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The Use of Faba Bean Cover Crop to Enhance the Sustainability and Resiliency of No-Till Corn Silage Production and Soil Characteristics

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Abstract: Sustainable corn production requires a dramatic shift toward natural soil fertility rather than relying solely on synthetic fertilizers. Cover crops play an important role in improving the productivity of subsequent row crops through improving soil properties. The main goal of this study was to investigate if increasing cover crop biomass through applying a higher density can enhance soil characteristics in the short term and contribute more nitrogen to succeeding corn silage. In a two-year field study (2018–2019), the influence of faba bean (*Vicia faba* L.) as a cover crop on soil characteristics and corn silage (*Zea mays* L.) production was evaluated. Treatments consisted of five levels of faba bean density (0, 25, 35, 40, and 80 plants m^{-2}) and four application rates of urea-based nitrogen fertilizer (0, 100, 200, and 300 kg ha^{-1}) in a no-till system. The measured soil characteristics were not significantly affected through increasing cover crop density to 80 plants m^{-2}. The faba bean roots comprised 33% of total biomass in densities ranging from 25–40 plants m^{-2}. The highest total N yield (root + shoot) was 133 kg N ha^{-1}, obtained from 40 faba bean plants m^{-2}. The faba bean root decomposed faster than the shoot, and the addition of N to the corn accelerated 50% N release from the roots but had no significant effect on shoot decomposition. Corn planted after 40 plants m^{-2} faba bean yielded 28% more than the corn with no faba bean. Corn yielded less in no-cover-crop fields even when it received the highest synthetic N rate (300 kg N ha^{-1}), indicating the value of including faba bean in rotation with corn.

Keywords: faba bean cover crop; biological nitrogen fixation; faba bean residue decomposition; nitrogen yield of roots and shoot; soil characteristics; sustainable corn production

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1. Introduction

In recent years, soil health has received considerable attention from both researchers and growers. A dramatic shift toward natural soil fertility to minimize the use of synthetic fertilizers is at the center of attention. The traditional production of corn in many countries includes the use of tillage and the application of considerable amounts of synthetic N fertilizer. For example, the current recommended rate of N application is around 200 kg N ha^{-1} for corn silage in Iran [1]. In a five-year field study, Halvorson et al. [2] reported that corn yield reached near maximum with an available N (soil + fertilizer N) level of 276 and 268 kg N ha^{-1} in the conventional tillage (CT) and no-till (NT) systems, respectively.

Due to changes in environmental conditions and the non-uniform fertility of agricultural lands, the determination of the optimum amount of N for maximizing the yield of corn is a challenge [3,4]. Isotope tracing studies indicated that even under appropriate management practices such as N side-dress timing, almost half of the applied N will be lost to the environment due to volatilization and leaching [5,6]. Additionally, continuous soil disturbance and the application of synthetic N fertilizers may impose a negative impact on soil biology and the environment [7,8]. Supporting soil biology is essential for the sustainability and resiliency of agricultural production. A 25-year experiment revealed that diversified rotation under the NT system resulted in better enhancement of soil health than rotating crops in conventional tillage systems [9].

Many reports indicated that the use of legumes in rotation and leaving plant residues on the soil surface considerably improved soil biology [4,10–12]. Additionally, avoiding soil disturbance has great potential for reducing soil erosion, fossil fuel consumption, and greenhouse gas emissions [13]. However, to maximize the sustainability and resiliency of crop production, the transition to the no-tillage system would be more beneficial when accompanied by other sustainable farming practices, including cover cropping, crop rotation, and intercropping [14,15].

Faba bean is an ancient food crop and, recently, its use as a cover crop has significantly increased. The use of faba bean as a cover crop or in rotation with other non-legume crops can considerably lower the need for off-farm N [16,17]. Etemadi et al. [7] reported that winter-killed faba bean cover crops accumulated up to 192 kg N ha^{-1}. However, in many milder areas of the world, spring faba bean, as a cover crop, is typically terminated at the flowering stage or even earlier [18]. At this stage of growth, the faba bean has not gained its potential biomass and N yield; therefore, the N contribution to the succeeding cash crop is not maximized.

Integrating faba bean as a cover crop, main crop, or dual-purpose into cropping systems is a common practice in many parts of the world [17,19]. Regardless of the main purpose of cultivating faba bean, the aerial parts will be eventually incorporated into the soil (in a conventional tillage system) or left on the soil surface (in a no-till system). The decomposition of cover crop residues in the no-till system where the aerial parts are left on the soil surface is slower than burying the residues [20]. Etemadi et al. [7] reported that the time for releasing 50% of N was delayed for approximately a month when compared with conventional tillage, resulting in better synchrony with N uptake and use efficiency by sweet corn. Obviously, when faba bean is used as a vegetable or for dual purposes, it significantly contributes less N to the succeeding crop, since the N-rich pods are entirely or partially harvested [17]. Additionally, including faba beans in crop rotation, especially in a no-till system, can be highly energy efficient [21], which could help to reduce greenhouse gas emissions from agricultural lands.

The root biomass of faba bean and its N contribution to the succeeding crop is generally overlooked. The percentage of root to the total biomass in field-grown faba bean is not well documented. A report by Muñoz-Romero et al. [22] indicated that root biomass and other root characteristics improved significantly in the NT system compared with CT. Similarly, Romaneckas et al. [23] reported that NT faba bean cultivation could improve soil health characteristics relative to plowed treatments.

This study aimed to evaluate (a) the short-term influence of increasing faba bean cover crop density on select soil characteristics, (b) the response of faba bean root and shoot biomass to increasing population density, (c) the decomposition trend of the roots and shoots of faba bean residues in a no-till corn silage system, and (d) the contribution of faba bean residues to the N need of succeeding corn silage.

2. Materials and Methods

2.1. Experiment Site

A field experiment was conducted in two growing seasons (2018 and 2019) at the research farm of the Faculty of Agriculture and Natural Resources, Mohaghegh Ardabili University, in Babolan village, Ardebil (latitude 38°15′ N and longitude 48°15′ E), 1350 m above the sea level. The soil of the experimental site was loamy with 35, 42, and 23 percent sand, silt, and clay, respectively. The weather conditions of the experimental site during the two-year experiment are shown in Figure 1. The experiments were conducted in the same plots in 2018 and 2019. The research site was fallow before the onset of the experiment (2018) but was covered with annual broadleaf weeds, mainly including common amaranth (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) in both years.

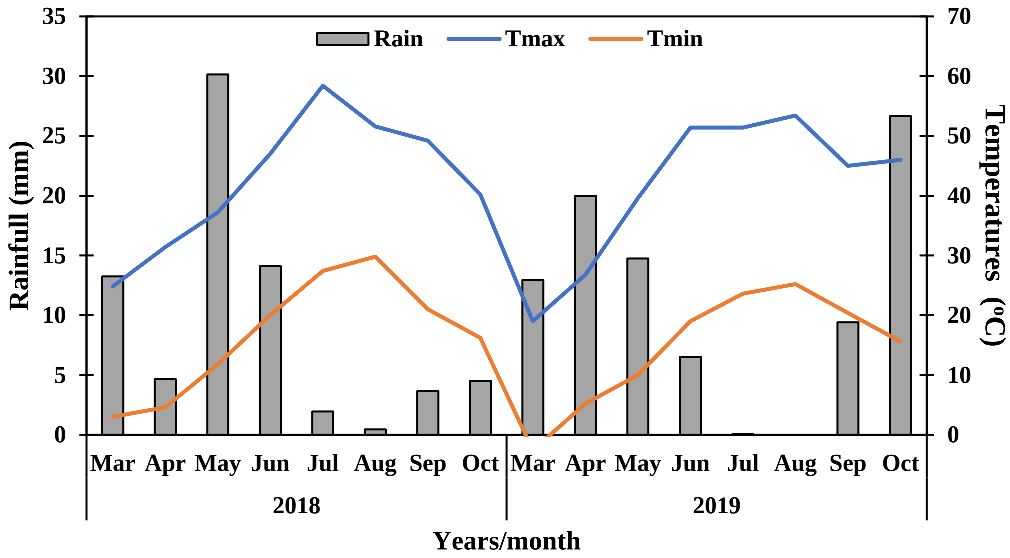

Figure 1. Rainfall, maximum and minimum temperatures at the experimental site during the two-year study period.

2.2. Field Establishment and Treatment Application

The experimental design was a factorial based on a randomized complete block with three replicates in each growing season. The experimental treatments consisted of faba bean densities (0, 25, 35, 40, and 80 plants m^{-2}) and N fertilizer rates applied to the corn silage (0, 100, 200, and 300 kg ha^{-1}). Experimental plots were 3 m × 4 m, separated by a 1 m path between the as well as between experimental plots. The faba bean cultivar used in this experiment was Shadan (*Vicia faba* L. cv. Shadan/G-Faba–133) (LineF6/Latt338/08), introduced by the Seed and Plant Improvement Institute of Iran in 2017. In 2018, prior to planting faba bean cover crop, the experimental site was lightly disked to control the weeds. However, no tillage was performed throughout the experiment in 2018 and 2019 (Table 1).

Table 1. Agronomic practices performed in 2018 and 2019 before faba bean cover crop planting.

Year	Seedbed Preparation	Starter N (kg ha^{-1})	Planting Time	Termination Time	The Inter-Row Space (cm)
2018	Light disk/Spring	20	3 March	10 June	20
2019	No till	20	3 March	7 June	20

In both years, faba bean seeds were hand-planted on 3 March after soaking in water overnight and then inoculated with Rhizobium leguminosarum var viciae, purchased from a local company. The experimental plots had no history of faba bean in the past; therefore, 20 kg N ha^{-1} fertilizer was applied at the planting as a starter. Faba beans were terminated at the onset of flowering (10 June) via mowing plants at 5 cm above the soil, and residues were left on the soil surface as mulch. Corn was no-till planted into the faba bean residues at a population of 80,000 plants ha^{-1} in rows spaced 50 cm apart. An early maturing hybrid (KSC 201) (a cross between K1263/17 × S61 inbred lines) was sown on 23 and 25 June 2018 and 2019, respectively. This cultivar was developed by the Seed and Plant Improvement Institute of Iran in 2016. Since the soil was calcareous and plants often show iron (Fe) deficiency, a foliar application of iron (Fe-EDTA) was carried out in three stages at 10-day intervals. Weed control was exercised in faba bean cover crops. Since corn was planted into faba bean mulch, weeds were not a major issue. However, weeds, especially in low-faba-bean-density plots, were handpicked a few times until the corn started their fast growth. Nitrogen fertilizer in the form of urea (46% N) was broadcast at the V5 stage of corn development. Corn was harvested on 30 September 2018 and 2 October 2019 at the 50% milk stage when plants contained 60–70% moisture. Soil moisture in corn plots was monitored, using a tensiometer, and irrigation was applied throughout the period of corn growth when needed. No chemicals, except urea fertilizer and iron, were used in this study.

2.3. Sampling and Measurements

To determine the initial chemical properties of the soil, including pH, organic matter, K^+, P, and total N, multiple sub-samples were collected at a depth of 0–30 cm, and results are shown in Table 2. Soil pH was measured in a 0.01 mol L^{-1} $CaCl_2$ suspension [24]. The chromic acid digestion method was used to determine soil organic matter [25]. Available P was determined using a spectrophotometer [26], and K^+ was extracted using a flame atomic absorption spectrophotometer [27]. Total N was measured using the Kjeldahl method [28].

Table 2. Chemical characteristics of the soil of the experimental site, taken at two depths in each growing season.

Years	Depth (cm)	pH	SOM (g dm^{-3})	K^+ (mg kg^{-1})	P (mg kg^{-1})	Total N (%)
2018	0–15	7.8	10.3	212	8.29	0.06
	15–30	7.6	6.88	143	6.5	-
2019	0–15	7.9	10.3	220	8.9	0.06
	15–30	7.7	6.88	152	6	-

Select physical and chemical soil properties were measured after faba bean termination in the second year. Soil samples were collected from a depth of 0–15 cm. The composite soil sample was dried and passed through a 2 mm sieve to determine physical and chemical properties, including organic carbon, electrical conductivity (EC), bulk density, and porosity. Properties such as water infiltration rate and soil moisture content were also evaluated before terminating the faba bean cover crop. The water infiltration rate was determined using a double-ring infiltrometer based on measuring the height of water infiltrated into the soil (three replicates per experimental unit between the two central plants) [29]. Soil organic carbon was determined using the method of Walkley and Black [30]. Organic matter (OM) was calculated by multiplying organic carbon by a factor of 1.724. Soil electrical conductivity was measured in a 1:25 soil/water solution using EC meters (model: Mi 180 Bench Meter) [31]. Bulk density was determined using the core method [32]. Total porosity (TP %) was calculated as follows: $TP = [1 - (BD/2.65)] \times 100$ [27]. The moisture content of the soil was determined using the gravimetric method (Equation (1)). The soil sample was weighed and then dried in an oven at 105 °C for 72 h and weighed again [33].

$$\text{Soil moisture content} = \frac{\text{wet soil weight (g)} - \text{dry soil weight (g)}}{\text{dry soil weight (g)}} \times 100 \quad (1)$$

Prior to termination of faba bean cover crop, 10 plants in each plot were randomly selected and dug out from 30 cm depth with extra caution. The roots were washed immediately and separated from the aerial parts. Root and aerial parts were dried in a forced-air oven to constant weight. The average dry weight of the roots and shoots of 10 plants were multiplied by the corresponding plant density to calculate biomass per m^{-2}. The nitrogen yield of faba bean cover crop was calculated using the following equation: Total N yield = root biomass × N content of root + shoot biomass × N content of shoot. The mesh (litter) bag technique [20] was used to assess the N mineralization of faba bean roots and shoot residues. Mesh bags were made of polyamide nylon with a size of 20 × 10 cm. A hundred grams of freshly chopped faba bean roots and shoots were separately placed in the litter bags. Root samples were buried 20 cm deep in the soil, and shoot samples were placed on the soil surface. Litter bags were harvested beginning the second week and weekly then after. At each harvest, roots and shoots bags were cleaned and dried in an oven at 70 °C to constant weight. The dried samples were weighed and finely ground and passed through a 2 mm sieve. The sieved samples were analyzed for total N, using the Kjeldahl method.

Three corn plants were randomly selected and hand-cut above the soil surface at the 50% milk stage (60–70% moisture). Harvested corn was oven dried at 70 °C to constant weight and then ground with a mill and passed through a 2 mm sieve. Total N was determined using the Kjeldahl method. Crude protein was calculated via multiplying %N by 6.25. Corn silage yield was hand harvested from 1 m^2, 10 cm above the soil, and weight was adjusted to 70% moisture content.

2.4. Statistical Analysis

All data homogeneity of variance was tested using Bartlett's test. The data were normally distributed ($W \geq 0.90$). Data were then analyzed using analysis of variance (ANOVA) using SPSS 16.0 (SPSS, Chicago, IL, USA) software to determine the main and interaction effects of the treatment. Effects were considered significant at $p \leq 0.05$ according to the *F* test. When the treatment was significant, mean separation was performed via LSD. The following non-linear regression models were used to determine the response trend of faba bean density and N content:

$$\text{Sigmoid: } Y = Y_{min} + Y\alpha/(1 + \exp(-(X - X_{50})/\text{slope}))$$

$$\text{Logistic: } Y = Y_{min} + Y\alpha/(1 + (-(X/X_{50})^{\text{slope}}))$$

$$\text{Single: } Y = Y_{min} + Y\alpha \times \exp^{(-\text{slope} \times x)}$$

$$\text{Symmetric: } Y = Y_{min} \times \text{abs}(X - X_{min})^{\text{slope}}$$

$$\text{Gaussian: } Y = Y_{max} \times \exp\,(-0.5 \times ((X - X_{max})/^{\text{slope}})^2)$$

$$\text{Lorentzian: } = Y_{max}/(1 + ((X - X_{max})/^{\text{slope}})^2)$$

where Y_{max} ($Y_{min} + Y_{\alpha}$) is maximum y, Y_{min} is minimum y, Y_{α} is the change of Y from Y_{max} to Y_{min}, X_{50} is the x value to reach 50% Y_{max}, X_{max} is the x value to reach Y_{max}, and X_{min} is the x value to reach Y_{min}.

3. Results

3.1. Weather Conditions

Environmental conditions in 2018 and 2019 during the months of March through October, with some minor exceptions, were similar (Figure 1). There was more precipitation in 2018 than in 2019; however, more rainfall in May and June 2018 was not an important factor since the faba bean was terminated on June 10 and corn was irrigated when needed. T_{max} and T_{min} in 2018 and 2019 were almost similar.

3.2. Influence of Faba Bean Cover Crop Density on Soil Characteristics

Organic carbon, organic matter, electrical conductivity (EC), bulk density, and the total porosity of the soil in the experimental plots were not affected significantly by faba bean cover crop density within a two-year span (Table 3). Among the measured soil properties, water infiltration and soil moisture content improved significantly. For example, the time for water infiltration decreased by about 27% (Table 3). However, the measured soil characteristics showed some improving trends at the end of the two-year experiment.

Table 3. Estimated parameter nonlinear regression and influence of faba bean (*Vicia faba* L.) cover crop density on select soil characteristics in 2018 and 2019.

Treatments	Levels	Water Infiltration Rate (cm s^{-1})	Soil Moisture Content (%)	Organic Carbon (%)	Organic Matter (%)	Electrical Conductivity (ds m^{-1})	Total Porosity (%)	Bulk Density (g cm^{-3})
Years	2018	34.4 ± 3.8 ^{a}	20.8 ± 0.79 ^{a}	0.52 ± 0.02 ^{a}	0.89 ± 0.04 ^{a}	377.1 ± 13.6 ^{a}	50.7 ± 2.0 ^{a}	1.31 ± 0.04 ^{a}
	2019	31.8 ± 3.7 ^{b}	22.1 ± 1.09 ^{a}	0.51 ± 0.02 ^{a}	0.88 ± 0.04 ^{a}	333.2 ± 17.2 ^{a}	53.1 ± 1.8 ^{a}	1.24 ± 0.05 ^{a}
	$LSD_{0.05}$	2.4	2.6	0.06	0.11	80.5	5.9	0.16
Density (plant m^{-2})	0	51.5 ± 1.8 ^{a}	18.1 ± 0.7 ^{c}	0.53 ± 0.06 ^{a}	0.83 ± 0.05 ^{a}	367.3 ± 26.2 ^{a}	50.7 ± 2.6 ^{a}	1.31 ± 0.07 ^{a}
	25	41.3 ± 1.4 ^{b}	19.6 ± 1.1 ^{c}	0.52 ± 0.04 ^{a}	0.89 ± 0.05 ^{a}	342.2 ± 10.8 ^{a}	50.5 ± 2.7 ^{a}	1.31 ± 0.07 ^{a}
	35	37.3 ± 2.1 ^{c}	20.9 ± 0.7 ^{bc}	0.52 ± 0.02 ^{a}	0.92 ± 0.04 ^{a}	333.1 ± 26.5 ^{a}	52.0 ± 2.9 ^{a}	1.27 ± 0.08 ^{a}
	40	22.8 ± 1.3 ^{d}	23.6 ± 0.9 ^{ab}	0.52 ± 0.03 ^{a}	0.89 ± 0.07 ^{a}	346.9 ± 42.5 ^{a}	52.6 ± 1.1 ^{a}	1.26 ± 0.03 ^{a}
	80	12.7 ± 1.3 ^{e}	25.1 ± 1.9 ^{a}	0.48 ± 0.03 ^{a}	0.92 ± 0.09 ^{a}	356.4 ± 15.8 ^{a}	52.6 ± 3.3 ^{a}	1.23 ± 0.11 ^{a}
	$LSD_{0.05}$	2.4	3.5	0.09	0.16	79.6	11.2	0.26
Regression	†† Trend	L	S	none	none	none	none	none
	Y_{max}	39.9 ^{ns}	25.2 ^{ns}	-	-	-	-	-
	Slope	−4.10 ^{ns}	4.30 ^{ns}	-	-	-	-	-
	D_{50}	36.2 *	36.2 **	-	-	-	-	-
	Y_{min}	10.8 *	18.5 **	-	-	-	-	-
	R^2	0.949	0.975	-	-	-	-	-
F value								
	Year (Y)	*	ns	ns	ns	ns	ns	ns
	Density (D)	**	*	ns	ns	ns	ns	ns
	Y × D	ns	ns	ns	ns	ns	ns	ns
Coefficient of variation (%)		13.4	13.4	15.5	14.7	18.3	17.7	17.1

ns—non-significant; *—significant at 0.05 level; **—significant at 0.01 level 1%; †† S—sigmoid; L—logistic; none—no significant model. Y_{max}—maximum Y or variable; Y_{min}—minimum Y or variable; D_{50}—half-maximal effective density; R^2—coefficient of determination. Values are means (n = 4) ± standard error, and columns with different letters are significantly different using the least significant difference (LSD) test (LSD; a = 0.05).

3.3. Influence of Faba Bean Density on Cover Crop Biomass and N Yield

The faba bean biomass and the associated N yield were not significantly different in the two years of experiments (Table 4). The interaction of year and faba bean density as well as year by N application to corn were not statistically different for the measured traits; therefore, an average of the two years was used to present the results. The response of root and shoot biomass and their N yield to the increased faba bean density followed a sigmoid trend (Table 4, Figure 2). The densest faba bean cover crop (80 plants m^{-2}) produced 14% and 13% higher root and shoot biomass, respectively, when compared with 40 plants m^{-2}. The ratio of root biomass to the total biomass was approximately 33% in densities ranging from 25–40 plants m^{-2}. However, when the density increased to 80 plants m^{-2}, the contribution of roots to the total biomass increased to 49%. The highest total cover crop biomass (9.69 Mg ha^{-1}) was obtained from 80 plants m^{-2} but was not statistically different from the biomass measured in 40 plants m^{-2} (Figure 2). The results indicated that faba bean as a cover crop does not respond well to very high population density. Interestingly, the N content of the roots and shoots in 40 plants m^{-2} was higher than in 80 plants m^{-2}; therefore, the total N yield of roots and shoots was similar in 40 and 80 plants m^{-2}. The roots and shoots of faba bean reached their D_{50} (half of the maximum effective density) at approximately 35 plants m^{-2} (Figure 2). The highest total N yield was 14.2 g $m^{-2,}$ which is equivalent to 140.2 kg N ha^{-1} and was obtained from 80 plants m^{-2} but was not statistically different from the N yield in 40 plants m^{-2} (Table 4).

Table 4. Estimated parameter nonlinear regression and the main effect response of faba bean (*Vicia faba* L.) cover crop biomass, N content, and N yield of roots and shoots in 2018 and 2019.

Treatments	Levels	Biomass ($g\ m^{-2}$)		N Content ($g\ kg^{-1}$)		N Yield ($g\ m^{-2}$)	
		Root	Shoot	Root	Shoot	Root	Shoot
Year	2018	243.2 ± 21.3 ^{a}	496.7 ± 46.8 ^{a}	7.7 ± 0.29 ^{a}	19.7 ± 0.35 ^{a}	1.8 ± 0.14 ^{a}	9.6 ± 0.78 ^{a}
	2019	243.6 ± 18.1 ^{a}	472.2 ± 36.7 ^{a}	7.9 ± 0.30 ^{a}	20.1 ± 0.36 ^{a}	1.9 ± 0.12 ^{a}	9.3 ± 0.60 ^{a}
	$LSD_{0.05}$	37.7	38.7	1.60	1.7	1.01	1.47
Density (plant m^{-2})	0	-	-	-	-	-	-
	25	157.3 ± 6.1 ^{d}	298.6 ± 19.3 ^{c}	8.4 ± 0.40 ^{a}	21.3 ± 0.36 ^{a}	1.3 ± 0.10 ^{b}	6.4 ± 0.44 ^{c}
	35	216.0 ± 14.2 ^{c}	424.0 ± 10.0 ^{c}	8.2 ± 0.26 ^{b}	20.2 ± 0.25 ^{b}	1.8 ± 0.15 ^{a}	8.6 ± 0.23 ^{b}
	40	278.3 ± 7.9 ^{b}	568.4 ± 15.0 ^{a}	7.8 ± 0.25 ^{c}	19.4 ± 0.25 ^{c}	2.3 ± 0.12 ^{a}	11.0 ± 0.28 ^{a}
	80	322.0 ± 5.6 ^{a}	646.8 ± 25.2 ^{a}	6.7 ± 0.33 ^{d}	18.7 ± 0.30 ^{d}	2.2 ± 0.10 ^{a}	12.0 ± 0.36 ^{a}
	$LSD_{0.05}$	49.5	102.7	0.11	0.12	0.45	1.79
Regression	†† Trend	S	S	Ed	Ed	S	S
	Y_{max}	321.9 *	646.7 *	8.54 *	22.27 *	3.03 *	12.0 *
	Slope	3.17 ^{ns}	2.79 ^{ns}	0.025 ^{ns}	0.067 ^{ns}	0.22 ^{ns}	2.57 ^{ns}
	cY	168.8 *	353.9 *	−1.72 *	−3.67 *	0.90 *	5.67 *
	D_{50}	36.6 ^{ns}	36.4 ^{ns}	-	-	34.9 ^{ns}	36.0 ^{ns}
	Y_{min}	153.1 *	292.8 *	6.82 *	18.6 *	2.20 *	6.3 *
	R^2	0.966	0.956	0.994	0.978	0.943	0.949
F value							
	Year (Y)	ns	ns	ns	ns	ns	ns
	Density (D)	**	**	**	**	*	**
	Y × D	ns	ns	ns	ns	ns	ns
Coefficient of variation (%)		9.9	10.1	1.4	1.2	10.4	9.2

ns—non-significant; *—significant at 0.05 level; **—significant at 0.01 level; †† S—sigmoid; L—logistic. Y_{max}—maximum Y or variable; Y_{min}—minimum Y or variable; D_{50}—half-maximal effective density; R^2—coefficient of determination. Values are means (n = 4) ± standard error, and columns with different letters are significantly different using the least significant difference (LSD) test (LSD; a = 0.05).

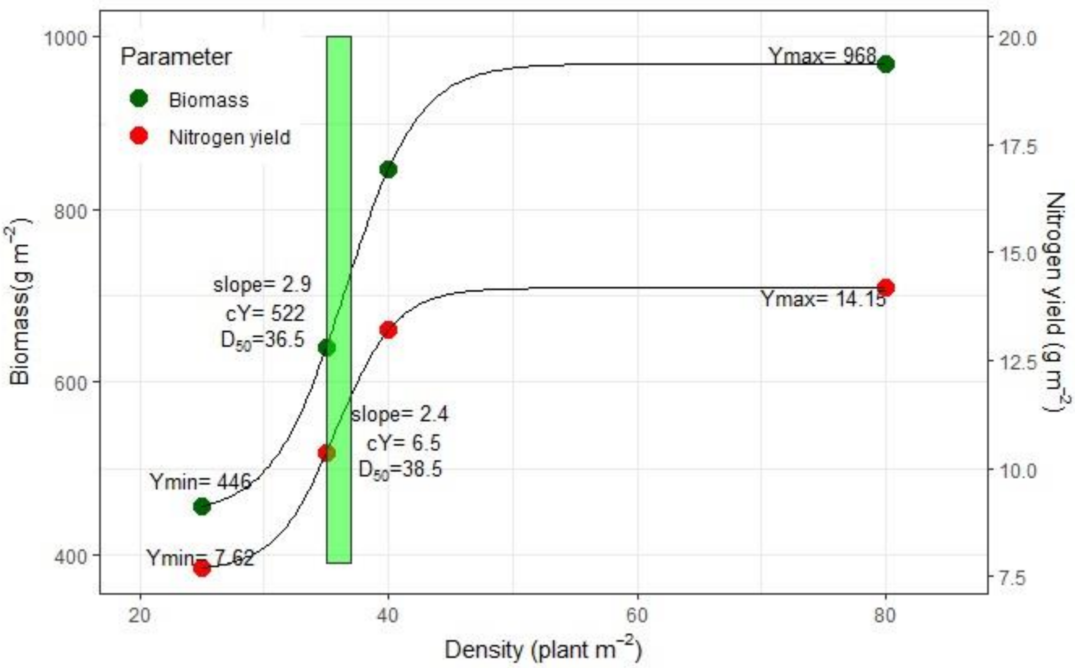

Figure 2. Nonlinear regression trend of faba bean (*Vicia faba* L.) biomass and total (roots + shoots) N yield influenced by cover crop density. Points are observed values and lines are predicted values. The green highlighted line indicates the half-maximal effective density (D_{50}).

3.4. N Release from Decomposing Faba Bean Roots and Shoot Residues

The decomposition of root and shoot residues of faba bean in the first 50 days after termination followed a linear trend (Figure 3A–D). Faba bean roots decomposed somewhat faster than the shoot. However, when 200 and 300 kg N ha^{-1} were applied to the corn silage, the decomposition of the roots and shoots was similar (Figure 3C,D). The application of synthetic N to the corn silage shortened the number of days required for 50% N release from the roots. The number of days for 50% N release from the roots was 54.5, 46.9, 43.1, and 40.6 days when 0, 100, 200, and 300 kg N ha^{-1}, respectively, was applied to the corn (Figure 3A–D). However, we found no distinct response trend of shoot decomposition to the N application to the corn. The interactive effect of faba bean density and N application rate is illustrated in Figure 4A–D. In the absence of off-farm N, 50% release of the total N (roots + shoot) occurred when corn reached the V8 stage, roughly 32 days after germination. The application of N fertilizer to corn accelerated the N release from faba bean residues, mainly due to its influence on root decomposition. On average, the NR_{50} of faba bean residues took place 5–7 days earlier than the V7 stage when N was applied and the V8 stage in the no-N treatment.

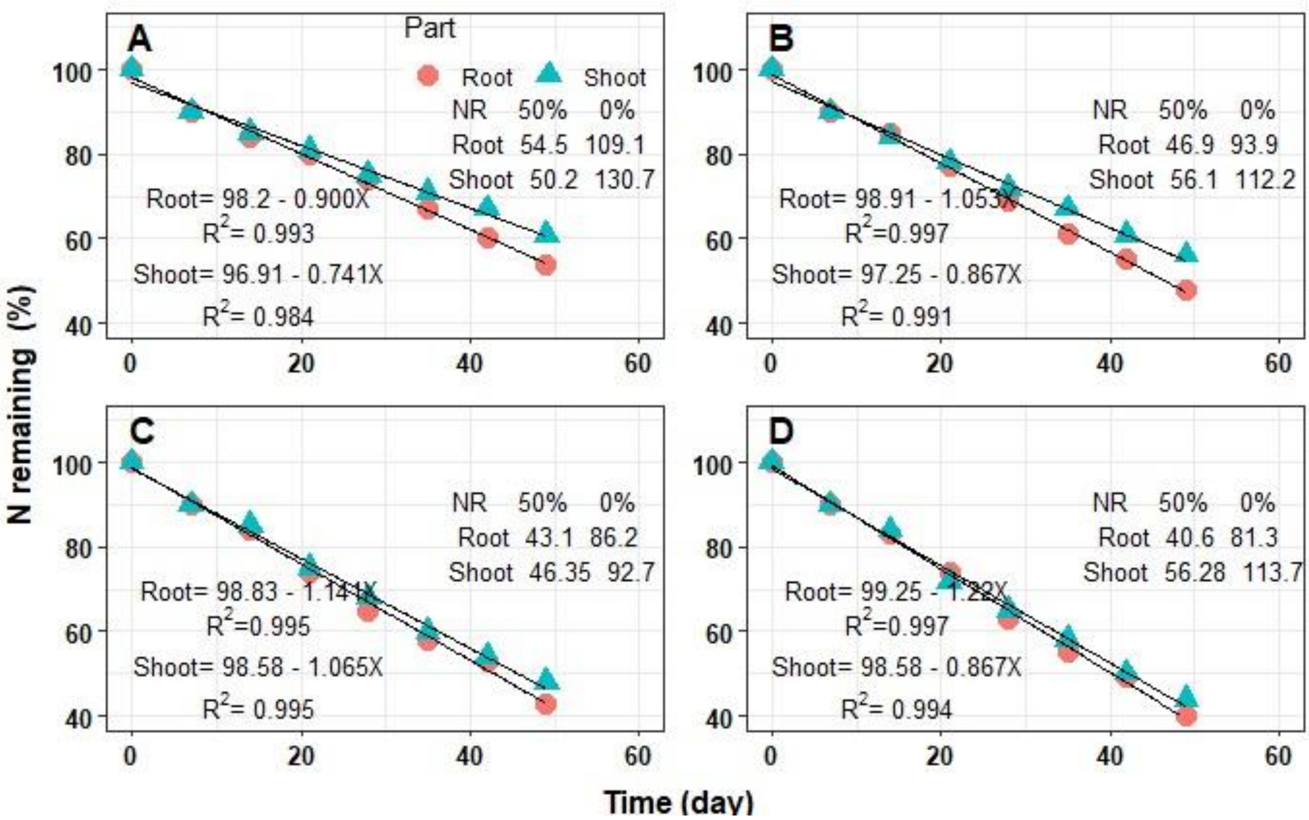

Figure 3. Influence of N application rates in corn silage on decomposition trend of roots and shoots of faba bean (*Vicia faba* L.) residues: (**A**) no nitrogen, (**B**) 100 kg N ha^{-1}, (**C**) 200 kg N ha^{-1}, and (**D**) 300 kg N ha^{-1}. Points are observed values and lines are predicted values. $NR_{50\%}$ = half-maximal effective time; $NR_{0\%}$ = end-maximal effective time.

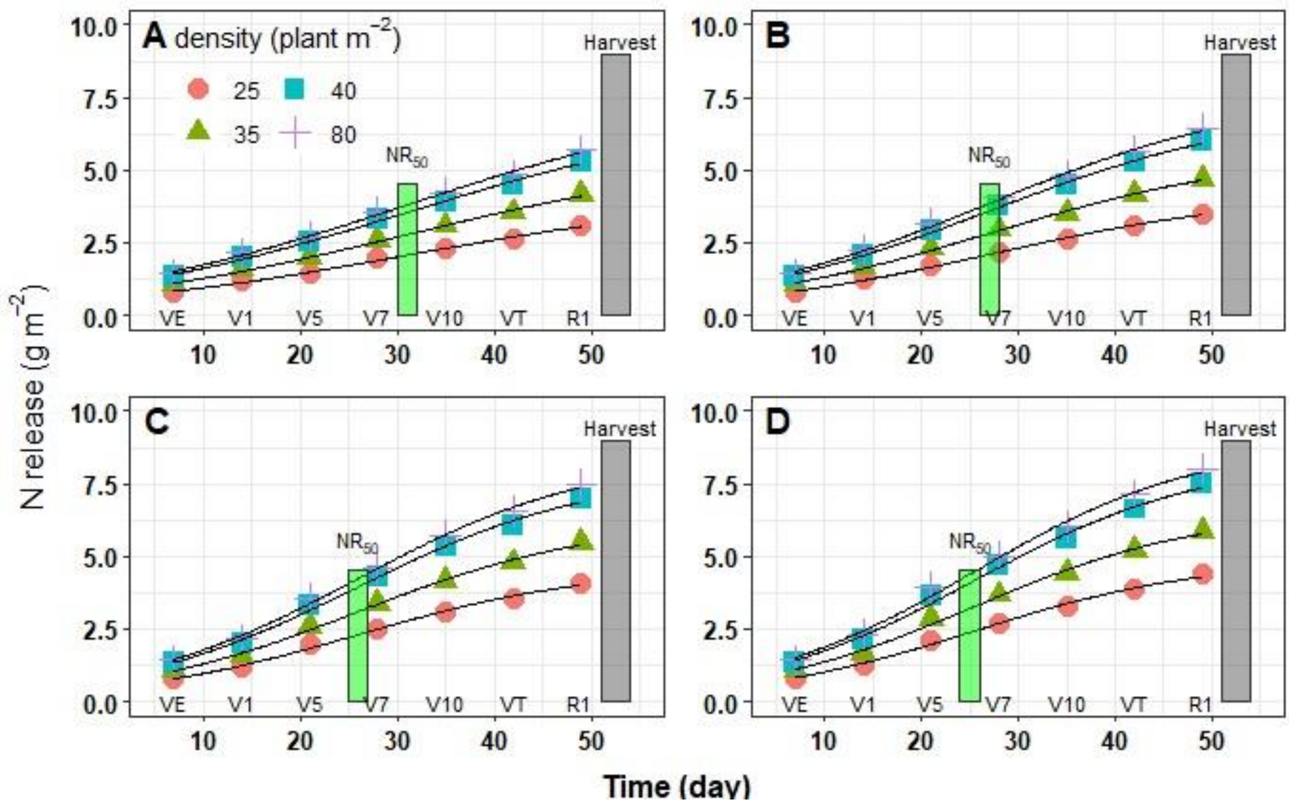

Figure 4. Nonlinear regression (Sigmoid) release of total N (root+ shoot) of faba bean (*Vicia faba* L.) influenced by an interactive effect of cover crop density and N application rates to corn silage during growth stages of corn: (**A**) no nitrogen, (**B**) 100 kg N ha^{-1}, (**C**) 200 kg N ha^{-1}, and (**D**) 300 kg N ha^{-1}. Points are observed values and lines are predicted values. VE–R1—corn growth stages; $NR_{50\%}$ (green highlighted line)—half-maximal effective time; gray highlighted line—corn harvest time. Values are averages of 2018 and 2019.

3.5. Effect of Faba Bean Density and N Application Rate on Yield and Quality of Forage Corn

The influence of faba bean density, N application rate to corn, and their interaction on the yield and quality indices of corn silage were significant (Table 5). The response of corn silage yield and quality, including N content, crude protein, and protein yield to increasing faba bean density, followed a Gaussian (G) trend and reached their peak values at 40 plants m^{-2} (Table 5). An exponential (Eg) trend was found for the response of corn silage yield and its quality to increasing N application rate and was maximized when the highest rate of N (300 kg ha^{-1}) was applied (Table 5). The highest corn yield (5.95 Mg ha^{-1}) was obtained when corn was planted after 40 plants m^{-2} faba bean, which was approximately 28% higher than the corn grown in the no-cover crop plots. The highest corn silage yield was obtained when 300 kg N ha^{-1} was applied, but it was only 1.5% more than the corn that received 200 kg N ha^{-1}. Obviously, there is no economic justification for the application of 100 kg N ha^{-1} extra to gain only 800 kg ha^{-1} more silage. The interaction of faba bean cover crop density and N application rate on the yield and quality of corn was highly significant (Tables 5 and 6, Figure 5). As expected, corn planted in no-cover crop plots benefited most from synthetic N application and reached its highest yield when about 300 kg N ha^{-1} was applied (Figure 5A). Interestingly, the application of the highest N rate (300 kg N ha^{-1}) did not compensate for the lack of faba bean cover crop presence. Corn planted after 40 plants m^{-2} cover crop out-yielded the corn planted after 80 plants m^{-2} when both received an additional 100 or 200 kg N ha^{-1}. The results indicate that integrating faba bean into the corn silage production system reduced the synthetic N application rate by 100–200 kg N ha^{-1}.

Table 5. Estimated parameter nonlinear regression and the main effect response of corn silage yield and quality to faba bean (*Vicia faba* L.) cover crop density and N application rate to corn in 2018 and 2019.

Treatments	Level	Corn Silage (kg m^{-2})	N Shoot Content (mg g^{-1})	Crude Protein (%)	Protein Yield (kg m^{-2})
Years	2018	5.23 ± 0.11 ^{a}	18.35 ± 0.57 ^{a}	11.4 ± 0.4 ^{a}	13.3 ± 0.7 ^{a}
	2019	5.26 ± 0.10 ^{a}	18.65 ± 0.57 ^{a}	11.6 ± 0.3 ^{a}	14.5 ± 0.8 ^{a}
	LSD $_{0.05}$	0.2	1.94	1.3	1.06
Density (plant m^{-2})	0	4.64 ± 0.17 ^{e}	11.84 ± 0.64 ^{d}	7.3 ± 0.4 ^{d}	7.9 ± 0.6 ^{d}
	25	5.03 ± 0.16 ^{d}	18.05 ± 0.40 ^{c}	11.2 ± 0.2 ^{c}	11.9 ± 0.5 ^{c}
	35	5.23 ± 0.13 ^{c}	20.26 ± 0.43 ^{b}	12.6 ± 0.3 ^{b}	15.4 ± 0.6 ^{b}
	40	5.95 ± 0.16 ^{a}	22.05 ± 0.68 ^{a}	13.7 ± 0.4 ^{a}	20.3 ± 1.7 ^{a}
	80	5.36 ± 0.12 ^{b}	20.30 ± 0.44 ^{b}	12.6 ± 0.3 ^{b}	13.9 ± 0.5 ^{bc}
Regression	LSD $_{0.05}$	0.09	0. 52	0.32	2.2
	†† Trend	G	G	G	G
	Y_{max}	6.95 ^{ns}	23.6 ^{ns}	14.73 ^{ns}	26.56 ^{ns}
	Slope	11.86 ^{ns}	32.13 ^{ns}	32.05 ^{ns}	16.10 ^{ns}
	D_{max}	57.69 *	56.97 *	56.84 *	55.55 *
	Y_{min}	4.76 *	8.60 ^{ns}	5.38 ^{ns}	8.13 ^{ns}
	R^2	0.934	0.996	0.996	0.978
N (kg ha^{-1})	0	4.33 ± 0.12 ^{d}	15.97 ± 0.82 ^{d}	9.9 ± 0.5 ^{d}	10.4 ± 0.7 ^{c}
	100	5.27 ± 0.13 ^{c}	17.83 ± 0.66 ^{c}	11.1 ± 0.4 ^{c}	13.5 ± 0.7 ^{b}
	200	5.65 ± 0.12 ^{b}	19.50 ± 0.75 ^{b}	12.1 ± 0.5 ^{b}	18.2 ± 1.6 ^{a}
	300	5.73 ± 0.08 ^{a}	20.70 ± 0.73 ^{a}	12.8 ± 0.5 ^{a}	13.5 ± 0.5 ^{b}
	LSD $_{0.05}$	0.04	0. 51	0.32	0.9
Regression	†† Trend	Eg	Eg	Eg	Lo
	Y_{max}	5.80 **	21.9 *	13.4 *	17.5 ^{ns}
	Slope	0.010 ^{ns}	0.002 ^{ns}	0.002 ^{ns}	211.3 ^{ns}
	cY	1.48 *	6.2 ^{ns}	3.49 ^{ns}	-
	N_{max}	-	-	-	193.8 ^{ns}
	Y_{min}	4.32 **	15.7 *	9.91 *	-
	R^2	0.999	0.999	0.999	0.911
F value					
	Year (Y)	ns	ns	ns	ns
	Density (D)	**	**	**	**
	N (N)	**	**	**	**
	Y × D	ns	ns	ns	ns
	Y × N	ns	ns	ns	ns
	D × N	**	**	**	**
	Y × D × N	ns	ns	ns	ns
Coefficient of variation (%)		9.1	10.2	10.6	14.0

ns—non-significant; *—significant at 0.05 level; **—significant at 0.01 level; †† G—Gaussian; Eg—exponential growth; Lo—Lorentzian. Y_{max}—maximum Y or variable; Y_{min}—minimum Y or variable; cY—change Y or variable in N; D_{50}—half-maximal effective density; N_{max}—maximal effective N; R^2—coefficient of determination. Values are means (n = 4) ± standard error, and columns with the different letters are significantly different using the least significant difference (LSD) test (LSD; a = 0.05).

Table 6. Estimated parameter models non-linear regression of interactive effect of faba bean cover crop density and N application rate on corn silage yield and quality. Values are averages of two growing seasons.

Traits	Density (Plant m^{-2})	†† Trend	Y_{max}	Slope	cY	N_{max} (kg ha^{-1})	Y_{min}	R^2
Corn Silage (kg m^{-2})	0	Eg	5.41 *	0.011 ns	2.03 ns	-	3.37 *	0.994
	25	Eg	5.88 **	0.007 **	1.80 **	-	4.08 **	0.999
	35	Eg	6.06 *	0.006 *	1.63 *	-	4.43 **	0.999
	40	Eg	6.35 *	0.003 ns	1.34 ns	-	5.01 *	0.991
	80	Eg	8.39 *	0.001 ns	3.98 ns	-	4.71 *	0.997
N shoot Content (mg g^{-1})	0	Eg	17.89 ns	0.003 ns	10.08 ns	-	7.81 ns	0.979
	25	Eg	21.30 *	0.004 ns	5.27 ns	-	16.03 *	0.993
	35	Eg	22.56 *	0.005 ns	4.53 ns	-	18.03 **	0.993
	40	Eg	22.46 *	0.003 ns	3.56 ns	-	18.90 *	0.937
	80	Eg	26.71 *	0.002 ns	8.61 ns	-	18.10 *	0.965
Crude Protein (%)	0	Eg	11.17 ns	0.003 ns	6.31 ns	-	4.86 ns	0.978
	25	Eg	13.48 *	0.004 ns	3.46 ns	-	10.02 **	0.994
	35	Eg	14.07 *	0.006 ns	2.75 ns	-	11.26 **	0.995
	40	Eg	13.07 *	0.002 ns	1.25 ns	-	11.82 *	0.936
	80	Eg	12.47 *	0.002 ns	1.18 ns	-	11.29 *	0.968
Protein Yield (kg m^{-2})	0	Eg	11.83 ns	0.006 ns	7.63 ns	-	4.20 *	0.998
	25	G	14.1 *	198.4 *	-	191.4 *	-	0.987
	35	G	17.7 *	218.9 ns	-	194.7 ns	-	0.950
	40	G	20.6 ns	189.2 ns	-	164.2 ns	-	0.701
	80	G	15.3 *	172.3 *	-	145.1 *	-	0.975

ns—non-significant; *—significant at 0.05 level; **—significant at 0.01 level; †† G—Gaussian; Eg—exponential growth. Y_{max}—maximum Y or variable; Y_{min}—minimum Y or variable; cY—change Y or variable in N; N_{max}—maximal effective N; R^2—coefficient of determination.

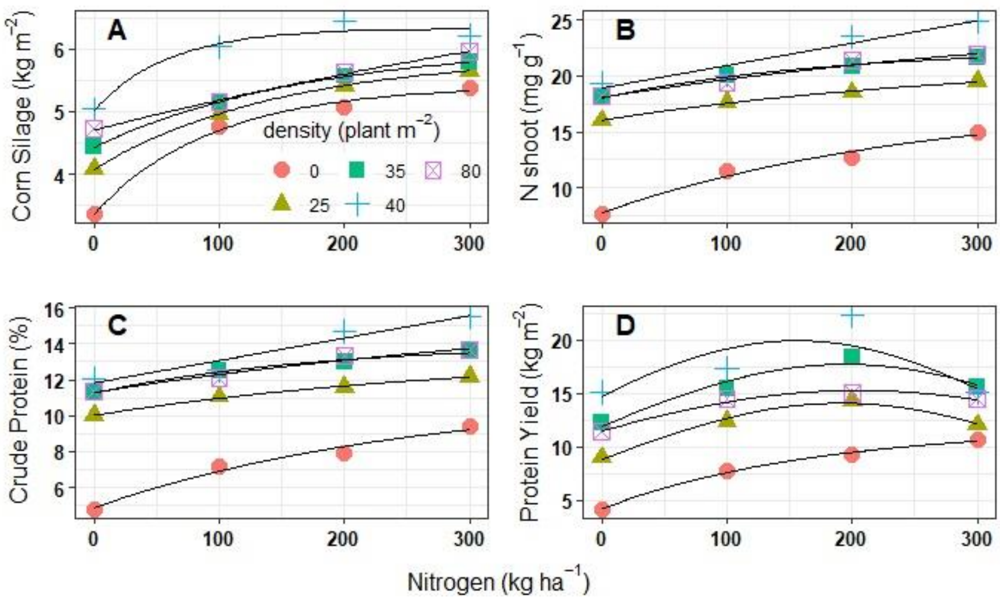

Figure 5. Interactive effect of faba bean cover crop density and N application rate to corn on (**A**) corn silage yield, (**B**) nitrogen content of shoot, (**C**) crude protein, and (**D**) protein yield. Points are observed values and lines are predicted values. Presented values are the average of two years (2018 and 2019). In addition to the higher forage yield, the N content of shoots, percentage of crude protein, and total protein yield per land area were somewhat better in corn grown into 40 plants ha^{-1} faba bean plots compared with those in 80 plants ha^{-1} (**B**–**D**).

4. Discussion

The present study was carried out to evaluate whether the integration of a faba bean cover crop into a no-till forage maize production system can improve soil properties and reduce the N need for harvesting optimum corn silage yield. We were particularly interested in whether increasing the sowing rate of faba bean would alleviate poor soil quality at the experimental site and contribute more N to high-N-demanding corn. The study also sought to investigate the contribution of roots to the total faba bean biomass and the decomposition trend of faba bean roots and shoot residues during corn growth.

4.1. Influence of Faba Bean Cover Crop on Soil Properties

The soils in arid and semi-arid areas are mostly considered marginal, and crop productivity is often limited. It is well documented that integrating cover crops in crop production and returning their biomass to the agricultural land improves various soil functional characteristics [7–12]. However, the influence of cover crops on soil characteristics is minimal in the short term [8]. We hypothesized that the presence of additional biomass through increasing faba bean cover crop density may enhance soil characteristics in the short term. However, overall, the use of faba bean cover crop in the corn production system did not make significant changes in measured soil characteristics, except the water infiltration rate, after two years. Nevertheless, increasing faba bean cover crop density demonstrated an improving trend in some soil properties, including soil organic matter, porosity, and bulk density. Long-term studies have shown positive changes to soil characteristics from NT faba beans [23] and the results of this study could show the beginning of a similar trend. The results confirmed the earlier conclusions by Çerçioğlu et al. [34], which stated that it takes up to six years to see significant changes in soil hydraulic properties, such as bulk density, through cover cropping. Similarly, in a two-year experiment conducted at the current research site, Ghahremani et al. [35] concluded that the influence of various cover crops grown as a monoculture or mixture on the soil health properties was minimal.

4.2. Influence of Faba Bean Density on Biological N Fixation

Corn is a popular high-energy forage crop and is often used for ensiling purposes. In temperate regions, corn occupies the land from May through September, making it a challenge to integrate legume cover crops into the corn production system. As a result, in many arid and semi-arid areas having marginally fertile soils, corn production entirely relies on the use of a considerable amount of synthetic N. In these areas, the application rate of synthetic N may well exceed 200 kg ha^{-1} [1,36]. Reports indicated that as much as 60% of the applied synthetic N is lost to the environment in various ways, including leaching, NH_3 volatilization, and nitrification [37]. The use of a high amount of synthetic N fertilizer not only increases the cost of production but also elevates the risk of environmental pollution [38].

Traditionally, the faba bean is grown for its nutritious immature seeds. However, in more recent years, due to its high potential for biological N fixation [7,17], the idea of using faba bean as a cover crop has gained considerable attention. We hypothesized that the use of faba bean as a cool-season legume prior to planting corn can provide multiple benefits, including soil health improvement, reduced synthetic N fertilizer consumption, and enhanced soil biology. Biologically fixed N by legumes is regarded as an environmentally friendly source of N in agriculture since the leaching and volatility from the system are minimal [39]. Faba bean is capable of fixing high amounts of atmospheric N [40,41] while supporting soil microbial activity and functionality better than many other crops [42].

In the present study, the total amount of biologically fixed N was considerably lower than in earlier reports. For example, Etemadi et al. [7] and Brasier et al. [43] reported that faba bean as cover crop fixed 192 and 200 kg N ha^{-1}, respectively. In the current study, the highest total N yield (shoot + root) was 133 kg N ha^{-1}, which was obtained from the 40 plants m^{-2} density. The lower N yield in the current study compared with the earlier reports can be partly due to the shorter growing period (March–May) and also the poorer soil quality of the research area. The experimental site had no history of faba bean cultivation. Although the faba bean seeds were inoculated with proper rhizobium prior to planting, the soil condition in the experimental site could have limited the symbiotic relationship between the faba bean root and the bacteria. Etemadi et al. [7] concluded that faba bean grown in the same experimental plots fixed 50% more N than in the second year, due to the higher bacterial population.

Many reports indicated that the adoption of strategies to increase the total cover crops biomass can provide more agroecological benefits [44,45]. The two most common strategies to maximize cover crops biomass include earlier sowing time and increasing the seeding rates. For example, earlier planting [46] and increased seeding rates [34,47] of cover crops resulted in the production of higher biomass and thus better weed suppression. Also, the earlier planting of winter annual rye [48] or the increased seeding rate of cover crop [49] produced more biomass, which resulted in capturing more residual N and prevented nitrate leaching. In temperate areas, faba bean as a cool season cover crop can be established in early March and be terminated in mid-May, just prior to the optimum time for planting corn. Since the earlier planting of faba bean in the experimental site was not an option due to severe cold conditions, we hypothesized that increasing biomass could be achieved through increasing the seeding rate of faba bean for maximizing biological N fixation. Therefore, in the current study, we used an extra-high population density (80 plants m^{-2}) to better evaluate our hypothesis. The total biomass (root + shoot) improved as faba bean density increased from 25 plants m^{-2} to 80 plants m^{-2}. The contribution of roots to the total biomass was 33% and remained unchanged in the densities ranging from 25 to 40 plants m^{-2}. However, the ratio of the root to total biomass in the highest cover crop density (80 plants m^{-2}) increased to 49%, indicating that at a certain density, plants invest more photosynthates in the roots than in their shoots. The N content (g kg^{-1}) of both roots and shoots demonstrated an exponentially decreasing trend with increased faba bean density. When faba bean density increased from 40 to 80 plants m^{-2}, the N content in the roots reduced by 15%, whereas the reduction in shoot N was only 4%. In other words, despite more investment in the root biomass, the reduction of N in the root was more than in the shoot; therefore, the N yield in 40 plants m^{-2} was statistically similar to the N yield in the 80 plants m^{-2} treatment. The result of the current study indicates that unlike weed suppression or improving soil C, there is a limit to the benefits of increasing cover crop biomass for higher biological N fixation.

4.3. Decomposition Trend of Faba Bean Root and Shoot Residues

The amount of N and the time for 50% N release from faba bean residues are influenced by the faba bean density. The total N release from the faba bean cover crop over time followed a sigmoid trend and increased with increased density from 25 plants m^{-2} to 40 plants m^{-2}. The reported optimum density of the faba bean varies significantly based on the seed size and time of planting, among other factors [50,51]. However, most references have identified 25–43 plants m^{-2} as the normal range for planting faba bean as a vegetable [52]. Spring-sown faba bean in temperate climate conditions and the use of faba bean as a cover crop or as a dual-purpose crop require a higher plant density due to the shorter vegetation period [53]. In the present research, we used an over-optimum density (80 plants m^{-2}) to evaluate whether the higher biomass of faba bean as a cover crop can compensate for the shorter vegetation period, thus increasing the total atmospheric N fixation. However, the results of this two-year study revealed that increasing the population density to 80 plants m^{-2} did not increase the amount of total biological N fixation. Nevertheless, the use of higher faba bean density shortened the time for 50% N release by approximately one week. The delay in N release may provide better synchrony between the N release from faba bean residues and the active growth of corn silage.

In the current study, the application of N fertilizer accelerated the decomposition of faba bean root residues. This is probably due to the higher growth of the microbial population, which has a higher N requirement and can obtain more energy from the faba bean residues [54,55]. However, the application of synthetic N to corn showed no meaningful trend in the decomposition of faba bean shoot residue. The lack of response of shoot decomposition to the off-farm N application could be at least in part related to the position of the shoot, which was left on the soil surface in the no-till corn system.

Corn silage yield and its protein content were influenced by faba bean residue biomass, N fertilizer application rate, and the interaction of faba bean residues and synthetic N fertilizer. In the absence of the faba bean cover crop, the highest yield was obtained when the highest N rate (300 kg ha^{-1}) was applied to the corn. However, integrating faba bean into the system significantly reduced the rate of synthetic N fertilizer application. Corn that was grown in 40 plants m^{-2} faba bean plots reached its peak yield (59.5 Mg ha^{-1}) when 100 kg N ha^{-1} was used. The integration of faba bean not only reduced the need for synthetic N fertilizer by approximately 200 kg ha^{-1}, but it also enhanced the corn yield by about 1.31 Mg ha^{-1} (28% increase) when compared with the highest yield of corn in the absence of faba bean. Franke et al. [56] concluded that the yield advantage of integrating faba bean into the corn production system was, on average, 0.49 Mg ha^{-1}, compared with continuous cereal.

Averaged over N application rates, the N content in corn silage was almost doubled when grown in 40 faba bean plants m^{-2} plots compared with no faba bean. The results indicate that N released from faba bean residues was captured by corn plants more efficiently than from synthetic fertilizer. Legumes in general demonstrate the lowest stability of CO_2 emissions over time [57], which is an indication of higher microbial activity than other crop species, including grasses and cereals. Our result confirms the earlier report by Paré et al. [58], who concluded that faba bean has a high N replacement value. Despite the large contribution of N from decomposing legumes, earlier reports have indicated that corn planted after a legume cover crop must be supplemented with an off-farm N source to reach its optimum yield [59,60]. In contrast, the results of the current study indicated that the optimum corn silage yield was obtained from 40 faba bean plants m^{-2} when supplemented with 100 kg N ha^{-1}. However, protein yield was maximized when corn was grown in 40 plants m^{-2} faba bean and an additional 200 kg N ha^{-1}. In the absence of faba bean cover crops, even the application of the highest level of synthetic N did not compensate for higher silage yield and forage quality. This could be partly due to the significant amount of losses of synthetic N to the environment and partly due to the additional benefits of cover cropping, such as a diverse microbial community [61]. This conclusion agrees with the results of Agyare et al. [62], who concluded that corn–soybean crop rotation can maintain high yield levels for years compared with corn monocropping.

5. Conclusions

Corn growers, particularly in arid and semi-arid areas, need tools to ensure achieving optimum corn yields while minimizing the use of synthetic N fertilizer. The influence of cover crops on soil health characteristics often requires a long period of time. We hypothesized that the use of an exceptionally high population density of faba bean cover crop (80 plants m^{-2}) may accelerate the enhancement of soil characteristics. The hypothesis seems not quite true, although some soil characteristics demonstrated an improving trend. The results strongly suggested that integrating faba bean as a cool-season legume can considerably contribute to the N need of corn silage. Additionally, N released from decomposing faba bean residues is more efficient than the application of synthetic N, due to better synchrony with the growth of the succeeding corn. The highest total N (shoot + root) fixed by faba bean was 133 kg N $ha^{-1,}$ which was considerably lower than earlier reports. However, considering that the soil of the experimental site lacked natural fertility, had no faba bean history, and had a short growing period prior to termination, the results seem promising. In the current study, the maximum total N yield was obtained from faba bean planted at 40 plants m^{-2} density. We concluded that, unlike some agroecological traits, doubling faba bean cover crop density does not necessarily result in higher biological N fixation. In this study, corn silage yield was significantly lower in no-cover crop treatment, even when it received the highest rates of synthetic N, compared with the corn grown in faba bean plots when supplemented with a minimal amount of N fertilizer. The results indicate the value of including faba bean in the corn silage production system.

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