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Impact of Cover Crops on Maize Yields by Applying Interseeding Cover Crop and Crop Rotation Agrotechniques

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Abstract

Maize is one of the most widely grown and used crops in the world. Nowadays, weather anomalies such as drought and sudden heavy rains due to climate change bring up serious challenges to maize production. One environmentally conscious approach that contributes to climate change resilience is cover cropping. In the production technology of corn-legume cover crops, corn as the cash crop was examined in two ways in a field small-plot experiment in four repetitions in randomized block design plots. In one case, the legume cover crops were sown as an interseeding cover crop in a corn monoculture; in the other case, the crop rotation agrotechnique was applied to what CCs could be included in the cereal-maize crop rotation after winter cereals. The experiment was set up in Vertisol and Chernozem. In all cases control treatment was included. Our results showed that pea vine and cowpea contributed to increased corn yield on both soil types and agrotechniques. White sweet clover cannot be recommended as a cover crop because this seemed too competitive with the cash crop. Field pea is recommended for the crop rotation agrotechnique. Trifolium species like Persian clover, red clover, and crimson clover show good adaptability to Vertisol.

Keywords: maize; corn; cover crops; legume cover crops; crop rotation; interseeding cover crop; maize yield; sustainable agriculture; intercropping; biological nitrogen fixation

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1. Introduction

1.1. Global Importance of Maize and Climate-Change Challenges

Maize is one of the most widely grown and used crops in the world [1,2]. Legumes, after cereals, play a particularly important role in the word's food supply as sources of protein that can also be sown for soil improvement [3,4]. Nowadays, weather anomalies such as drought and sudden heavy rains due to climate change create serious challenges to maize production [5–7].

1.2. General Benefits of Legume Cover Crops

Legume cover crops are well suited to mitigate erosion damage and increase water infiltration into the soil [8,9]. They reduce fluctuations in soil moisture and soil temperature; in other words, they act as a buffer against extreme environmental conditions [10]. Cover crops mitigate the negative impacts of climate change through ecosystem services [11,12].

Deep-rooted plants are able to draw water from deep into shallow soil sayers and transfer it to shallow-rooted plants in dry environments [13]. Cover crops as green mulch reduce evaporation losses and conserve groundwater [14,15]. Cover crops have the potential to trap dew, and dew can compensate for the soil moisture utilized for cover crop biomass production. Dew entrapment is only feasible when the cover crop is interseeded because most dew events occur during the summer months (July and August) [16]. Soil degradation associated with reduced microbial activity contributes to poorer adaptability, increased plant stress, and reduced crop security. Cover crops increase soil microbial richness, activity, and diversity [17–20]. Cover crops can increase soil organic carbon (SOC) fixation by providing additional organic carbon (OC) residues, building beneficial soil microbiota, and improving soil aggregation and structure [21–23]. Soils under legumes contained higher amounts of microbially derived C in mineral-associated organic matter (MAOM) than non-legume cover crops [24,25]. Cover crops reduce compaction resulting from cultivation and improve nutrient supply to the cash crop [26,27].

1.3. Specific Mechanisms of Legume Cover Crops

From an ecological and economic perspective, fertilizers, and especially N, have a significant impact on maize productivity [28,29]. Legumes perform biological nitrogen fixation (BNF), which becomes available for the next crop [30,31]. BNF N reduces the amount of synthetic N fertilizers used in agriculture and natural ecosystems [32]. This, in turn, reduces production costs, greenhouse gas emissions (GHG), and surface and groundwater pollution [33]. They can also provide N to the cash crop by releasing root acids and using interseeding cover crop technology [34]. Legumes can actively transfer nitrogen to maize through their mycorrhizal network [35]. Due to their favorable C/N ratio (<25), legumes decompose faster than other cover crops [36]. Their nutrient supply capacity is also outstanding [37]. However, legumes are less effective in reducing nitrogen leaching than non-legumes [38–40]. The amount of nitrogen in green manure is usually 40–60% of the total amount found in the legume [41].

1.4. Advantages and Limitations of Legume Cover Cropping

Results show that earlier termination dates can reduce N and water competition with the next cash crop without increasing nitrate leaching and preserving their ecosystem services [14]. In interseeding cover crop technology, plant species should be selected based on their ability to help each other [42]. If plant species are not compatible, they can weaken each other by competition for water, light, and nutrients [43–45]. Maize yield increased by 34–53% after green manure application in a crop rotation system [46]. Cover cropping is an environmentally conscious approach that helps build climate change resilience [47,48]. Diversification with legumes in maize cropping systems is a fundamental example of sustainable agriculture [49].

1.5. The Aims of the Reserach

The aim of the study was to develop a corn production technology that uses the legume cover crops as a living mulch to increase soil organic matter, release and replenish nutrients, and enhance biodiversity. The monoculture corn and crop rotation experiments were model experiments that examined cover crops that can be grown after and with summer and fall-harvested crops focusing on corn as the cash crop. It was investigated which legume cover crops can be successfully grown during (co-cultivation or interseeding cover cropping) as well as after (late summer-autumn-winter-early spring) the growing season of corn. It was observed how cover crops grown after the harvest of the precrop and grown concurrently with maize affect maize yield.

2. Materials and Methods

2.1. Experimental Site and Soil Characteristics

Two types of maize–legume cultivation technologies were tested on two production areas. The production areas were relatively close to each other, approximately 3000 m apart as the crow flies, but their soil classifications were different and were determined based on The World Reference Base (WRB). Experiment location I. was set up on calcareous Chernozem (Table A1), which has a crumbly structure, warms up relatively early, has good water storage and water permeability, but the cultivated layer can be prone to dusting and compaction. Experiment location II. was set up on Vertisol (Figure 1), which is low-warming with good water management but is very difficult to cultivate and where deep cracks form in the area in dry weather. At both experimental locations, interseeding cover crop (IS) and crop rotation (CR) experiments were established.

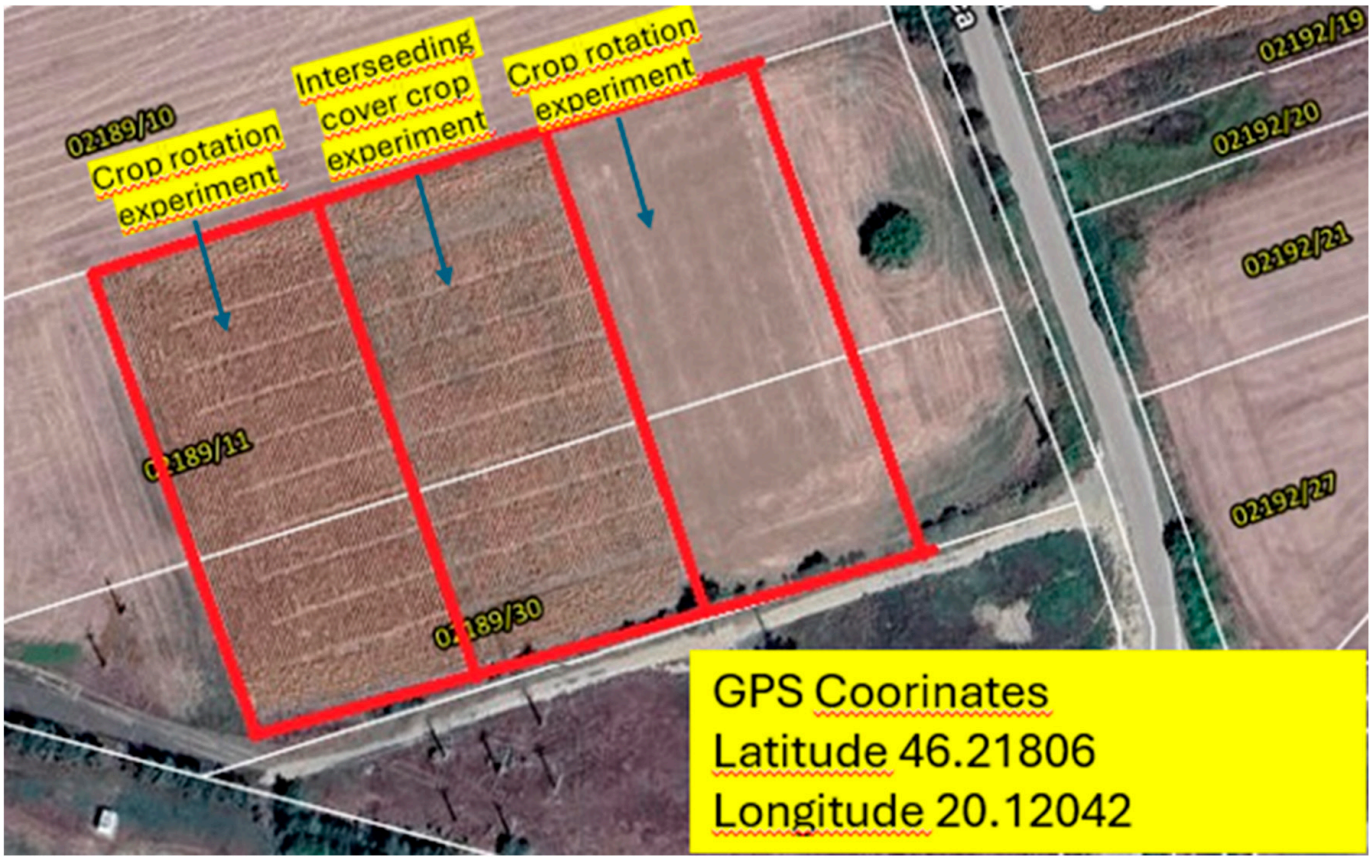


Figure 1. Experimental design on Vertisol.

2.2. Experimental Design and Treatments

In the production technology of corn–legume cover crops, corn as the cash crop was examined in two ways in a field small-plot experiment over 3 crop years.

In one case, the legume cover crops were shown as an interseeding cover crop (IS) (Figure 1) in a corn monoculture (corn after corn). The aim was to examine the interseeding cover crops sown between the rows when the corn had 6–8 leaves. There was a distance of 75 cm between two corn rows. The legume cover crops were sown here at an equal distance of 3 × 25 cm from each other.

A total of four rows of corn formed a plot, in which three inter-rows were planted with cover crops (CCs), which covered the soil as a living mulch. The plots had a gross area of 24 m^2 (net area 10.5 m^2 $plot^{-1}$). Only the two middle corn rows were used for sampling. The two other rows were the buffer rows. In this production technology, maize and CCs

grew together until the corn harvest, when the CCs remained on the ground and continued to grow. Some of the CCs were winterkilled, and the remaining CCs were terminated 6 weeks before the maize was sown. This was followed by a regeneration period for the soil to prepare for the cash crop.

In the other case, we observed crop rotation (CR) to see what CCs could be included in the cereal–maize crop rotation after winter cereals in this agroecological environment. Here cereals were sown in autumn, and, after the cereals were removed, leguminous CCs were sown, which overwintered and covered the soil for 6 weeks before sowing the next cash crop, when they were terminated. Then, in the spring, we sowed the corn, which was our cash crop to be tested. A total of four rows of corn formed a plot, in which three inter-rows were planted with CCs, which covered the soil as a living mulch. The plots had a gross area of 24 m^2 (net area 10.5 m^2 $plot^{-1}$). Only the two middle corn rows were used for sampling. The two other rows were the buffer rows. In this case, we examined the effect of the cereal grain and the leguminous CCs as preceding crops.

The CC treatments (Table 1) were tested in four repetitions in randomized block design plots. In each experiment, in addition to the CC treatments, a control treatment with no CC was also included (number 13).

Table 1. The following legume CCs were used in experiments.

Number	Common Name (Scientific Name)
1.	afalfa (*Medicago sativa* L.)
2.	red clover (*Trifolium pratense* L.)
3.	crimson clover (*Trifolim incarnatum* L.)
4.	sainfoin (*Onobrychis viciifolia Scop*)
5.	kidney vetch (*Anthyllis vulneralia* L.)
6.	birdsfoot trefoil (*Lotus corniculatus* L.)
7.	Persian clover (*Trifolium resupinatum* L.)
8.	white sweet clover (*Melilotus albus Desr.*)
9.	field pea (*Pisum sativum arvense* L. *Asch*)
10.	cowpea (*Vigna sinensis* L.)
11.	pea vine (*Lathyrus sativus* L.)
12.	common vetch (*Vicia sativa* L.)

2.3. Agrotechnical Operations

In the fall of 2022, we performed a 20 cm deep autumn ploughing of the entire experimental area. We applied 300 kg ha^{-1} of NPK 15-15-15 fertilizer to all experimental areas. Our objective was to start with a base like conventional farming (CF). We attempted to model a transition from traditional, rotational, bare-soil farming to a sustainable maize farming system using legume cover crops (CCs) and minimum tillage (MT). In subsequent years, we did not apply fertilizer to the areas. The corn yield was determined by the nutrients released from organic plant residues. CCs were terminated with a soil tiller, and the working depth was max. 10 cm. We chose this equipment for termination for agrotechnical and agroecological reasons. The experiment is ecological in approach and aims to minimize input use. In Hungary, it is a common practice to eliminate CCs with glyphosate, but the continued use of this total herbicide is questionable, which is why it is necessary to investigate alternative options. The other agrotechnical argument is that the accumulated CC residues make subsequent mechanical work more difficult. There is a soil-related aspect to choose this practice. Decomposers in the soil can only break down the residues if they are introduced into the soil [50]. There are soil animals that draw some organic residues into the soil, but this is negligible compared to such a large biomass.

During the decomposition of plant residues left on the soil surface, several nutrients are wasted. In the cause legume CCs, this valuable N is produced.

2.4. Interseeding Cover Crop Experiment

Combined tillage equipment was used before sowing in 2023. The corn was sown (Table 2) with a precision sowing machine, where the sowing control software provided feedback on the accuracy of the seed depth and plant spacing, so that very even sowing was achieved. This was important because, in the maize with interseeding cover crops experiment, we performed mechanical weeding with a cultivator. The seeder is also suitable for direct sowing. The corn hybrid was an early FAO 330 hybrid. The recommended plant density, which is 75 thousand plants ha^{-1}, was reduced to 55 thousand plants ha^{-1} due to interseeding. The maize sowing depth was 6 cm. The legume CCs were sown between the 75 cm corn rows by a Wintersteiger Plotman type plot seeder in three rows 25 cm apart, sowing depth was 5 cm. The maize was harvested with a Wintersteiger Quantum plot combine, taking care of the CCs. The legume CCs remained on the field after the maize was harvested and CCs were terminated with a soil tiller. The 2023 crop year was average (Figure A1), but in the 2024 crop year our plants faced a 10-day period of temperatures above 35 °C, with the heat rising to 41 °C. The lower four to five leaves of the corn were dried up. Some of the CCs were also dried out. At that time, the drought stress strategy of the legume CCs was clearly visible. Very sensitive plants, such as green peas, were permanently destroyed. The moderately sensitive legumes, e.g., pea vine, common vetch, quickly produced seeds, which were scattered, and with the next rain they sprouted again and covered the soil, creating living and dead mulch. There were plants, e.g., cowpea of African origin or a Hungarian landscape variety of alfalfa, which proved to be resistant to drought. The 2025 crop year also saw a lack of precipitation.

Table 2. Dates of agrotechnical operations in the IS experiment.

Maize Sowing Date	Maize Harvest Date	Cover Crops Sowing Date	Cover Crops Termination Date
20 April 2023	3 October 2023	30 May 2023	24 February 2024
3 April 2024	7 September 2024	2 May 2024	24 February 2025
11 April 2025	10 September 2025	21 May 2025	1 March 2026

2.5. Crop Rotation Experiment

In the 3-year experiment, two rotations were implemented (Table 3). The winter wheat was sown with a Vaderstad Rapid seeder in one pass. An important aspect of the experiment was to minimize work operations and avoid unnecessary soil disturbance. After the winter wheat was harvested, the straw was scattered all across the experimental area to act as a mulch to reduce summer water loss and increase organic matter. The legume CCs were sown with a Wintersteiger Plotman type plot seeder in eight rows, 12.5 cm apart, and sowing depth was 5 cm. The CCs were terminated with a soil tiller. The corn hybrid was an early FAO 330 hybrid, plant density was 55 thousand plants ha^{-1}, row spacing was 75 cm, sowing depth was 6 cm. In the experimental years, the sowing time and emergence of the CCs were also very hectic due to autumn precipitation anomalies.

Table 3. Chronological dates of agrotechnical operations in the CR experiment.

Winter Wheat Sowing Date	Cover Crops Sowing Date	Cover Crops Emergence Date	Cover Crops Termination Date	Maize Sowing Date	Maize Harvest Date
21 October 2022	30 August 2023	1 October 2023	24 February 2024	3 April 2024	7 September 2024
17 October 2023	27 September 2024	4 October 2024	24 February 2025	11 April 2025	10 September 2025

2.6. Measurements

Corn yield was measured during the full ripening period by a Wintersteiger Quantum plot combine (Tables 2 and 3). The net harvested area was 10.5 m^2 $plot^{-1}$. Only the two middle corn rows were used for sampling, with one buffer row on the right and one on the left.

2.7. Statistical Methods

In order to identify relationships between interseeding cover crops and the yield of maize, to determine how the crop rotation technology affects the yield of maize, and to compare how the interseeding cover crop technology and the crop rotation technology affect the yield of maize, Two-way Random Block Design (2RBD) ANOVA at a 0.05 probability level was used. The random factor was the four repetitions. According to the normal distribution of data (Kolmogorov–Smirnov test) and equal variances across groups (Levene's test) was used. In some cases, the homogeneity of variance was slightly impaired; therefore, pairwise comparisons of treatments were performed using the Games–Howell post hoc test; in other cases, the Tukey post hoc test was used. Data analysis was performed using the IBM SPSS software (Version 27, Armonk, NY, USA).

3. Results

3.1. The Effect of Interseeding Cover Crop Technology on the Yield of Maize as a Cash Crop on Chernozem

Applying Two-way Random Block Design (2RBD) ANOVA, the cover crop effect was not significant $F(12;114) = 1.46$, $p = 0.146$. There was a significant difference between the years under research $F(2;114) = 93.17$, $p < 0.001$ significance level. The cover crop * year interaction was also significant $F(24;114) = 2.08$, $p < 0.01$ significance level.

In 2023, the highest yield was significantly achieved with the birdsfoot trefoil (Figure 2). A yield difference of 1.45 t ha^{-1} was measured between the highest and lowest yield. Yields above the three-year average were recorded with interseeding CC cultivation.

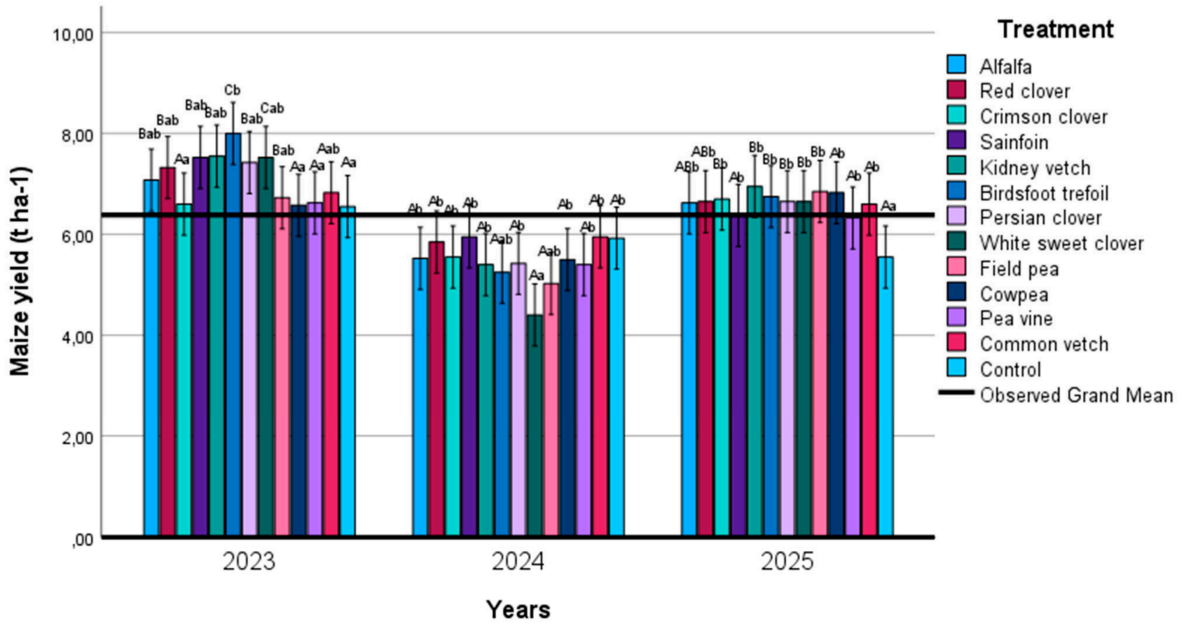


Figure 2. The effect of interseeding cover crop technology on the yield of maize as a cash crop on Chernozem. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a, b) represent cover crop treatments' effect on maize yields. Capital letters (A–C) represent cover crop treatments' effect on crop year. The letters start from the lowest value.

The year 2024 was the weakest crop year on Chernozem. The average yields were below the three-year average. In this year, the control treatment did not differ significantly from most CC treatments. The exception was the white sweet clover treatment, which was the least effective treatment this year.

In 2025, yields above the three-year average were again achieved. The control treatment performed significantly worse than the CC treatments. There was a yield difference of 21% between the best cover crop treatment result and the control treatment result.

Over the three years of the experiment, the white sweet clover, kidney vetch, and birdsfoot trefoil treatments showed significant yield fluctuations.

3.2. The Effect of Interseeding Cover Crop Technology on the Yield of Maize as a Cash Crop on Vertisol

Applying Two-way Random Block Design (2RBD) ANOVA, a significant effect of the cover crops was observed $F(12;114) = 3.29$, $p < 0.001$ significance level. There was also a significant difference between the years under research $F(2;114) = 322.68$, $p < 0.001$ significance level. The cover crop * year interaction was not significant $F(24;114) = 1.12$, $p = 0.33$.

In 2023, the sainfoin provided the best yield and was the only plant that could exceed the three-year average yield in this year (Figure 3). The pea vine, the white sweet clover, and the control also produced significantly higher yields in this year compared to 2025. The field pea treatment resulted in the worst corn yield.

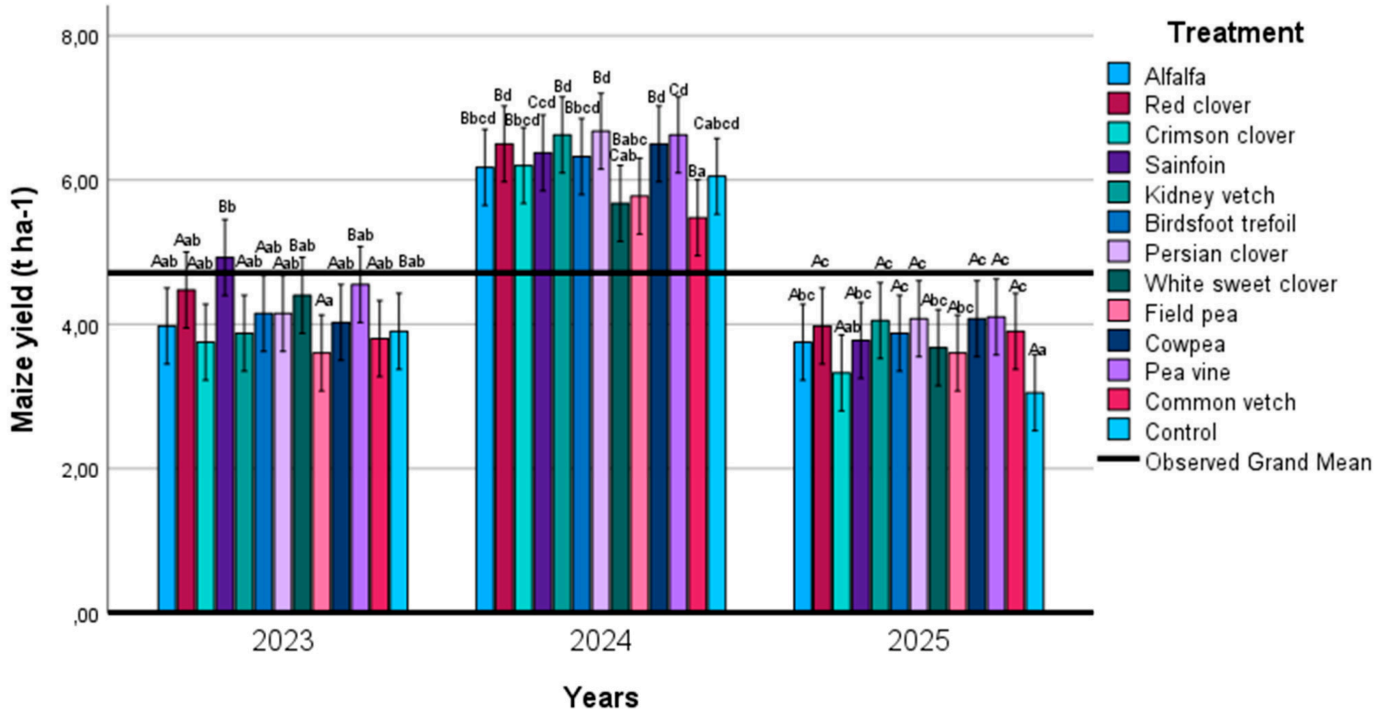


Figure 3. The effect of interseeding cover crop technology on the yield of maize as a cash crop on Vertisol. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–d) represent cover crop treatments' effect on maize yields. Capital letters (A–C) represent cover crop treatments' effect on crop year. The letters start from the lowest value.

In the 2024 crop year, 37% better yield was recorded compared to the average of the other two years of the experiment. The red clover, kidney vetch, Persian clover, cowpea, and pea vine treatments achieved the highest yield. The control treatment was not significantly lower than the other CC treatments, and, in fact, it had the best yield of the three crop years

this year. The sainfoin, the white sweet clover, and the pea vine responded most markedly to this crop year.

In 2025, the yield of maize in the control and crimson clover treatments was significantly lower than in the other treatments. For the 13 treatments, a yield difference of 1 t ha^{-1} was detected between the highest and the lowest yield results for corn. The highest yield results were measured with kidney vetch, Persian clover, cowpea, and pea vine treatments.

During the 3 crop years, the yield of maize fluctuated most significantly, with the sainfoin and the white sweet clover treatments.

3.3. The Effect of Crop Rotation Technology on the Yield of Maize as a Cash Crop on Chernozem

Applying Two-way Random Block Design (2RBD) ANOVA, the cover crop effect was not significant F(12;75) = 1.53, p = 0.131. There was a significant difference between the years under research F(1;75) = 13.26, $p < 0.001$ significance level. The cover crop * year interaction was also significant F(12;75) = 2.36, $p < 0.01$ significance level.

In the 2025 harvest year higher yields were measured. On average, the yields of maize in 2024 were 4.8 t ha^{-1} and in 2025 were 5.3 t ha^{-1} (Figure 4). However, the individual CCs responded markedly to the crop year effect. The sainfoin achieved the lowest yield in 2024, while it significantly achieved the highest in 2025. The crimson clover treatment also achieved significantly higher yields in 2025. The field pea, the cowpea, and the pea vine responded equally well to the two crop years. These plants performed stably above the average for the two crop years.

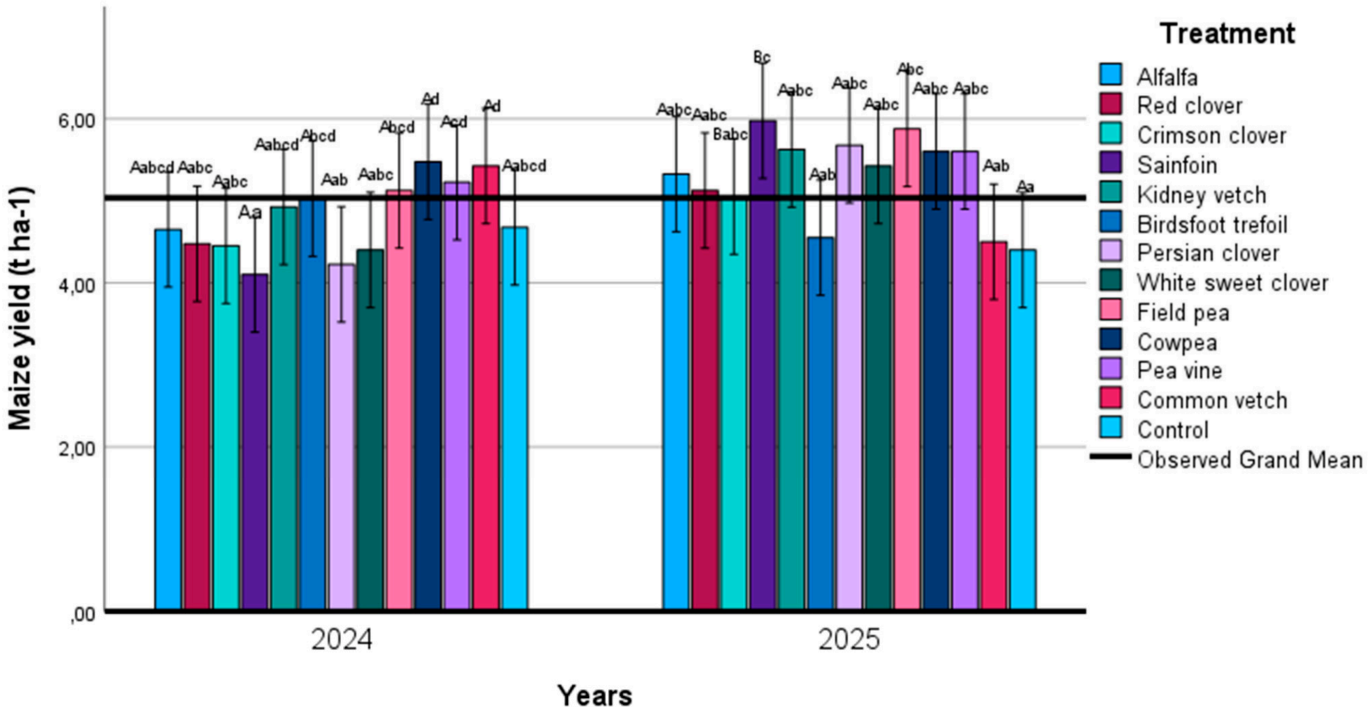


Figure 4. The effect of crop rotation technology on the yield of maize on Chernozem. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–d) represent cover crop treatments' effect on maize yields. Capital letters (A, B) represent cover crop treatments' effect on crop year. The letters start from the lowest value.

3.4. The Effect of Crop Rotation Technology on the Yield of Maize as a Cash Crop on Vertisol

Applying Two-way Random Block Design (2RBD) ANOVA, the cover crop effect was not significant F(12;75) = 1.57, p = 0.11 There was a significant difference between the

years under research F(1;75) = 358.63, $p < 0.001$ significance level. The cover crop * year interaction was not significant F(12;75) = 0.75, $p = 0.70$.

In terms of crop year effect, significantly higher yields were recorded in 2024 compared to those in 2025 (Figure 5). On average of treatments, 5.9 t ha^{-1} was noted in 2024 and only 3.7 t ha $^{-1}$ was recorded in 2025. In 2024 the pea vine treatment showed the highest yield. In 2025 the crimson clover was the most effective treatment.

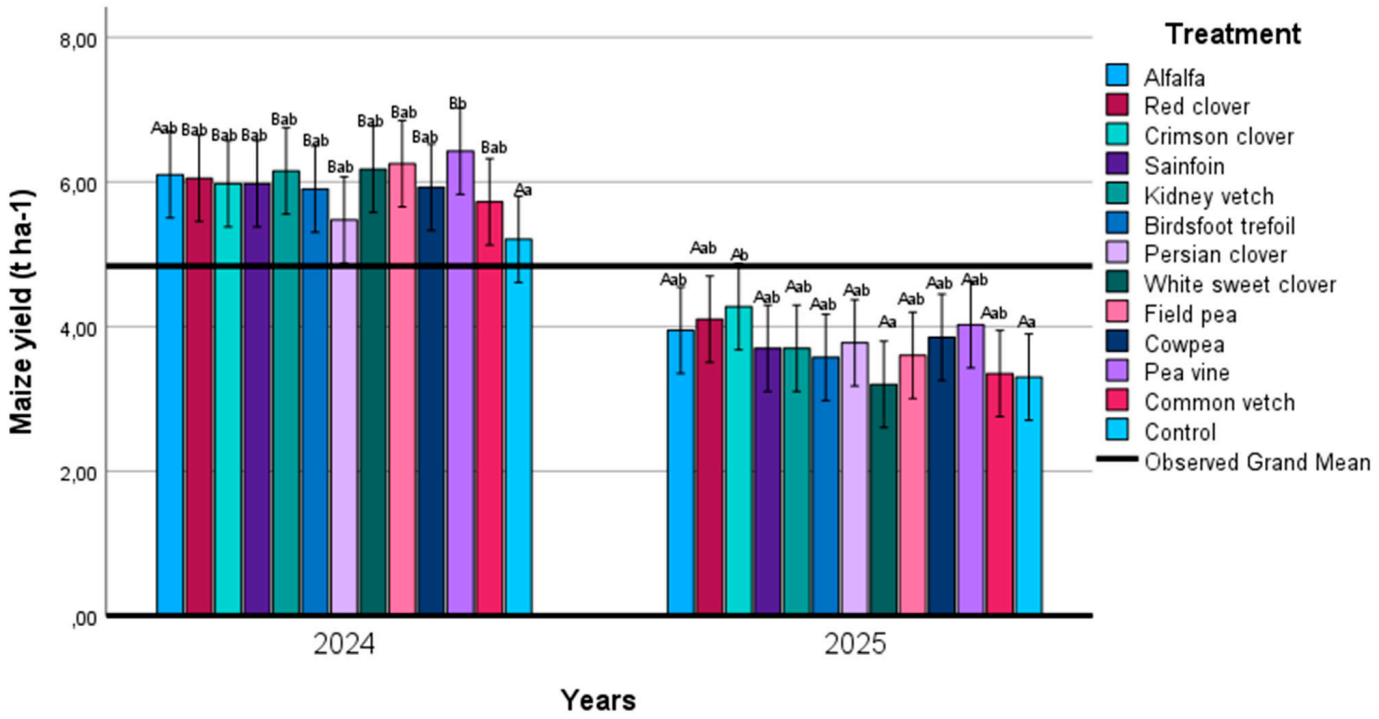


Figure 5. The effect of crop rotation technology on the yield of maize on Vertisol. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a, b) represent cover crop treatments' effect on maize yields. Capital letters (A, B) represent cover crop treatments' effect on crop year. The letters start from the lowest value.

3.5. The Effect of Two Agrotechnological Methods the Interseeding Cover Crop and the Crop Rotation Technology on the Yield of Maize as a Cash Crop on Vertisol in 2024

Applying Two-way Random Block Design (2RBD) ANOVA, the cover crop effect was not significant F(12;75) = 1.73, $p = 0.07$. There was no significant difference between the applied agrotechniques F(1;75) = 0.34, $p = 0.38$. The cover crop * applied agrotechniques' interaction was not significant F(12;75) = 1.5, $p = 0.14$.

In the case of the interseeding cover crop agrotechnique, the highest yield results were measured in the red clover, kidney vetch, Persian clover, cowpea, and pea vine treatments (Figure 6). In the crop rotation agrotechnique, the yield was significantly higher in the pea vine treatment compared to the control.

3.6. The Effect of Two Agrotechnological Methods the Interseeding Cover Crop and the Crop Rotation Technology on the Yield of Maize as a Cash Crop on Vertisol in 2025

Applying Two-way Random Block Design (2RBD) ANOVA, a significant effect of the cover crops was observed F(12;75) = 2.21, $p < 0.01$ significance level. There was no significant difference between the applied agrotechniques F(1;75) = 0.46, $p = 0.49$. The cover crop * applied agrotechniques' interaction was not significant F(12;75) = 1.37, $p = 0.19$.

In the case of crimson clover, significantly higher yield (1.7 t ha^{-1}) was observed with the application of the crop rotation agrotechnique, which also meant the largest fluctuation in this comparison (Figure 7). In the other treatments, the difference between the two

agrotechniques was not significant. The crimson clover, kidney vetch, Persian clover, cowpea, pea vine, and common vetch treatments were the most successful among the CCs in the case of the interseeding agrotechnique. The cowpea, pea vine, and red clover CCs produced above-average balanced yield results with both agrotechniques.

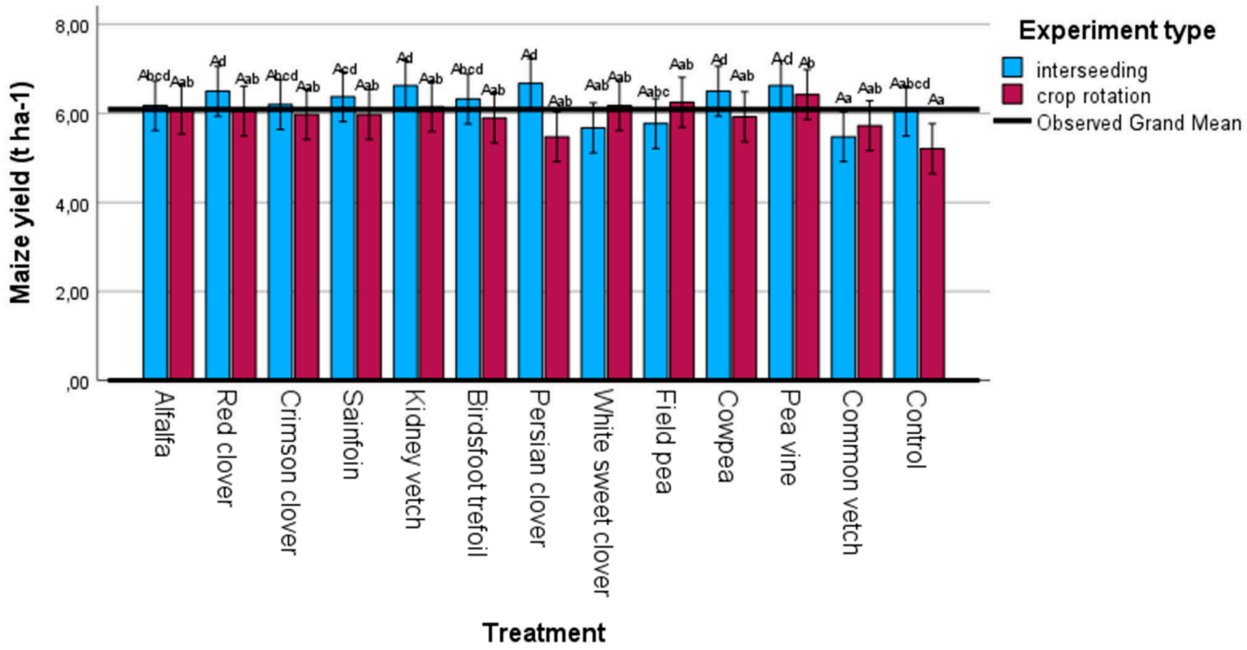


Figure 6. The effect of two agrotechnological methods—the interseeding cover crop and the crop rotation technology—on the yield of maize on Vertisol in 2024. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–d) represent cover crop treatments' effect on maize yields. Capital letter (A) represents agrotechnique. The letters start from the lowest value.

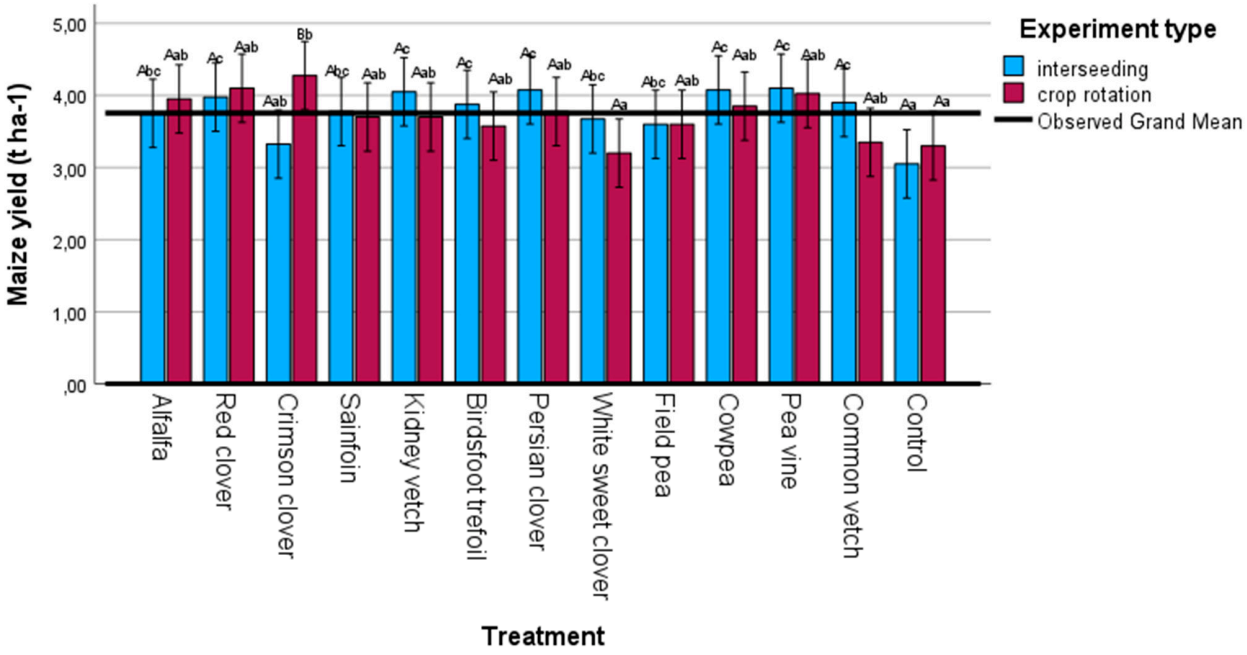


Figure 7. The effect of two agrotechnological methods—the interseeding cover crop and the crop rotation technology—on the yield of maize on Vertisol in 2025. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–c) represent cover crop treatments' effect on maize yields. Capital letters (A, B) represent agrotechniques. The letters start from the lowest value.

3.7. The Effect of Two Agrotechnological Methods the Interseeding Cover Crop and the Crop Rotation Technology on the Yield of Maize as a Cash Crop on Chernozem in 2024

Applying Two-way Random Block Design (2RBD) ANOVA, a significant effect of the cover crops was observed $F(12;75) = 2.09$, $p < 0.05$ significance level. A significant difference was also found between the applied agrotechniques $F(1;75) = 33.47$, $p < 0.001$ significance level. The cover crop * applied agrotechniques' interaction was also significant $F(12;75) = 2.11$, $p < 0.05$ significance level.

All treatments of interseeding cover crop agrotechnology (except field pea) resulted in higher yield results for maize than crop rotation agrotechnology (Figure 8). In addition to the crop rotation agrotechnique, common vetch and cowpea produced significantly the highest yield results. The lowest result in the case of crop rotation was registered for sainfoin. A difference of 1.37 t ha^{-1} was measured between cowpea and sainfoin. In the case of the interseeding agrotechnique, sainfoin was one of the best performing CCs, and therefore the largest yield fluctuation was observed between the two agrotechnique applications. Significant yield fluctuation was also observed in the case of the crimson clover, Persian clover, and red clover treatments in relation to the two agrotechnique applications. White sweet clover performed poorly in the case of the interseeding CC agrotechnique and crop rotation agrotechnique, and there was almost no difference in the yield of maize between the two agrotechniques. With both agrotechnical applications, above-average yield results were measured for the cowpea, pea vine, and common vetch treatments.

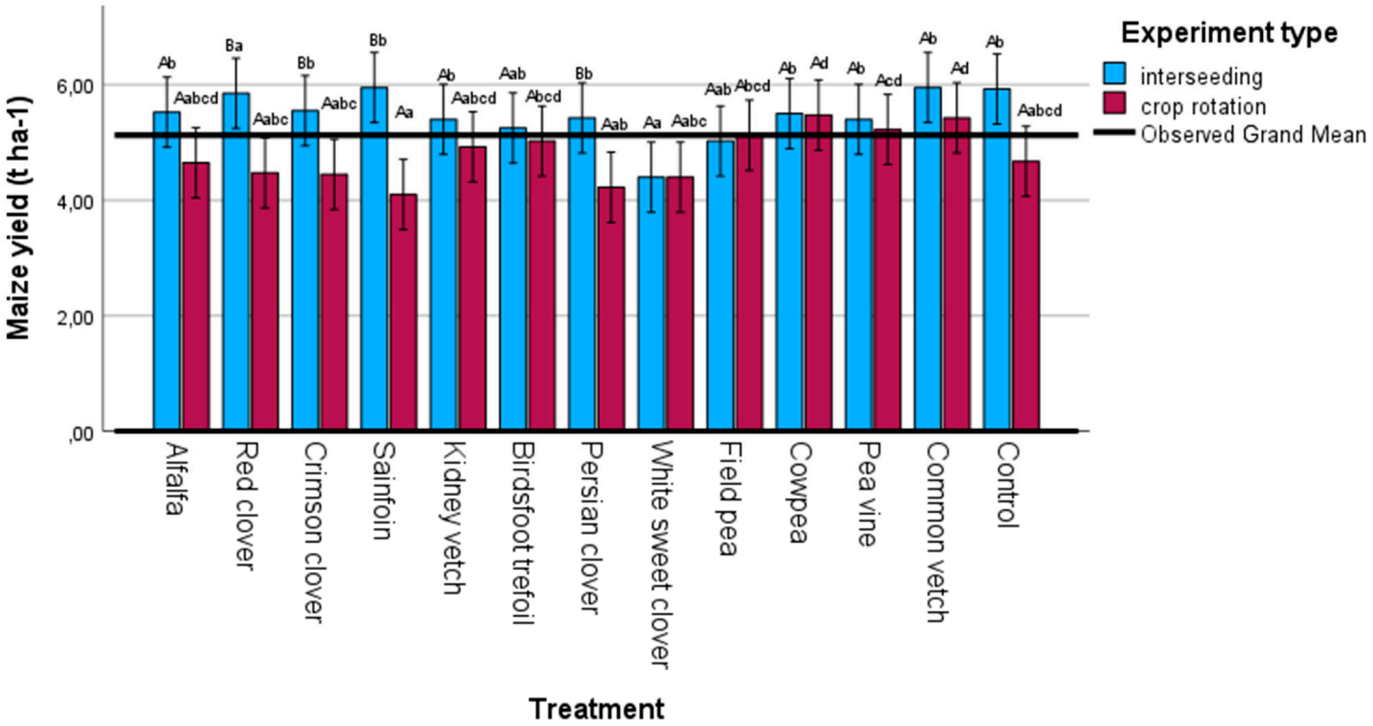


Figure 8. The effect of two agrotechnological methods—the interseeding cover crop and the crop rotation technology—on the yield of maize on Chernozem in 2024. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–d) represent cover crop treatments' effect on maize yields. Capital letters (A, B) represent agrotechniques. The letters start from the lowest value.

3.8. The Effect of Two Agrotechnological Methods the Interseeding Cover Crop and the Crop Rotation Technology on the Yield of Maize as a Cash Crop on Chernozem in 2025

Applying Two-way Random Block Design (2RBD) ANOVA, a significant effect of the cover crops was observed $F(12;75) = 2.55$, $p < 0.01$ significance level. A significant difference was also found between the applied agrotechniques ($F(1;75) = 99.82$, $p < 0.001$

significance level. The cover crop * applied agrotechniques' interaction was not significant $F(12;75) = 1.15$, $p = 0.33$.

Applying the interseeding cover crop agrotechnique generally results in significantly higher yields in comparison to the crop rotation agrotechnique (Figure 9). With the interseeding CC agrotechnique, significantly higher yield results were detected in the CC treatments relative to the control treatment. Implementing the interseeding CC agrotechnique, the CC treatments did not fluctuate compared to each other in this crop year. In the case of crop rotation, however, larger yield differences are visible between the individual CC treatments. With crop rotation, sainfoin provided the highest yield results. In the case of birdsfoot trefoil and common vetch, as well as the control treatments, the yield results were lowest with crop rotation.

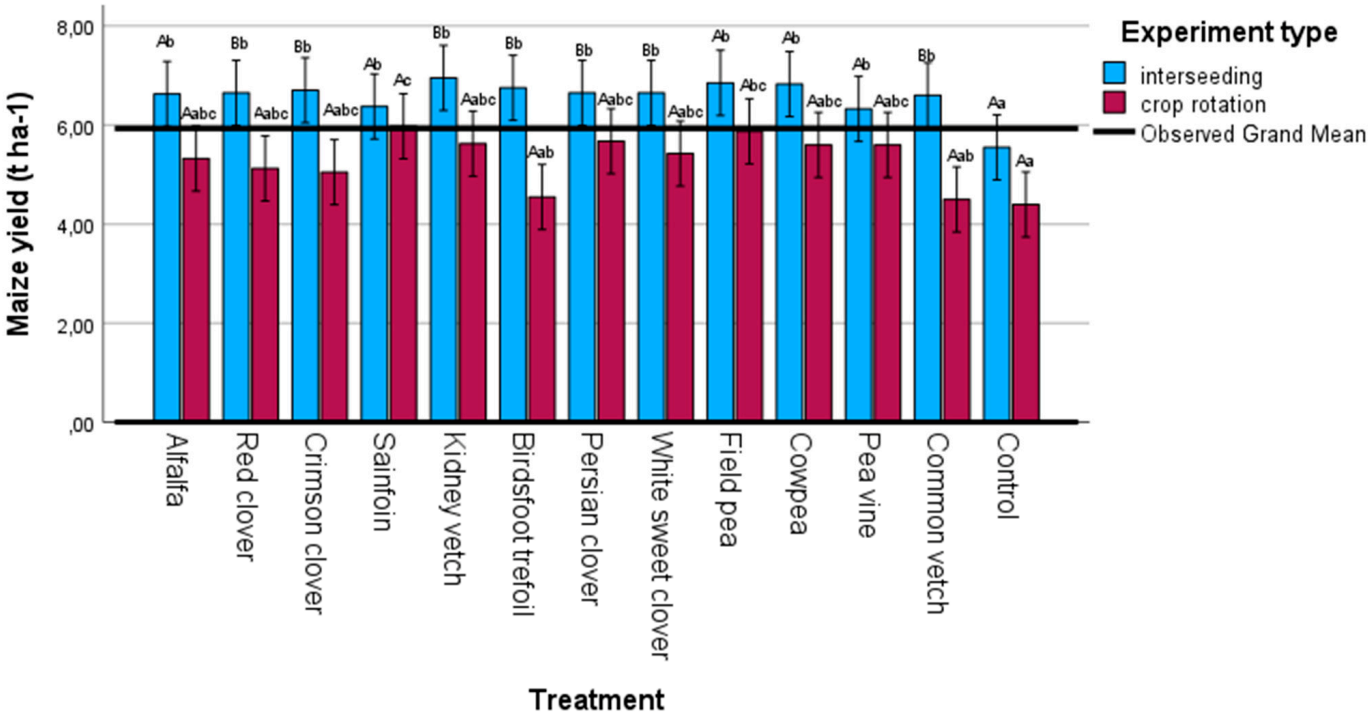


Figure 9. The effect of two agrotechnological methods—the interseeding cover crop and the crop rotation technology—on the yield of maize on Chernozem in 2025. Different letters are significantly different at the $p < 0.05$ significance level. Small letters (a–c) represent cover crop treatments' effect on maize yields. Capital letters (A, B) represent agrotechniques. The letters start from the lowest value.

4. Discussion

4.1. Application of Interseeding Cover Crop Agrotechnique on Vertisol and Chernozem 2023–2025

In the 2023 crop year, our observations were the following during the interseeding cover crop experiment on Chernozem. In terms of precipitation, this year was the most advantageous of the three-crop year. At that time, neither water nor nutrients were limiting factors, and therefore sufficiently rapid growth could be observed in the CCs, so the tubes also started to fix N early, and therefore the highest corn yield was recorded in the birdsfoot trefoil treatment, a legume CC which is also found in the natural plant associations of this agroecological area of Hungary [51]. CC treatments were not significantly inferior to conventional cultivation. CCs' effects on corn yield depended on annual precipitation, CC species, tillage system, and number of years of CC management [52].

In 2024, the interseeding CC experiment on Chernozem demonstrated the soil-drying effect of CCs. In early July, with temperatures reaching nearly 40 °C for 10 days, most of the CCs suddenly withered, and water was also withdrawn from the maize. In areas with

low rainfall, CCs can lead to groundwater depletion, reducing commercial crop yields [53]. Maize yield was significantly lowest with the white sweet clover treatment, which produces high biomass. It appears that evaporation further worsened the corn's struggle for water. Our measurements showed a significant decrease in maize yield with field pea treatment. Other authors have also demonstrated that field pea has rapid early shoot growth, high lateral root extension, and better soil N uptake. These characteristics may result in better competitiveness with neighboring plants; in our case, it took up N from the soil from corn at the beginning of its life cycle [53]. However, when it was able to fix atmospheric N, it suddenly withered and was unable to resprout either vegetatively or generatively.

In the 2025 crop year interseeding cover crop experiment on Chernozem, a significant difference was already visible between the cover crop treatment and the control treatment. In the experiment, no N fertilizer was applied during the three crop years, and only nutrients from plant residues were utilized by the plants. Other researchers also found that the CC technology had a positive effect on the yield at low N > 90 kg ha^{-1} [16,52,54]. However, another study observed evidence of biologically fixed N in the interseeded maize at the July sampling. As this sampling occurred prior to alfalfa senescence, it suggests there was direct transfer of N from alfalfa to maize which can occur through root exudates or mycorrhizal connections [55].

Vertisol showed a lower overall yield over the three-crop year average than Chernozem. Comparing the experiment on Vertisol with Chernozem, we observed the opposite reaction to the sudden dry period, that is, higher yields were measured on Vertisol in 2024. It is likely that the water-holding capacity of Vertisol and the already accumulated organic residues could also have played a role in the positive response to climatic stress. CCs reduce the fluctuations in soil moisture and soil temperature, that is, they act as a buffer in extreme environmental conditions [10]. In this case, the soil texture is of course primary, but the ecosystem services of the CCs may also have played a role in the positive outcome [11,12]. However, here too, the other side of the balance was revealed, as the existing CCs also consume water in the experimental area.

In 2023 on Vertisol, there was no significant difference between the CC treatments and the uncovered control treatment on Vertisol, as has been repeatedly stated in the literature [16,52]. However, there was one treatment, the sainfoin, which produced significantly higher results on Vertisol compared to the other treatments on average over the three years studied. It also performed stably in the other two years on Vertisol; therefore, its cultivation can be specifically recommended for this soil type. Pea vine was also considered a good and reliable CC on Vertisol. Our study shows that pea vine can be combined well with corn when sown in the spring at the time the corn has seven leaves and does not interfere with the development of the cash crop [17]. Pea vine can be found in several phenophases during the corn growing season. Pea vine can self-seed between the corn's rows. If a sudden drought occurs, it covers as dead mulch, but if it rains, it germinates again from seeds. Because of this, there are continuous degradable residues entering the soil, stimulating microbial life [17–20]. A study reports that a legume rapidly released N in the soil within two weeks after its death [56]. This can provide repeated N supply to the maize through the growing season.

In the 2024 crop year, the treatments of red clover, kidney vetch, and Persian clover performed well on Vertisol during a 10-day temperature anomaly of around 40 °C. Our approach is that their success lies in being very small plants, with a maximum height of 10 cm, close to the soil, with low biomass, and therefore their evapotranspiration is lower compared other CCs. Cover crop decreased evapotranspiration (ET) by 6.2% and increased water-use efficiency (WUE) by 5.0% compared to no cover crop [57]. The other CC that consistently performed well is the African cowpea, which is also remarkable in drought-

prone regions. Of course, under such dry conditions, the uncovered control treatments also achieved outstanding results, since here there was no competition for water with the cash crop. In the third year of the experiment, the same CCs achieved the largest yields as in 2024.

4.2. Application of Crop Rotation Agrotechnique on Vertisol and Chernozem 2024–2025

Considering the crop rotation agrotechnique 2024–2025 on Chernozem, it can be stated that cowpea and pea vine proved to be a smart option as a preceding crop for the maize as a cash crop in this agrotechnique as well. Field pea is not recommended for the interseeding cover crop agrotechnique, while it provides to be a promising candidate preceding crop for the crop rotation agrotechnique. However, it should be noted that cowpea is not always suitable as an autumn CC, as this plant experiences freezing injury at around 0 °C. Our results were obtained in years when the winters were very mild, which is why cowpea was able to thrive. In addition to the pea vine crop rotation agrotechnique, it also resulted in the highest corn yields on Vertisol. Legume WCCs resulted in subsequent higher corn yields by 30% to 33% when N fertilizer rates were low or the tillage system shifted from conventional tillage (CT) to no-tillage (NT) [58].

4.3. The Effect of the Two Agrotechnological Methods Interseeding Cover Crop and Crop Rotation on the Yield of Maize as a Cash Crop on Vertisol and Chernozem 2024–2025 Crop Year

The treatment differences were much more moderate on Vertisol compared to Chernozem. In the experimental year 2024, no significant difference was detected between the two tested agrotechnologies on Vertisol. In the next crop year, our research confirmed a significant difference in one out of 13 treatments, namely in the case of crimson clover. However, the effect was opposite to what our research usually observed. Using crimson clover CC in a crop rotation agrotechnique produced higher yields on Vertisol. Compared to Chernozem, significantly higher yields were detected with the interseeding CC agrotechnique. Our research shows that Trifoliums like crimson clover, red clover, and Persian clover perform strongly on Vertisol.

On Chernozem, however, our investigation showed stronger treatment effects. In our opinion, due to soil properties, faster material and energy flow occurs. The decomposition of biomass produced by legume CCs and the uptake of its nutrients are also more intense than on Vertisol. All treatments of interseeding cover crop technology (except of field pea) resulted in higher yield results for maize than the crop rotation agrotechnique. In addition to the crop rotation agrotechnique, common vetch and cowpea produced by far the highest results. The lowest result in the case of crop rotation was registered for sainfoin. A difference of 1.370 t ha^{-1} was measured between cowpea and sainfoin. In the case of the interseeding agrotechnique, sainfoin was one of the best performing CCs, and therefore the largest yield fluctuation was observed between the two agrotechnique applications. Significant yield fluctuation was also observed in the case of the crimson clover, the persian clover, and the red clover treatments in relation to the two agrotechnique applications. These CCs are very similar in appearance and taxonomy, and even small-seeded, maintained at maximum high of 10 cm close to the ground. These CCs provided higher yields to the cash crop with the interseeding cover crop agrotechnique. They have low competitive ability and low lateral root extension ability. At the beginning of a crop cycle, they can leave a larger part of the available N to the cash crop [54]. White sweet clover produced low yields under both the interseeding cover crop and crop rotation agrotechniques, with almost no difference in corn yield between the two technologies. Above-average yields were measured under both agrotechniques with cowpea, pea vine, and common vetch.

In the 2025 crop year, applying the interseeding cover crop agrotechnique generally results in significantly higher yields in comparation to the crop rotation agrotechnique. In the experimental years, spring CCs increased biomass and covered the field for a longer period, approximately 9 months, while autumn CCs had remained in the fields for around 4 months. High N_2-fixing legume cover crops can have more rapid and greater effects on increasing crop yields than cover crops with low or no N_2-fixing capacity. Specifically, summer legume cover crops are more effective at increasing crop yields than winter cover crops because of higher potential biomass and N inputs [59]. Applying autumn CCs requires great flexibility in determining the sowing time. Climate change in Hungary has modified conventional working times, as the end of summer has often shifted to autumn and winter has frequently showed autumnal climatic features. For this reason, autumn CCs were sown in August one year, but in the other year they were only sown at the very beginning of October, as the soil was not in a cultivable condition. According to other studies, CCs can cause a cash crop yield deficit in the first few years, especially in the case of single-species wheat CCs in the first year of maize. The yield reduction caused by wheat CCs suggest that wheat residues decompose slowly and use up a lot of N [42]. This finding is also supported by our experiments, since in the crop rotation winter wheat as a preceding crop was sown, and all its straw was returned to the soil. Overall, interseeding CC treatments yielded higher yields for the cash crop compared to crop rotation. With the interseeding CC agrotechnique, significantly higher yield results were detected in CC treatments related to the control treatment in the third year of the experiment, which is supported by the literature data [53].

5. Conclusions

The study highlighted the potential of legume CCs for climate resilient, sustainable farming. The selection of CCs for the given agroecological environment is considered important.

Our results showed that pea vine and cowpea contributed to increased corn yield on both soil types and agrotechnique.

Under the conditions of this study, white sweet clover cannot be appropriate as a cover crop, because this plant gave poor yield results in crop rotation and, in the case of interseeding cover crops, seemed too competitive with the cash crop.

Field pea is recommended for the crop rotation agrotechnique.

Trifolium species like Persian clover, red clover, and crimson clover show good adaptability to Vertisol.

In Chernozem, the interseeding cover crop agrotechnique provides higher yield results for the cash crop compared to the crop rotation agrotechnique.

In the case of sainfoin, our research observed large yield fluctuations. However, in years favorable for sainfoin, it can greatly contribute to increasing the yield of maize, so it may be worth including it in the CC mix. Further studies are required to find what determines the appearance of the positive CC effect of sainfoin.

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Abbreviations

The following abbreviations are used in this manuscript:

CC	Cover crop
SOC	Soil organic carbon
OC	Organic carbon
MAOM	Mineral-associated organic matter
BNF	Biological nitrogen fixation
GHG	Greenhouse gas
CT	Conventional farming
MT	Minimum tillage
WRB	The World Reference Base
CR	Crop rotation
2RBD	Two-way Random Block Design
ANOVA	Analysis of Variance
ET	Evapotranspiration
WUE	Water-use efficiency
WCC	Winter cover crops
CT	Conventional tillage
NT	No-tillage

Appendix A

Table A1. Soil characteristic of experimental sites.

	Vertisol	Chernozem
pH (KCl)	6.8	7.6
Total Salinity m m%$^{-1}$	0.12	0.05
$CaCO_3$ m m%$^{-1}$	1	6.5
Humus m m%$^{-1}$	1.83	2.72
NO3-N mg kg^{-1}	21.7	20.6
P_2O_5 mg kg^{-1}	227	66
K_2O mg kg^{-1}	257	251
Mg mg kg^{-1}	120	371
Na mg kg^{-1}	59	34
Zn mg kg^{-1}	0.7	1.1
Cu mg kg^{-1}	1.5	6.2
Mn mg kg^{-1}	70	143
SO_4^{2-} mg kg^{-1}	12.2	11.4

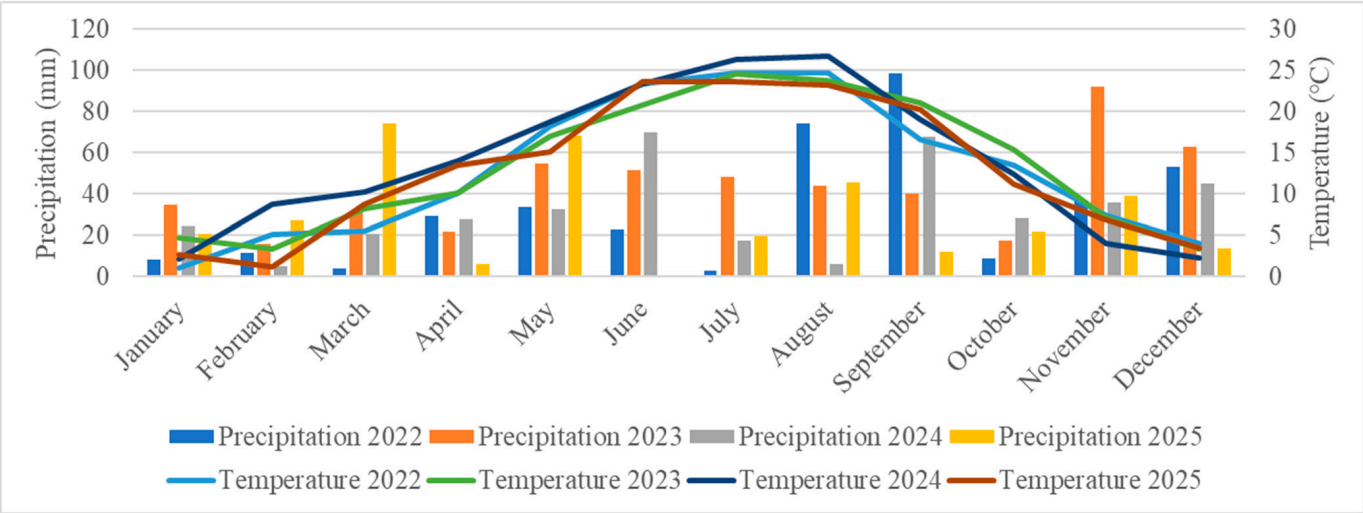


Figure A1. Monthly precipitation sum (mm) and average temperature (°C) during the examination years.

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