, and DW23 on the same field in Larino, CB, Italy.

Crop	Year	Yield		PN		AGBc		AGBw	
		Mg ha^{-1} (SE)		no. m^{-2} (SE)		g m^{-2} (SE)			
Field bean	2021	2.08	(±0.21)	46.1	(±2.40)	348.5	(±33.8)	84.1	(±18.4)
Sunflower	2022	3.69	(±0.19)	3.93	(±0.20)	1006	(±42.1)	0	
Durum wheat	2023	2.11	(±0.21)	252	(±20.8)	481	(±47.2)	149.5	(±16.8)

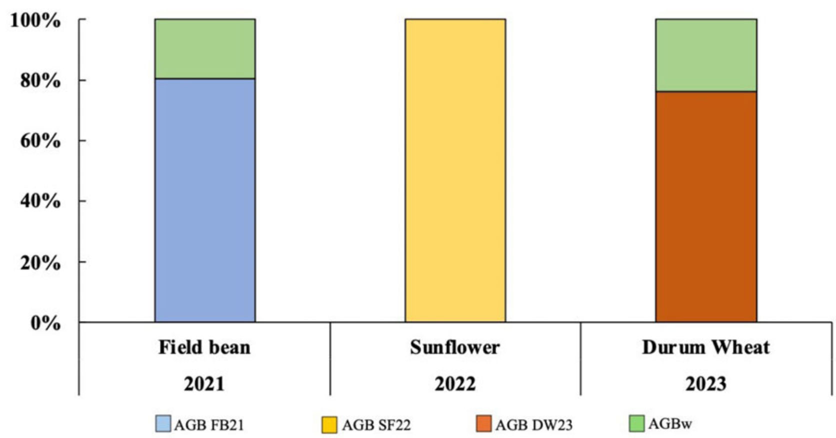

Figure 4. Crop–weed relative density of crop aboveground biomass (AGB) and weeds aboveground biomass (AGBw) of field bean 2021 (FB21), sunflower 2022 (SF22), and durum wheat 2023 (DW23), respectively, in Larino, CB, Italy.

Relative Biomass Index

The weed relative biomass, density, and LAS were calculated as follows:

$$\text{Weed relative biomass} = \frac{\text{AGBw}}{\text{AGBw} + \text{AGBc}} \times 100 \qquad [1]$$

Weed relative biomass was calculated on the basis of the total AGBw related to the total AGB of crop and weeds per square meter (Equation 1) for FB21, SF22, and DW23. In addition, the weed relative density for AGBm and AGBd was evaluated for FB24.

$$\text{Weed relative density} = \frac{\text{PNw}}{\text{PNw} + \text{PNc}} \times 100 \qquad [2]$$

Weed relative density was calculated on the basis of the total PNw related to the total PN of crop and weeds per square meter (Equation 2). Weed relative density for PNm and PNd for FB24 was evaluated.

$$\text{Weed relative LAS} = \frac{\text{LASw}}{\text{LASw} + \text{LASc}} \times 100 \qquad [3]$$

Weed relative LASm and d were also evaluated to FB24 (Equation 3). Higher weed density signifies a more prominent weed presence, which can compete with crops for resources like water, sunlight, and nutrients and potentially decrease crop yields (Rana and Kumar 2014). This index formula closely follows Rana and Kumar (2014) index formula, and it can be used to study weed dynamics in organic farming, although those authors applied it to weed populations in response to herbicide application.

Statistical Analysis

Within each experiment, 3-yr crop rotation data were evaluated based on the means and SEs (standard errors) of each crop and weed presence, the benchmark (higher or lower) was not adjusted due to the differences among crops. The comparison between FB21 and FB24 was subjected to one-way ANOVA of the treatment (C and Fs). Field bean (FB24) data were subjected to one-way ANOVA of the treatment (Fs and C) and two-way ANOVA of treatments (C and Fs) and different growth stages (G, LD, FL, FR, and RI); replications were treated as a random effects, and the interaction between the treatments and growth stages was tested with Tukey's test (Rasmussen 2024) at the significant level $P < 0.05$ least significant difference (LSD). The normal distribution of the experimental data was evaluated by applying the Shapiro-Wilk test. Homogeneous groups were determined by Tukey's multiple-range test to compare the main effects using consecutive letters starting from "a", the highest value, to "c", the lowest value; and interaction comparisons were calculated using the appropriate SE terms following Gómez and Gómez (1984) and Helios et al. (2021). The Statistica (StatSoft, Tulsa, OK, USA) and OriginPRO (Origin Lab Corporation, Northampton, MA, USA) packages were used for this purpose (Gómez and Gómez 1984).

Results and Discussion

IWM Evaluation on Three-Year Crop Rotation

The analysis of IWM strategies on crop rotation started in 2020 to 2021 on the FB21 crop; sunflower (SF22), and durum wheat (DW23) were evaluated. The mean crop yield for FB21 was 2.08 Mg ha^{-1} with an AGBc of about 350 g m^{-2} and 46 plants m^{-2} at harvest (Table 3). The total AGBw was 84.1 g m^{-2}. In FB21, the AGBw% reached 19.4% of total AGB (crop + weeds) (Figure 4).

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Table 4. Field bean yield (yield), crop aboveground biomass (AGBc), crop plant number (PNc), crop plant height (PHc), leaf area surface (LASc), weed aboveground biomass (AGBw), weed plants number (PNw), weed plant height (PHw), and weed leaf area surface (LASw) of field bean 2024 conventional (FB24C) and field bean 2024 false seedbed (FB24Fs) in a study in Larino, CB, Italy. T = F-value [a].

		Crop					Weeds			
		Yield	AGBc	PNc	PHc	LASc	AGBw	PNw	PHw	LASw
Treatment		Mg ha^{-1}	g m^{-2}	no. m^{-2}	cm	cm^2	g m^{-2}	no. m^{-2}	cm	cm^2
C		2.06a	318a	45.8a	69a	11004a	115b	12.8	99.1a	3115b
Fs		0.89b	141b	30.4b	58.3b	5658b	510a	16.4	61.4b	15,690a
	df									
T	1	37.7*	13.5*	6.02*	5.29*	18.9**	7.73*	0.67 ns	7.12*	9.77*

[a]ANOVA one-way and post hoc Tukey test results. Significant at: *P < 0.05; **P < 0.01; ns = nonsignificant. df, degrees of freedom.

The FB21 yield was within the range reported by Lakić et al. (2022), who found that a field bean yield ranged from 1.26 to 2.09 Mg ha^{-1} with biostimulant treatment; some authors also reported that the grain yield of field bean in short-season rainfed Mediterranean conditions ranged from 1.1 to 1.92 Mg ha^{-1} in central Italy (Mariotti et al. 2018) to 1 to 2.5 Mg ha^{-1} (Lombardo et al. 2016) and 1.98 to 3.3 Mg ha^{-1} (Polignano et al. 2015) in southern Italy. The weed biodiversity found in the early growth stages of cultivation has since been reduced during the crop cycle to two species, namely wild mustard (*Sinapsis arvensis* L.) and wild oat (*Avena fatua* L.). SF22 showed a yield mean value of 3.7 Mg ha^{-1}, with 4 plants m^{-2} and AGBc of 1,006 g m^{-2}; no weeds were found. The AGBw% in DW23 was 23.7% of the total AGB (Figure 4). In FB21, the main species at harvest was *A. fatua* (80%), although weed populations at early growth stages of autumn–winter crops included *S. arvensis* (1), annual bluegrass (*Poa annua* L.) (2), Italian ryegrass (*Lolium perenne* L.) (1), Canada thistle [*Cirsium arvense* (L.) Scop.] (1), common poppy (*Papaver rhoeas* L.) (3), *A. fatua* (3), German chamomile (*Matricaria recutita* L.; syn.: *Matricaria chamomilla* L.) (3), field bindweed (*Convolvulus arvensis* L.) (2), meadow foxtail (*Alopecurus pratensis* L.) (13), and broomrape (*Orobanche crenata* Forssk.) (1). Notably, no yield reduction and weed infestation were reported in the SF22 cropping season. To address this concern, sunflower was included as a summer crop to prevent weed abundance in the next cropping season in accordance with Anderson et al. (2010), who reported that sunflowers reduced winter annual weeds adapted to low germination temperatures. DW23 yield was 2.1 Mg ha^{-1}, 252 plants m^{-2}, with an AGBw of 149.5 g m^{-2}. Despite the absence of weeds in SF22, the weed evolution since FB21 resurfaced again in DW23. Durum wheat 'Saragolla' still maintains the top position under the organic farming system (Fagnano et al. 2012). This cultivar is adaptable to the lower N availability (Fagnano et al. 2012) and limiting factor of water availability (Garofalo et al. 2009). The yield in DW23 was about 30% lower than the highest yield recorded in the same production areas (Marino 2023), and 23% of the total AGB was weed related, mainly *A. fatua* and *C. arvense*. As a result, the plant number in DW23 (252 plants m^{-2}) was 25% lower compared with the plant number recorded by Fagnano et al. (2012).

Field Bean Agronomic and Weed Trait Analysis for Conventional and False Seedbed Treatments

Table 4 shows the crop and weed traits with different tillage preparation and sowing date treatments. Crop yield showed a significant difference between C and FS with a mean value of 2.06 Mg ha^{-1} and 0.89 Mg ha^{-1}, respectively. The AGBc and PNc showed the same statistical results, with a mean value of 318 g m^{-2} of AGBc, and 45 plants m^{-2} PNc for FB24C and significant differences with FB24Fs (AGB mean of 141 g m^{-2} and 30 plants m^{-2} PN). The Ph and PNw showed no significant differences between the treatments. However, in the Fs treatment, AGBw (510 g m^{-2}) and LASw (15,690 cm^2) were significantly higher than in the C treatment (115 g m^{-2} for AGBw and 3,115 cm^2 for LASw). AGBw in FB24Fs was 66.2% out of AGBt, in FB24C, AGBw was 24.2% out of AGBt. Despite Fakkar and Mohamed (2018) reporting that crop rotation improved crop growth and yield traits and produced the highest seed yield of field bean, in our study, weed infestation negatively affected the yield in FB24Fs. However, the FB24Fs yield fell outside the range, and it seems the weed control efficiency of the false seedbed against weeds was lower than expected. While Morishita and Till (1988) found a yield loss of up to 75% in barley (*Hordeum vulgare* L.) in the presence of *A. fatua* due to the allelopathic potential. Some authors have reported that soil tillage treatments employing subsoiling, moldboard plowing (Gruber and Claupein 2009), harrowing and rotary tiller, and spike tooth harrowing (Benvenuti et al. 2021; Lestingi et al. 2011) are less effective against weeds. Tillage did not affect weed species richness but had a major role in determining the composition of the weed community (Giambalvo et al. 2012). Furthermore, secondary tillage was ineffective when the weather conditions (sufficient soil moisture, temperature, light) were not met, failing to trigger weed germination (Riemens et al. 2022). Hardly any studies have demonstrated the adaptation capacity of weeds to cultural and mechanical operations (Riemens et al. 2022). Overall, weed dynamics under diverse tillage and crop establishment systems can vary greatly due to the complex interaction between weed and tillage practices (Kakraliya et al. 2024). If the aim is to reduce weed seedbank of certain predominant weed seedbanks (spring–summer or autumn–winter life cycle), soil tillage needs to be carried out during the most suitable periods (early or late spring) (Benvenuti et al. 2021).

In our study another aspect that has favored the competitiveness of weeds was the late sowing date. Our finding is in line with Rasmussen (2004), who reported there was a significant yield reduction due to false seedbed and/or late sowing. The sowing date of FB24c was on December 4 (Table 1), the total precipitation was 10.9 mm (Figure 2) from December 4 to 10, supporting the germination stage. Notably, no rain occurred after the FB24Fs sowing (December 11, 2024). Although there was only a week difference with soil moisture, temperature conditions, and sowing depth considered, it delayed crop germination. Planting time is one of the major factors affecting field bean phenological stages, as the turning phase depends on photothermal conditions such as temperature (Amalfitano et al. 2018). Indeed, field bean ('Corsaro')

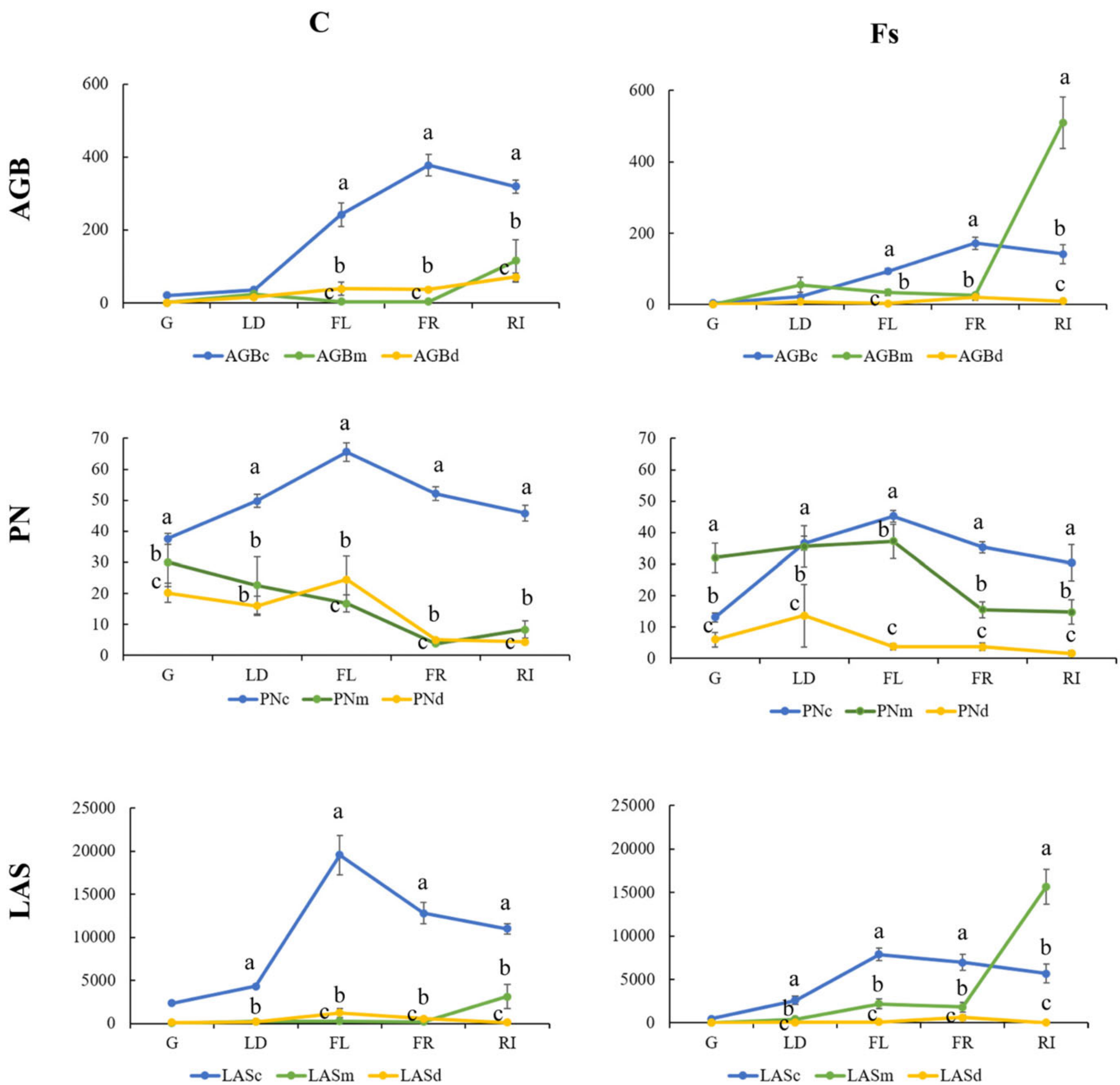

Figure 5. Results of a study in Larino, CB, Italy, for field bean field 2024 (FB24): conventional tillage (C) and false seedbed (Fs) treatments, crop aboveground biomass (AGB), plant number (PN), and leaf area surface (LAS) of crop (c), monocotyledon weeds (m), and dicotyledon weeds (d) at germination (G), leaf development (LD), flowering (FL), fruit development (FR), and ripening (RI) stages.

was cold tolerant and suitable for marginal areas. Nevertheless, soil characteristics were more likely to affect the AGBc% in the Fs treatment; the chemical soil properties such as total nitrogen of 0.14%, available P of 0.316 mg kg^{-1}, organic matter of 1.44%, and organic carbon 8.40 (g kg^{-1}) were lower than in the C treatment (Table 2).

Figure 5 shows crop and weed traits at G, LD, FL, FR, and RI stages. The AGBc was significantly higher than AGBw (AGBm + AGBd) starting from FL for both treatments. Statistical differences were found between AGBc versus AGBw (AGBm and AGBd) in the C treatment at the FL, FR, and RI stages. Notably, the AGBc was higher than the AGBm at RI stage in the C treatment. In the Fs treatment, AGBm conquered the area at the LD growth stage, giving rise to AGBm reaching 510 g m^{-2} at the RI stage, while AGBc was only 141 g m^{-2}, corresponding to 21% of the total AGB.

The PNc increased from germination to flowering for both treatments. In the C treatment, PNc increased gradually from G to FL with a value range from 37 to 65 plants m^{-2}, while PNm decreased slowly from G to RI with a value from 30 to 8.4 plants m^{-2}, and PNd decreased from G (20 plants m^{-2}) to RI (4 plants m^{-2}). In the Fs treatment, the PNc was 13 plants m^{-2} at germination, with PNm of 32 plants m^{-2} and PNd of 6 plants m^{-2}. The mean PNc at FL was 45 plants m^{-2} with a PNm of 37 plants m^{-2} and PNd of 4 plants m^{-2} in the Fs treatment.

Although we applied high seeding rates to enhance crop superiority, it was not apparent on FB24Fs, where the higher PN

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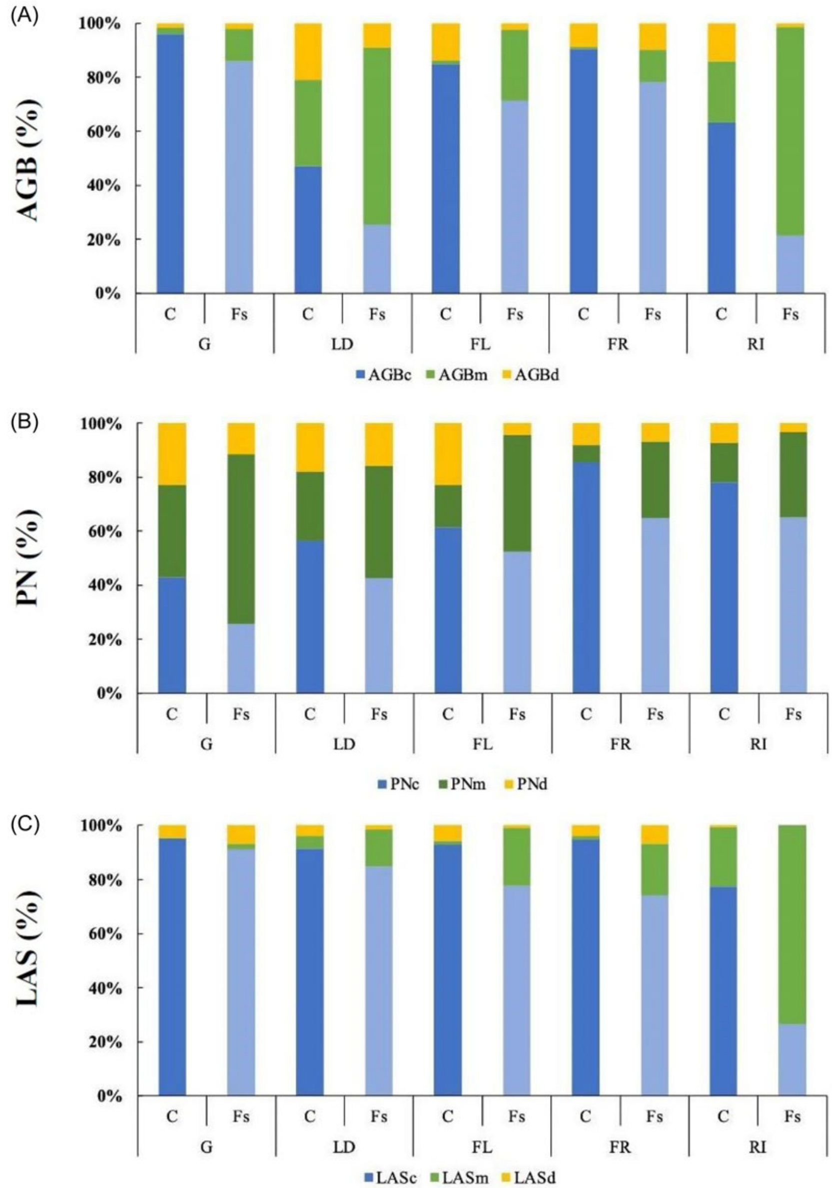

Figure 6. Crop–weed relative density of conventional tillage (C) and false seedbed (Fs) treatments of crop aboveground biomass (AGB%), plant number (PN%), and leaf area surface (LAS%) of crop (c), monocotyledon weeds (m), and dicotyledon weeds (d) at germination (G), leaf development (LD), flowering (FL), fruit development (FR), and ripening (RI) stages, in Larino, CB, Italy.

was 45 plants m^{-2} in C, while it was only 30 plants m^{-2} in Fs. The recommendation for the seeding rate of field bean to reach the maximum agronomic yield was about 50 seeds m^{-2} when considering all environments (Pratchler 2019). Increasing seeding rates reduced both yield loss and *A. fatua* seed production (Wildeman 2004). However, Helios et al. (2021) stated that the high sowing density (>75 plants m^{-2}) caused competition between plants in field bean, leading to yield reduction. In our case, the yield reduction was not correlated to competition between plants, but more likely between crops and weeds (Figure 1D and 1F).

Notably, LAS shows the same trend as AGB. Averaged weed pressure was evident in AGBw (mainly monocotyledon weeds) and LASw in the Fs treatment, leading to a more than 50% decrease in the final yield. The weed population at G stage in both treatments was inconsistent. Initially, monocotyledon weeds (PNm) dominated both areas, then conquered the FB24Fs significantly. Gruber and Claupein (2009) discovered the highest number of monocotyledon weeds occurred in the chisel plow (10-cm depth) treatment (48 plants m^{-2} in 2005 and 24 plants m^{-2} in 2007). This means that their stubble and shallow tillage did not kill monocotyledon weeds, the same as our false seedbed technique. This finding is also similar to our study, where FB24Fs with a field cultivator (5- to 10-cm depth) failed to reduce weed germination at the early stages, leading to the highest monocotyledon weed of 37 plants m^{-2} at the FL stage. AGBm and LASm were not correlated to PNm, probably due to the difference in abiotic conditions (soil, temperature, water, total N). Ntatsi et al. (2018) recorded *S. arvensis* as having one of the highest weed densities in field bean with a value ranging from 8 to 43 plant m^{-2}. Frenda et al. (2013) mentioned that *S. arvensis* dominated the field bean plot at crop emergence. In our study, the highest PNd of *S. arvensis* was recorded at the FL stage in the C treatment of 24 plant m^{-2} and Fs

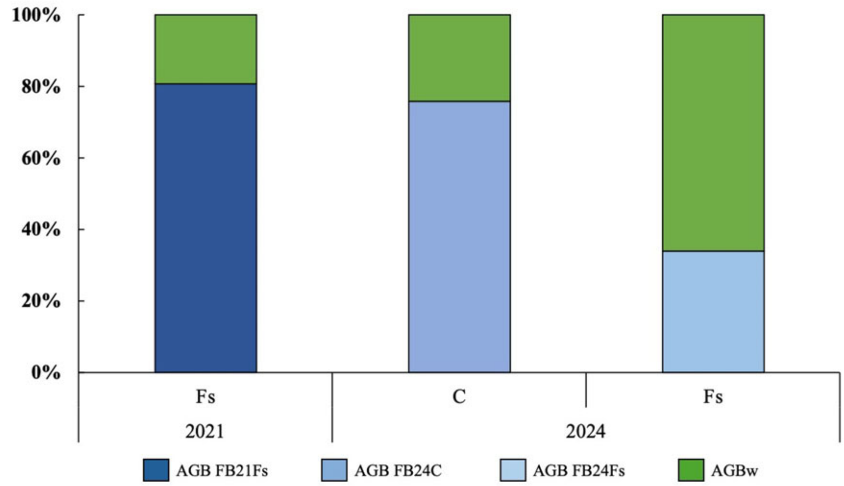

Figure 7. Crop weed relative density of crop aboveground biomass (AGB) and weed aboveground biomass (AGBw) of field bean 2021 false seedbed (FB21Fs), field bean 2024 conventional (FB24C), and field bean 2024 false seedbed (FB24Fs), in Larino, CB, Italy.

treatment of 13 plant m^{-2}. Interestingly, the highest AGBd (*S. arvensis*) was recorded at the RI stage of 70 g m^{-2} in FB24C. In line with our study, *S. arvensis* is one of the most abundant species found during the study period in field bean with conventional tillage (moldboard plow) (Giambalvo et al. 2012). From our soil data, total nitrogen was higher in FB24C (0.24%) than in FB24Fs (0.14%); more likely, total N affects this weed. Our data was confirmed by Fracchiolla et al. (2018), who found that *S. arvensis* is triggered by the higher dose of N on the conventional tillage treatment; however, a study about the relation between soil N and *S. arvensis* is elusive.

The evaluation of crop/weed percentage of FB24C and FB24Fs treatments at five growth stages is illustrated in Figure 6. The AGBc values between C and Fs were significantly different at G, LD, FL, FR, and RI stages. The highest percentage of AGBw (AGBm + AGBd) was found in the Fs treatment. The AGBc of C and Fs at G stage was 96% and 86%, respectively. AGBc in the C treatment was always higher than 40% from G to RI stage; in contrast, in the Fs treatment, it reached the lowest percentage at RI stage, about 20% out of the total AGBt.

Moreover, about 66% of total AGB was related to *A. fatua* in FB24Fs at harvest, in contrast to 24% of AGBw recorded in FB24C, probably a result of the low intensity of mechanical weed control, resulting in early weed germination and high competitiveness. Our data related to the impact of *A. fatua* on field bean yield agree with Marino (2023), who reported the presence of *A. fatua* with an average value of 250 g m^{-2} negatively affected the yield component of winter wheat (*Triticum aestivum* L.), and Morishita and Till (1988) found the effect of *A. fatua* on *H. vulgare* yield is greater when *A. fatua* emerges before the crop. In addition, we agree with Rasmussen (2024), who highlighted the importance of treatment intensity evaluation.

Interestingly, the number of plants per square meter was apparent at the G stage, where the PNc% reached 42% (C) and 25% (Fs). Particularly, increasing PNc% and decreasing PNw% (PNm% and PNd%) were evident in the C treatment from the beginning to the end of the growth stages. In the Fs treatment, PNc increased from G to RI stage with values of 25% and 65%, respectively. In contrast, PNw decreased with a value of 74% at G and 35% at RI, with a prevalence of PNm with a range from 62% at G and 31% at RI stage.

We found a considerable variation in weed population in FB24C and FB24Fs. However, a remarkably high density of *A. fatua* and *S. arvensis* occupied both areas, with predominance of *S. arvensis* in FB24C (Figure 1D) and *A. fatua* in FB24Fs (Figure 1F), increasing from the G to the RI stage. *Avena fatua* and *S. arvensis* were the most competitive weed species studied (Wildeman 2004).

The LASc, LASm, and LASd percentages are reported in Figure 6. The LASc of the C treatment shows continuous trends (93%), it was only at the RI stage that LASc was 77% and LASm reached 21%. In contrast, LASc (Fs treatment) decreased extremely from 91% at G to 26% at RI stage. In the Fs treatment, LASm% contributed 73% in the last RI stage. Benvenuti et al. (2021) found *S. arvensis* contributed to 40% of the total weed seedbank in an organic cropping system, and Frenda et al. (2013) found *S. arvensis* accounted for more than 85% in an field bean experimental site. In our study, the lowest and highest PNd% (mostly *S. arvensis*) contributed only 3% for Fs and 23% for C, which is lower compared with their findings. In 2024, conventional management of the tillage and an earlier sowing date compared with false seedbed led the crop to have greater competition against weeds. On the other hand, the false seedbed, by not destroying all the germinated *A. fatua* plants, offered an essential competitive advantage for the weeds compared with the crop, leading to a lower production of more than 50% compared with conventional tillage treatment in 2024 and false seedbed in 2021. The FB21Fs and FB24Fs data evaluation revealed that the same approach did not always produce the same outcome (Figure 7).

IWM methods such as crop rotation, seeding density, false seedbed, sowing date, and certified seeds are essential for proper weed management in organic farming. Because most weed species have high phenotypic plasticity, they can adapt to repeated management tactics and escape control measures aimed at their eradication, such as false seedbed, earlier or later sowing dates, and mechanical weeding operations (Riemens et al. 2022). The false seedbed technique aims at reducing weed germination (Bàrberi 2002); in this case, in combination with the growing environment and weather conditions, it favored the competitive advantage of weeds over the crop in FB24. The use of the same IWM strategies can lead over time to the selection of a few competitive and dominant weed species. Therefore, alternating the IWM methods over the years is recommended, especially to reduce crop–weed competition and improve weed biodiversity.

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