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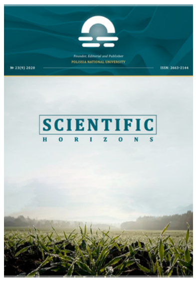

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Forage productivity of combined crops of seed oats, maize, and Sudanese sorghum with white lupine

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Abstract. Research aimed at the accumulation and effective use of nitrogen, its symbiotic fixation from the air by white lupine plants, by selecting the best cereal components, optimizing their ratio and methods of placement when growing in compatible crops under different fertilization systems in the Forest Steppe is insufficient. The purpose of this study was to establish the best cereal components, their ratio and methods of placement with white lupine when sowing in joint crops under different fertilizer systems to produce grass fodder in the Forest-Steppe of

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Ukraine. The following methods were used: field, laboratory, mathematical-statistical, calculation-comparative. It was established that the highest productivity on the background without fertilizers (4.21-4.86 t·ha^{-1} of dry matter) was provided by single-species crops of maize and white lupine, as well as their combined crops, which were formed by continuous row and strip methods, which by 2.60-3.17 t·ha^{-1} of dry matter or 1.8-2.6 times more compared to crops of oats and its mixture with white lupine and by 1.13-1.58 t·ha^{-1} or 1.4-1.5 times more compared to crops of Sudanese sorghum and its mixture with white lupine. Through the accumulation and use of symbiotic nitrogen fixation, the productivity of lupine-oat mixtures increased from 1.90 to 2.70-3.21 t·ha^{-1} of dry mass or 1.4-1.7 times, and that of lupine-sorghum – from 3.17 to 3.43-3.47 or 1.1 times. The most effective ratio of each cereal component to legume in binary intercropping was 25:75% of the sowing rate in single-species agrocenoses when dry biomass productivity was the greatest. Compared to the variant without fertilizers, the most significant (by 1.3-2.0 times) increase in the productivity of all fodder agrocenoses under study was ensured by the application of $N_{45}P_{30}K_{50}$, while the application of $P_{30}K_{50}$ or humigran organic fertilizer at a dose of 250 kg·ha^{-1} – only by 1.2-1.3 times. The research results can be used in the development of scientific and methodological recommendations and the education about the formation of highly productive agrophytocenoses for conveyor production of high-quality grass fodder for animal feeding

Keywords: solid and strip agrocenoses; mineral and organic fertilizers; annual cereals; crude protein; compatible and single-species crops; dry mass; grass fodder

INTRODUCTION

In creating a strong fodder base for animal husbandry in Ukraine, a major role belongs to improving the efficiency of using legumes as a source of cheap symbiotic nitrogen. They are a source of cheap grass fodder (hay, silage, green fodder, artificially dried grass fodder), which is well-balanced in terms of protein, minerals, and vitamins (Demidas & Prorochenko, 2018; Demidas & Galushko, 2018; Kurhak *et al.*, 2020). Improving the efficiency of using cheap symbiotic nitrogen of legumes by enriching them with cereal coenoses is not only an important reserve for increasing fodder production, but is aimed at reducing energy costs, reducing environmental pollution with nitrogen fertilizers, improving soil fertility, etc. The need for fodder production in the Polissia and Forest-Steppe of Ukraine can be provided at least by half through using the potential of perennial and annual leguminous crops when grown in both single-species and combined crops (Kurgak & Karbivska, 2020).

In Western European countries, the dependence of fodder production on mineral nitrogen is also already decreasing by using the potential of leguminous perennial and annual grasses, the need to partially replace mineral nitrogen with symbiotic ones is increasing because the production of nitrogen fertilizers is a very energy-intensive and expensive process, the introduction of elevated doses of mineral nitrogen pollutes the environment, production, and the application of nitrogen fertilizers to fodder lands is insufficient. Therefore, it is not by chance that within the framework of the International Biological Program of UNESCO and the International Society of Soil Scientists, nitrogen fixation, along with photosynthesis, is highlighted as one of the main physiological processes on which the production of agricultural products largely depends. Increasing the use of leguminous perennial and annual grasses in forage production is the most important component of the program for the introduction of energy-saving technologies in the world (Nilsdotter-Linde *et al.*, 2016; Hannaway *et al.*, 2018).

Legumes, thanks to their positive consortial relationships with symbiotrophs (rhizobia), not only feed themselves with symbiotic nitrogen, but also accumulate nitrogen in the soil. This has a positive effect on cereals that grow together with them in phytocenoses (Hetman *et al.,* 2019; Kurgak & Karbivska, 2020).

When creating models of mixtures of annual forage crops, it is necessary that their components are compatible in terms of morphological characteristics and biological features of their growth and development, while simultaneously increasing productivity and improving the quality of feed in terms of crude protein content. These requirements are met by legume and cereal agrophytocenoses (Demidas & Proroshenko, 2018; Kurhak *et al.,* 2020).

The studies of various scientists have developed and recommended legume-cereal fodder agrophytocenoses with a productivity of 5-6 t/ha of fodder units, which ensure the production of high-quality fodder crude materials to produce herbal fodder for animals and the production of ecologically safe animal husbandry products for humans, namely, milk and meat (Hetman *et al.,* 2019; Ratoshniuk, 2020; Dzyubaylo *et al.,* 2020). In this context, it is important to obtain complete feeds from leguminous-cereal mixtures not only of perennial grasses, but also of potential with an expanded assortment and the use of conventional crops and new introducers of annual crops in early intermediate crops and crops involving highly productive drought-resistant late-ripening crops in the chain of green or raw material conveyor. To create stable, highly productive fodder agrocenoses in the conditions of aggravation of arid phenomena in the Northern Forest-Steppe of Ukraine, growing attention is being paid to crops that form high productivity in conditions of a lack of atmospheric precipitation and a deficit of moisture in the soil, namely, maize and Sudanese sorghum, which are characterized by high production potential not only in single-species crops, but also in mixtures. Sudanese sorghum tolerates a lack of moisture in the soil better than low average daily temperatures. Even during frequent dry periods, it generates prominent yields of fodder biomass (Slyusar, 2017; Slyusar & Oksymets 2018).

However, until recently, the issues of the optimal ratio and methods of placing the components of lupine-cereal mixtures under different fertilization systems (organic and mineral) and the influence of these factors on the forage productivity of crops and the quality of grass fodder are still understudied. In the green or raw material conveyor system, it is necessary to substantiate the wider use of lupine-cereal binary mixtures along with oats for sowing drought-resistant corn and sorghum, which is vital in the modern conditions of aggravation of drought phenomena due to aridization of the climate. These are the questions that the present study is aimed at, the results of which are presented in this paper.

The purpose of this study was to establish the features of the formation of one-year highly productive fodder agrophytocenoses with different ratios and methods of placement of cereal components with white lupine when sowing in binary compatible crops under different fertilization systems for conveyor production of highly nutritious grass fodder in the Forest Steppe of Ukraine.

MATERIALS AND METHODS

A study on the fodder productivity of white lupine, oats, maize, and Sudanese sorghum in single-species crops and lupine-cereal mixtures with different ratios and methods of placement under different fertilizer systems (organic and mineral) was conducted during 2016-2018 in the Forest-Steppe zone of Ukraine on dark grey podzolized coarse-pollinated-light loamy soil in the National Research Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine" (Chabany village, Kyiv region). Humus content in the 0-20 cm soil layer is 2.4%; pH (saline) – 5.2; the content of alkaline hydrolyzed nitrogen – 13.1, mobile phosphorus – 17.1 and exchangeable potassium 12.9 mg·100g^{-1} of soil. The depth of the humus horizon is 35-40 cm, and the groundwater occurrence is about 3 m.

The climate of the region where the study was conducted is temperate continental. The average annual air temperature is 6-7°C, while the maximum temperature in the summer months reaches 37-39°C, and the lowest temperature is 36°C in winter. Precipitation averages 480-620 mm per year, and 423 mm during the growing season. Weather conditions during the research years were favourable for the vegetation of perennial grasses. The least favourable year was 2017, when the least precipitation fell during the growing season (335 mm) and when the lowest fodder productivity of all the crops and their mixtures under study was formed. The scheme of the experiment is presented in Table 1.

Table 1. *Experiment scheme*

Sward factor – crops and their mixtures and seed sowing rate, kg·ha^{-1} (%)
White lupine, 300 (100)
Seed oats, 160 (100)
Seed oats, 80 (50) + white lupine, 150 (50) – strip sowing*
Seed oats, 40 (25) + white lupine, 225 (75)
Seed oats, 80 (50) + white lupine, 150 (50)
Seed oats, 120 (75) + white lupine, 75 (25)
Maize, 70 (100)
Maize, 35 (50) + white lupine, 150 (50) – strip sowing*
Maize, 17.5 (25) + white lupine, 225 (75)
Maize, 35 (50) + white lupine, 150 (50)
Maize, 52.5 (75) + white lupine, 75 (25)
Sudanese sorghum, 30 (100)
Sudanese sorghum, 15 (50) + white lupine, 150 (50) – strip sowing*
Sudanese sorghum, 7.5 (25) + white lupine, 225 (75)
Sudanese sorghum, 15 (50) + white lupine, 150 (50)
Sudanese sorghum, 22.5 (75) + white lupine, 75 (25)

Note: ** Strip sowing method with a strip width of 1.5 m. On the remaining agrocenoses, there was a continuous sowing of components in one row with row spacing of 0.15 m. The experiment was conducted on four fertilizer backgrounds: without fertilizers; $N_{45}R_{30}K_{50}$; $P_{30}K_{50}$; Humigran – 250 kg·ha^{-1}*
Source: *compiled by the authors*

Mineral fertilizers were introduced for pre-sowing cultivation in the form of ammonium nitrate, superphosphate, and potassium chloride, while organic fertilizer humigran (granulated vermicompost) was applied to the rows when sowing annual grasses. The area of the sown plot is 30 m^2, the accounting plot is 25 m^2.

The repetition of the experiment was fourfold. Agricultural techniques for growing mixtures were generally accepted for the Right-Bank Forest-Steppe. Pre-sowing soil treatment was carried out with the Europak-600 combined unit to a depth of 6-8 cm, which ensured levelling and crushing of the soil to a fine-grained state.

The crops under study and their mixtures were sown in optimal agrotechnical terms with a mounted Seeder CH-16A in an aggregate with a tractor t-25A in the usual lowercase way with row spacing of 15 cm, including sowing during the formation of strip agrocenoses. The seeding rate of forage crops is consistent with the experiment scheme in the corresponding variants. During sowing, the experiment used zoned varieties of annual crops, mainly selected by the NSC "Institute of Agriculture of the National Academy of Sciences".

Harvest accounting was carried out differentially, as the harvest maturity of the dominant crops of the corresponding agrophytocenoses, namely, the phase of milky maturity of cereals (oats, maize, and Sudanese sorghum) and in the phase of physiological maturity of the seeds in the lower tier of white lupine, continuous mowing of the green mass with accounting area followed by weighing.

Field studies were conducted according to generally accepted methods in feed production (Methods of conducting experiments on feed production, 1994). Harvest accounting was carried out by continuous mowing of biomass in the accounting area at the time of harvesting maturation for harvesting grass fodder in fourfold repetitions, and the determination of the content of dry matter in biomass during harvest accounting was carried out by drying biomass in a drying cabinet at 105°C (DSTU 8044:2015, 2018).

In the dry plant mass, the content of crude protein, crude fat, crude fibre, digestibility of the dry matter of feed was determined *in vitro* – according to the method of infrared spectroscopy per (DSTU 4117:2007, 2008); the content of nitrogen-free extractive substances (NFES) – by calculation (DSTU 4674:2006, 2008). The agrochemical parameters of the soil were determined before starting the experiment in the 0-20-cm layer of the soil according to generally accepted methods, namely: humus – according to Tiurin (DSTU 4289:2004, 2006); nitrogen that is easily hydrolyzed by alkali – according to Cornfield (DSTU 7863:2015, 2018); mobile phosphorus and potassium – according to Kirsanov and Machygin (DSTU 4115-2002, 2004); pH (saline) – potentiometrically (DSTU ISO10390:2001, 2008). Mathematical processing of the obtained experimental performance data in the experiment was carried out according to the method of variance analysis.

RESULTS AND DISCUSSION

The results of the study on the formation of fodder productivity of single-species (white lupine, seed oats, maize, and Sudanese sorghum) and lupine-cereal binary combined crops with different ratios and placement of components upon sowing under different fertilizer options on average for 2016-2018 are presented in Table 2. The analysis of the study results showed that against a background without fertilizers, the productivity of these agrocenoses ranged within 1.90-4.86 t·ha^{-1} of dry matter (mass) and 0.16-0.85 t·ha^{-1} of crude protein. The highest productivity (on the background without fertilizers, 4.21-4.86 t·ha^{-1} of dry matter) was provided by single-species crops of maize and white lupine and their mixtures with continuous row and strip sowing methods, which prevailed over oats and their mixtures with white lupine by 2.60-3.17 t·ha^{-1} of dry matter or 1.8-2.6 times, while Sudanese sorghum and its mixture with white lupine – by 1.13-1.58 t·ha^{-1} or 1.4-1.5 times.

Table 2. *Productivity of mixtures of annual cereal fodder crops with white lupine depending on the ratio and methods of placing components upon sowing*

Crops and their mixtures, seeding rate, kg·ha^{-1} (%)	Fertilizer	Dry mass by year, t·ha^{-1}			Average for 2016-2018		
		2016	2017	2018	Dry mass, t·ha^{-1}	Crude protein, t·ha^{-1}	The share of lupine in the crop, %
1	2	3	4	5	6	7	8
White lupine, 300 (100)	Without fertilisers	4.84	3.63	5.08	4.52	0.88	94
	$N_{45}P_{30}K_{50}$	6.40	4.80	6.72	5.97	1.24	95
	$P_{30}K_{50}$	6.15	4.61	6.46	5.74	1.16	94
	Humigran	5.58	4.19	5.86	5.21	1.07	94
Seed oats, 160 (100)	Without fertilisers	2.04	1.53	2.14	1.90	0.16	–
	$N_{45}P_{30}K_{50}$	3.30	2.48	3.47	3.08	0.29	–
	$P_{30}K_{50}$	2.64	1.98	2.77	2.46	0.21	–
	Humigran	2.49	1.87	2.61	2.32	0.23	–
Seed oats, 80 (50) + White lupine, 150 (50) – strip sowing*	Without fertilisers	3.44	2.58	3.61	3.21	0.45	66
	$N_{45}P_{30}K_{50}$	4.85	3.64	5.09	4.53	0.68	63
	$P_{30}K_{50}$	4.40	3.30	4.62	4.11	0.60	67
	Humigran	4.14	3.11	4.35	3.87	0.58	67
Seed oats, 40 (25) + white lupine, 225 (75)	Without fertilisers	3.40	2.55	3.57	3.17	0.45	68
	$N_{45}P_{30}K_{50}$	4.82	3.62	5.06	4.50	0.70	65
	$P_{30}K_{50}$	4.41	3.31	4.63	4.12	0.61	69
	Humigran	4.10	3.08	4.31	3.83	0.61	69

Table 2, Continued

Crops and their mixtures, seeding rate, kg·ha⁻¹ (%)	Fertilizer	Dry mass by year, t·ha⁻¹			Average for 2016-2018		
		2016	2017	2018	Dry mass, t·ha⁻¹	Crude protein, t·ha⁻¹	The share of lupine in the crop, %
1	2	3	4	5	6	7	8
Seed oats, 80 (50) + white lupine, 150 (50)	Without fertilisers	3.04	2.28	3.19	2.84	0.41	55
	$N_{45}P_{30}K_{50}$	4.68	3.51	4.91	4.37	0.68	52
	$P_{30}K_{50}$	4.26	3.20	4.47	3.98	0.59	57
	Humigran	3.88	2.91	4.07	3.62	0.58	56
Seed oats, 120 (75) + white lupine, 75 (25)	Without fertilisers	2.89	2.17	3.03	2.70	0.37	43
	$N_{45}P_{30}K_{50}$	4.52	3.39	4.75	4.22	0.64	41
	$P_{30}K_{50}$	4.02	3.02	4.22	3.75	0.54	44
	Humigran	3.71	2.78	3.90	3.46	0.54	43
Maize, 70 (100)	Without fertilisers	5.21	3.91	5.47	4.86	0.53	–
	$N_{45}P_{30}K_{50}$	9.00	6.75	9.45	8.40	1.02	–
	$P_{30}K_{50}$	6.36	4.77	6.68	5.94	0.68	–
	Humigran	6.87	5.15	7.21	6.41	0.81	–
Maize, 35 (50) + white lupine, 150 (50) – strip sowing*	Without fertilisers	5.03	3.77	5.28	4.69	0.76	43
	$N_{45}P_{30}K_{50}$	7.70	5.78	8.09	7.19	1.19	40
	$P_{30}K_{50}$	6.26	4.70	6.57	5.84	0.93	44
	Humigran	6.29	4.72	6.60	5.87	0.95	44
Maize, 17.5 (25) + white lupine, 225 (75)	Without fertilisers	5.00	3.75	5.25	4.67	0.85	42
	$N_{45}P_{30}K_{50}$	8.33	6.25	8.75	7.78	1.51	38
	$P_{30}K_{50}$	6.00	4.50	6.30	5.60	1.04	45
	Humigran	6.35	4.76	6.67	5.93	1.18	45
Maize, 35 (50) + white lupine, 150 (50)	Without fertilisers	4.70	3.53	4.94	4.39	0.72	36
	$N_{45}P_{30}K_{50}$	8.02	6.02	8.42	7.49	1.32	33
	$P_{30}K_{50}$	5.67	4.25	5.95	5.29	0.89	38
	Humigran	6.01	4.51	6.31	5.61	1.01	38
Maize, 52.5 (75) + white lupine, 75 (25)	Without fertilisers	4.51	3.38	4.74	4.21	0.67	30
	$N_{45}P_{30}K_{50}$	7.69	5.77	8.07	7.18	1.24	27
	$P_{30}K_{50}$	5.53	4.15	5.81	5.16	0.86	31
	Humigran	5.68	4.26	5.96	5.30	0.95	30
Sudanese sorghum, 30 (100)	Without fertilisers	3.40	2.55	3.57	3.17	0.28	–
	$N_{45}P_{30}K_{50}$	6.83	5.12	7.17	6.37	0.64	–
	$P_{30}K_{50}$	4.00	3.00	4.20	3.73	0.35	–
	Humigran	4.33	3.25	4.55	4.04	0.43	–
Sudanese sorghum, 15 (50) + white lupine, 150 (50) – strip sowing*	Without fertilisers	3.72	2.79	3.91	3.47	0.53	53
	$N_{45}P_{30}K_{50}$	6.58	4.94	6.91	6.14	1.02	50
	$P_{30}K_{50}$	4.57	3.43	4.80	4.27	0.68	54
	Humigran	4.55	3.41	4.78	4.25	0.69	54
Sudanese sorghum, 7.5 (25) + white lupine, 225 (75)	Without fertilisers	3.68	2.76	3.86	3.43	0.55	52
	$N_{45}P_{30}K_{50}$	6.34	4.76	6.66	5.92	1.02	48
	$P_{30}K_{50}$	4.33	3.25	4.55	4.04	0.66	55
	Humigran	5.01	3.76	5.26	4.68	0.83	55
Sudanese sorghum, 15 (50) + white lupine, 150 (50)	Without fertilisers	3.69	2.77	3.87	3.44	0.52	46
	$N_{45}P_{30}K_{50}$	6.00	4.50	6.30	5.60	0.92	43
	$P_{30}K_{50}$	4.01	3.01	4.21	3.74	0.59	48
	Humigran	4.73	3.55	4.97	4.42	0.75	48
Sudanese sorghum, 22.5 (75) + white lupine, 75 (25)	Without fertilisers	3.68	2.76	3.86	3.43	0.49	40
	$N_{45}P_{30}K_{50}$	6.35	4.76	6.67	5.93	0.92	37
	$P_{30}K_{50}$	4.34	3.26	4.56	4.05	0.60	41
	Humigran	5.00	3.75	5.25	4.67	0.70	40
LSD_{05}, by factors							
Sward		0.27	0.22	0.29	0.26		
Fertilizer		0.23	0.20	0.25	0.23		
Share of factors, %							
Sward		59	61	63	61		
Fertilizer		41	39	37	39		

Note. ** Strip sowing method with a strip width of 1.5 m. On the remaining agrocenoses, there was a continuous sowing of components in one row with row spacing of 0.15 m*
Source*: compiled by the authors*

Compared with single-species agrocenoses of cereal crops, the productivity of fodder biomass of lupine-oat mixtures increased from 1.90 t/ha to 2.70-3.21 t·ha^{-1} of dry weight or by 1.4-1.7 times, and of lupine-sorghum – from 3.17 to 3.43-3.47 t·ha^{-1} or 1.1 times. The exception was the productivity of lupine-maize agrocenoses, which did not have an advantage over single-species maize sowing in terms of yield from 1 ha of dry mass. However, in terms of yield from 1 ha of crude protein, lupine-maize agrocenoses prevailed over one-species sowing of maize by 1.3-1.6 times.

According to these data, the best ratio of the cereal component to the legume in the continuous row method of sowing the mixture was 25:75% of the sowing rate in single-species sowing, when the productivity of dry biomass was the highest upon growing white lupine with seeded oats and maize. With this ratio, the productivity of 1 ha of dry biomass and crude protein of these lupine-cereal mixtures increased by 1.1-1.3 times compared to the ratio of cereal to legume component as 75:25%. With the ratio of these components as 50:50%, the productivity of these coenoses occupied an intermediate position. In lupine-sorghum mixtures, an increase in the proportion of the legume component in the ratio during sowing considerably increased productivity in terms of the yield of crude protein from 1 ha.

For the ratio of the cereal component to the leguminous component at 25:75%, the share of white lupine in the harvest was the largest, which varied between 65-69% in the lupine-oat agrocenosis, 38-45% in lupine-maize, and 48-55% in lupine-sorghum, which is 12-26% more than for a ratio of 75:25%. The largest share of the legume component in the harvest was in lupine-oat mixtures, and the smallest – in lupine-maize mixtures.

According to these data, the method of sowing (strip method with a strip width of 1.5 m with alternating placement and continuous sowing in one row of cereal and leguminous components with a ratio of 50:50% of leguminous-cereal mixtures had little effect on the productivity of the fodder agrophytocenoses under study. In most cases, there was a tendency to prefer strip agrocenosis over continuous agrocenosis when growing in compatible lupine crops with oats and maize.

According to the data of this study, the share of the leguminous component in lupine-cereal mixtures decreased by 3-7% from the introduction of N_{45} against the background of $P_{30}K_{50}$. Compared to the option without fertilizers, the most significant (1.3-2.0 times) increase in the productivity of all fodder agrocenoses under study was provided by the application of $N_{45}P_{30}K_{50}$, while the application of $P_{30}K_{50}$ or organic fertilizer humigran at a dose of 250 kg/ha – only by 1.2-1.3 times.

According to these data, the cultivation of cereal crops in mixtures with white lupine, in comparison with single-species sowing of cereal crops in the variant without fertilization, increased the content of crude protein in dry fodder biomass from 8.6-11.1 to 14.0-18.1 or by 5.4-7.0% (Table 3). At the same time, the content of protein and crude fat increased and the content of crude fibre and nitrogen-free extractive substances (NFES) decreased, as well as the digestibility of the dry weight of the feed improved, which increased from 47-54% to 57-61% or by 7-10%. With an increase in the amount of the leguminous component in fodder agrocenoses, the content of crude protein and protein in the dry biomass increased and the content of crude fibre and NFES decreased, as well as the digestibility of the dry mass *in vitro improved*. The highest content of crude protein and protein was characterized by a single-species sowing of white lupine, where they accumulated 19.5% and 17.0% in the dry mass in the version without fertilizers, respectively. Among the fertilizers, the application of $N_{45}P_{30}K_{50}$ had the greatest effect on the accumulation of crude protein and protein. The amount of crude protein in the dry mass of fodder in this case increased by 1.1-1.3% compared to the option without fertilizers.

Table 3. *Chemical composition of mixtures of annual cereal fodder crops with white lupine depending on the ratio and methods of placement of components during sowing, % in dry weight (average for 2016-2018)*

Crops and their mixtures, seeding rate, kg·ha^{-1} (%)	Fertilizer options	Crude protein	Protein	Crude fat	Crude fibre	NFES	Digestibility
		3	4	5	6	7	8
White lupine, 300 (100)	Without fertilisers	19.5	17.0	3.5	23.9	45.9	67
	$N_{45}P_{30}K_{50}$	20.7	18.8	3.1	22.7	46.7	68
	$P_{30}K_{50}$	20.2	18.3	3.0	22.8	47.1	67
	Humigran	20.5	18.5	3.3	22.0	46.3	69
Seed oats, 160 (100)	Without fertilisers	8.6	7.8	3.0	31.0	51.1	47
	$N_{45}P_{30}K_{50}$	9.6	8.6	2.6	28.6	52.2	48
	$P_{30}K_{50}$	8.8	7.8	2.7	28.8	52.7	48
	Humigran	10.1	8.9	2.7	28.5	51.3	49
Seed oats, 80 (50) + White lupine, 150 (50) – strip sowing	Without fertilisers	14.0	12.8	3.3	27.0	48.5	57
	$N_{45}P_{30}K_{50}$	15.1	13.6	2.9	25.7	49.5	58
	$P_{30}K_{50}$	14.6	13.1	2.9	25.8	49.9	59
	Humigran	14.9	13.3	3.0	25.3	48.8	59

Table 3, Continued

Crops and their mixtures, seeding rate, kg·ha⁻¹ (%)	Fertilizer options	Crude protein	Protein	Crude fat	Crude fibre	NFES	Digestibility
		3	4	5	6	7	8
Seed oats, 40 (25) + white lupine, 225 (75)	Without fertilisers	14.5	13.3	3.1	24.6	46.9	64
	$N_{45}P_{30}K_{50}$	15.8	14.1	3.0	23.2	47.6	66
	$P_{30}K_{50}$	15.0	13.6	3.1	23.5	47.8	65
	Humigran	16.3	14.8	3.1	22.9	47.1	67
Seed oats, 80 (50) + white lupine, 150 (50)	Without fertilisers	14.6	13.4	3.3	26.8	45.0	64
	$N_{45}P_{30}K_{50}$	15.9	14.2	3.2	25.4	45.7	65
	$P_{30}K_{50}$	15.1	13.7	3.1	25.6	46.2	65
	Humigran	16.4	14.9	3.3	25.1	45.2	66
Seed oats, 120 (75) + white lupine, 75 (25)	Without fertilisers	14.1	13.3	3.3	24.9	47.1	64
	$N_{45}P_{30}K_{50}$	15.4	14.1	3.3	23.6	47.6	65
	$P_{30}K_{50}$	14.6	13.6	3.3	23.8	48.0	64
	Humigran	15.9	14.8	3.0	23.2	47.6	66
Maize, 70 (100)	Without fertilisers	11.1	10.4	3.4	26.8	49.3	54
	$N_{45}P_{30}K_{50}$	12.4	10.2	3.1	25.9	49.8	55
	$P_{30}K_{50}$	11.6	9.7	3.2	26.0	50.1	55
	Humigran	12.9	10.9	3.1	25.5	49.4	56
Maize, 35 (50) + white lupine, 150 (50) – strip sowing	Without fertilisers	16.3	14.7	3.5	25.4	47.6	61
	$N_{45}P_{30}K_{50}$	16.6	14.5	3.1	24.3	48.3	62
	$P_{30}K_{50}$	15.9	14.0	3.1	24.4	48.6	61
	Humigran	16.2	14.2	3.2	23.8	47.9	63
Maize, 17.5 (25) + white lupine, 225 (75)	Without fertilisers	18.1	16.6	3.7	24.8	42.2	71
	$N_{45}P_{30}K_{50}$	19.4	17.4	3.6	23.6	42.8	72
	$P_{30}K_{50}$	18.6	16.9	3.5	23.8	43.3	72
	Humigran	19.9	18.1	3.4	23.2	42.7	73
Maize, 35 (50) + white lupine, 150 (50)	Without fertilisers	16.6	14.4	3.8	25.9	42.8	69
	$N_{45}P_{30}K_{50}$	17.9	16.2	3.6	24.9	43.2	70
	$P_{30}K_{50}$	17.1	15.7	3.4	25.1	43.8	69
	Humigran	18.4	16.9	3.5	24.5	43.0	71
Maize, 52.5 (75) + white lupine, 75 (25)	Without fertilisers	16.0	14.5	3.6	22.9	46.6	67
	$N_{45}P_{30}K_{50}$	17.3	15.3	3.8	21.6	47.0	69
	$P_{30}K_{50}$	16.6	14.9	3.7	21.8	47.4	68
	Humigran	17.9	16.1	3.6	21.1	46.9	69
Sudanese sorghum, 30 (100)	Without fertilisers	9.0	7.5	3.0	28.0	52.2	48
	$N_{45}P_{30}K_{50}$	10.3	9.3	2.9	27.8	51.7	49
	$P_{30}K_{50}$	9.5	8.8	3.0	28.0	52.0	49
	Humigran	10.8	10.0	3.0	27.4	51.3	50
Sudanese sorghum, 15 (50) + white lupine, 150 (50) (strip sowing)	Without fertilisers	15.3	13.3	3.3	24.0	49.1	58
	$N_{45}P_{30}K_{50}$	16.6	14.1	3.1	25.3	49.2	59
	$P_{30}K_{50}$	15.9	13.6	3.0	25.4	49.6	58
	Humigran	16.2	14.8	3.2	24.7	48.8	60
Sudanese sorghum, 7.5 (25) + white lupine, 225 (75)	Without fertilisers	16.2	14.5	3.1	24.6	45.1	68
	$N_{45}P_{30}K_{50}$	17.5	15.3	3.1	23.1	45.8	69
	$P_{30}K_{50}$	16.7	14.8	2.9	23.2	46.4	69
	Humigran	18.0	16.0	3.4	22.8	45.0	70
Sudanese sorghum, 15 (50) + white lupine, 150 (50)	Without fertilisers	15.5	14.4	3.2	24.9	45.7	67
	$N_{45}P_{30}K_{50}$	16.8	15.2	3.2	23.5	46.3	68
	$P_{30}K_{50}$	16.0	14.7	3.1	23.6	46.9	67
	Humigran	17.3	15.9	3.3	23.2	45.8	69
Sudanese sorghum, 22.5 (75) + white lupine, 75 (25)	Without fertilisers	14.2	12.6	3.0	29.8	47.8	52
	$N_{45}P_{30}K_{50}$	15.5	13.4	2.5	28.6	48.8	53
	$P_{30}K_{50}$	14.7	12.9	2.8	28.7	48.9	52
	Humigran	14.9	13.0	2.9	28.1	48.1	54
Zootechnical norm		14	–	3.5	25-30	–	50-70
LSD_{05}, by factors							
Sward		0.6	0.5	0.2	1.1	1.5	2
Fertilizer		0.5	0.4	0.2	1.0	1.2	2

***Source**: compiled by the authors*

Thus, the patterns of changes in the specific features of the formation of the botanical composition and fodder productivity of lupine-cereal agrophytocenoses, as well as indicators of the chemical composition and digestibility of dry biomass *in vitro*, which were obtained under the researched factors and presented in this paper, confirm the results of earlier studies by various authors. The presented study confirmed the experimental data obtained by Kurgak & Karbivska (2020), as well as Kovtun *et al.* (2020) that the inclusion of leguminous grasses in grass mixtures of perennial and annual crops increases their productivity.

The studies conducted by Ratoshniuk (2020), Holodna (2018) and Holodna & Stolyar (2018) indicate that a prominent positive effect is ensured by inclusion of white lupine in leguminous-cereal mixtures involving seed oats or maize or Sudanese sorghum because white lupine acts as a source of cheap symbiotic nitrogen, provides not only an elevated yield of green mass and hay, but also enriches the fodder with protein, vitamins, amino acids, etc.

Previous studies by Hetman *et al.* (2019), Senyk (2020, 2021) and Kurhak *et al.* (2020) found that the productivity of legume-cereal agrocenoses increases with an increase in the share of the legume component, the amount of which can be adjusted by increasing its share in grass mixtures. This is conditioned upon the fact that, according to these authors, the optimal ratio of legumes and cereals, both in early- and late-maturing mixtures, contributes to more efficient use of moisture, photosynthetically active radiation, soil nutrients, etc.

The study by Senyk (2020) proved that when growing grass mixtures of seeded oats with seeded peas, the highest productivity (7.26 t·ha^{-1} of dry matter) is provided by the ratio of 75% leguminous and 25% cereal components from the norm of sowing seeds in single-species sowing combined with the use of other intensification factors, including fertilizers.

Not only Ukrainian researchers, namely Kurhak *et al.* (2020) and Demidas & Prorochenko (2018), as well as foreign scientists (Hannaway *et al.*, 2018) note that in the conditions of a substantial increase in the cost of mineral nitrogen, the maximum possible use of elements of biologization of feed production due to the increase in the efficiency of the use of symbiotic nitrogen of the best fodder legumes cultures has no alternative. This makes it possible to obtain high productivity (6-8 t·ha^{-1} of dry fodder biomass and more) of fodder land, save 50-300 kg·ha^{-1} of mineral nitrogen, preserve and increase soil fertility, preserve the environment, and produce organic fodder raw materials.

According to Petrychenko *et al.* (2018, 2020), cereal mixtures are inferior in productivity to legumes and cereals. The increase in the yield of green mass on legume-cereal grass mixtures in comparison with cereals on average over the years of research is 6.27 t/ha.

Slyusar (2017) and Slyusar & Oksymets (2018) noted that in the conditions of increasing aridity of the climate, it is advisable to expand the crops of not only perennial, but also annual fodder crops when growing them in mixtures with legumes. Such agrophytocenoses make better use of ecological niches and do not react so sharply with productivity to air drought and lack of moisture in the upper soil layer.

Kurhak *et al.* (2020) and Senyk (2020) proved that the use of leguminous grasses as components of legume-cereal grass mixtures not only increases the productivity of forage land, but also improves the quality of fodder. In comparison with cereal herbage, in this case, the dry mass of feed increases the content of crude protein by 5-9%. At the same time, the amount of protein increases and its amino acid composition improves, primarily in terms of the content of essential amino acids, specifically, the amount of lysine increases, which is quite enough for balanced feeding of cattle. Thanks to legume components in the fodder, the concentration of metabolic energy increases and the content of crude fibre decreases, as well as the digestibility of dry mass improves. At the same time, the mineral composition of the fodder improves, due to an increase in the content of calcium and magnesium and some trace elements.

CONCLUSIONS

On the dark gray soils of the Forest Steppe of Ukraine, the fodder productivity of single-species (white lupine, seed oats, maize, and Sudanese sorghum) and lupine-cereal binary combined crops with different ratios and placement of components when sowing under different options on a background without fertilizers ranges within 1.90-4.86 t·ha^{-1}t/ha of dry matter (mass) and 0.16-0.85 t·ha^{-1} of crude protein.

The highest productivity (on the background without fertilizers, 4.21-4.86 t·ha^{-1} of dry matter) is characterized by maize and white lupine in single-species sowing, as well as their combined sowing under continuous row and strip sowing methods. Oats and its mixtures with white lupine in terms of productivity are superior by 2.60-317 t·ha^{-1} of dry matter or by 1.8-2.6 times, and Sudanese sorghum in single-species sowing and its mixture with white lupine – by 1.13-1.58 t·ha^{-1} or 1.4-1.5 times. In comparison with single-species agrocenoses of cereals, the productivity of fodder biomass of lupine-oat mixtures increased by 1.4-1.7 times and lupine-sorghum mixtures – by 1.1 times.

The best ratio of the cereal component to the legume (white lupine) in the continuous row method of sowing the mixture is 25:75% of the sowing rate in single-species crops, when the productivity of dry biomass is the greatest. Compared to the option without fertilizers, the most significant (1.3-2.0 times) increase in the productivity of all fodder agrocenoses under study is provided by the application of $N_{45}P_{30}K_{50}$, while the application of $P_{30}K_{50}$ or organic fertilizer humigran at a dose of 250 kg/ha – only by 1.2-1.3 times.

Cultivation of cereals in mixtures with white lupine in comparison with single-species crops of cereals in the version without fertilization increases the content of crude protein in dry fodder biomass by 5.6-8.0%. At the same time, the content of protein and crude fat increases and the content of crude fibre and nitrogen-free extractive substances (NFES) decreases, as well as the digestibility of the dry weight of the feed improves, which increased from 47-54% to 57-61% or by 7-10%.

Research into ways to increase the efficiency of using cheap symbiotic nitrogen in leguminous crops in fodder production by enriching cereal phytocenoses with them, involving a larger number of species of this family, has the prospect of continuing in different soil and climatic conditions of Ukraine. This will contribute not only to increasing the production of cheap grass fodder and improving its quality, but also to reducing energy and money costs, reducing environmental pollution with nitrogen fertilizers and improving soil fertility, and on this basis, strengthening the fodder base of Ukrainian livestock breeding.

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CONFLICT OF INTEREST

None.

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Кормова продуктивність сумісних посівів вівса посівного, кукурудзи і сорго суданського з люпином білим

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Анотація. Досліджень, спрямованих на накопичення та ефективне використання азоту симбіотичної його фіксації з повітря рослинами люпину білого, шляхом добору кращих злакових компонентів, оптимізації їх співвідношення та способів розміщення при вирощуванні у сумісних посівах з ним за різних систем удобрення в Лісостепу ще не проведено. Мета – встановити кращі злакові компоненти, їх співвідношення та способи розміщення з люпином білим при сівбі в сумісних посівах за різних систем удобрення для виробництва трав'яних кормів в Лісостепу України. Було використано наступні методи: польовий, лабораторний, математико-статистичний, розрахунково-порівняльний. Було встановлено, що найбільшу продуктивність на фоні без добрив (4,21-4,86 $t \cdot ha^{-1}$ сухої речовини) забезпечили одновидові посіви кукурудзи та люпину білого, а також їх сумісні посіви, які сформовано суцільним рядовим та смуговим способами, що на 2,60-3,17 $t \cdot ha^{-1}$ сухої речовини або в 1,8-2,6 рази більше порівняно з посівами вівса та його суміші з білим люпином і на 1,13-1,58 $t \cdot ha^{-1}$ або в 1,4-1,5 рази більше в порівнянні з посівами сорго суданського і його суміші з білим люпином. За рахунок накопичення та використання азоту симбіотичної фіксації продуктивність люпино-вівсяних сумішей збільшилася від 1,90 до 2,70-3,21 $t \cdot ha^{-1}$ сухої маси або в 1,4-1,7 рази, а люпино-соргових – від 3,17 до 3,43-3,47 або в 1,1 рази. Найбільш ефективним співвідношенням кожного злакового компонента до бобового в бінарних сумісних посівах було як 25:75 % від норми висіву в одновидових агроценозах, коли продуктивність сухої біомаси була найбільшою. Порівняно з варіантом без добрив найбільш суттєво (в 1,3-2,0 рази) збільшення продуктивності всіх досліджуваних кормових агроценозів забезпечило внесення $N_{45}P_{30}K_{50}$, тим часом як внесення $P_{30}K_{50}$ чи органічного добрива гумігран у дозі 250 $kg \cdot ha^{-1}$ – лише у 1,2-1,3 рази. Результати досліджень можуть бути використані при розробленні науково-методичних рекомендацій та навчальному процесі стосовно формування високопродуктивних агрофітоценозів з метою конвеєрного виробництва якісних трав'яних кормів для годівлі тварин

Ключові слова: агроценози суцільні та смугові; мінеральні та органічні добрива; однорічні злакові культури; сирий протеїн; сумісні та одновидові посіви; суха маса; трав'яні корми