The Journal of Agricultural Science

cambridge.org/ags

Crops and Soils Research Paper

Cite this article: Górski R, Płaza A (2023). Content and uptake of macroelements in green fodder of mixtures of narrowleaf lupin with spring triticale. *The Journal of Agricultural Science* **161**, 563–571. https://doi.org/10.1017/S0021859623000448

Received: 5 April 2023
Revised: 25 July 2023
Accepted: 11 August 2023
First published online: 31 August 2023

Keywords:
cereal; legumes; proportion of components; harvest stage; mineral nutrients

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Content and uptake of macroelements in green fodder of mixtures of narrowleaf lupin with spring triticale

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Abstract

This paper presents the results of a study conducted in 2016–2018 in the temperate conditions to evaluate the content and uptake of P, K, Ca and Mg in mixtures of narrowleaf lupin with spring triticale grown for green fodder. Two factors were analysed in the experiment: A – the proportion of components in the mixture: narrowleaf lupine 100%, narrowleaf lupine + spring triticale 75 + 25%, 50 + 50%, 25 + 75%, and spring triticale 100%; B – the harvest stage the flowering stage of narrowleaf lupine, the stage of flat green pod of narrowleaf lupine. Increasing the proportion of spring triticale in the sown mixtures in relation to narrowleaf lupine resulted in a decrease in the content of the analysed macroelements by 8.9%–28.7% on a g/kg DM basis. The greatest uptake on a kg/ha basis of macroelements was found in the mixture with an equal share of both components. Harvesting mixtures at a later stage of development increased the uptake of P, K, Ca and Mg by 98.7%–111.8% because of greater DM yield, but reduced the content of these macroelements by 12.6%–20.8% in the more mature fodder. Mixtures of narrowleaf lupine with spring triticale can provide valuable mineral nutrients for livestock.

Introduction

Progressive climate change and the increasing development of sustainable and organic agriculture are generating interest in the use of legume-cereal mixtures (Maxin *et al.*, 2017). According to Pelzer *et al.* (2012) and Lithourgidis *et al.* (2011), the cultivation of legume-cereal mixtures makes it possible to increase the self-sufficiency of farms in feed supply, and bring environmental and agronomic benefits. There is a global increase in demand for livestock products (FAO, 2022) and a decreasing area of land devoted to cultivation due to the development of urban areas (Ahmada *et al.*, 2007). This creates a challenge for agriculture to provide livestock feed in sufficient quantity and quality (Soufan and Al-Suhaibani, 2021). In the opinion of Księżak *et al.* (2023) legume-cereal mixture crops can be grown for grain feed, green fodder, silage or green manure. As stated by Bacchi *et al.* (2021), mixed crops increase crop yields and guarantee high quality forage compared to monoculture crops. The greater yield of mixtures is due to the more efficient use of light, water and nutrients by mixture crops (Księżak *et al.*, 2023). Additionally, an important benefit of growing legumes in mixtures with cereals is the symbiosis of legumes with bacteria of the Rhizobium that convert atmospheric nitrogen into a plant-available organic form (Amine-Khodja *et al.*, 2022). As stated by Swarnalakshmi *et al.* (2020), nitrogen can be utilized both by the legume and by plants grown in mixture with them. The recent significant increase in the cost of mineral fertilizers and their negative impact on the environment has prompted farmers to seek alternative forms of nitrogen and management such as mixed cropping (Księżak *et al.*, 2023). The feed provided to livestock should have a high macroelements content, ultimately complying with NRC (2000). Feeding livestock feed with inadequate macroelements content can result in lower milk yields (Hadžimusić and Krnić, 2012). According to Radwińska and Żarczyńska (2014), inadequate levels of minerals in feed can lead to many diseases in livestock such as diseases of the nervous system and locomotor system. Studies conducted by other authors on legume-cereal mixtures indicate a more favourable macroelements composition of feed obtained from such crops compared to cereal crops (Gill and Omokanye, 2018; Zaeem *et al.*, 2021; Demydas and Veiler, 2022; Panasiewicz, 2022). In addition, the different yield levels and quality of forage obtained from legume-cereal mixtures at different proportions of components in the mixture and harvesting dates support the research of such cultivation of these mixtures (Genc-Lermi, 2018; Pflueger *et al.*, 2020; Peprah *et al.*, 2021; Bo *et al.*, 2022). In the research hypothesis of this study, it was assumed that the share of components in the mixture of narrowleaf lupine with spring triticale and the harvest date of the mixtures would significantly affect the content and uptake of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in the green fodder obtained. The objective of this study was to evaluate the content and uptake of macroelements in the green forage of mixtures of narrowleaf lupine with spring triticale and to assess the suitability of green forage for livestock.

Materials and methods

Research methodology

The experiment was conducted at the Agricultural Experimental Station in Zawady, Poland (52° 03' 39" N, 22° 33' 80" E) belonging to the University of Natural Sciences and Humanities in Siedlce in 2016–2018. The field experiment was established on a Stagnic Luvisols soil. The content of available mineral nutrients in the soil was: P 81.0 mg/kg, K 122.0 mg/kg, and Mg 52.0 mg/kg. The humus content was 1.39%, determined indirectly by titration method by oxidation with dichromate (IV) in the sulphuric acid (IV) medium, as a result of multiplying the organic carbon content by a factor of 1.724. The experiment was conducted in a split-block design, in three replications. The original plot size was 20 m^2 (5×4). The data of weather conditions was obtained from Zawady Meteorological Station. Weather conditions varied in the study years (Fig. 1).

Agrotechnological practices

Two factors were tested in the experiment: A – the share of components in the mixture (M): narrowleaf lupin pure sowing, spring triticale pure sowing, narrowleaf lupin 75% + spring triticale 25%, narrowleaf lupin 50% + spring triticale 50%, narrowleaf lupin 25% + spring triticale 75%; B – harvest stage (H): flowering stage of narrowleaf lupin, flat green pod stage of narrowleaf lupine. The agrotechnical treatments applied during the field experiment are shown in Table 1.

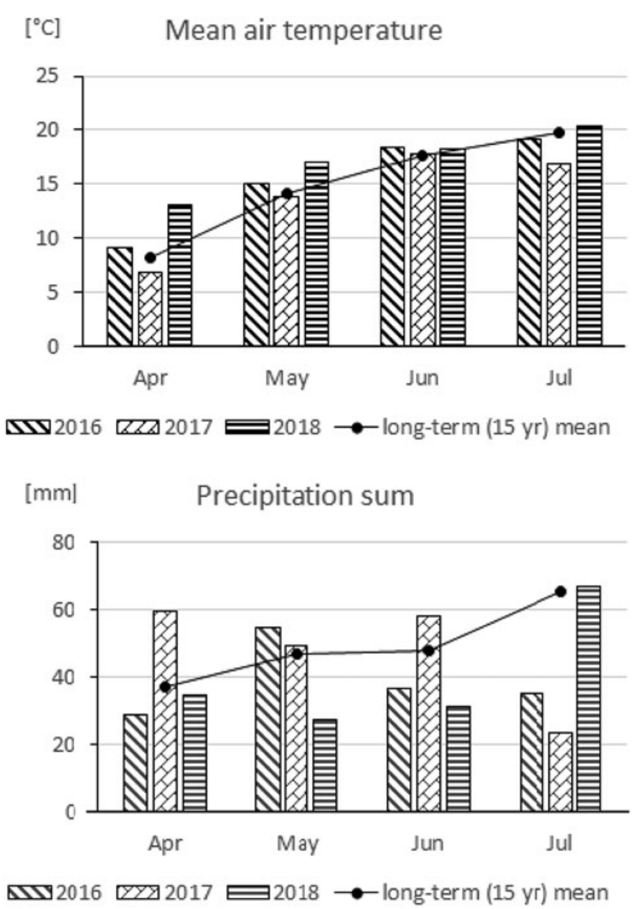

Figure 1. Weather conditions during the growing season of narrowleaf lupin/spring triticale mixtures according to the Zawady Meteorological Station.

Chemical analyses

During harvest of mixtures, fresh matter samples were collected from 1 m^2 in each plot. The representative sample from a 1 kg plot canopy was shredded and dried in the room with free air flow of ambient temperature. In the sample, P, K, Ca and Mg contents in dry matter were determined by the inductively coupled plasma excitation–optical detector (ICP – OES) emission method using a Perkin Elmer Optima 8300 emission spectrometer. The uptake of P, K, Ca and Mg by narrowleaf lupin and spring triticale mixtures was calculated by multiplying as the result of macroelements content by the dry matter yield obtained from the mixtures. The Pearson correlation coefficient between dry matter yield of mixtures, macroelements content and uptake was calculated.

Statistical analyses

Each of the characteristics studied was analysed by means of ANOVA for the split-block arrangement, following the mathematical model Eqn (1):

$$Y_{ijl} = n + a_i + g_j + e_{ij}^{(1)} + b_l + e_{jl}^{(2)} + ab_{il} + e_{ijl}^{(3)} \qquad (1)$$

where: Y_{ijl} – the value of the characteristic; n – number of replicates; a_i – the effect of the i-th level of factor A; g_j – effect of replicates (blocks); $e_{ij}^{(1)}$ – error 1 resulting from the interaction: factor $A \times$ replicates; b_l – the effect of the l-th level of factor B; $e_{jl}^{(2)}$ – error 2 from the interaction: factor $B \times$ replicates; ab_{il} – effect of the interaction: factor $A \times$ factor B; e_{ijl} – random error. Comparison of means for significant sources of variation was achieved by means of Tukey's HSD test at the significance level of $P \leq 0.05$. All the calculations were performed in STATISTICA, version 12.0, and MS Excel.

Results

The share of components in the mixture of narrowleaf lupine and spring triticale ($P < 0.001$), the date of harvesting the mixtures ($P < 0.001$) and the interaction of the experimental factors (P: $P = 0.029$; K, Ca: $P < 0.001$; Mg: $P = 0.027$) significantly differentiated the content of the analysed macroelements in the green fodder of the mixtures (Table 2). The greatest content of P, K, Ca and Mg was found in the narrowleaf lupine, while the least was found in spring triticale. Among mixtures, the greatest content of the analysed macroelements was revealed in a mixture with a 75% share of narrowleaf lupine and 25% of spring triticale. Increasing the share of spring triticale to 50% of the components in the mixture resulted in a decrease in the content of P in green fodder by 11.2%, K by 8.9%, Ca by 14.4% and Mg by 10.5%. A mixture with 25% of narrowleaf lupine and 75% of spring triticale resulted in a reduction content of P by 25.5%, K by 19.2%, Ca by 28.7% and Mg by 20.9% compared to a legume-predominant mixture at seed sowing. Harvesting mixtures of narrowleaf lupine with spring triticale at the later of the analysed developmental

https://doi.org/10.1017/S0021859623000448 Published online by Cambridge University Press

Table 1. Agrotechnical treatments performed during the field experiment

Month	Treatment	Quantity	Comments
October	Phosphorus (P) fertilisers	34.8 kg/ha	46% P_2O_5 (triple superphosphate)
	Potassium (K) fertilizers	99.2 kg/ha	60% K_2O (potassium salt)
April	Nitrogen (N) fertilizers	30.0 kg/ha	34% N as NH_4NO_3 (ammonium nitrate)
	Sowing seeds	Narrowleaf lupin 240 kg/ha (120 seed/m^2) spring triticale 220 kg/ha (600 seed/m^2)	For pure sowing; mixtures with factor I, respectively
May	N fertilizers	50.0 kg/ha	Spring triticale plots
	N fertilizers	30.0 kg/ha	Mixtures plots
June	Green fodder harvest	–	Narrowleaf lupin flowering stage
July	Green fodder harvest	–	Narrowleaf lupin flat green pod stage

stages of narrowleaf lupine caused a significant ($P < 0.001$) reduction in the content of analysed macroelements in the green fodder of mixtures. In the green fodder of mixtures harvested at the flat green pod stage of narrowleaf lupine, lower contents of P by 18.3%, K by 20.8%, Ca by 19.9% and Mg by 12.6% were obtained compared to mixtures harvested at the flowering stage of narrowleaf lupine. The interaction of the share of components in the mixture and the harvesting date was shown, from which it was concluded that harvesting all analysed mixtures at the flowering stage in relation to the flat green pod stage of narrowleaf lupine allows obtaining a greater concentration of the analysed macroelements.

The growing season conditions of narrowleaf lupine/spring triticale mixtures significantly ($P < 0.001$) influenced the content of macroelements in the green fodder of the mixtures (Table 3). The greatest content of the analysed macroelements was found in the green fodder of mixtures of narrowleaf lupin with spring triticale harvested in 2018. P content in mixtures harvested in 2016 and 2017 was significantly ($P < 0.001$) less, by 6.3% and 7.8%, respectively, compared to 2018. P contents in mixtures harvested in 2016 and 2017 were not significantly different. Significantly ($P < 0.001$) less contents of K, Ca and Mg were revealed in mixtures harvested in 2016, while significantly ($P < 0.001$) the least in mixtures harvested in 2017. In mixtures of narrowleaf lupin with spring triticale harvested in 2016 there was a reduction in K content by 10.7%, while in 2017 by 14. 6% relative to 2018. Ca content in mixtures harvested in 2016 was less by 14.7%, in 2017 by 18.9% relative to 2018. Mg concentration in green fodder of mixtures harvested in 2016 was less by 19.2%, in 2017 by 25.8% relative to 2018.

Table 2. The content of macroelements in narrowleaf lupin/spring triticale mixtures depending on harvest stage (means across 2016–2018), g/kg DM

	P			K			Ca			Mg		
	Harvest stage (H)											
Mixtures[a] (M)	I[b]	II	Means	I	II	Means	I	II	Means	I	II	Means
1	5.47	4.68	5.07	41.17	32.49	36.83	14.87	12.18	13.53	1.98	1.81	1.90
2	4.72	3.93	4.33	38.21	30.17	34.19	12.74	11.06	11.90	1.80	1.62	1.71
3	4.24	3.45	3.84	34.82	27.44	31.13	11.29	9.08	10.19	1.65	1.41	1.53
4	3.55	2.90	3.22	30.47	24.75	27.61	9.94	7.04	8.49	1.43	1.28	1.35
5	3.00	2.18	2.59	28.11	21.98	25.05	7.70	5.91	6.80	1.29	1.00	1.14
Means	4.19	3.43		34.56	27.37		11.31	9.05		1.63	1.42	
$HSD_{0.05}$												
M	0.11			0.67			0.13			0.06		
H	0.04			0.24			0.03			0.02		
M × H	0.12			0.51			0.13			0.07		
P values												
M	<0.001			<0.001			<0.001			<0.001		
H	<0.001			<0.001			<0.001			<0.001		
M × H	0.029			<0.001			<0.001			0.027		

[a]1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.
[b]I - flowering stage of narrowleaf lupin, II - flat green pod stage of narrowleaf lupine.

Table 3. The content of macroelements in narrowleaf lupin/spring triticale mixtures according to component share in the mixture in 2016–2018, g/kg DM

	P			K			Ca			Mg		
	Years (Y)											
Mixtures[a] (M)	2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018
1	5.01	4.95	5.26	36.12	34.66	39.72	13.12	12.63	14.83	1.82	1.70	2.16
2	4.26	4.20	4.51	33.42	32.13	37.02	11.53	11.04	13.14	1.63	1.52	1.98
3	3.78	3.72	4.03	30.36	29.07	33.97	9.79	9.30	11.47	1.46	1.34	1.80
4	3.16	3.10	3.41	26.84	25.55	30.44	8.10	7.60	9.77	1.28	1.16	1.62
5	2.52	2.46	2.78	24.29	22.96	27.89	6.37	5.94	8.10	1.07	0.95	1.41
Means	3.75	3.68	4.00	30.21	28.87	33.81	9.78	9.30	11.46	1.45	1.33	1.80
$HSD_{0.05}$												
Y	0.07			0.44			0.09			0.04		
Y × M	0.20			1.16			0.23			0.10		
P values												
Y	<0.001			<0.001			<0.001			<0.001		
Y × M	0.027			<0.001			0.019			0.032		

[a]1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.

In the study conducted, the share of components in the mixture ($P < 0.001$) and the harvest date of the mixtures ($P < 0.001$), as well as the interaction of the experimental factors ($P < 0.001$), significantly differentiated the uptake of macroelements by mixtures of narrowleaf lupine with spring triticale (Table 4). The greatest uptake of P, K, Ca and Mg was found in the green fodder of mixtures of narrowleaf lupin with spring triticale with an equal share of both components. The least uptake of the analysed macroelements was recorded in the green forage of spring triticale. In the case of Ca and Mg uptake, there were additionally no statistically significant differences between the green fodder of narrowleaf lupine and the mixture with 75% share of narrowleaf lupine and 25% share of spring triticale. Significantly ($P <$ 0.001) greater uptake of macroelements was found in mixtures of narrowleaf lupine with spring triticale harvested at the flat green pod stage of narrowleaf lupine compared to the flowering stage of narrowleaf lupine. Harvesting the mixtures at the later of the analysed developmental stages of narrowleaf lupine resulted in an increase in the uptake of P by 98.7%, K by 91.6%, Ca by 94.4% and Mg by 111.8%. In the conducted experiment, the interaction of the share of components in the mixture and the harvest date was shown, from which it follows that, harvesting the analysed mixtures at the later developmental stage of narrowleaf lupine causes a significant ($P < 0.001$) increase in the uptake of macroelements regardless of the mixture components.

Our own research showed a significant ($P < 0.001$) influence of growing season conditions of mixtures of narrowleaf lupine with spring triticale on the uptake of the analysed macroelements (Table 5). The highest uptake of P was found in mixtures harvested in 2018, while the least was found in the mixtures harvested in 2016 and 2017. In mixtures of narrowleaf lupin with spring triticale harvested in 2016 and 2017, there were no significant differences in the uptake of P. In mixtures harvested in 2016 and 2017, less P uptake was found by 24.9% and 26.1%, respectively, compared to 2018. Mixtures of narrowleaf lupin with spring triticale grown in 2018 uptake the greatest amounts of K, Ca and Mg. Less uptake of these macroelements was found in 2016 and significantly ($P < 0.001$) the least in 2017. In the case of K, mixtures grown in 2016 uptake less of this macroelement by 28.6%, and in 2017 by 31.8% compared to the year with the greatest uptake. Growing season conditions when growing mixtures in 2016 resulted in less Ca uptake by 37.7%, while in 2017 it was 35.1% less than in 2018. In 2016, there was less uptake of Mg by mixtures of narrowleaf lupine with spring triticale by 35.1%, in 2017 by 40.4% compared to 2018.

In this study, the share of components in the mixture and the harvest date caused changes in the Ca/P and K/(Ca + Mg) ratio in green fodder (Table 6). The smallest Ca/P ratio was recorded in the spring triticale crop and in the mixture with 25% of narrowleaf lupine and 75% of spring triticale. The highest Ca/P ratio was characterized by a mixture with a 75% share of narrowleaf lupine and 25% of spring triticale. The smallest K/(Ca + Mg) ratio was found in the green fodder of narrowleaf lupine, and the highest in spring triticale. Among the mixtures analysed, the smallest K/(Ca + Mg) ratio was found in a mixture with a 75 + 25% share of narrowleaf lupine and spring triticale components, respectively. The smallest Ca/P and K/(Ca + Mg) ratios were exhibited by mixtures of narrowleaf lupine and spring triticale harvested at the flat green pod stage compared to mixtures harvested at the flowering stage of narrowleaf lupine.

Growing season conditions during the cultivation of narrowleaf lupine/spring triticale mixtures influenced changes in Ca/P

Table 4. The uptake of macroelements by narrowleaf lupin/spring triticale mixtures depending on harvest stage (means across 2016–2018), kg/ha

	P			K			Ca			Mg		
	Harvest stage (H)											
Mixtures[a] (M)	I[b]	II	Means	I	II	Means	I	II	Means	I	II	Means
1	45.3	91.4	68.3	341.8	636.3	489.0	123.6	238.8	181.2	16.5	35.6	26.1
2	44.8	83.3	64.1	363.9	641.6	502.8	121.6	235.6	178.6	17.3	34.6	25.9
3	48.6	96.3	72.4	401.1	769.9	585.5	130.7	255.5	193.1	19.2	39.8	29.5
4	23.2	55.0	39.1	200.1	471.3	335.7	65.5	134.7	100.1	9.5	24.5	16.9
5	14.7	24.8	19.8	138.5	250.5	194.5	38.2	67.5	52.8	6.4	11.4	8.9
Means	35.3	70.2		289.1	553.9		95.9	186.4		13.8	29.2	
$HSD_{0.05}$												
M	1.7			9.4			3.4			1.1		
H	0.9			6.4			2.1			0.3		
M × H	2.3			10.3			3.8			1.3		
P values												
M	<0.001			<0.001			<0.001			<0.001		
H	<0.001			<0.001			<0.001			<0.001		
M × H	<0.001			<0.001			<0.001			<0.001		

[a]1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.
[b]I - flowering stage of narrowleaf lupin, II - flat green pod stage of narrowleaf lupine.

and K/(Ca + Mg) ratios and green fodder of the mixtures (Table 7). The smallest Ca/P ratio was obtained in mixtures harvested in 2017, greater in 2016 and the greatest in 2018. On the other hand, the least K/(Ca + Mg) ratio was revealed in mixtures of narrowleaf lupin with spring triticale harvested in 2018, the ratio was higher in 2016 and highest in 2017.

Discussion

According to studies conducted by other authors (Zaeem *et al.*, 2021; Demydas and Veiler, 2022), legumes have greater concentrations of P, K, Ca and Mg compared to cereals. This is consistent with the results obtained in our own research. In the opinion of

Table 5. The uptake of macroelements by narrowleaf lupin/spring triticale mixtures according to component share in the mixture in 2016–2018, kg/ha

	P			K			Ca			Mg		
	Years (Y)											
Mixtures[a] (M)	2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018
1	63.2	63.1	78.7	447.1	434.1	586.0	163.7	159.2	220.7	23.3	22.0	32.9
2	58.2	57.2	76.9	450.9	431.6	625.9	158.5	151.3	226.1	22.7	20.9	34.2
3	64.3	62.0	91.1	512.3	480.2	764.2	165.9	154.2	259.2	25.0	22.5	41.1
4	35.1	34.5	47.7	297.9	283.3	425.9	86.4	80.7	133.2	14.5	13.2	23.2
5	17.9	17.9	23.3	175.6	170.2	237.7	45.7	43.7	69.1	7.7	6.9	12.1
Means	47.7	46.9	63.5	376.7	359.9	527.9	124.1	117.8	181.7	18.6	17.1	28.7
$HSD_{0.05}$												
Y	1.1			6.1			2.2			0.7		
Y × M	2.9			16.3			5.9			1.9		
P values												
Y	<0.001			<0.001			<0.001			<0.001		
Y × M	<0.001			<0.001			<0.001			<0.001		

[a]1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.

https://doi.org/10.1017/S0021859623000448 Published online by Cambridge University Press

Table 6. Mass ratios of macroelements in narrowleaf lupin/spring triticale mixtures depending on harvest stage (means across 2016–2018)

Mixtures[a]	Ca/P			K/(Ca + Mg)		
	Harvest stage					
	I[b]	II	Means	I	II	Means
1	2.72	2.60	2.67	2.44	2.32	2.39
2	2.70	2.82	2.75	2.63	2.38	2.51
3	2.66	2.63	2.65	2.69	2.62	2.66
4	2.80	2.43	2.63	2.68	2.98	2.81
5	2.57	2.71	2.63	3.13	3.18	3.15
Means	2.70	2.64		2.67	2.61	

[a]1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.
[b]I - flowering stage of narrowleaf lupin, II - flat green pod stage of narrowleaf lupine.

Schoebitz *et al.* (2020), the cultivation of lupins increases acid phosphatase activity in the soil compared to the cultivation of cereals. Thus, legumes can recover P from inaccessible forms by secreting organic acids that lower the pH of the rhizosphere and release P from inaccessible compounds (Sammama *et al.*, 2021). The difference in P concentration in legumes compared to cereals, as stated by Stagnari *et al.* (2017), may also be due to differences in root systems that have access to different soil layers and thus different forms of P. As claimed by Rengel and Damon (2008), the efficiency of K uptake by plants depends on their ability to dissolve inaccessible forms into plant-available ones and their ability to transport them through the plasma membrane of root cells to other parts of the plant. According to the authors, this is important due to the fact that, K is transported to the roots by diffusion which is a slow process. In the opinion of Wong *et al.* (2000), on light soils, due to leaching, it is advantageous to grow plants that put down roots and uptake more K from deep in the soil profile and transport it to aboveground plant parts. Thus, it is advantageous to grow legumes with a long root system. Witter and Johansson (2001) showed that deep-rooted legumes uptake greater amounts of K from the soil compared to plants with fibrous root systems. As Xue *et al.* (2016) stated, Ca uptake from the soil environment varies significantly among plant species, but legumes concentrate greater amounts of Ca compared to cereals. As stated by these authors, uptake of Ca by plants through compensatory proton release leads to soil acidification by rhizobium N_2 fixation in legume roots. Such soil acidification, as mentioned earlier, increases P availability to plants. As reported by Xie *et al.* (2021) Mg, due to its highest hydrated ionic radius and correspondingly poor adsorption to soil colloids, is very susceptible to leaching. Therefore, it is reasonable to assume that legumes concentrate a greater amount of Mg compared to cereals due to their deeper developed root system. Farhat *et al.* (2016) additionally reports that Mg is the least absorbable nutrient. The authors attribute the low ability to concentrate Mg to both root tissues and other plant organs. This statement is confirmed in our own research, as among the minerals analysed, the concentration of Mg in the mixtures was the lowest. Xie *et al.* (2021) also point to a reduction in Mg uptake by plants when K availability in the soil is high. In our study, the availability of K in the soil where the field experiment was conducted was relatively high. Thus, this could have been the reason for the relatively low Mg content in our own study compared to the studies of other authors (Gill and Omokanye, 2018; Jakubus and Graczyk, 2022). In our study, different levels of concentrations of the analysed macroelements was as follows K > Ca > P > Mg. Also other authors obtained an analogous relationship of macroelements content in other grain legume

Table 7. Mass ratios of macroelements in narrowleaf lupin /spring triticale mixtures according to component share in the mixture in 2016–2018

Mixtures[1]	Ca/P			K/(Ca + Mg)		
	Years					
	2016	2017	2018	2016	2017	2018
1	2.62	2.55	2.82	2.42	2.42	2.34
2	2.71	2.63	2.91	2.54	2.56	2.45
3	2.59	2.50	2.85	2.70	2.73	2.56
4	2.56	2.45	2.86	2.86	2.92	2.67
5	2.52	2.41	2.92	3.27	3.33	2.93
Means	2.61	2.52	2.87	2.69	2.72	2.55

1 - narrowleaf lupin pure sowing, 2 - narrowleaf lupin 75% + spring triticale 25%, 3 - narrowleaf lupin 50% + spring triticale 50%, 4 - narrowleaf lupin 25% + spring triticale 75%, 5 - spring triticale pure sowing.

https://doi.org/10.1017/S0021859623000448 Published online by Cambridge University Press

mixtures and pure sowings (Gill and Omokanye, 2018; Turan *et al*., 2020; Ibrahim and El-Sawah, 2022; Panasiewicz, 2022).

In our research, harvesting narrowleaf lupine and spring triticale mixtures at the flat green pod stage of narrowleaf lupine resulted in a significant reduction in the content of P, K, Ca and Mg compared to mixtures harvested at the flowering stage of narrowleaf lupine. Other authors have also obtained a reduction in macroelements content in other legume and cereal crop mixtures harvested at later stages of plant development (Asci *et al*., 2018; Peprah *et al*., 2021; Bo *et al*., 2022). According to Molla *et al*. (2018), the decrease in macroelements content with plant maturation is related to natural dilution and movement of nutrients from the vegetative part to the root system. Other authors (Maillard *et al*., 2015; Etienne *et al*., 2018) point out the remobilization of macroelements from the vegetative parts to the seeds with plant maturation. Thus, it is reasonable to assume that during seed formation with the simultaneous growth of biomass and low uptake of macronutrients by the root at this stage of growth (Etienne *et al*., 2018) there is a reduction in the macroelements content of the total of the above-ground parts of the plants. In our study, the sensitivity of macroelements to percentage reduction in concentration with delayed harvest date was as follows: K > Ca > P > Mg.

The own research revealed an increase in the concentration of the analysed macroelements in the growing season with less total precipitation and high average temperature compared to seasons with greater total precipitation and lower average temperature. The results obtained in our own research are in line with the results obtained by other authors in studies on legume-cereal mixtures (Gill and Omokanye, 2018; Turan *et al*., 2020). In the opinion of other authors (Bhattacharya, 2021; Ghafar *et al*., 2021; Wahab *et al*., 2022), water shortages change the architecture and morphology of crop roots. As stated by these authors, as a result of abiotic stresses, plants increase root mass, mainly by increasing root length. Thus, it can be assumed that as a result of water shortages, the deeper developed root systems of plants my access to greater amounts of minerals in the soil, and increased root mass allows uptake of greater amounts of minerals thereby increasing the concentration in vegetative parts. On the other hand, other authors (Kaushal and Wani, 2016; Khatun *et al*., 2021; Zeroual *et al*., 2023) report that plants, as a result of water stress, take up smaller amounts of macroelements from the soil environment. In addition, reported by many authors (Kamal *et al*., 2019; Venugopalan *et al*., 2022; Wahab *et al*., 2022), the effect of water shortages is a reduction in crop yields. Analysing the statements of other authors, it can be assumed that as a result of reduced development of vegetative parts of plants due to drought, despite the lesser uptake of macroelements from the soil, the dilution of these nutrients in the biomass will be less. Alghamdi (2009) also came to similar conclusions. In our ~~own~~ study, the greatest percentage reduction as a result of great water availability was recorded for Mg, followed by Ca, K and the least for P concentration.

Green forage from mixtures of narrowleaf lupine and spring triticale reached the required P level of 1.6 g/kg DM for dry gestating beef cows. In contrast, only the green fodder obtained from spring triticale failed to meet the requirements for lactating cows at 2.6 g/kg DM (NRC, 2000). The K content of the green forage obtained from the crops analysed was well above the required value of 7.0 g/kg DM (NRC, 2000). Adequate Ca values for dry gestating beef cows (1.8 g/kg DM) and lactating cows (5.8 g/kg DM) (NRC, 2000) were also achieved by all crops. The suggested Mg content of 1.2 g/kg DM for dry gestating beef cow (NRC, 2000) was also met. In contrast, the requirement for lactating cows of 2.0 g/kg DM (NRC, 2000) was achieved only in the green forage derived from narrowleaf lupine. All other mixtures were below the suggested content.

Another study by the authors (Górski and Płaza, 2023) on the presented field experiment also revealed a high content of total carbohydrates, water-soluble carbohydrates, crude ash and crude fat in the green forage of mixtures of narrowleaf lupine with spring triticale. Similarly to the content of macroelements, the highest concentration of nutritive value components was revealed in mixtures with the highest proportion of narrowleaf lupine at sowing. As in the case of macroelements, also harvesting mixtures at a later developmental stage of narrowleaf lupin resulted in lower content of nutritive value components. Also, growing season conditions had an analogous effect on the content of nutritive value components as well as on the content of macroelements in green forage. A higher content of nutritive value components was obtained in a year with low total precipitation and high average temperature compared to seasons with higher total precipitation and lower average temperature.

Studies conducted by other authors (Ginwal *et al*., 2019; Solangi *et al*., 2021) on legumes and cereal crops showed greater uptake of minerals by legumes compared to cereals. This is consistent with the results obtained in our own studies. Legumes generally produce less aboveground biomass compared to cereals, but the greater macroelements content allows for higher uptake overall. In our study, the greatest uptake of P, K, Mg and Ca was obtained in a mixture with an equal proportion of both components. Mixtures of legumes and cereals make it possible to obtain significantly greater yields compared to pure sowing (Pflueger *et al*., 2020; Bacchi *et al*., 2021). According to the authors (Ajal *et al*., 2021; Li *et al*., 2021), it is due to better use of available resources, and positive interaction of plants grown in a mixture with each other. Thus, greater yields of green fodder from mixed crops guarantee the achievement of higher uptake of macroelements. This is confirmed by results obtained by other authors (Ginwal *et al*., 2019; Arif *et al*., 2022). Also, analysing the calculated correlation coefficient (Table 8), it can be concluded that the greatest correlation occurred between the dry matter yield of the mixtures and the uptake of macroelements. The correlation between macroelements content and uptake was much less, while for K it was not significant. The harvesting of mixtures at the later of the analysed development phases resulted in a significant increase in the uptake of the analysed

Table 8. Correlation coefficients among dry matter yield, content and uptake P, K, Mg and Ca in narrowleaf lupin/spring triticale mixtures

	Correlation coefficients among			
Macroelements	Dry matter yield and uptake	*P* values	Content and uptake	*P* values
P	0.912	<0.001	0.339	0.001
K	0.941	<0.001	0.104*	0.331
Ca	0.890	<0.001	0.392	<0.001
Mg	0.920	<0.001	0.439	<0.001

*not significant.

https://doi.org/10.1017/S0021859623000448 Published online by Cambridge University Press

macroelements. In the period from the flowering stage to the flat green pod stage, there is a significant increase in biomass (Gecaitė *et al.*, 2021). Thus, in spite of a decrease in macroelements content in dry matter, there was an increase in the uptake of P, K, Ca and Mg. In our study, an approximately twofold increase in the uptake of all analysed macroelements was obtained. The greatest increase was recorded for Mg followed by P, Ca and K. In our study, the greatest uptake of macroelements was revealed in a year with deficient precipitation. Other authors point out less crop yield under water deficit conditions (Venugopalan *et al.*, 2022; Wahab *et al.*, 2022), but in our study, a much greater macroelements content in dry matter compensated for less yield.

In the feed provided to livestock, the interrelationship among the macroelements is as important as their content. In the opinion of Kumar and Soni (2014), Ca and P metabolism are interrelated. In addition, as stated by the authors, Mg is related to the functions that Ca and P play in the livestock body. As stated by Turan *et al.* (2020), the Ca/P ratio in livestock feed should be between 1 and 2, while K/(Ca + Mg) should be less than 2.2. According to Başbağ *et al.* (2018) and Özyazıcı and Açıkbaş (2019), feeding livestock feeds with higher than optimal Ca/P before longer periods can lead to health disorders. On the other hand, as stated by Crawford *et al.* (1998), too high K/(Ca + Mg) ratio in feed can lead to hypomagnesemia in livestock. In our study, all of the green feed samples analysed showed greater than optimal Ca/P ratios. Studies conducted by Turan *et al.* (2020) on other legume-cereal mixtures also revealed excessively high Ca/P ratios. In this study, the increase in Ca/P in years with less water availability was due to a much greater increase in Ca content in dry matter in relation to P. In the case of harvesting mixtures at a later developmental stage of narrowleaf lupine, the reduction in Ca/P ratio was due to a greater reduction in Ca content in dry matter in relation to the reduction in P. Also Asci *et al.* (2018) in their study noted a reduction in Ca/P ratio in mixtures harvested at later developmental stages. In the presented study, also the K/(Ca + Mg) ratio in the green forage of all analysed samples was greater than optimal. Similar results were also obtained by Turan *et al.* (2020) and Asci *et al.* (2018). In our own study, the lesser K/(Ca + Mg) ratio in the year with the highest total precipitation was due to a more intense reduction in K content in relation to Ca + Mg under conditions of optimal water availability. A similar relationship was observed as a result of harvesting mixtures at the later of the analysed development phases. On the other hand, the observed increase in the K/(Ca + Mg) ratio with increasing the proportion of spring triticale in the mixture with narrowleaf lupine can be attributed to a greater reduction of Ca + Mg in dry matter (especially Ca) in relation to K. Also, Asci *et al.* (2018) observed an increase in K/(Ca + Mg) with an increase in the proportion of the cereal crop in the mixture with the legume. However, the authors observed an increase in K/(Ca + Mg) when the crop was harvested at a later stage, which is not consistent with the results of their own study.

Conclusion

The cultivation of legume-cereal mixtures makes it possible to obtain green fodder with P, K, Ca and Mg content fully meeting the needs of dry gestating beef cows. However, in the case of lactating cows, the forage should be additionally supplemented with Mg in small amounts. The green fodder obtained from mixtures of narrowleaf lupine with spring triticale should not be used as the sole feed for livestock due to excessively high Ca/P and K/(Ca + Mg) ratios. The high uptake of minerals by mixtures with equal proportions of both components may also suggest the possibility of using the mixtures as green manure.

Authors' contributions

RG and AP conceived and designed the study. RG and AP conducted data gathering. RG performed statistical analyses. RG and AP wrote the article.

Funding statement

This research was funded by Ministry of Science and Higher Education, grant number 30/20/B.

Competing interest. None.

Ethical standards. Not applicable

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