

## Article

# Sources of Nitrogen for Winter Triticale (*Triticosecale* Wittm. ex A.Camus) Succeeding Pea (*Pisum sativum* L.)

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**Abstract:** Atmospheric nitrogen biologically reduced in legumes root nodule and accumulated in their postharvest residues may be of great importance as a source of this macronutrient for succeeding crops. The aim of the study was to determine nitrogen uptake by winter triticale from pea postharvest residues, including N fixed from atmosphere, using in the study fertilizer enriched with the  $^{15}\text{N}$  isotope. Triticale was grown without nitrogen fertilization at sites where the forecrops had been two pea cultivars (multi-purpose and field pea) and, for comparison, spring barley. The triticale crop succeeding pea took up more nitrogen from the soil (59.1%) and less from the residues of the forecrop (41.1%). The corresponding values where the forecrop was barley were 92.1% and 7.9%. In the triticale, the percentage of nitrogen derived from the atmosphere, introduced into the soil with pea crop residues amounted to 23.8%. The amounts of nitrogen derived from all sources in the entire biomass of triticale plants grown after harvesting of pea were similar for both pea cultivars. The cereal took up more nitrogen from all sources, when the soil on which the experiment was conducted had higher content of carbon and nitrogen and a greater amount of N was introduced with the pea residues. Nitrogen from pea residues had high availability for winter triticale as a succeeding crop cultivated on sandy soils.

**Keywords:** cereals; fertilizer; isotope  $^{15}\text{N}$ ; legumes; nitrogen fixation; nitrogen utilization



**Citation:** Wysokinski, A.; Lozak, I.; Kuziemska, B. Sources of Nitrogen for Winter Triticale (*Triticosecale* Wittm. ex A.Camus) Succeeding Pea (*Pisum sativum* L.). *Agronomy* **2021**, *11*, 527. <https://doi.org/10.3390/agronomy11030527>

Academic Editor: Borjana Arsova

Received: 22 January 2021

Accepted: 9 March 2021

Published: 11 March 2021

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## 1. Introduction

Recent years have seen increased interest in the cultivation and use of legumes. The seeds of pea, soybean and lupine have high protein content, which makes them useful and difficult to replace in many branches of industry, especially the food and feed industries [1]. Furthermore, leguminous plants are an extremely important element in the crop rotation, leaving a valuable site for the succeeding crops: cereals, root crops and industrial crops [2–4]. Legumes are usually grown using low levels of nitrogen fertilizer, because they can live in symbiosis with bacteria that reduce atmospheric nitrogen  $\text{N}_2$  to ammonium forms available for the plant in its root nodules [5].

Cultivation of legumes can play an important role in reducing the negative effects of intensified crop production by introducing sustainable production methods that make the most efficient use of fertilizers and natural processes [3,6,7]. The most important benefit of leguminous plant cultivation is enrichment of soil with nitrogen from the nitrogen fixation process (biological reduction of atmospheric nitrogen), which is also utilized by the succeeding plants in the crop rotation [3,8,9]. The amounts of nitrogen taken up from this source by legumes and the factors determining them are fairly well documented in the literature [10–15]. However, there is a lack of current data describing the utilization of nitrogen introduced to the soil in the form of residues of legume crops, including nitrogen derived from biological reduction.

In addition to their high nitrogen content, the biomass of whole legume plants has a small C:N ratio, which accelerates the rate of mineralization of organic matter and

significantly increases utilization of nitrogen and other nutrients by succeeding crops [16]. A long interval between the pea crop and the succeeding crop can lead to losses of mineral nitrogen released in the mineralization process, and thus reduce the role of the forecrop as a source of this macronutrient [17]. Cultivation of plants sown shortly after harvesting of the forecrop (winter crops) improves utilization of nitrogen left in the soil by legumes in comparison to spring crops [17–19]. Therefore, to limit losses of nitrogen left by pea in the autumn, the succeeding crop used in the present study was winter triticale.

The aim of the study was to determine nitrogen uptake by winter triticale from soil reserves and from spring barley as well as pea crop residues, including N fixed by pea from the atmosphere.

It was hypothesized that different amounts of nitrogen introduced into the soil with post-harvest residues of the forecrops (pea and spring barley) would differentiate the yield, as well as the amount of nitrogen taken up from various sources by the succeeding crop—winter triticale.

## 2. Materials and Methods

### 2.1. Field Experiment

The field experiment was carried out in 2015/2016 and 2016/2017 in Siedlce, Poland (52°10'12" N, 22°17'15" E). This experiment was conducted on soil whose selected properties are given in Table 1. The soil was classified among Luvisols (LV), consisting of 81% sand, 17% silt and 2% clay. Plots with an area of 1 m<sup>2</sup> were marked out in a growing crop of winter triticale (*Triticosecale* Wittm. ex A.Camus) in a traditional soil cultivation system. In this cultivation system, plowing, cultivating and harrowing were performed before sowing the seeds. In the single-factorial experiment, in three replications, three factor levels in two successive years were tested (Table 2). Factor levels were kind of forecrop: two pea (*Pisum sativum* L.) cultivars ("Milwa" (field pea) and "Batuta" (multi-purpose) cultivars) and spring barley (*Hordeum vulgare* L.) ("Ella" cultivar) as reference plant. All forecrops plants were sown on 8 April on both years and harvested on 28 July in 2015 and on 26 July in 2016, at full maturity stage separately from each plot. All plants on seeds/grain and crop residues (roots and all aboveground parts, without seeds/grain) were divided. Crop residues were introduced and mixed with the soil on the same plots on which they were grown.

**Table 1.** Some properties of soil in the layer 0–0.25 m before foundation of experiment in 2015 and 2016.

Soil Properties	Unit	Year	
		2015	2016
pH <sub>of soil in KCl solution (1:2.5 ratio)</sub>	-	6.6	6.5
C <sub>total</sub>	g·kg <sup>-1</sup>	34.2	23.5
N <sub>total</sub>		2.10	1.45
N-NH <sub>4</sub> <sup>+</sup>	mg·kg <sup>-1</sup>	5.75	4.06
N-NO <sub>3</sub> <sup>-</sup>		1.21	0.74
P <sub>Egnera-Rhiema</sub>		309.0	301.0
K <sub>Egnera-Rhiema</sub>		86.0	111.0
Fe *		1327	1189
Mo *	mmol(+).kg <sup>-1</sup>	0.015	0.013
B *		0.806	0.278
Sorption capacity		484	425

\* It was extracted in 1 mol·dm<sup>-3</sup> HCl solution.

**Table 2.** Scheme of experiment and the amount of nitrogen introduced into soil with postharvest residues of forecrops, kg N·ha<sup>−1</sup>.

Forecrop— Studied Factor	Year of Forecrop Cultivation	The Amount of Nitrogen Introduced into Soil with Postharvest Residues, kg N·ha <sup>−1</sup>				Successive Plant in 2016 and 2017—Tested Plant in Study
		Total	In This Derived from			
			Atmosphere	Mineral Fertilizer	Soil Reserves	
Pea Milwa cv	2015	57.0	37.2	3.7	16.1	Winter triticale, Borowik cv
	2016	42.9	19.9	3.2	19.8	
Pea Batuta cv	2015	61.2	38.6	4.2	18.4	
	2016	52.8	28.5	3.4	20.9	
Spring barley Ella cv	2015	22.7	-	4.2	18.5	
	2016	20.1	-	2.8	17.3	

Hyphens indicate not determined.

Before peas and barley sowing (forecrops plants) in first decade of April nitrogen was introduced into the soil at a dose corresponding to 30 kg N·ha<sup>−1</sup>, in a water solution in the form of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, with 10% excess of <sup>15</sup>N isotope. This gave the possibility to calculate the amount of nitrogen taken up by peas from the atmosphere, mineral fertilizer and soil reserves by the isotope dilution method, as well as by barley from mineral fertilizer and soil reserves. The detailed description of these studies was presented in the manuscript of Wysokinski and Lozak [20]. Moreover, the amounts of nitrogen taken up from these sources and introduced into the soil with their crop residues (both species as forecrops) were determined (Table 2).

Triticale grain, “Borowik” variety, were sown in the second decade of September in both years of the experiment in the amount of 500 germinating grains per 1 m<sup>2</sup>. No additional nitrogen fertilization was used in its cultivation, and the sources of this macronutrient were pea or barley crop residues and soil reserves. The phosphorus and potassium doses were determined after specifying the available amounts for plants of these element forms in soil (Table 1). Potassium was applied in an amount corresponding to 100 kg K·ha<sup>−1</sup>. Phosphorus fertilization was not applied because the soil showed a very high content of this macronutrient in forms available to plants. No herbicides were used in all plants cultivation, and weeds were removed manually.

All triticale plants were harvested at full maturity phase by hand, being dug out from the soil with a spade to a depth of 0.25 m, separately from each plot.

## 2.2. Laboratory Analyses

Plant’s materials into roots, grain and remaining aboveground part were separated. The aboveground part included all the aboveground organs of triticale, except for the yield of grain.

The following was determined in all samples of the test plants:

- Dry matter yield (i.e., d.m.)—70 °C
- Total nitrogen content—by Kjeldahl method
- Enrichment with the <sup>15</sup>N isotope—on the NOI-6e emission spectrometer (Leipzig, Germany), after prior wet mineralization of samples using the Kiejdahl method and distillation to an acid solution (5% HCl);

## 2.3. Weather Conditions

Analyzing the course of weather during the growing season of triticale, it was found that the thermal and humidity conditions in given years were variable (Table 3). The Selyaninov’s hydrothermal index indicates that the 2016 months of vegetation were: April, moderately wet; May and June, dry; and July, wet. In 2017, they were: April, extremely wet; and May, June and July, moderately dry.

**Table 3.** Values of the Selyaninov hydrothermal index ( $k$ ) during the vegetation periods of triticale and moisture characteristics ( $w_m$ ) of individual months.

Month	Year			
	2016		2017	
	$k$	$w_m$	$k$	$w_m$
IV	1.9	mw	3.9	ew
V	0.8	d	1.1	md
VI	1.0	d	1.1	md
VII	2.2	w	1.3	md

$k \leq 0.4$ , extremely dry (ed);  $0.4 < k \leq 0.7$ , very dry (vd);  $0.7 < k \leq 1.0$ , dry (d);  $1.0 < k \leq 1.3$ , moderately dry (md);  $1.3 < k \leq 1.6$ , optimum (o);  $1.6 < k \leq 2.0$ , moderately wet (mw);  $2.0 < k \leq 2.5$ , wet (w);  $2.5 < k \leq 3.0$ , very wet (vw);  $k > 3.0$ , extremely wet (ew).

#### 2.4. Calculations of Nitrogen Sources

The percentages of nitrogen derived from different sources: from forecrop's residues (Nd<sub>fcr</sub>; in the from of: atmosphere (Nd<sub>fcr\_a</sub>), i.e., only from pea's crop residues, and mineral fertilizer (Nd<sub>fcr\_f</sub>) and from soil reserves (Nd<sub>fs</sub>). In triticale, they were calculated using the formulas given by Harris and Hesterman [21], Wysokinski et al. [19] and own study:

- Percentage of nitrogen derived in triticale (successive plant) from pea's crop residues, %Nd<sub>fcr</sub>:

$$\%Nd_{fcr} = {}^{15}N_{triticale} / {}^{15}N_{pea} \cdot 100 \quad (1)$$

where  ${}^{15}N_{triticale}$  is the  ${}^{15}N$  isotope in enrichment triticale mass (%) and  ${}^{15}N_{pea}$  is the  ${}^{15}N$  isotope enrichment in pea's crop residues (%);

- The amount of nitrogen derived in triticale from pea's crop residues, Nd<sub>fcr</sub>:

$$Nd_{fcr} = \%Nd_{fcr} \cdot TN / 100 \quad (2)$$

where %Nd<sub>fcr</sub> is the percentage of nitrogen derived in triticale from forecrop's residues and TN is the total nitrogen uptake by triticale.

- The amount of nitrogen derived in triticale from the atmosphere, introduced into the soil with pea's crop residues (N<sub>2</sub> biologically reduced in nitrogen fixation process), Nd<sub>fcr\_a</sub>:

$$Nd_{fcr_a} = \%Nd_{fa} \cdot Nd_{fcr} / 100 \quad (3)$$

where %Nd<sub>fa</sub> is the percentage of nitrogen derived from atmosphere (biologically reduced) in pea's crop residues and Nd<sub>fcr</sub> is the amount of nitrogen derived in triticale from pea's crop residues.

- The amount of nitrogen derived in triticale from mineral fertilizer, introduced into the soil with pea's crop residues, Nd<sub>fcr\_f</sub> [own study based on Point 3]:

$$Nd_{fcr_f} = \%Nd_{ff} \cdot Nd_{fcr} / 100 \quad (4)$$

where %Nd<sub>ff</sub> is the percentage of nitrogen derived from mineral fertilizer in pea's crop residues and Nd<sub>fcr</sub> is the amount of nitrogen derived in triticale from pea's crop residues.

- Nitrogen utilization by triticale from pea's crop residues, %NU:

$$\%NU = Nd_{fcr} / N_{cr} \cdot 100 \quad (5)$$

where Nd<sub>fcr</sub> is the amount of nitrogen derived in triticale from pea's crop residues and N<sub>cr</sub> is the amount of nitrogen introduced into the soil with pea's crop residues;

In these calculations, the succeeding crop is assumed to utilize nitrogen introduced to the soil in the forecrop residues proportionally to the amount accumulated by the

forecrop from various sources, and thus the values calculated for the coefficient of nitrogen utilization from the forecrop residues simultaneously describe the utilization of nitrogen derived from the atmosphere and mineral fertilizer.

- The amount of nitrogen taken up by winter triticale from the soil is a value that includes nitrogen from all sources other than forecrop residues introduced to the soil. Hereafter, this is referred to as “nitrogen from the soil”, “nitrogen from soil reserves”, or  $N_{dfs}$ :

$$N_{dfs} = TN - N_{dfr} \quad (6)$$

where  $TN$  is the total nitrogen uptake by triticale and  $N_{dfr}$  is the amount of nitrogen derived in triticale from pea's crop residues.

## 2.5. Statistical Analysis

The results of the experiments were analyzed by two-way ANOVA:

$$y_{ijk} = \mu + a_i + b_j + (ab)_{ij} + e_{ijk} \quad (7)$$

where  $\mu$  is the mean value of all treatments;  $a_i$  is the effect of forecrops;  $b_j$  is the effect of research years (second source of variability);  $ab_{ij}$  is the interaction of forecrops and years; and  $e_{ijk}$  is the random effect (error).

The significance of sources of variation was checked with the Fisher–Snedecor test, and mean values were separated with the Tukey's test at the significance level of  $p < 0.05$ . The Polish version of Statistica 13.1 PL (StatSoft Inc., Tulsa, OK, USA) was used for these calculations.

## 3. Results

### 3.1. Dry Weight, Nitrogen Content and $^{15}\text{N}$ Enrichment of Triticale

The weight of the above-ground crop residues, grain and whole triticale plant was significantly dependent on the species of the forecrop (Table 4). The weight of these parts and the entire plant did not differ between triticale crops succeeding the two cultivars of pea, but it was higher than where the forecrop was spring barley. The weight of the triticale roots did not depend significantly on the species of the forecrop.

**Table 4.** Dry weight of winter triticale,  $\text{Mg} \cdot \text{ha}^{-1}$  (averages  $\pm$  SD).

Studied Factor		Plant's Part			Sum
		Root	Aboveground Crop Residues	Grain	
Forecrop	Pea “Milwa”	$0.914 \pm 0.269$ a	$4.906 \pm 0.839$ b	$2.800 \pm 0.495$ b	$8.620 \pm 1.123$ b
	Pea “Batuta”	$0.954 \pm 0.307$ a	$4.951 \pm 0.693$ b	$2.933 \pm 0.370$ b	$8.838 \pm 1.066$ b
	Spring barley	$0.923 \pm 0.219$ a	$4.391 \pm 0.590$ a	$2.046 \pm 0.294$ a	$7.360 \pm 0.761$ a
Year	2016	$0.683 \pm 0.068$ a	$5.404 \pm 0.463$ b	$2.910 \pm 0.518$ b	$8.997 \pm 1.002$ b
	2017	$1.178 \pm 0.129$ b	$4.095 \pm 0.286$ a	$2.276 \pm 0.379$ a	$7.549 \pm 0.880$ a

Interactions: forecrop/years are not significant. a, b, different letters in each column indicate significant differences between averages for studied factor,  $p < 0.05$ .

The weight of all separated parts and of the entire triticale plants was significantly different in the two years of the study (Table 4). In the growing conditions of 2016, the weight of the above-ground residues, grain yield and total weight were greater than in 2017. In the case of root weight, the pattern was reversed.

The nitrogen content in all separate parts and on average in the whole triticale plants was not significantly dependent on the species and cultivar of the forecrop (Table 5). The  $^{15}\text{N}$  isotope enrichment of all separate parts and on average for the whole triticale plants was greater when it was preceded by both pea cultivars than when the forecrop was spring barley. The values of this parameter were similar for the triticale crops succeeding both pea cultivars. The nitrogen content in the roots, grain and on average in the whole triticale

plants was greater in the experimental conditions of 2016 than in 2017. The  $^{15}\text{N}$  enrichment of the roots, grain and whole triticale plants on average was greater in 2017 than in 2016. Nitrogen content and enrichment with the  $^{15}\text{N}$  isotope in the above-ground crop residues did not differ significantly between the two years of the study.

**Table 5.** Nitrogen content ( $\text{Nc}$ ) ( $\text{g N}\cdot\text{kg}^{-1}$ ) and enrichment with  $^{15}\text{N}$  ( $^{15}\text{N}_{\text{en}}$ ) (%) in winter triticale's dry weight (averages  $\pm$  SD).

Studied Factor		Plant's Part						Weighted Averages	
		Root		Aboveground Crop Residues		Grain		$\text{Nc}$ ( $\text{g N}\cdot\text{kg}^{-1}$ )	$^{15}\text{N}_{\text{en}}$ (%)
		$\text{Nc}$ ( $\text{g N}\cdot\text{kg}^{-1}$ )	$^{15}\text{N}_{\text{en}}$ (%)	$\text{Nc}$ ( $\text{g N}\cdot\text{kg}^{-1}$ )	$^{15}\text{N}_{\text{en}}$ (%)	$\text{Nc}$ ( $\text{g N}\cdot\text{kg}^{-1}$ )	$^{15}\text{N}_{\text{en}}$ (%)		
Forecrop	Pea "Milwa"	7.38 $\pm$ 0.84	0.241 $\pm$ 0.026	5.00 $\pm$ 0.49	0.255 $\pm$ 0.024	17.53 $\pm$ 2.08	0.288 $\pm$ 0.028	9.32 $\pm$ 0.099	0.274 $\pm$ 0.019
	Pea "Batuta"	6.93 $\pm$ 1.05	0.244 $\pm$ 0.033	4.94 $\pm$ 0.69	0.280 $\pm$ 0.024	17.66 $\pm$ 2.41	0.294 $\pm$ 0.030	9.37 $\pm$ 1.31	0.286 $\pm$ 0.024
	Spring barley	7.34 $\pm$ 1.13	0.128 $\pm$ 0.016	4.68 $\pm$ 0.58	0.118 $\pm$ 0.012	17.40 $\pm$ 2.14	0.118 $\pm$ 0.017	8.54 $\pm$ 1.13	0.120 $\pm$ 0.014
Year	2016	7.83 $\pm$ 0.88	0.182 $\pm$ 0.040	5.13 $\pm$ 0.54	0.205 $\pm$ 0.056	18.79 $\pm$ 1.83	0.214 $\pm$ 0.065	9.73 $\pm$ 1.08	0.210 $\pm$ 0.057
	2017	6.60 $\pm$ 0.86	0.227 $\pm$ 0.051	4.61 $\pm$ 0.56	0.229 $\pm$ 0.060	16.26 $\pm$ 1.82	0.252 $\pm$ 0.067	8.42 $\pm$ 0.96	0.242 $\pm$ 0.059

Interactions: forecrop/years are not significant. a, b, different letters in each column indicate significant differences between averages for studied factor,  $p < 0.05$ .

### 3.2. Amount and Percentage of Nitrogen Uptake from Different Sources

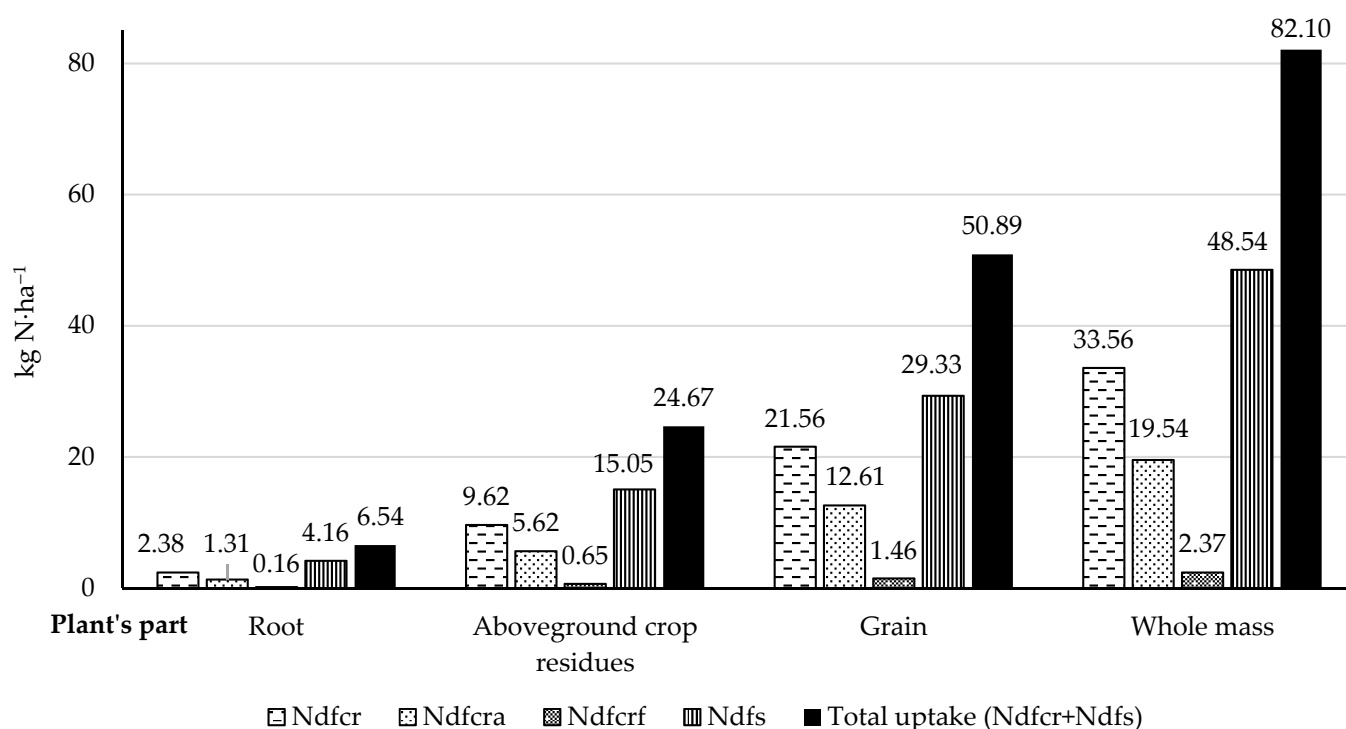
The amount of nitrogen in the winter triticale (separate parts and whole plants) derived from soil reserves and from pea residues, including from biological reduction of  $\text{N}_2$  and mineral fertilizer, as well as the total uptake of this macronutrient, were not significantly dependent on the pea cultivar (Table 6). Accumulation of nitrogen from the above-mentioned sources and the total uptake by the whole triticale plant on average for both pea cultivars was 48.54, 33.56, 19.54, 2.37 and 85.10  $\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}$ , respectively (Figure 1). The amount of nitrogen taken up by triticale (all separate parts and whole plants) from spring barley residues, including N derived from mineral fertilizer, were lower than in the crop succeeding pea, but this dependency was reversed in the case of the amount of nitrogen taken up from soil reserves.

**Table 6.** Nitrogen uptake by winter triticale from different sources depending on the forecrop,  $\text{kg N}\cdot\text{ha}^{-1}$  (averages  $\pm$  SD).

N Sources	Forecrop	Plant's Part			Whole Mass
		Root	Aboveground Crop Residues	Grain	
Ndfcr	Pea "Milwa"	2.29 $\pm$ 0.68 b	9.01 $\pm$ 2.52 b	20.47 $\pm$ 5.67 b	31.77 $\pm$ 8.47 b
	Pea "Batuta"	2.46 $\pm$ 0.97 b	10.23 $\pm$ 2.76 b	22.66 $\pm$ 6.92 b	35.35 $\pm$ 10.00 b
	Spring barley	0.56 $\pm$ 0.20 a	1.48 $\pm$ 0.34 a	2.58 $\pm$ 0.46 a	4.62 $\pm$ 0.92 a
Ndfcra	Pea "Milwa"	1.22 $\pm$ 0.23 a	5.20 $\pm$ 1.98 a	11.85 $\pm$ 4.73 a	18.27 $\pm$ 7.55 a
	Pea "Batuta"	1.40 $\pm$ 0.61 a	6.05 $\pm$ 1.85 a	13.36 $\pm$ 3.58 a	20.81 $\pm$ 4.54 a
Ndfcrf	Pea "Milwa"	0.16 $\pm$ 0.06 b	0.62 $\pm$ 0.14 b	1.41 $\pm$ 0.29 b	2.19 $\pm$ 0.49 b
	Pea "Batuta"	0.17 $\pm$ 0.12 b	0.69 $\pm$ 0.22 b	1.51 $\pm$ 0.37 b	2.37 $\pm$ 0.51 b
	Spring barley	0.09 $\pm$ 0.03 a	0.24 $\pm$ 0.05 a	0.41 $\pm$ 0.06 a	0.74 $\pm$ 0.15 a
Ndfs	Pea "Milwa"	4.34 $\pm$ 1.38 a	15.62 $\pm$ 3.65 a	29.07 $\pm$ 7.69 a	49.03 $\pm$ 10.43 a
	Pea "Batuta"	3.98 $\pm$ 1.15 a	14.47 $\pm$ 5.81 a	29.59 $\pm$ 11.40 a	48.04 $\pm$ 15.55 a
	Spring barley	6.06 $\pm$ 1.16 b	19.19 $\pm$ 5.16 b	33.26 $\pm$ 8.49 b	58.51 $\pm$ 13.45 b
Total uptake (Ndfcr + Ndfs)	Pea "Milwa"	6.63 $\pm$ 1.97 a	24.63 $\pm$ 5.74 b	49.54 $\pm$ 14.32 b	80.80 $\pm$ 19.75 b
	Pea "Batuta"	6.44 $\pm$ 2.42 a	24.70 $\pm$ 7.47 b	52.25 $\pm$ 12.49 b	83.39 $\pm$ 27.07 b
	Spring barley	6.62 $\pm$ 1.17 a	20.67 $\pm$ 4.67 a	35.84 $\pm$ 9.55 a	63.13 $\pm$ 14.37 a

Interactions: forecrop/years for all N sources are not significant. a, b, different letters separately for each nitrogen source (Ndfcr, Ndfcra, Ndfcrf, Ndfs and total uptake, respectively) and separately in each column (root, aboveground crop residues, grain and whole mass, respectively) indicate significant differences between averages for studied factor,  $p < 0.05$ . Ndfcr, nitrogen derived from peas or barley crop residues, respectively; Ndfcra, nitrogen derived from the atmosphere, introduced into soil with peas crop residues; Ndfcrf, nitrogen derived from fertilizer, introduced into soil with peas or barley crop residues; Ndfs, nitrogen derived from soil reserves, i.e., sources other than Ndfcr.





**Figure 1.** Nitrogen uptake from different sources by winter triticale succeeding pea (means for pea cultivars),  $\text{kg N}\cdot\text{ha}^{-1}$ . Ndfs, N derived from soil reserves; Ndfcr, N derived from peas or barley crop residues, respectively; Ndfcra, N derived from the atmosphere, introduced into soil with peas crop residues; Ndfcrf, N derived from fertilizer, introduced into soil with peas or barley crop residues.

The year of the research was found to significantly affect the amount of nitrogen from each source and the entire amount accumulated in the whole triticale plants (Table 7). The level of nitrogen uptake from soil reserves and from forecrop residues, including from mineral fertilizer and from nitrogen fixation by pea, as well as the total accumulation of this macronutrient in the whole triticale plant, was lower in 2017 than in 2016, by 30.9%, 19.3%, 17.1%, 38.4% and 27.5%, respectively. The amount of nitrogen from these sources in the above-ground crop residues and grain of the triticale was greater in the first year of the experiment than in the second year, but, in the case of the roots, the tendency was reversed. The year of the study was not shown to affect the percentage of nitrogen in the triticale derived from soil reserves and from pea residues, including N from mineral fertilizer. In the entire biomass of the succeeding crop, the percentage of nitrogen from nitrogen fixation by pea was higher in the conditions of the 2016 experiment than those in 2017.

### 3.3. Coefficient of Nitrogen Utilization from the Forecrop

The values for the coefficient of utilization of nitrogen introduced to the soil with the pea crop, calculated for the roots, aerial parts, grain and entire triticale plant, were significantly dependent on the species of the forecrop (Table 8). Nitrogen utilization calculated for all separate parts and the whole triticale plant was similar in the case of both pea cultivars as the forecrop. The values for this parameter for the separate parts and whole triticale plant grown after spring barley were lower than in the case of the two pea cultivars. The average value of the coefficient obtained for the entire triticale plant in the crop succeeding pea was 62.7%, of which the greatest amount (40.1%) was noted for the grain, less for the above-ground residues (17.9%) and the least (4.7%) for the roots (Figure 2). In the case of the triticale crop succeeding barley, the corresponding values were 21.8%, 12.2%, 6.6% and 2.7%, respectively. According to the methodology of the experiment, the values for the coefficient of nitrogen utilization from the forecrop residues simultaneously describe the

utilization of nitrogen in the forecrop residues derived from the atmosphere (only in the case of pea) and from fertilizer (for both forecrop species).

**Table 7.** Nitrogen uptake by winter triticale from different sources depending on the year of research, kg N·ha<sup>−1</sup> (averages ± SD).

N Source	Year	Plant's Part			Whole Mass
		Root	Aboveground Crop Residues	Grain	
Ndfcr	2016	1.22 ± 0.66 a	7.94 ± 5.06 b	17.31 ± 11.52 b	26.47 ± 17.60 b
	2017	2.32 ± 1.19 b	5.88 ± 3.42 a	13.15 ± 9.60 a	21.35 ± 12.90 a
Ndfcra	2016	1.06 ± 0.23 a	7.18 ± 1.42 b	15.95 ± 2.63 b	24.19 ± 5.30 b
	2017	1.56 ± 0.51 b	4.07 ± 0.93 a	9.26 ± 2.12 a	14.89 ± 3.08 a
Ndfcrf	2016	0.10 ± 0.04 a	0.59 ± 0.28 b	1.24 ± 0.65 b	1.93 ± 0.93 b
	2017	0.18 ± 0.07 b	0.44 ± 0.19 a	0.98 ± 0.44 a	1.60 ± 0.71 a
Ndffs	2016	4.13 ± 1.41 a	19.83 ± 4.83 b	37.40 ± 7.84 b	61.36 ± 12.87 b
	2017	5.46 ± 1.28 b	13.03 ± 3.29 a	23.88 ± 5.29 a	42.37 ± 7.29 a
Total uptake (Ndfcr + Ndffs)	2016	5.35 ± 1.16 a	27.77 ± 5.76 b	54.71 ± 13.54 b	87.83 ± 23.40 b
	2017	7.78 ± 1.76 b	18.91 ± 2.89 a	37.03 ± 8.06 a	63.72 ± 14.49 a

Interactions: forecrop/years for all N sources are not significant. a, b, different letters separately for each nitrogen source (Ndfcr, Ndfcra, Ndfcrf, Ndffs and total uptake, respectively) and separately in each column (root, aboveground crop residues, grain and whole mass, respectively) indicate significant differences between averages for studied factor,  $p < 0.05$ . Ndfcr, nitrogen derived from peas or barley crop residues, respectively; Ndfcra, nitrogen derived from the atmosphere, introduced into soil with peas crop residues; Ndfcrf, nitrogen derived from fertilizer, introduced into soil with peas or barley crop residues; Ndffs, nitrogen derived from soil reserves, i.e., sources other than Ndfcr.

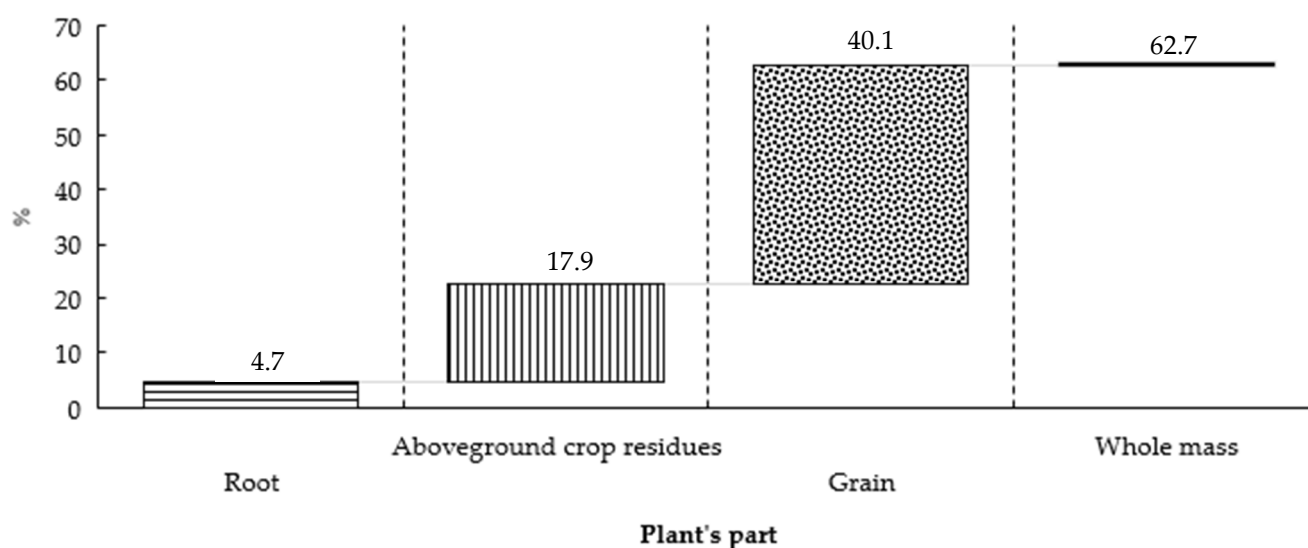
**Table 8.** Utilization coefficient of nitrogen introduced into the soil with forecrop residues by winter triticale, % (averages ± SD).

Studied Factor		Plant's Part			Sum
		Root	Aboveground Crop Residues	Grain	
Forecrop plant	Pea "Milwa"	4.9 ± 2.2 b	17.9 ± 2.5 b	40.5 ± 6.3 b	63.3 ± 7.8 b
	Pea "Batuta"	4.5 ± 1.7 b	17.8 ± 3.6 b	39.7 ± 5.6 b	62.0 ± 7.7 b
	Spring barley	2.7 ± 1.0 a	6.9 ± 1.0 a	12.2 ± 3.0 a	21.8 ± 4.6 a
Year	2016	2.4 ± 0.9 a	14.7 ± 8.3 a	31.4 ± 20.3 a	48.5 ± 29.4 a
	2017	5.6 ± 1.9 b	13.8 ± 5.7 a	30.2 ± 13.8 a	49.5 ± 21.3 a
Averages		4.0 ± 2.2	14.2 ± 7.2	30.8 ± 17.6	49.0 ± 25.8

Interactions: forecrop/years are not significant. a, b, different letters in each column indicate significant differences between averages for studied factor,  $p < 0.05$ .

Utilization of nitrogen introduced to the soil with forecrop residues, calculated for the above-ground residues, grain and entire triticale plants, did not differ significantly between the years of the study (Table 8). The value of the coefficient of nitrogen utilization calculated for the roots of the cereal grown in 2017 was higher than for those in 2016.





**Figure 2.** Utilization coefficient of nitrogen introduced into the soil with pea residues by winter triticale (means for peas cultivars), %.

#### 4. Discussion

Many authors have reported that succeeding crops produce higher yield when legumes are included in the crop rotation [2,22–28]. In our study, the conditions left by pea as the forecrop were more beneficial for the yield of winter triticale than the conditions left by spring barley. The grain yield and the total harvested weight of the triticale crop succeeding pea were 40.1% and 18.6% higher, respectively, than in the case of the crop succeeding spring barley. The beneficial effect of legumes as forecrops on the yield of winter triticale is well described in the literature [29,30]. Buraczyńska and Ceglarek [31] showed an increase in the grain yield of winter triticale succeeding field pea relative to the grain yield of crops succeeding spring triticale and spring wheat, by 25.5% and 18.6%, respectively. The yield of winter triticale depends not only on the forecrops but also on many other factors, e.g., weather conditions during the growing season [32–35]. In the present study, the grain yield and total weight of winter triticale was greater in 2016 than in 2017, by 0.634 and 1.448 Mg·ha<sup>−1</sup>, respectively (on average for the crops succeeding the two pea cultivars and barley). This may have been due to the somewhat higher nitrogen content in the soil on which the experiment was conducted in the first year than in the second year, as well as the slightly larger amount of nitrogen introduced to the soil with the forecrop residues in the first year (on average 47.0 kg·ha<sup>−1</sup> for both cultivars) than in the second year (on average 38.6 kg·ha<sup>−1</sup>). The moisture and temperature conditions for cultivation of triticale in the first and second years of the experiment were not optimal, and it is difficult to say which growing season was more favorable in this respect. In 2016, after a fairly wet April, the next two months were dry, while July was wet, with an air temperature higher than the long-term average in every month of the growing season. In 2017, after an extremely wet April, the next three months were dry, and the temperature was lower than the long-term average in April and July but higher in June. Substantial variation in winter triticale grain yield depending on the year of research (air temperatures and rainfall) has been reported by other authors [36]. Factors influencing the yield can also affect the amount of nitrogen uptake by this cereal from various sources. In the total pool of nitrogen taken up by winter triticale succeeding pea, nitrogen from soil reserves accounted for a higher percentage (on average 59.1%) than nitrogen from pea residues (on average 40.9%). Of the total nitrogen uptake by triticale, on average 23.8% was from the atmosphere, and thus this pool was the effect of symbiosis of pea and rhizobia. Different results may be obtained in experiments conducted on different types of soil than in this study. Wysokiński et al. [19], in an experiment conducted in field conditions, obtained a lower percentage of nitrogen (17.2%) taken up from residues of the forecrop—yellow lupine—including N derived from nitrogen fixation (11.8%), in the total accumulation of

this element in spring triticale. In similar studies [18], in which winter rye was the subsequent plant cultivated after yellow lupine, these values were 59.2% and 40.6%, respectively. In that study, however, 100.2 kg N·ha<sup>-1</sup> had been introduced with yellow lupine residues. The smaller amounts of nitrogen introduced to the soil in the present study (on average 53.5 kg N·ha<sup>-1</sup> for both pea cultivars and 21.4 kg N·ha<sup>-1</sup> for spring barley) may explain the lower percentage of this macronutrient taken up by triticale from the forecrop residues in this study than in the one cited. In comparison with the present study, a pot experiment conducted in a greenhouse, in which the succeeding crop—spring barley—was sown in the spring, found a much lower percentage of nitrogen from pea residues (37.3%), including N from nitrogen fixation (4.1%), in the total uptake [17]. Our data and those cited from the literature [17,19] clearly indicate that plants should be sown within a short time after legumes have been harvested.

In the present study, the average nitrogen uptake by winter triticale from pea residues was 33.6 kg N, of which 19.5 kg was nitrogen from the atmosphere. These values were 37.7 and 24.2 kg N·ha<sup>-1</sup>, respectively, in the first year of the study and 29.4 and 14.9 kg N·ha<sup>-1</sup> in the second year. The higher nitrogen uptake in 2016 than in 2017 from the sources described may be indicative of the effect of the somewhat greater amount of nitrogen introduced into the soil with the forecrop postharvest residues in the first year of the study (on average 59.1 kg N·ha<sup>-1</sup> for both pea cultivars, including 37.9 kg N·ha<sup>-1</sup> from the atmosphere) than in the second year (on average 47.8 kg N·ha<sup>-1</sup> for both cultivars, including 24.2 kg N·ha<sup>-1</sup> from the atmosphere). In the study cited above [18], in which more nitrogen was introduced (100.2 kg N·ha<sup>-1</sup>) with the yellow lupine residues, including 65.3 kg N·ha<sup>-1</sup> from atmosphere, uptake of this macronutrient by winter rye was greater, amounting to 85.8 and 54.9 kg N·ha<sup>-1</sup> from these sources. The results of research using the <sup>15</sup>N isotope show that succeeding crops take up less than 30% of nitrogen from residues of legume crops [19,37–39]. Jensen [40] determined that winter barley recovered about 15% of the nitrogen from pea residues, while Stevenson and van Kessel [23] reported a value of 12% for wheat. In the present study on winter triticale, the coefficient of utilization of nitrogen introduced to the soil with pea residues, including nitrogen from the atmosphere, was on average 62.7% and did not depend on the cultivar of the forecrop or on the year of research. These results indicate that nitrogen from pea residues has high availability for winter triticale as a succeeding crop cultivated on sandy soils.

The average given above (33.6 kg N·ha<sup>-1</sup>), specifying the nitrogen uptake by triticale from pea residues, corresponds to the content of nitrogen in 100 kg of ammonium nitrate. However, after taking into account the coefficient of nitrogen utilization from mineral fertilizers, amounting to about 50%, in order for the plant to take up 34 kg N·ha<sup>-1</sup>, 200 kg of this fertilizer would have to be applied to the soil. Of this amount (33.6 kg N·ha<sup>-1</sup>), on average 19.5 kg N·ha<sup>-1</sup> was nitrogen from the atmosphere, which can be regarded as a net gain of pea cultivation, while the remainder (14.1 kg N·ha<sup>-1</sup>) was recovery of nitrogen derived from soil and fertilizer. The amount of nitrogen from pea residues available for the succeeding crop should be taken into account in planning fertilization with this nutrient.

## 5. Conclusions

The pea cultivar grown as a forecrop was not shown to significantly affect the total weight or grain yield of the succeeding crop (winter triticale) or the percentage and amount of nitrogen taken up by the plant from pea residues (including N from nitrogen fixation) and soil reserves. The total uptake and the amount of nitrogen derived from each source by winter triticale were greater in the conditions of the experiment conducted in 2016 than those in 2017, i.e., on soil with higher nitrogen content and following the introduction of more nitrogen into the soil with forecrop residues. Given the high nitrogen utilization of pea crop residues, when planning fertilization with this macronutrient of the subsequent plant, the amount of nitrogen available from the forecrop residue should be taken into account in order to rationally manage this biogenic element.

**Author Contributions:** Conceptualization, A.W.; methodology, A.W., I.L. and B.K.; resources, A.W., I.L. and B.K.; writing—original draft preparation, A.W., B.K. and I.L.; writing—review and editing, A.W. and B.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Polish Ministry of Science and Higher Education, grant number 143/15/MN and 37/20/B.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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