

## Article

# Weed Diversity, Abundance, and Seedbank in Differently Tilled Faba Bean (*Vicia faba* L.) Cultivations

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**Abstract:** Differently tilled faba bean cultivations, in particular, require a comprehensive study of weed diversity, abundance, and seedbank due to the lack of experimental data. Therefore, in 2016–2018, field trials were conducted at Vytautas Magnus University on the basis of a long-term tillage experiment. Conventional deep and shallow plowing, deep chiseling, shallow disking, and no-tillage systems were investigated. According to the results of the investigations, the air temperature and amount of precipitation during the vegetative season had a greater influence on the total number of weeds ( $r = 0.538$  and  $0.833$   $p > 0.05$ ) than the types of tillage systems investigated. However, on average, a reduction in tillage intensity did not change the weed number, especially in disked and not tilled plots. On average, the biomass of weeds varied little between the treatments (from 105.9 to 125.7 g m<sup>-2</sup>) and mainly depended on the volume of forecrop residues ( $r_{\text{annual}} = -0.982$   $p \leq 0.01$  and  $r_{\text{perennial}} = 0.890$   $p \leq 0.05$ ). Higher total weed seedbanks were found in the disked (+43.0%) and not tilled (+21.6%) soils compared to deeply plowed ones. The weed seedbank was almost similarly distributed between the treatments, irrespective of the tillage depth and method used.

**Keywords:** conservation tillage; weed diversity; weed seedbank



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## 1. Introduction

Conservation agriculture systems aim to minimize the soil tillage intensity in order to ensure that there is a permanent layer of crop residues on the topsoil to diversify crop rotation and optimize weed management [1,2]. Tillage reduction has positive aspects: it saves time, protects the soil from erosion [3], saves machinery and fuel costs [4,5], improves the soil quality, and decreases nutrient and pesticide leaching [4]. Germination and the spread of weeds are most strongly influenced by the climatic and meteorological conditions [6,7] (length of vegetative season, precipitation rate and distribution, air temperature, and sum of active temperatures), on which soil moisture, oxygen, and the organic C content depend. The vertical distribution of weed seeds also has an impact [8] as the seeds of different weed species require different amounts of light for germination [9,10]. Moreover, germination conditions in the soil change as the water absorption of weed seeds increases or decreases [11]. These changes depend on the tillage system or type of crop rotation used [8,12–14]. It has been documented that the use of annual conventional deep plowing mainly ensures a higher crop yield and reduces the weed density [15,16], while conservation tillage technologies increase the abundance of annual weeds [14], and no-tillage technologies are more conducive to the spread of perennial weed species [17,18], especially under conditions of ineffective herbicide technology [19]. Weeds producing a lot of small seeds have been found to predominate in areas where no-tillage system is used [20], while the use of conservation tillage technologies leads to the domination of weeds with larger

seeds of later flowering phenology [21]. Short and early flowering weed species are typical of deep tillage systems [22].

The spread of weeds also depends, to a large extent, on how many “fresh” weed seeds enter the seedbank in the soil and on how big the bank is in general [23]. Some researchers believe that tillage has a more pronounced effect on the weed seedbank size and composition than crop rotation [24], while other researchers believe the opposite [25]. Tillage affects the soil weed seedbank by promoting the germination of some seeds and even causing the extinction of other seeds [2,26]. Over time, seed germination can be influenced by soil properties (aggregation and crust formation, penetration resistance, bulk density, and others), which vary with depth; however, depth is not the most important variable. Even in the topsoil, there are many micro sites that can become seedbeds for weeds and have different moisture conditions, temperatures, and oxygen contents, thus, affecting the seed bank [27]. Intensive surface tillage usually reduces weed seedbank located close to the soil surface [1]. When plowing the soil, weed seeds are evenly distributed throughout the entire plow layer, which makes it more difficult to control their quantity.

In most European countries, the cultivation area of faba bean has decreased compared with the area that was present in 1981–1990 [28]. However, since 2015, the EU Greening regulation has encouraged farmers to grow more legume crops. According to the data from the farmland and crop declaration, faba beans accounted for about 2% of the total crop area in Lithuania in 2019 [29]. In general, cereal crops are more competitive against weeds than legumes. Faba beans are sensitive to shading, especially at the stage of pod emergence [30]. However, there is a lack of information on the flora and abundance of weeds in faba bean crops in north-eastern Europe. In addition, in Lithuania, it is at that time that most inefficiently controlled weeds or those thriving in sparse crops (e.g., *Chenopodium album* L., *Persicaria lapathifolia* L., *Echinochloa crus galli* (L.) P. Beauv., *Cirsium arvense* L., *Sonchus arvensis* L.) reach their maximum height and can start dominating in the crops.

This study hypothesizes that, under conditions of tillage intensity reduction and minimal chemical weed control, the abundance and biomass of weeds will progressively increase due to the low competitiveness of beans. Under reduced tillage and no-tillage conditions, the accumulation of weed seedbank in the topsoil will be initiated. The objectives of the research are to establish (a) the abundance and biomass of the most widespread weeds; (b) the seedbank composition and distribution; and (c) the interactions among meteorological conditions, forecrop residue volume, weed number and air-dried biomass, and the weed seedbank in different primary tillage and no-tillage conditions during three faba bean vegetative seasons. The experimental findings will increase our knowledge about which of the factors—long-term tillage systems or meteorological conditions—has a greater impact on weed flora and abundance in short-term investigations in faba bean cultivations. Such information will help us more accurately predict crop weediness under the increasingly volatile meteorological conditions caused by the climate change.

## 2. Materials and Methods

### 2.1. Site Description

Field investigation were conducted in 2016, 2017, and 2018 at the Experimental Station of Vytautas Magnus University Agriculture Academy (Central Lithuania, 54°52' N, 23°49' E). The annual average air temperature at the experimental site is 6.7° C and the precipitation rate is 590–625 mm. The length of the vegetative period is approximately 150–160 days with 350–450 mm of precipitation. The warmest and the wettest month is July. The variation in meteorological conditions is very high between the growing seasons and growth stages because of the uneven subarctic intermediate maritime-continental climate.

The investigations were performed as part of a long-term tillage experiment that has been in progress since 1988. The no-tillage treatment condition was introduced in 2001. The soil at the experimental site is silt loam (45.6% sand, 41.7% silt, 12.7% clay) Planosol [31], that is, on average, neutral in reaction (pH 7.0), high in phosphorus (279 mg kg<sup>-1</sup>), and

has medium proportions of potassium ( $151 \text{ mg kg}^{-1}$ ), total nitrogen (0.144%), and humus (1.75%).

## 2.2. Experimental Treatments and Agronomic Practices

This experiment involved the creation of environmentally friendly agro-technologies for sustainable (*sin.* conservation, integrated) agriculture. The first element of sustainability is the use of plowless or no-till systems. Second, minimal chemical pests, diseases, and weed control methods (integrated approach) are used. In these investigations, the use of pesticides and mineral fertilizers was reduced twice as much as the levels that have been recommended during the last three decades. Third, there was no removal of residues from the top of the experimental plots.

The following five tillage treatments were implemented in autumn: (1) deep moldboard plowing at a depth of 22–25 cm (control treatment, DP); (2) shallow moldboard plowing at a depth of 12–15 cm (SP); (3) deep cultivation-chiseling at a depth of 25–30 cm (DC); (4) shallow cultivation-disking at a depth of 10–12 cm (SC); and (5) no-tillage (direct drilling, NT). The reason for choosing such tillage practices was to ascertain the influence of the tillage intensity on soil nutrients, biological and physical properties, and its conservation. Also  $\text{CO}_2$  gas mitigation, weed abundance, yield, and quality of crops were investigated with a long-term perspective, because arable soils degrade more and more rapidly every year [32–34]. The common tillage practice in Lithuania is annual autumn reversible plowing at the depth of up to 22–25 cm (DP), which is one of the most soil-damaging tillage methods. More sustainable non-reversible tillage and no-till methods are becoming popular but are still not practiced enough.

A four-course crop rotation method was used: winter oilseed rape–winter wheat–faba bean–spring barley. The experiment was performed with four replications for each tillage treatment, and a randomized complete block design (RCBD) was used. The size of each experimental plot was  $126 \text{ m}^2$  ( $14 \text{ m} \times 9 \text{ m}$ ). The experimental data from the faba bean plots (20 plots) are presented as the results of a single factor experiment.

After the harvesting of winter wheat, a forecrop of faba bean, all experimental plots, except for the NT ones, were disked with a disc harrow. The plots were sprayed with glyphosate in spring, before sowing. DP and SP plots were plowed with a plow with semi-helix shellboards. Deep chiseling (DC) was performed with a ridge cultivator (chisel). SC plots were repeatedly disked with a disc harrow. Faba bean was grown using a conventional technology that has been comprehensively described by Romaneckas et al. [35]. Faba bean was sown on 25 April, 2016; 8 May, 2017; and 24 April, 2018, when the topsoil had reached physical maturity (decomposed into structural aggregates during pre-sowing tillage). Local fertilization (NPK 7:16:32,  $300 \text{ kg ha}^{-1}$ ) was used during the sowing operation. The distance between rows was 25 cm, the sowing rate was  $200\text{--}220 \text{ kg ha}^{-1}$  ( $40\text{--}45 \text{ seeds m}^{-2}$ ), the sowing depth was 5–6 cm, and the variety used was “Fuego”. Before sowing, the sowing material was inoculated with a *Rhizobium leguminosarum* bacterial preparation (approximately 200 mL of preparation for 100 kg of seeds). A single background application of the herbicide Fenix  $3.0 \text{ l ha}^{-1}$  (a.i. acetonifin  $600 \text{ g l}^{-1}$ ) was used shortly after faba bean sowing.

## 2.3. Methods

The forecrop (winter wheat) residue coverage on the soil top was evaluated by the line transect method after the sowing of faba bean crops in spring. A 10 m measuring roulette tape was used. The number of times that a marked line intersected with the residue stubble every 10 cm (100 points per plot) was counted, and the results are expressed as percentages.

The weed species composition and weed density were evaluated at the beginning (BBCH 25–27) and end (BBCH 75–79) [36] of the faba bean vegetative period in 10 randomly selected spots for each plot. A set of  $20 \times 30 \text{ cm}$  metal frames was used for this purpose. The data was converted to  $\text{m}^2$ . The same frames were used to establish the biomass of the weed aerial part ( $\text{g m}^{-2}$ ) at the end of the faba bean vegetative period using the Stancevičius [37]

method. Fresh biomass of weeds was dried under laboratory conditions. The air-dried biomass is presented in this study.

The size of the weed seed bank in the soil was determined at the depths of 0–15 and 15–25 cm shortly after the primary tillage in the autumn for at least 10 spots per plot. Soil samples were collected with an agrochemical auger, mixed, and a composite sample was formed. The soil sample (100 g) was dried and sieved through a 0.25 mm sieve and washed with running water until the soil particles were removed. Weed seeds and the remaining part of the mineral soil were separated from the organic part by a saturated saline solution [38].

#### 2.4. Statistical Analysis

The experimental data were analyzed by one-way ANOVA, and the treatment effect was estimated with the  $p$  test and the least significant difference (LSD). Sigma Stat and SYSTAT software were employed. The data from weed studies that did not conform to a normal distribution were transformed using the function (1) before statistical evaluation:

$$y = \lg_{10}(x + 10) \quad (1)$$

A correlation analysis was performed with STAT software. The analysis matrix included data on the meteorological conditions, crop residue volume, weed seed germination, weed number and air-dried biomass, and weed seedbank.

### 3. Results

#### 3.1. Meteorological Conditions

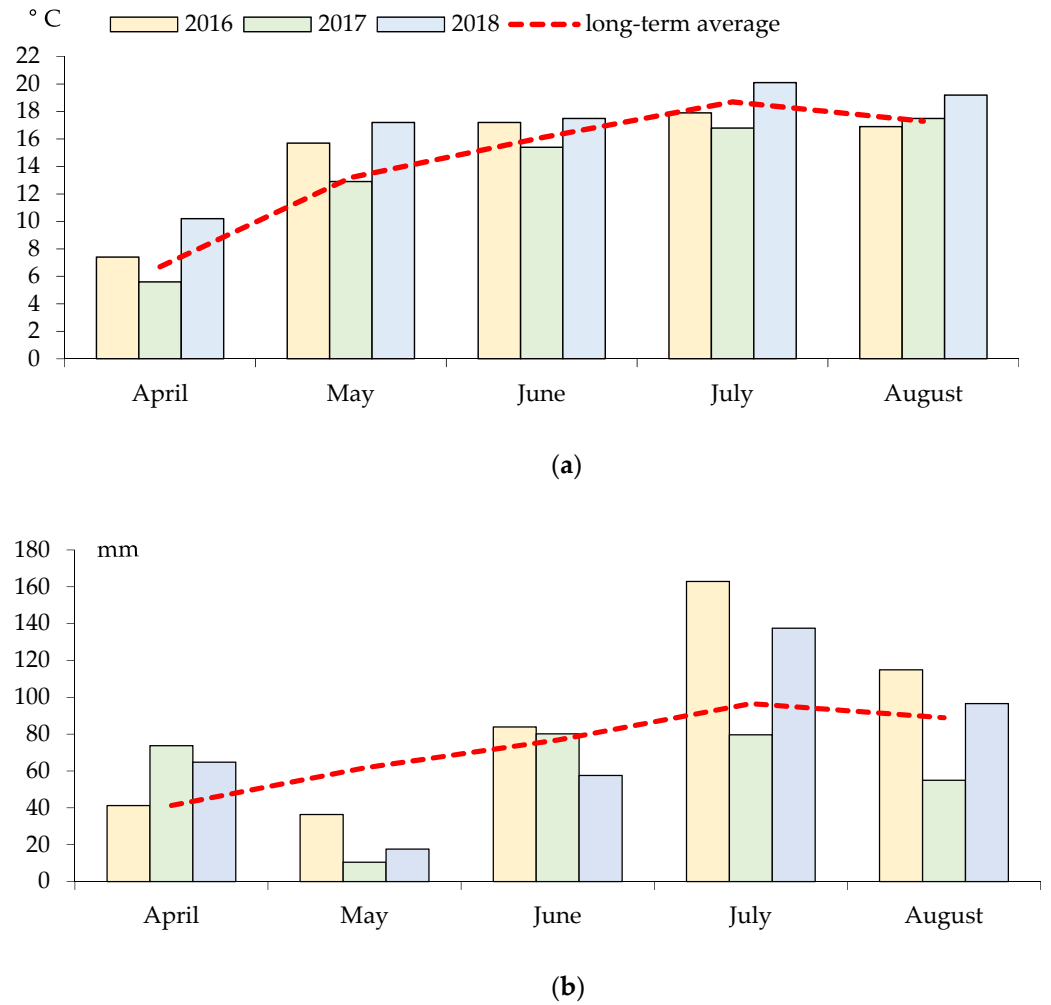
The vegetative period in 2016 (except May) can be described as mainly warm and more humid than the long-term (1974–2016) average (Figure 1). The precipitation rates in May during the three experimental years was 2–6 times lower than usual. These conditions adversely affected crop germination and development.

During the 2017 vegetative period, the average air temperature was similar to or slightly lower than the long-term average (Figure 1). Precipitation rates varied markedly between the months. The beginning of the vegetative period was excessively humid, but during other growth stages, the weather was dry, especially in May, July, and August. The 2018 vegetative period was warmer than usual. May and June were dry, but at the end of the vegetative period, there was excess of moisture. In summary, the meteorological parameters of the three growing seasons differed from one another and from the long-term average conditions (since 1974). Under these conditions, it was difficult to predict the spread of weeds and their influence on crop development and productivity.

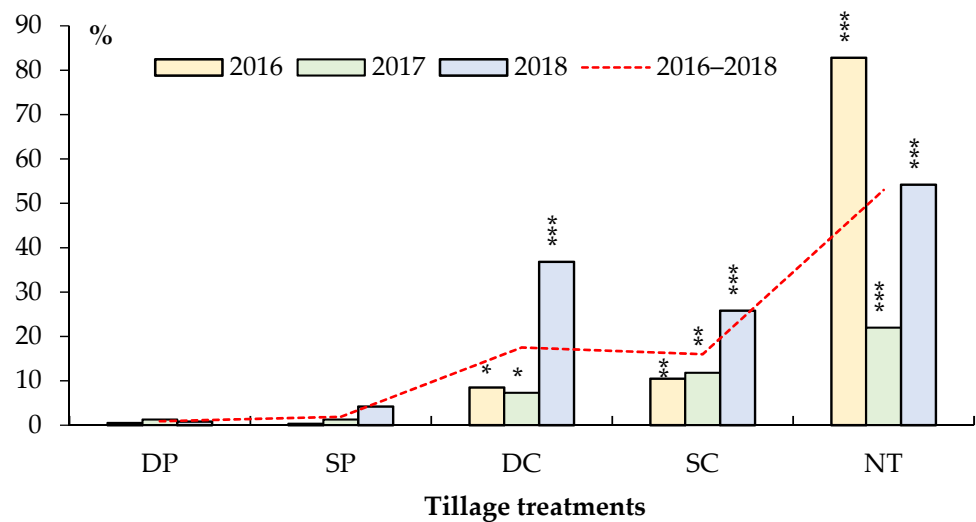
#### 3.2. Topsoil Residue Coverage

During the three experimental years, the topsoil coverage with winter wheat residues varied from 0.3 to 82.8% in 2016, from 1.3 to 22.0% in 2017, and from 0.8 to 54.2% in 2018. The volumes of residues did not differ significantly between the plowing treatments (Figure 2).

The differences between the control treatment (DP) and DC, SC, and NT were significant at different probability levels. The highest topsoil coverage with winter wheat straw, an average of 53%, was recorded for the NT plots, and this was nearly 60 times higher than in the control treatment. This affected not only the physical, chemical, and biological properties of the soil, but also the spread of weeds.



**Figure 1.** Average air temperature (a) and precipitation rate (b) during faba bean growing seasons at the Kaunas Meteorological Station in 2016–2018.



**Figure 2.** The volume of fore crop residues in the topsoil of differently tilled soil after faba bean sowing. DP—deep plowing (control treatment), SP—shallow plowing, DC—deep cultivation, SC—shallow cultivation, NT—no-tillage (direct drilling). \* significant difference at  $0.01 < p \leq 0.05$ , \*\* at  $0.001 < p \leq 0.01$ , \*\*\* at  $p \leq 0.001$ .  $p > 0.05$  indicates no significant difference compared with DP.

### 3.3. Weed Species Composition and Density

In our experiment, the predominant annual weed species were *Echinochloa crus galli* (L.) P. Beauv., *Fallopia convolvulus* (L.) A. Löve, *Persicaria lapathifolia* L., *Chenopodium album* L., *Galeopsis tetralix* L., *Sinapis arvensis* L., *Veronica arvensis* L., etc. Among the perennial weeds, the prevalent species were *Taraxacum officinale* F. H. Wigg., *Plantago major* L., *Sonchus arvensis* L., *Equisetum arvense* L., *Elytrigia repens* L., and *Cirsium arvense* L. (Table S1).

In 2016, at the beginning of faba bean vegetative period (BBCH 25–27), there were fewer annual weeds (27 and 54%) than in 2017 and 2018 because May was warm but drier than usual. The different tillage methods generally did not have a significant impact on the abundance of weeds, except in some isolated cases (Table 1, Table S2).

**Table 1.** Weed density (number m<sup>-2</sup>) at different faba bean growth stages, as influenced by the tillage system in 2016–2018.

Weed Groups	Tillage Systems				
	DP	SP	DC	SC	NT
<b>2016</b>					
BBCH 25–27					
Annual	59.5ab	74.1a	71.2a	72.0a	50.8b
Perennial	4.5b	6.6b	14.1b	19.5ab	34.5a **
Total	64.1a	80.7a	85.4a	91.6a	85.4a
BBCH 75–79					
Annual	35.8a	36.6a	24.1a	38.7a	25.4a
Perennial	0.8b	3.3b	12.5ab	16.2ab	30.4a *
Total	36.6a	39.9a	36.6a	54.9a	55.8a
<b>2017</b>					
BBCH 25–27					
Annual	104.6a	97.5a	103.7a	119.1a	20.9b **
Perennial	2.9a	5.4a	3.3a	4.5a	4.1a
Total	107.5a	102.9a	107.0a	123.6a	25.0b **
BBCH 75–79					
Annual	27.9a	17.0a	18.7a	17.6a	17.9a
Perennial	2.5a	4.6a	2.9a	1.2a	5.4a
Total	30.4a	21.6a	21.6a	18.8a	23.3a
<b>2018</b>					
BBCH 25–27					
Annual	103.7b	130.4b	132.9b	117.3b	226.6a *
Perennial	2.9b	14.2ab	9.5 ab	25.4a *	19.6 ab
Total	106.6b	144.6b	142.4b	142.7b	246.2a *
BBCH 75–79					
Annual	45.8b	40.0b	42.5b	39.1b	62.3 *a
Perennial	0.8b	12.9a *	10.0ab	8.4ab	19.5a *
Total	46.6b	52.9b	52.5b	47.5b	80.8a *

DP—deep plowing (control treatment), SP—shallow plowing, DC—deep cultivation, SC—shallow cultivation, NT—no-tillage (direct drilling). \* significant difference at  $0.01 < p \leq 0.05$ , \*\* at  $0.001 < p \leq 0.01$ .  $p > 0.05$  indicates no significant difference compared with DP. Different letters indicate significant differences between all treatments at  $p \leq 0.05$ .

A significant 3.7-fold reduction in the number of *E. crus galli* was identified in the no-tillage (NT) plots compared with the control (DP). In the SP plots, the number of *S. arvensis* plants was significantly higher (by 7.6-fold) than in the DP plots (Table S2).

Similar annual weed species predominated at the beginning (BBCH 25–27) and at the end of the faba bean vegetative period (BBCH 75–79) (Table 1). The different tillage



methods generally did not have a significant effect on the number of annual weeds, but their number was almost twice as low as at the beginning of the growing season. As an exception, the NT plots were found to have the significantly highest number of *P. lapathifolia* plants (11.2 weeds m<sup>-2</sup>) than the DP plots (Table S2).

At the beginning of the faba bean vegetative period, *P. major* was the most common perennial weed in all tillage systems (Table S2). As the tillage intensity decreased, the number of perennial weeds consistently increased, and in the NT plots, there were significantly more (7.7-fold) than in the DP plots (Table 1). The number of perennial weeds in the NT plots was the highest, but only the number of *C. arvensis* and *E. arvensis* plants were significantly higher than in the other tillage systems (Table S2). At the end of the vegetative period (BBCH 75–79), the numbers of perennial weeds in the experimental plots were similar, but they differed between the tillage systems in a similar way to at the beginning of the vegetative period (Table 1). The most prevalent weed species were *C. arvensis* and *P. major* (Table S2).

Overall, in 2016, the use of different tillage practices did not have a significant effect on the total number of all weeds at either the beginning or end of the vegetative stage (BBCH 75–79); however, at the beginning of the vegetative period, the number of weeds was almost twice as high as at the end of the growing season. DP plots tended to have the lowest total number of all observed weed species. Annual weeds predominated; therefore, their influence on the total number of weeds was significant ( $r = 0.940^*$ ).

In 2017, at the beginning of the vegetative period (BBCH 25–27), NT plots had significantly lower numbers of all annual weeds (about five times lower) than other plots (Table 1). Similar trends persisted in the overall prevalence of annual weeds at both the beginning and end of the vegetative period, but the differences were not significant at the end of the vegetative stage. The differences were mainly caused by the abundance of *E. crus galli* and *F. convolvulus* weeds (Table S2).

Having investigated the abundance of perennial weeds, it was found in 2017 that, unlike in 2016 and 2018, there were fewer perennial weeds (by about 3–4 times), and tillage systems did not have a significant effect on the abundance of weeds at either the beginning or end of the vegetative period (Table 1). At the end of the vegetative stage, only *P. major* was significantly affected by deep cultivation (DC).

The analysis of the total weed incidence in 2017 revealed that, at the beginning of the vegetative period, NT plots had a significantly lower number of weeds than the other plots (Table 1). At the end of the vegetative season, the number of weeds in the plots levelled off and the differences became small.

Summarized data from the year 2017 show that there were more weeds at the beginning of the vegetative period than in 2016 (about 27%) because it was wetter. During this period, NT plots had significantly fewer weeds than other plots; however, there were no differences at the end of the vegetative season. Nevertheless, in the plowless and NT plots, there were fewer weeds than in the control plots.

In 2018, the beginning of the vegetative period was warmer than in 2016 and 2017, which was conducive to the spread of weeds, particularly annual ones (Table 1). Unlike in 2016 and 2017, in the NT plots, there was a significantly higher number of annual weeds at the beginning of the vegetative period. The trend was similar in otherwise tilled plots. *C. album*, *E. crus galli*, and *P. lapathifolia* were the predominant species (Table S2). By the end of the vegetative stage, compared to the beginning, the number of annual weeds had decreased by 2–4 times, especially in the NT plots (Table 1).

At the beginning of vegetative season, the lowest number of perennial weeds was found in the control plots (DP), while the greatest number of weeds was recorded in the SC plots, but this was only significant in comparison with the DP plots (Table 1). The significant difference was due to the high incidence of *C. arvensis* in the SC plots (Table S2). At the end of the vegetative period, the number of perennial weeds slightly decreased compared with at the beginning of the vegetative period, and the NT plots had significantly the highest weed number, but this was only significant in comparison with the control

plots. The difference was determined due to the highest incidence of *P. major* (Table S2). The number of perennial weeds in SP plots was also higher in the SP plots than in the DP plots.

In 2018, the largest densities ( $p < 0.01$ ) of all weeds, occurring at both the beginning (1.7–2.3 times) and end (1.5–1.7 times) of the vegetative period, were recorded in the NT plots. The situation was different than in the previous experimental years, where the number of weeds had levelled off by the end of the vegetative period. This was due to higher air temperatures in the second half of the vegetative stage.

### 3.4. Weed Biomass

In 2016, at the end of the vegetative period, *E. crus galli* weeds were found to have the highest air-dried biomass as their incidence in the plots was the highest (Table S3). Annual weed species did not significantly differ in the terms of biomass (Table 2); only more pronounced, isolated differences were observed (e.g., *P. lapathifolia* in the NT plots) (Table S3).

**Table 2.** Air-dried biomass ( $\text{g m}^{-2}$ ) of the aerial part of weeds at faba bean BBCH 75–79 growth stages as influenced by the tillage system in 2016–2018.

Weed Groups	Tillage Systems				
	DP	SP	DC	SC	NT
2016					
Annual	104.5a	77.3ab	71.8ab	64.2ab	47.9b *
Perennial	1.0a	4.3a	28.1ab	19.9ab	93.6b *
Total	105.5a	81.6a	100.0a	84.1a	141.5a
2017					
Annual	34.4a	34.0a	34.7a	36.7a	21.2a
Perennial	1.3a	8.2a	6.4a	2.5a	9.6a
Total	35.7a	42.2a	41.1a	39.2a	30.8a
2018					
Annual	203.2a	154.6a	155.5a	159.7a	185.9a
Perennial	0.6b	39.4ab	63.7a *	45.8ab	18.9ab
Total	203.8a	194.0a	219.2a	205.5a	204.8a

DP—deep plowing (control treatment), SP—shallow plowing, DC—deep cultivation, SC—shallow cultivation, NT—no-tillage (direct drilling). \* significant difference at  $0.01 < p \leq 0.05$ .  $p > 0.05$  indicates no significant difference compared with DP. Different letters indicate significant differences between all treatments at  $p \leq 0.05$ .

On average, the NT plots had significantly less biomass than the other plots—nearly twice as low as in the DP plots, although the density did not differ significantly between the treatments.

The biomass of perennial weeds was significantly higher in the NT plots compared with other plots, being approx. 5–94 times higher than in other treatments (Table 2). *C. arvensis* (NT) and *P. major* accounted for the largest proportion in the total dry biomass of weeds (Table S3). Overall, in 2016, the use of different tillage systems did not have a significant effect on the total biomass of all weed species; although, in the NT plots, the weed biomass was about 25% higher than in the DP plots and 42% higher than in the SP plots. A strong relationship ( $r = 0.951$  \*) was found between the density and biomass of perennial weeds.

In 2017, none of the reduced tillage systems significantly affected the biomass of species of annual and perennial weeds (Table 2). The highest biomass was counted for the annual weeds *E. crus galli*, *F. convolvulus*, and the perennial weed *E. repens*, although the incidence was low (Table S3). A strong correlation was found between the number of annual weeds at the beginning of the vegetative period and their air-dried biomass



( $r = 0.999^{**}$ ). The total biomass of weeds of all species varied from 30.8 to 42.2 g m<sup>-2</sup> and was 3–4 times lower than in 2016. In 2017, the weed number was nearly twice as low.

In 2018, there was a greater biomass of weeds (twice as much, on average, compared with 2016 and four times higher than in 2017) than in previous experimental years. The use of different tillage systems generally did not have a significant effect on the total biomass of annual weeds (Table 2). More weed species were distinguished by having a higher biomass than in the previous experimental years. This included *C. album*, *E. crus galli*, and *P. lapathifolia* (Table S3). Of the perennial weed species, *P. major* produced the greatest biomass, particularly in the DC plots, where its biomass was significantly the highest. While summarizing the biomass data of all weed species, it was found that different tillage systems did not have a significant effect.

### 3.5. Weed Seedbank

In our experiment, the weed seedbank was abundant, and in individual years and differently tilled plots, this amounted up to 222,000 seeds m<sup>-2</sup> or 2.22 million seeds ha<sup>-1</sup> in the arable layer.

In 2016, seeds of *C. album*, *E. crus galli*, *F. convolvulus*, and *S. arvensis* predominated in the soil, as the incidence of these weeds was high in the faba bean crop (Table S4). In the topsoil (0–15 cm), the SC plots were found to significantly have the greatest number of annual weed seeds, and this had a significant effect on the differences in the number of seeds of all weed species (Table 3). The number of perennial weed seeds did not differ significantly. The lowest numbers of seeds of all weed species were found in the topsoil layer of the NT plots compared with the DP and SP plots.

In contrast to the upper layer, greater differences in weed seed numbers were found in the deeper (15–25 cm) soil layer. With a decreasing tillage intensity, the number of incorporated weed seeds decreased and was significantly the highest in the DP plots. *C. album* weeds had the greatest effect on these findings (Table S4).

The number of *C. album* seeds was from 2.1 to 4.9 times lower in the reduced tillage and NT plots (Table S4). More perennial weed seeds were found in the bottom layer of the plow layer (Table 3). The highest numbers of perennial weed seeds (11.9 and 11.6 times) were found in the SC and NT plots. Of the perennial weeds, the seeds of *J. bufonius* were most abundant, although their density in the faba bean crop was relatively low. This meant that *J. bufonius* seeds could remain undestroyed in the soil for a longer time (Table S4).

In 2017, like in 2016, the lowest number ( $p < 0.01$ ) of annual weed seeds was recorded in the upper layer of the plow layer of the NT plots, while the highest seed number was found in the SC plots (Table 3). Unlike in 2016, with a decreasing tillage intensity, the number of perennial weed seeds consistently increased but did not reach the limit of significant difference. Like in 2016, significantly the highest number of seeds of all weed species was found in the SC plots.

In the 15–25 cm soil layer, significantly, the highest number of annual weeds was found in the SP plots; it was about three times higher than in the NT plots. Similar to 2016, with a decreasing of tillage intensity, the number of perennial weed seeds increased; however, the highest weed seed number was found in the SC plots, not in the NT plots. *J. bufonius* predominated with the highest density in the SC and NT plots (Table S4). These weed species develop best in the soils with elevated moisture, and in SC and NT plots, the moisture content was usually the greatest (data not shown).

In the deeper section of the plow layer, there were more seeds of all weed species than in the upper layer. In reduced tillage systems, the soil generally had more weed seeds (by 1.3 to 40.0 times) (Table 3).

In 2018, there were more weed seeds in the plow layer than in the previous years of the experiment, because the total weediness of the crop was also higher. Unlike in the previous years of the investigations, the average number of weed seeds mainly did not differ significantly between the plots of the tillage treatments (Table 3). No significant differences were identified when comparing the data with the control treatment (DP). Significant

differences were only found in single cases between the weed species: *S. arvensis*, *C. album*, and *E. crus galli* (Table S4). Like in the previous years of the experiment, there were fewer weeds in the upper soil layer than in the bottom layer.

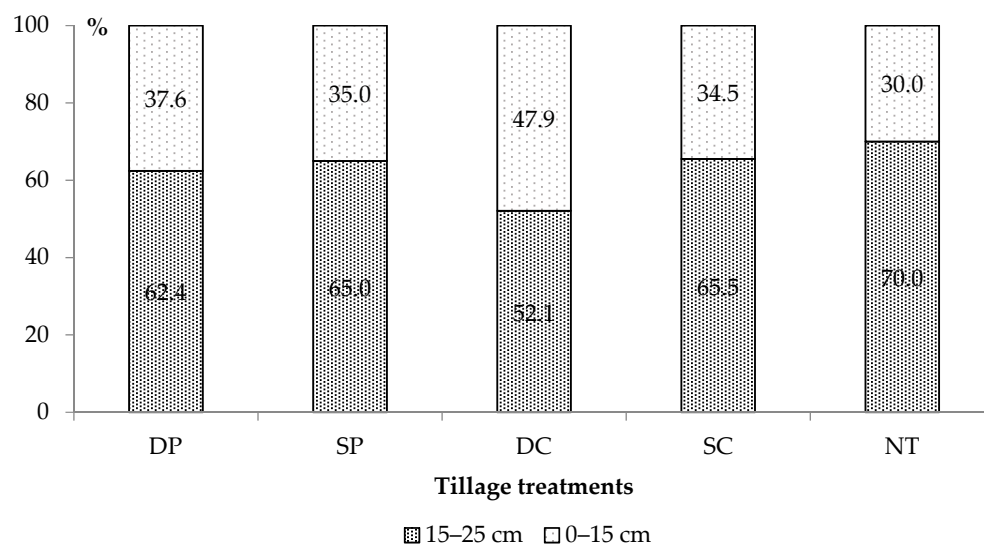
**Table 3.** Weed seedbank (thousand weed seeds m<sup>-2</sup>) in different soil layers, as influenced by the tillage system in 2016–2018.

Weed Groups	Tillage Systems				
	DP	SP	DC	SC	NT
<b>2016</b>					
0–15 cm					
Annual	64.5b	65.1b	77.7ab	88.4a **	63.0b
Perennial	6.3a	6.3a	12.0a	4.2a	6.8a
Total	70.8b	71.4b	89.7a *	92.6a *	69.8b
15–25 cm					
Annual	133.8a	85.7b *	37.6c ***	28.0c ***	42.0bc ***
Perennial	9.7b	31.5b	44.6b	115.5a ***	112.8a ***
Total	143.5a	117.2b *	82.2c *	143.5a	154.8a
<b>2017</b>					
0–15 cm					
Annual	55.1a	44.6ab	45.6ab	64.5a	30.9b *
Perennial	1.5a	3.1a	7.8a	6.8a	8.4a
Total	56.6b	47.7bc	53.4b	71.3a *	39.3c *
15–25 cm					
Annual	55.2b	94.5a *	47.2b	48.1b	29.7b
Perennial	0.8b	17.5b	26.5b	174.1a **	114.6ab
Total	56.0d	112.0bc	73.7cd	222.1a *	144.3b *
<b>2018</b>					
0–15 cm					
Annual	77.7a	92.4a	112.8a	107.6a	91.3a
Perennial	1.5a	0.0a	4.2a	0.0a	0.0a
Total	79.2c	92.4bc	117.0a *	107.6ab	91.3bc
15–25 cm					
Annual	96.2a	151.3a	89.2a	149.6a	167.1a
Perennial	47.2a	12.2a	37.6a	0.0a	1.7a
Total	143.4a	163.6a	126.8a	149.6a	168.8a

DP—deep plowing (control treatment), SP—shallow plowing, DC—deep cultivation, SC—shallow cultivation, NT—no-tillage (direct drilling). \* significant difference at  $0.01 < p \leq 0.05$ , \*\* at  $0.001 < p \leq 0.01$ , \*\*\* at  $p \leq 0.001$ .  $p > 0.05$  indicates no significant difference compared with DP. Different letters indicate significant differences between all treatments at  $p \leq 0.05$ .

With a decreasing tillage intensity, the distribution of weed seeds in the plowed layer was similar ( $p > 0.05$ ) (Figure 3).

Summarizing the data of the three years of experimentation, it can be concluded that, on average, the highest number of seeds of all weed species was found in the SC plots and NT plots, but these differences were small compared with the other treatments where the number of weed seeds varied within the range of 180.9–201.4 thousand seeds m<sup>-2</sup>.



**Figure 3.** Weed seedbank distribution between soil layers. DP—deep plowing (control treatment), SP—shallow plowing, DC—deep cultivation, SC—shallow cultivation, NT—no-tillage (direct drilling).  $p > 0.05$ .

## 4. Discussion

### 4.1. Topsoil Residue Coverage

In the experiment, the greatest level of topsoil coverage with forecrop straw was found in the NT plots (Figure 2). This affected the abundance of weeds. Our finding agrees with that reported by Buchanan et al. [39], who showed that winter wheat crop residues had a reduced weed density by up to 50%. Cover crops growing has a similar effect as forecrop residues [40]. An analysis of our research data showed a moderate negative correlation between the volume of forecrop residue coverage in the topsoil and the number of weeds at the beginning of the faba bean vegetative period (BBCH 25–27). Forecrop residues limited the germination of annual weeds ( $r = -0.784$ ) and biomass accumulation ( $r = -0.748$ ). Conversely, a thicker residue cover, which formed due to the more favorable heat and moisture regime, promoted the spread of perennial weeds at both the beginning of the vegetative period ( $r = 0.923$  \*) and at the end ( $r = 0.905$  \*) and increased their biomass ( $r = 0.982$  \*\*). Similarly, in our earlier investigations, we found a strong correlation between the total air-dried biomass of living mulches, which acted as continuous soil coverage during the maize vegetative stage, and the air-dried biomass of annual, perennial, and total weeds [41].

### 4.2. Weeds Species Composition and Density

The studies of weed flora showed that the 12 main weed species that compete with faba bean in Southern Europe are the broadleaved species *Anthemis arvensis* L., *C. album*, *Papaver rhoeas* L., *S. arvensis*, *Fumaria officinalis* L., *Veronica* spp., *Lamium amplexicaule* L., and *C. arvense* and the grass species *Avena sterilis* L., *Phalaris* spp., *Lolium rigidum* Gaud., and *Alopecurus myosuroides* Huds. [42,43]. Lithuanian winters differ in terms of the lowest temperature reached (average January air temperature is approx.  $-5.4^{\circ}$  C) compared with the average in southern Europe, resulting in fewer annual fallow/winter weed species being present (Table S1). *Lolium* spp., *Alopecurus* spp., and *Papaver* spp. are rare species. On the other hand, most of the annual winter weeds emerge in the autumn before primary tillage. In Lithuania, faba bean crops are sown in spring. Thus, the remaining weeds are destroyed again. In our experiment, in addition to the above-mentioned weeds (*C. album*, *S. arvensis*, *Veronica* spp., and *C. arvense*) [42,43], the predominant annual weed species were *E. crus galli*, *F. convolvulus*, *P. lapathifolia*, and *G. tetrahit*. The prevalent perennial species were *T. officinale*, *P. major*, *S. arvensis*, *E. arvense*, *E. repens*. Shahzad et al. [44] showed that different tillage systems have marked effects on the total density of broadleaved and

grass weeds and that an NT system is more conducive to the spread of weeds. According to the group of researchers, tillage had a significant effect on the composition of weed communities and their functional properties in different crop cultivations [21,45,46]. Al-moussawi et al. [14] found that the use of reduced tillage increased the abundance of annual weed species, including *Viola arvensis* and *Fumaria officinalis*, but investigations of other scientists [3,45,47] highlighted the increase of perennials. Carter and Ivany [48] have found that the weed species diversity presented when DP system was used was lower compared with when shallow tillage and NT were used, which is partly consistent with the results of our investigations. The following species were predominant: *Gnaphalium uliginosum* L., *Ranunculus repens* L., and *C. album*. However, other scientists found less clear trends [45,49]. Thomas et al. [50] suggested that perennial species (*C. avense* and *S. arvensis*) and annual species (e.g., *Setaria viridis*) generally predominate with the use of NT systems. These findings agree with those reported by other researchers [17,18,51].

In a study by Stancevičius et al. [52], it was found that when traditional deep plowing was replaced by a shallow plowing or deep and shallow loosening, weed seeds and vegetative reproductive organs became closer to the soil surface and germinated and regenerated faster, resulting in increased weed infestation in the crop stand. The incidences of perennial vegetatively propagating weeds (*E. repens*, *S. arvensis*) and small-seeded annual weeds (*Poa annua* L., *Tripleurospermum perforatum* (Meat), and *Stellaria media* L.) were particularly high. Colbach et al. [8] have documented that surface tillage, which leaves seeds on the soil surface, increases the weed density, while heavy-seeded weeds predominate in plowed soil. Conversely, Hernández Plaza et al. [20] have reported that weeds containing a lot of small seeds predominated when NT system is used.

Armengot et al. [53] and Légère et al. [45] pointed out that non-inversion tillage may increase weed infestation; however, this tendency depends on the type of crop and varies in time. In our experiment, in 2016 and 2017, the use of different tillage practices did not have a significant effect on the total number of all weeds present at both the beginning and end of the growing season, except for in single cases (Table 1 and Table S2). Similarly, Santín-Montanyá et al. [54] found that the weed density in a wheat stand differed between years, but the differences were not significant. In 2018, the highest numbers of all weeds were recorded at both the beginning and end of the vegetative stage in the NT plots.

Summarizing the three experimental years, it can be stated that the meteorological conditions had a greater impact on weed abundance than the type of tillage systems used. Hossain et al. [46] also highlighted the significant impact of year conditions. Alarcón Villora et al. [6] suggested that climate has the most important influence on weed seed emergence. Alarcón Villora et al. [7] have corroborated our findings in a 9-year experiment in a cereal–legume crop rotation. Environmental variability was found to be more important than the type of tillage system applied for determining the weed species diversity and density. Less common weed species were more strongly affected by tillage than dominant species, which were the same with all tillage systems. The correlation analysis of our experimental results obtained over the 2016–2018 period showed strong relationships between the mean daily temperature ( $x$ ) and the density of weeds of all species at the beginning ( $r = 0.978^{**}$ ) and end ( $r = 0.538$ ) of the vegetative period and also between the amount of precipitation and the density of weeds of all species at the beginning ( $r = 0.770$ ) and end ( $r = 0.833$ ) of the vegetative period. Different weed species responded differently to climatic factors, the effect being weaker on annual weeds than on perennial weeds. The perennial weed *P. major* was found to be particularly sensitive to the changing meteorological conditions. Its spread was more abundant under warmer ( $r = 0.689$ ) and wetter ( $r = 0.984^{**}$ ) conditions. This effect was also observed at the end of the vegetative stage ( $r = 0.667$  and  $0.967^{**}$ ). Therefore, in the warmer and wetter year, 2018, the density of weeds was, on average, almost twice as high as in previous years (Table 1). The density of weeds during the vegetative period decreased by 2–3 times, and in most cases, the differences between the treatments were small, except for in 2018, when the number of weeds in the NT plots remained significantly higher than in the DP plots. The

species composition of weeds did not differ considerably between the experimental years, with *E. crus galli*, *F. convolvulus*, and *P. major* being the most prevalent species (Table S2). Although the density of weeds in the faba bean crops decreased, correlations were found between the numbers of annual and perennial weeds and the total weed densities at the beginning and end of the vegetative period ( $r = 0.411$ ,  $0.997^{**}$ , and  $0.636$ ). For some weed species, the correlation was more pronounced, and in most cases, it was significant, e.g., for *E. crus galli* ( $r = 0.879^*$ ), *F. convolvulus* ( $r = 0.924^*$ ), *P. lapathifolia* ( $r = 0.826$ ), *C. arvense* ( $r = 0.889^*$ ), and *P. major* ( $r = 0.920^*$ ).

#### 4.3. Weed Biomass

In our experiment, the air-dried biomass of weeds was high because the faba bean seed rate was slightly too low, as we were limited by the technical capabilities of the drill. Similarly, Alba et al. [55] concluded that, with an increased lentil sowing rate, it would be possible to reduce the weed biomass by up to 16%.

In our experiment, the total weed biomass was not significantly affected by the different tillage systems investigated (Table 2 and Table S3). However, in 2016, in the NT plots, the total weed biomass was about 25% higher than in the DP plots and 42% higher than in the SP plots. Similarly, in a study by Matloob et al. [56], the lowest weed biomass was found in the DP system, but this effect was not significant. This result is in agreement with a study by Hernández Plaza et al. [20], which found that the weed biomass in the NT plots was lower than in plowed and plowless plots. Similarly, Samarajeewa et al. [57] found that the weed biomass in a soy stand that was exposed to no-tillage treatment was higher than in reduced tillage or plowed plots. Susha et al. [58] also found a reduction (by 14.0%) of total weed biomass in wheat crop.

The data averages over the period 2016–2018 suggest that the air-dried biomass of all weed species is barely affected by the air temperature and precipitation rate of the vegetative period, but for individual weed groups or species, this influence was found to be marked. With an increasing air temperature and precipitation rate, the biomass of annual weeds decreased ( $r = -0.869$  and  $-0.689$ ), while that of perennial weeds increased ( $r = 0.445$  and  $0.458$ ). This effect was even greater in *P. major* ( $r = 0.667$  and  $0.967^{**}$ ).

The abundance of plant residues of the forecrop, in contrast to the air temperature and amount of precipitation, was found to be the key parameter that had a considerable effect on weed biomass. With the increasing of amount of plant residues on the topsoil, the biomass of annual weeds decreased ( $r = -0.748$ ). On the contrary, this had significant positive effects ( $r = 0.903^*$  and  $0.996^{**}$ ) on the weeds *E. crus galli* and *P. lapathifolia*. The abundance of forecrop residues also increased the biomass of perennial weeds, and the biomass of total weeds ( $r = 0.982^{**}$  and  $0.890^*$ ). The effect on the perennial weed *C. arvense* was profound and significant ( $r = 0.996^{**}$ ).

#### 4.4. Weed Seedbank

In our experiment, *C. album*, *E. crus galli*, and *S. arvensis* were the most widespread, and the seeds of these species were predominant in the seedbank in the soil (Table S4). Similarly, Wei et al. [59] found that the aboveground part of weeds had the greatest effect on the weed seedbank. The correlation analysis of our experimental results showed a moderate relationship ( $r = 0.583$ ) between the number of annual weeds present at the beginning of vegetative stage (BBCH 25–27) and the seedbank of annual weeds in the 0–15 cm soil layer, although this relationship was stronger and more significant ( $r = 0.919^*$ ) for *E. crus galli*. Similar relationships were found between the number of weeds of all species and the seedbank at the beginning ( $r = 0.620$ ) and at the end (BBCH 75–79) ( $r = 0.660$ ) of the vegetative period. The abundance of perennial weeds at the end of the vegetative stage considerably influenced their seedbank in the 15–25 cm soil layer ( $r = 0.874$ ).

One of the most important measures in reducing weed incidence in crop fields is soil protection against infestation with weed seeds. The quality of weed control depends largely on the ability to limit the entry of new weed seeds into the soil [23]. In our experiment, in



most cases, the highest concentration of seeds of all weed species was found in the SC plots, but the difference was not always significant compared with the other treatments (Table 3, Figure 3). This is in contrast to the findings of Hernández Plaza et al. [20], which suggested that the number of weed seeds present when NT system was used was higher than when DP and CT (conservation tillage) treatments were used. Similarly, after 14 years of research, Buhler et al. [60] found that a larger and more diverse weed population was present in the sustainably tilled plots compared with the conventionally tilled plots. Weeds producing many small seeds predominate when NT system is used [20], and those producing larger seeds and with later flowering phenology predominate when DP practice is used [21]. Otherwise, plowing distributes weed seeds into deeper soil layers. Large seeds have higher sprouting energy and greater success in emerging from deeper layers than the small ones. This is why weeds with large seeds dominate in plowed soils (Gardarin et al. 2009) [61]. In contrast, Fried et al. [22] found that early-flowering weed species with small weed seeds predominate when the soil is tilled at a greater depth. In addition, Fenner and Thompson [62] and Peco et al. [63] suggested that small weed seeds persist longer in the soil than many large ones. However, investigations of Armengot et al. [21] do not support this relationship.

In our experiment, contrary to what was assumed in the hypothesis, even with a decreasing tillage intensity, the distribution of weed seeds in the plow layer changed little. Contrarily, Scherner et al. [13] found that plowless tillage initiated numerous weed seeds distribution in the upper (0–5 and 5–10 cm) soil layers and less in the 10–20 cm layer. In plowed soil, the distribution of seeds was more even. Similar conclusions were also made by many other researchers [14,17,18,21,64]. We suggest that, under the NT conditions, small weed seeds enter the deeper soil layers and remain there for a long time, especially with periods of higher rainfall after drier periods at the end of the faba bean vegetative period when the seeds of most annual weeds ripen. The correlation analysis of the experimental data showed a moderate correlation ( $r = 0.716$ ) between the amount of rainfall present during the vegetative period and the abundance of the seedbank of annual weeds in the 0–15 cm soil layer. For the weed *F. convolvulus*, this relationship was the most pronounced and significant ( $r = 0.932^*$ ).

To summarize, the unstable meteorological conditions caused by the climate change have a greater impact on weed abundance and seedbank distribution in the soil than long-term sustainable tillage practices. This suggests that the use of weed control strategies for sustainable farming systems may need to be quickly reviewed.

## 5. Conclusions

On average, a reduction in tillage intensity was associated with a slight increase in the weed density and biomass in faba bean plots, especially in disked and not-tilled plots. The volume of forecrop residues was found to be the key parameter of tillage practice that affected the weed biomass. In plowless or not-tilled plots with a higher volume of residues on the topsoil, the biomass of annual weeds decreased and that of perennial weeds increased.

On average, more weed seeds were found in the soil of disked and not-tilled plots compared with deeply plowed ones. The weed seedbank in the soil was almost evenly distributed between the layers (0–15 cm and 15–25 cm), and contrary to expectations, it did not differ significantly between the tillage systems.

In summary, the short-term meteorological conditions present during the three years of investigations had a greater impact on weed abundance and seedbank distribution than the use of long-term sustainable tillage practices.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/2073-4395/11/3/529/s1>, Table S1: The list of weed species in the experiment. Table S2: Density (number  $m^{-2}$ ) of the most widespread weeds at different faba bean growth stages, as influenced by the tillage system in 2016–2018. Table S3: Air-dried biomass ( $g m^{-2}$ ) of aerial part of the most widespread weeds at faba bean BBCH 75–79 growth stages as influenced by the tillage system in 2016–2018.



Table S4: The most widespread weed seedbank (thousand weed seeds m<sup>-2</sup>) in different soil layers, as influenced by the tillage system in 2016–2018.

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