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Productivity and forage quality of smooth brome and alfalfa in monocultures and crop mixture in semiarid climate

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Abstract. Perennial grasses are vital for livestock feed and play a critical role in maintaining and enhancing soil fertility. This study evaluated the productivity of perennial grasses, specifically alfalfa (*Medicago sativa* L.) and smooth brome (*Bromus inermis* Leyss.), grown as monocultures and in a binary mixture, under rainfed conditions in a semiarid climate on dark-chestnut soil. The research aimed to elucidate the dynamics of formation of forage yield across multiple years of cultivation. The study was performed in the field trials with randomized design in four repetitions; the outcomes were analyzed through common analysis of variance with estimation of the Fisher's least significant difference. The results revealed that the monocultures of smooth brome and alfalfa exhibited significantly lower yields (in terms of dry matter and feed units) compared with the alfalfa-brome mixture. Over the study period, the alfalfa's initial dominance in the mixture gradually declined, with smooth brome becoming the dominant species by the end of the cultivation cycle. The forage quality, assessed according to crude protein and fat content, was highest in the alfalfa monoculture and the alfalfa-brome mixture, whereas the smooth brome monoculture was inferior. Although the smooth brome monoculture provided the lowest yields of feed units and digestible protein, they contributed essential crude fiber in the mixture, which supports healthy digestion in cattle. The alfalfa-brome mixture extracted the highest amount of nitrogen from the soil but, due to alfalfa's nitrogen-fixing capacity, maintained sufficient nitrogen return to sustain soil fertility. By contrast, the smooth brome monoculture extracted the least nitrogen and did not contribute to soil nitrogen accumulation. The alfalfa monoculture exhibited the highest coefficient of nitrogen fixation, though the difference compared with the mixture was statistically non-significant. Consequently, the mixture of alfalfa and smooth brome, with varying dominance over the years of cultivation, enhances dark-chestnut soil fertility and provides balanced green fodder for cattle without requiring mineral nitrogen fertilizers or irrigation.

Keywords: *Bromus inermis*; feed units; *Medicago sativa*; nitrogen fixation; steppe zone; yield.

Introduction

Perennial grasses play a crucial role in modern agriculture, especially taking into account aggravation of global climate change and land degradation. Their deep root systems and year-round ground cover help reduce soil erosion, restore its fertility through carbon sequestration, making them effective tools for rehabilitating degraded and marginal lands, while supporting food security and ecosystem health, as well as reducing emission of carbon dioxide (Arije et al., 2024). Cultivating perennial grasses such as silvergrass (*Miscanthus giganteus*) and switchgrass (*Panicum virgatum*) on marginal or abandoned croplands can provide renewable bioenergy, deliver negative carbon emissions, while also increasing soil organic carbon content and reducing greenhouse gas emissions, compared with annual crops (Fernando et al., 2015; Carlsson et al., 2017; Iordan et al., 2023). These grasses also improve regional climates by cooling surface temperatures and increasing summer rainfall, which can enhance the productivity and resilience of other crops in the area (He et al., 2022; Zhang et al., 2024). Perennial grass systems require fewer external inputs such as fertilizers and pesticides, thus minimizing environmental impacts and supporting biodiversity (Mosier et al., 2021). Mixtures of perennial grass species, especially those including legumes, further enhance soil fertility through natural nitrogen fixation and contribute to higher humus production, which is vital for long-term soil health (Kobyrenko, 2023). In semiarid and Mediterranean regions, perennial grasses have shown significant potential to restore soil organic carbon and improve water retention, offering sustainable solutions for agriculture in water-limited environments, which is increasingly important considering current lack of freshwater for agricultural purposes (Ingrao et al., 2023). Overall, integrating perennial grasses into agricultural landscapes offers a multifunctional approach to climate change mitigation, reversing land degradation, and promoting sustainable, resilient food and energy systems.

Alfalfa (*Medicago sativa* L.) is a highly valued perennial legume, widely recognized for its exceptional role in fodder production and enhancement of soil fertility. Its high protein content and compatibility with perennial grasses make it a superior forage crop, providing balanced nutrition for livestock and supporting high yields, especially when grown in mixtures with grasses such as orchard grass or festulolium, which also improve silage quality and drought resilience (Samuil et al., 2015; Tucak et al., 2021; Holátko et al., 2024). Alfalfa's deep root system and the ability to fix atmospheric nitrogen not only reduce the need for synthetic fertilizers but also increase soil organic matter, improve soil structure, and enhance water retention, making it particularly beneficial for restoring degraded or low-fertile soils (Mussina et al., 2022; Xu et al., 2024). Studies show that introducing alfalfa into grass pastures boosts soil microbial biomass and fungal populations, which are key indicators of improved soil health (Bhandari et al., 2020). Alfalfa cultivation has been linked to significant increases in sequestration of soil organic carbon (SOC), especially in surface soils and over longer cultivation periods, contributing to climate change mitigation and long-term soil health improvement (Xu et al., 2024). Additionally, alfalfa's positive effect on the nitrogen balance in crop rotations leads to higher subsequent yields of crops and overall sustainability of the agroecosystem. Its resilience to environmental stresses, low input requirements, and ability to control soil erosion further underscore its ecological and economic importance (Mussina et al., 2022; Latif et al., 2023). Overall, integrating alfalfa into pasture systems and crop rotations is highly recommended for sustainable fodder production and soil fertility management.

Another valuable perennial grass is smooth brome (*Bromus inermis*). It is widely valued in agriculture for its high-quality fodder and its role in soil restoration. It is highly adaptable, tolerating drought, low temperatures, and salinity, which makes it suitable for diverse environments and resilient under challenging conditions. As a forage crop, smooth brome provides substantial biomass yields – up to 13 tons of dry matter per hectare –

and is recognized for its nutritional value for livestock, especially in hay and grazing systems (Kang et al., 2023; Mackiewicz-Walec et al., 2024). It produces high yields of green mass and hay on all types of soil except saline soil, but the most suitable for its cultivation are light chernozems, sandy loam, and sandy soils. After grazing animals or mowing for hay, under high precipitation, smooth brome grows back intensively and therefore is a valuable component for creating pastures and hayfields in all climatic zones of Ukraine. Two ecotypes of smooth brome have been introduced into cultuvation: meadow, or northern, and steppe, or southern. Compared with the meadow ecotype, the steppe ecotype has a deeply penetrating root system, which is why it is characterized by higher drought resistance during the summer growing season. Varieties of the meadow ecotype have higher demands for moisture, and withstand flooding for up to 40-45 days. The highest yields of green mass and hay are formed in the second or third years of vegetation. With timely fertilization – particularly nitrogen fertilizers – in monocultures and grass mixtures for haymaking, this ecotype can be maintained as part of mono- and polycultures for up to 10 years or more (Vozhehova et al., 2021). In soil restoration, *B. inermis* is effective at preventing erosion, improving soil structure, and enhancing fertility. Its deep, fibrous root system significantly increases soil shear strength and stability, even under changing moisture conditions (Saadati et al., 2023). In addition, its presence in agrophytocenoses also boosts the aboveground biomass and biodiversity, and it can sequester carbon, contributing to climate mitigation efforts (Zhang et al., 2020).

Achieving high productivity of smooth brome and alfalfa monocultures under long-term fertility restoration on degraded rainfed lands in the southern steppe zone, a region characterized by semiarid climate, necessitates a substantial presence of these species in the botanical composition of perennial grasses throughout their years of cultivation. The application of mineral fertilizers, particularly nitrogen, is crucial for maintaining highly productive plant species within grass mixtures over extended periods and for regulating the fodder quality of perennial cereals and legumes. However, imbalanced application of high doses of mineral nitrogen fertilizers can lead to an intensive growth and development of cereal components, consequently affecting the overall perennial grass stand. Smooth brome is widely utilized in both monocultures and as a component of legume-grass crop mixtures for fodder production and the establishment of various types of natural grazing lands across many countries.

The objectives of this study were to determine the productivity of smooth brome and alfalfa in monoultures and in a mixture, to understand the unique characteristics of their nutritional value formation, and to assess their potential effects on soil health when cultivated under the semiarid climatic conditions of the steppe zone.

Materials and methods

The field experiments were conducted from 2018 to 2020 at the State Enterprise Experimental Farm Kopani of the Institute of Irrigated Agriculture, National Academy of Agrarian Sciences of Ukraine. The field trials were repeated four times, and the study design was randomized.

The soil at the experimental site is classified as residual, slightly solonetzic, dark-chestnut soil. The agrochemical analysis indicated a slightly acidic soil solution reaction (pHKCl = 5.6–5.7). The organic carbon content, examined using the Tyurin's method, ranged 2.02–2.34% (FAO, 2021). The soil exhibited high availability of exchangeable potassium (330–413 mg/kg soil), and moderate levels of mobile phosphorus (24.2–36.3 mg/kg soil) and nitrate nitrogen (8.0–12.3 mg/kg soil). The humic horizon, with a depth of 30–35 cm, was characterized by a dark grey color with a brownish tint. The transitional illuvial horizon (B1), extending from 35 to 58 cm, was dark brown and exhibits a subangular blocky structure. The second transitional horizon (B2) transitions into the calcic illuvial horizon. The sum of adsorbed bases did not exceed 24.63–27.32 meq per 100 g of soil, and the base saturation reached 90.9–94.4%.

The study utilized alfalfa (*Medicago sativa*, Veselka cultivar) and smooth brome (*Bromus inermis*, Tavriiskyi cultivar). In the monocultures, the seeding rates were 20.0 kg/ha for smooth brome, and 22.0 kg/ha for alfalfa. For the alfalfa-brome mixture, the seeding rates were 14 kg/ha for brome and 12 kg/ha for alfalfa. The seeds were sown at a depth of 2.0–3.0 cm using a close-growing drilling method (Vozhehova et al., 2021). The trials were carried out using common agrotechnological practices in the conditions of natural humidification (without irrigation).

The yield measurement across the experimental plots was performed using the mowing method. The chemical composition of the air-dry samples of aboveground biomass was determined via spectrometry using an NIP Systems 4500 infrared analyzer. The output of feed units, gross energy, and metabolizable energy was calculated based on the chemical composition of the forages, incorporating digestibility coefficients and productive action of nutrients.

The feed units were calculated from the chemical analysis of the individual grass species and mixture. The gross and metabolizable energy was determined according to classic methodology (Dmitrochenko, 1978). The botanical composition of the sward was assessed by the gravimetric method. The sward density was determined annually in early spring on fixed 50×50 cm plots for each experimental variant, in two non-contiguous repetitions. The vertical distribution of aboveground biomass for different grass species and their mixture was determined before mowing from 0.25 m^2 quadrats.

The primary method used to quantify the atmospheric nitrogen fixed by the perennial legumes in our field experiments on dark-chestnut soil was a comparative method with smooth brome. This method assumes that under identical growing conditions, both plant species absorb the same amount of nitrogen from the soil. The observed difference in nitrogen uptake between the yields from alfalfa and smooth bromegrass, adjusted for seed nitrogen, was attributed to nitrogen fixed from the air by alfalfa. The plant nitrogen content was determined using the Kjeldahl's method (Sáez-Plaza et al., 2013).

The statistical analysis of the yield data was conducted in MS Excel spreadsheet processor add-in AgroStat through two-factor analysis of variance (ANOVA), including post-hoc Fisher's least significant difference (LSD) test at $P < 0.05$ (Agbangba et al., 2024). Standard deviation was estimated using common methodology based on within-variant deviations of the studied parameters by replications (Altman & Bland, 2005).

Results

Over the three-year study period, the average absolute yield of dry matter from the smooth brome monoculture in its first year of cultivation was 4.47 t/ha. For alfalfa, it was 5.36 t/ha, and for the alfalfa-brome mixture, 5.52 t/ha. Notably, a significant increase in absolute dry matter yield was observed in both alfalfa monoculture and alfalfa-brome mixtures compared with the smooth brome monoculture. This increase, regardless of the agrophytocenosis composition, ranged 0.89–1.05 t/ha, or 19.9–23.5%.

In the second year of cultivation, the absolute dry matter yield of the brome monoculture did not exceed 4.36 t/ha. Pure alfalfa yielded 4.90 t/ha, while the mixture of alfalfa and smooth brome produced 5.22 t/ha. Compared with smooth brome, the increase in absolute yield of dry matter from the alfalfa monoulture was 0.54 t/ha, or 12.4%, and in the alfalfa-brome mixture it was 1.16 t/ha, or 26.6% (Table 1).

By the third year of cultivation, the absolute yield of dry matter from the smooth brome monoculture reached 3.61 t/ha. The alfalfa monoculture yielded 4.15 t/ha, and the alfalfa-brome mixture produced 4.61 t/ha. The increase in dry matter yield of the alfalfa monoculture in the third year, compared with smooth brome, did not exceed 0.54 t/ha, while for the alfalfa-brome mixture it was 1.00 t/ha, or 27.7%. A significant increase in the absolute dry matter yield from both alfalfa monoculture and alfalfa-brome mixture was observed in the first and second years of cultivation compared with the third year.

The substantial decline in the absolute dry matter yield and productivity of the seeded perennial grass, particularly in the second and third years of cultivation, is primarily attributed to changes in the botanical species composition of the monocultures of alfalfa and smooth brome, as well as the mixture of alfalfa and smooth brome. The contribution of smooth brome to the total yield remained consistently high throughout all years of cultivation, reaching 75.5% in the first year, 81.9% in the second, and 85.7% in the third.

The botanical composition of the alfalfa-brome mixture exhibited notable shifts over the years. In the first year, alfalfa constituted no more than 55.2% of the total yield. This proportion declined significantly to 31.2% in the second year and further to 12.1% in the third year. Conversely, smooth brome, a component of this mixture, accounted for 40.9% of the total yield in the first year of cultivation. Its share increased to 51.2% in the second year and a substantial 74.0% in the third year. The proportion of volunteer palatable species within the sward did not exceed 3.9% in the first year, rising to 17.6% in the second year, and then decreasing slightly to 13.9% in the third year.

The changes observed in the absolute yield of dry matter from alfalfa, smooth brome, and the alfalfa-brome mixture, are attributed to shifts in their botanical composition. Alfalfa demonstrated strong competitive ability only during the first and second years of growing, comprising 81.3–83.3% and 59.9–61.5% of the botanical composition, respectively. Concurrently, the proportion of various unpalatable plants in the pure alfalfa monoculture did not exceed 18.2–39.5% of the total yield. The increase in these plants during the early spring period was primarily due to the annual weed *Capsella bursa-pastoris* L. (shepherd's-purse), which corroborates the general trend of decreasing alfalfa content and, conversely, an increasing share of the steppe ecotype of smooth brome over the years of cultivation.

Table 1
Average absolute dry matter yield of smooth brome, alfalfa, and alfalfa-brome mixture, average for three years of the study (n = 4)

Year of cultivation	Types of grasses	Yield, t/ha	Yield increase	
			t/ha	%
1st	smooth brome	4.47 ± 0.56^{a}	–	–
	alfalfa	5.36 ± 0.52^{b}	0.89	19.9
	alfalfa + smooth brome	5.52 ± 0.58^{b}	1.05	23.5
2nd	smooth brome	4.36 ± 0.34^{a}	–	–
	alfalfa	4.90 ± 0.34^{b}	0.54	12.4
	alfalfa + smooth brome	5.22 ± 0.22^{b}	1.16	26.6
3rd	smooth brome	3.61 ± 0.29^{a}	–	–
	alfalfa	4.15 ± 0.41^{b}	0.54	15.0
	alfalfa + smooth brome	4.61 ± 0.29^{c}	1.00	27.7

Note. Superscript letters (^{a}, ^{b}, ^{c}) indicate significant differences within each year for each parameter based on LSD_{05} values; means sharing the same letter are not significantly different (difference ≤ LSD); means with different letters are significantly different (difference > LSD).

By the third year of perennial grass cultivation, the relative amount of alfalfa in the botanical composition of the monoculture decreased to 13.6–14.7%. Correspondingly, the proportion of unpalatable plants (*Capsella bursa-pastoris* L.) increased to 85.3–86.3%. The decline in the alfalfa content was not substantially compensated, and in the first year of cultivation, it did not exceed 24.5% of the total yield, decreasing to 18.1% in the second year and 14.3% in the third.

Vertical distribution analysis of the above-ground biomass for the monocultures of alfalfa and brome and the mixture of alfalfa and brome was conducted at 10 cm height intervals, coinciding with the early heading stage of the grass component and the budding stage of alfalfa. This analysis revealed both commonalities and significant differences depending on the species and the combination of components. A general characteristic of the vertical distribution of phytomass across all types (alfalfa, smooth brome, and their mixture) was the concentration of biomass at heights of 20–30, 30–40, and 40–50 cm. These layers collectively contained 40.5–54.2% of the total stem and leaf biomass.

The monoculture of smooth brome, a typical rhizomatous grass with an erect growth habit, showed an increasing percentage of leaves only from 20–30 to 50–60 cm. The stem content, however, increased from 0–10 cm to 30–40 cm, reaching 11.3–14.8% of the total.

In the alfalfa monoculture, the leaf content at heights of 0–10 and 10–20 cm was relatively low, not exceeding 2.4–3.2%. The concentration of the aboveground biomass between 20 and 50 cm reached 53.4%, with the leaves accounting for 25.9% and the stems for 27.5%. Above 50–60 and 60–70 cm, the aboveground biomass content was also minimal, reaching only 15.5%, of which 10.9% was the leaves and only 4.7% was the stems. At a height of 60–70 cm, the relative proportions of leaves and stems became more balanced, with their share increasing to 0.92. A high share of stems, based on these indicators of biomass distribution, was also observed in the mixture of alfalfa and smooth brome, reaching 62.3%.

Achieving high yields of perennial legumes and cereal grasses under rainfed conditions hinges on high sward density. This is crucial for establishing a desirable botanical composition, promoting the dominance of valuable forage species while minimizing the presence of unwanted forbs. Therefore, establishing optimal sward density and ensuring high leafiness of the stems are vital for maximizing perennial grass yields across all agroclimatic zones of Ukraine.

The aboveground biomass was harvested differently based on precipitation levels. In years with adequate moisture (5% probability of low rainfall), two cuts were made during the spring-summer period. However, in years with average (50%), moderately dry (75%), or dry (95%) rainfall conditions, only a single cut was made. Prolonged drought in moderately dry (75%) and dry (95%) years, particularly during summer, significantly influenced the subsequent year's sward density.

In the first year of cultivation, the alfalfa monoculture exhibited a high density of 1,306 shoots/m^2. The share of rogue forbs was low, not exceeding 194 shoots/m^2, which accounted for no more than 14.8% of the total shoot count. The smooth brome monoculture in the first year of cultivation had a total shoot count of 1,588 shoots/m^2. Smooth brome itself constituted a high proportion of this density, reaching 1,435 shoots/m^2, or 90.4%. The share of various forbs in was minimal, accounting for only 153 shoots/m^2, or 9.6% of the total.

In the mixture of alfalfa and smooth brome, the total shoot count in the first year of cultivation was 1,573 shoots/m^2. Alfalfa contributed 1,010 shoots/m^2, representing 64.2% of the total density. Overall, the sward density during the second year of cultivation was the highest, reaching 1,544–1,667 shoots/m^2 regardless of the composition. A distinguishing feature of the mixture's density in the second year was a significant decrease in alfalfa's contribution and a partial increase in smooth bromegrass's presence within the sward.

Over the three-year study, the number of alfalfa shoots in the monoculture declined significantly. Compared with the first year, there was an average decrease of 35.3% in the second year and a dramatic 92.4% decrease in the third year. In the monoculture of smooth brome, the density of rogue forbs remained relatively stable in the second year compared with the first, ranging 152–186 shoots/m^2. The reduction in alfalfa's contribution to the alfalfa-smooth brome mixture in the second and third years, compared with the first, was substantial, ranging 44.3–88.7%.

The population of rogue plant species, particularly unpalatable species such as shepherd's purse (*Capsella bursa-pastoris* L.), significantly increased in the mixture of alfalfa and smooth brome during the second and third years of cultivation, growing by 71.2–115.0% compared with the alfalfa monoculture in their first year. This increase was most pronounced in alfalfa during the second and third years, where the density of forbs rose by 260.3–379.9% (to 505–737 shoots/m^2) compared with their initial count in the first year (Table 2). The changes in botanical composition of alfalfa, smooth brome, and their mixture over the years significantly affected both forage yield and nutritional quality. Consequently, the selection of appropriate perennial legume and grass species, as well as their combinations in mixtures, proved to be a critical determinant of their overall productivity and forage quality.

Table 2
Sward density depending on botanical composition and year of cultivation, average for three years of the study (n = 4)

Year of cultivation	Types of grasses	Total shoots/m^2	Including		
			smooth brome	alfalfa	rogue plant species
1st	smooth brome	$1{,}306 \pm 65^{b}$	–	1306 ± 44^{a}	194 ± 6^{a}
	Alfalfa	$1{,}588 \pm 70^{a}$	1435 ± 15^{a}	–	153 ± 8^{b}
	alfalfa + smooth brome	$1{,}573 \pm 63^{a}$	483 ± 8^{b}	1010 ± 6^{b}	80 ± 6^{c}
2nd	smooth brome	1544 ± 40^{b}	–	845 ± 18^{a}	699 ± 62^{a}
	Alfalfa	$1{,}667 \pm 37^{a}$	$1{,}515 \pm 2^{a}$	–	152 ± 6^{c}
	alfalfa + smooth brome	$1{,}659 \pm 35^{a}$	760 ± 6^{a}	727 ± 6^{b}	172 ± 6^{b}
3rd	smooth brome	$1{,}030 \pm 100^{c}$	–	99 ± 7^{b}	931 ± 83^{a}
	alfalfa	$1{,}434 \pm 122^{a}$	$1{,}248 \pm 37^{a}$	–	186 ± 6^{c}
	alfalfa + smooth brome	$1{,}333 \pm 110^{b}$	$1{,}048 \pm 7^{a}$	148 ± 7^{b}	137 ± 6^{c}

Note. See Table 1.

When livestock are fed diets lacking balance in essential organic compounds and mineral composition, particularly digestible protein, there is a significant increase in feed consumption per unit of livestock products compared with recommended feeding standards, leading to reduced animal productivity. The nutritional value of forage is not constant; it fluctuates throughout the growing season and is influenced by the species composition of legume-grass mixtures. For instance, the content of crude protein content in the alfalfa monoculture during the first year of cultivation averaged 23.5% of the absolute dry matter over three years of the study (Table 3).

Table 3

Chemical composition of alfalfa, smooth brome, and the alfalfa-brome mixture (% of the absolute dry matter, average for three years of the study, n = 4)

Year of cultivation	Types of grasses	Crude protein	Fat	Crude fiber	Crude ash	Nitrogen-free extractives (NFE)	Content in 1 kg of dry matter		
							forage units, kg	gross energy, MJ	metabolizable energy, MJ
1st	alfalfa	23.53 ± 3.41^{a}	4.87 ± 0.60^{a}	22.81 ± 2.01^{a}	9.72 ± 0.10^{b}	39.07 ± 1.89^{b}	0.72 ± 0.01^{a}	18.97 ± 0.35^{a}	10.84 ± 0.19^{a}
	smooth brome	17.54 ± 3.38^{b}	3.88 ± 0.57^{c}	26.57 ± 2.11^{b}	9.92 ± 0.15^{a}	42.09 ± 1.95^{a}	0.70 ± 0.01^{b}	18.42 ± 0.34^{b}	10.53 ± 0.15^{b}
	alfalfa + smooth brome	22.99 ± 3.40^{a}	5.08 ± 0.62^{a}	23.29 ± 2.05^{a}	9.81 ± 0.13^{ab}	38.83 ± 1.84^{b}	0.76 ± 0.03^{a}	18.98 ± 0.34^{a}	10.85 ± 0.19^{a}
2nd	alfalfa	23.44 ± 2.05^{a}	2.66 ± 0.17^{b}	30.62 ± 1.38^{ab}	11.38 ± 0.30^{a}	31.90 ± 3.02^{c}	0.67 ± 0.08^{a}	18.23 ± 0.04^{ab}	10.42 ± 0.03^{ab}
	smooth brome	16.65 ± 1.98^{c}	3.42 ± 0.22^{a}	32.19 ± 1.44^{a}	10.90 ± 0.27^{b}	36.84 ± 3.09^{a}	0.54 ± 0.03^{c}	18.23 ± 0.03^{ab}	10.42 ± 0.03^{ab}
	alfalfa + smooth brome	20.20 ± 2.03^{b}	3.11 ± 0.19^{a}	28.41 ± 1.35^{b}	10.89 ± 0.31^{b}	37.12 ± 3.21^{a}	0.63 ± 0.06^{b}	18.30 ± 0.07^{a}	10.46 ± 0.06^{a}
3rd	alfalfa	22.63 ± 1.62^{a}	3.39 ± 0.12^{b}	32.59 ± 1.72^{a}	12.22 ± 0.91^{a}	29.17 ± 0.79^{c}	0.63 ± 0.03^{a}	18.39 ± 0.13^{a}	10.51 ± 0.07^{a}
	smooth brome	17.20 ± 1.51^{c}	3.20 ± 0.10^{b}	32.48 ± 1.71^{a}	11.07 ± 0.87^{b}	36.05 ± 0.89^{a}	0.59 ± 0.01^{b}	18.20 ± 0.11^{b}	10.40 ± 0.05^{b}
	alfalfa + smooth brome	20.17 ± 1.54^{b}	3.95 ± 0.18^{a}	31.57 ± 1.74^{a}	9.68 ± 0.82^{c}	34.63 ± 0.90^{b}	0.62 ± 0.02^{ab}	18.61 ± 0.12^{a}	10.64 ± 0.09^{a}

Note. See Table 1.

Fat plays a crucial role in cattle nutrition, as its oxidation in the animal's body releases approximately 9.3–9.5 kcal per gram, compared with 4.1 kcal from protein and carbohydrates. Optimal fat content in feed, especially with a high concentration of saturated fatty acids such as oleic, linoleic, and linolenic acids, positively impacts pregnancy, lactation, and growth in all animal species. In our study, the crude fat content in both perennial legume and cereal grass monocultures, and in the legume-grass mixture in the first year of cultivation, was high, ranging 3.88–5.08% of the absolute dry matter.

Crude fiber content is another critical indicator of forage quality. A high level of crude fiber in feed promotes intensive synthesis of low-molecular-weight fatty acids (acetic, propionic, butyric), which are primary determinants of milk fat in animals. A characteristic feature of crude fiber in green bulky forages is its high digestibility, as cellulose lignification in most forage plants occurs primarily in later developmental stages, with minimal lignification during active plant growth. The optimal fiber content in feed is generally 18–24% of the absolute dry matter (Vozhehova et al., 2021). In our field trials, the crude fiber content across all treatments, irrespective of the year of cultivation, generally fell within optimal ranges. However, significant deviations were observed during the second and third years of cultivation: crude fiber accounted for 30.6–32.6% and 30.6–32.6% of the absolute dry matter in the alfalfa and brome monocultures, respectively. In the mixture of alfalfa and brome, the content of crude fiber was within the maximum permissible range, at 28.4–31.6% of the absolute dry matter. Regarding nitrogen-free extractives (NFE), there are no universally established feeding standards for animals in Ukraine and most other countries. Nevertheless, NFE is a significant energy source in feed, with its content reaching up to 40–50% per kilogram of dry matter. The breakdown of 1 gram of NFE yields 3–4 kcal of energy. In alfalfa, the NFE content ranged 29.2–39.1%, and in smooth brome it was 36.1–42.1% of the absolute dry matter, irrespective of the year of cultivation. The NFE content in the alfalfa-brome mixture reached 34.6–38.8% of the absolute dry matter.

In livestock feeding practices, the mineral composition of feed significantly influences metabolism and animal productivity. Imbalances in mineral content within rations lead to increased feed consumption, and severe deficiencies can result in diseases such as osteomalacia and hypomagnesemia (Rahman et al., 2022). Our studies into crude ash content revealed it to be within optimally permissible limits. It ranged 9.9–11.1% in smooth brome, 9.7–12.2% in alfalfa, and 9.8–10.9% in the alfalfa-brome mixture, all expressed as a percentage of absolute dry matter. Across the study years, the dry matter of forages from the first, second, and third years of cultivation exhibited high levels of nitrogen (2.81–3.79%) and potassium (2.13–2.23%), but low content of phosphorus (0.49–0.50%).

Due to the high mineral nutrient content in the harvested yield, the nutriaent uptake by alfalfa was as follows: nitrogen – 179 kg/ha, phosphorus – 23 kg/ha, and potassium – 112 kg/ha. The nutrient uptake per unit of absolute dry matter yield of smooth brome in its first year of cultivation was also substantial: nitrogen – 119 kg/ha, phosphorus – 21 kg/ha, and potassium – 90 kg/ha. The nitrogen uptake by the by alfalfa-brome mixture ranged 166–224 kg/ha, phosphorus 23–33 kg/ha, and potassium 111–138 kg/ha. The content of main organic compounds in alfalfa, irrespective of the year of cultivation, was: crude protein – 22.6–23.5%, crude fat – 2.7–4.9%, crude fiber – 22.8–32.6%, crude ash – 9.7–12.2%, and NFE – 29.2–39.1% of absolute dry matter. The gross energy concentration in 1 kg of dry matter of the alfalfa monoculture reached 18.23–18.97 MJ, and that of metabolizable energy was 10.42–10.84 MJ. In smooth brome, the crude protein content did not exceed 16.7–17.5% of absolute dry matter. Crude fiber ranged 26.6 to 32.5%, crude fat 3.2 to 3.9%, crude ash 9.9 to 11.1%, and nitrogen-free extractives 36.1 to 42.1%. The feed unit content per 1 kg of absolute dry matter significantly depended on the botanical species composition in the monocultures and their mixture. In the alfalfa monoculture, irrespective of the year of cultivation, it ranged 0.67–0.72 kg. In the smooth brome monoculture, the feed unit content per 1 kg of dry matter decreased to 0.54–0.70 kg. In the alfalfa-brome mixture, irrespective of the year of cultivation, the content of the main organic compounds and metabolizable energy was sufficiently high: crude protein – 20.2–23.0%; crude fat – 3.1–5.1%; crude fiber – 23.3–31.6%; crude ash – 9.7–10.9%; and nitrogen-free extractives – 34.6–38.8% of absolute dry matter. The gross energy concentration per 1 kg of dry matter in the mixture of alfalfa and smooth brome did not exceed 18.30–18.98 MJ, with metabolizable energy reaching 10.46–10.85 MJ.

The total yield of feed units from the alfalfa monoculture in the first year of cultivation averaged up to 3.86 t/ha, digestible protein up to 0.97 t/ha, and metabolizable energy up to 57.8 GJ/ha. In the second year, these figures were 3.38 t/ha, 0.84 t/ha, and 50.6 GJ/ha, respectively, and in the third year, 2.93 t/ha, 0.89 t/ha, and 54.0 GJ/ha (Table 4).

Important parameters that remain insufficiently studied when selecting different perennial legume and cereal species and their mixtures for grassland establishment on degraded arable lands include forage quality, regrowth capacity, competitive ability of cultivars, changes in botanical composition, and productive longevity of sward.

The yield of main nutrients from the brome monoculture was significantly lower. In the first year of cultivation, it did not exceed 3.13 t/ha feed units, 0.46 t/ha digestible protein, and 47.2 GJ/ha metabolizable energy. In the second year, these values were 2.44, 0.40, and 45.6, respectively, and in the third year, 2.47 t/ha, 0.42 t/ha, and 46.1 GJ/ha. The productivity of the alfalfa-brome mixture was also significantly higher compared with smooth brome alone. In the first year of cultivation, this mixture yielded: 4.14 t/ha feed units, 0.90 t/ha digestible protein, and 59.2 GJ/ha metabolizable energy. In the second and third years of cultivation, the yield of feed units from the alfalfa-brome mixture remained quite high, ranging 3.23–3.39 t/ha feed units, 0.78–0.82 t/ha digestible protein, and 54.6–56.5 GJ/ha metabolizable energy.

A crucial final step in assessing the feasibility of establishing perennial legumes on degraded arable lands, in our view, is determining the volume of nitrogen fixation from the atmosphere. Under the semiarid climate conditions, alfalfa is recognized across all farm types as the most productive forage crop (Tyshchenko et al., 2020). This is because, in addition to its high content of feed units and digestible protein, it can accumulate 150–250 kg/ha of symbiotic nitrogen per growing season through nodule bacteria, depending on soil type, moisture conditions, and cultivation technology.

Table 4
Productivity of legume, cereal, and the legume-cereal mixture depending on composition and year of cultivation (average for three years of the study, n = 4)

Year of cultivation	Types of grasses	Yield per 1 ha			
		absolute dry matter, t	feed units, t	digestible protein, t	metabolizable energy, GJ
1st	alfalfa	5.36 ± 0.56[a]	3.86 ± 0.46[a]	0.97 ± 0.04[a]	57.8 ± 6.6[a]
	smooth brome	4.47 ± 0.48[b]	3.13 ± 0.40[b]	0.46 ± 0.02[c]	47.2 ± 6.2[b]
	alfalfa + smooth brome	5.52 ± 0.62[a]	4.14 ± 0.51[a]	0.90 ± 0.04[b]	59.2 ± 6.9[a]
2nd	alfalfa	4.90 ± 0.34[ab]	3.38 ± 0.59[a]	0.84 ± 0.04[a]	50.6 ± 2.5[b]
	smooth brome	4.36 ± 0.32[b]	2.44 ± 0.41[c]	0.40 ± 0.01[c]	45.6 ± 1.9[c]
	alfalfa + smooth brome	5.22 ± 0.40[a]	3.39 ± 0.59[a]	0.78 ± 0.04[b]	54.6 ± 2.6[a]
3rd	alfalfa	4.15 ± 0.29[b]	2.93 ± 0.41[b]	0.89 ± 0.04[a]	54.0 ± 1.6[ab]
	smooth brome	3.61 ± 0.22[b]	2.27 ± 0.37[c]	0.42 ± 0.03[b]	46.1 ± 1.0[c]
	alfalfa + smooth brome	4.61 ± 0.33[a]	3.23 ± 0.45[a]	0.82 ± 0.04[a]	56.5 ± 1.6[a]

Note. See Table 1.

The primary method used to quantify atmospheric nitrogen fixed by perennial legumes in our field experiments on dark-chestnut soil was a comparative method with smooth brome. This method assumes that under identical growing conditions, both plant species absorb the same amount of nitrogen from the soil. The observed difference in the nitrogen uptake between the yields of alfalfa and smooth bromegrass, adjusted for seed nitrogen, was attributed to nitrogen fixed by alfalfa from the air.

The plant nitrogen content, determined using the Kjeldahl's method, and its uptake varied by plant species. Regardless of the year of sward vegetation, nitrogen uptake reached 131–168 kg/ha in alfalfa, 114–151 kg/ha in smooth brome, and 149–203 kg/ha in the alfalfa-brome mixture (Table 5). The symbiotic fixation of atmospheric nitrogen by alfalfa nodule bacteria significantly depended on the absolute dry matter yield formed during the growing season, the year's rainfall supply, and the nitrogen content in the plants, as well as the duration of cultivation. In the first year, the symbiotic nitrogen fixation by the alfalfa monoculture was 75 kg/ha, and for the binary mixture (alfalfa and smooth brome) it was 77 kg/ha, with nitrogen fixation coefficients of 37.3% and 37.9%, respectively.

The accumulation of symbiotic nitrogen by alfalfa in the monoculture and by alfalfa in the mixture with smooth brome was equivalent to 217–223 kg/ha of mineral nitrogen in the form of ammonium nitrate, or 18.9–19.4 GJ/ha of total energy. In the second year of alfalfa cultivation, the symbiotic fixation of atmospheric nitrogen by the crop remained high, reaching 53–68 kg/ha, with nitrogen fixation coefficients of 31.4–37.0%, irrespective of the agrophytocenosis composition. The accumulation of symbiotic nitrogen by alfalfa nodule bacteria at these levels was equivalent to 154–197 kg/ha of mineral nitrogen, or 13.4–17.1 GJ/ha of total energy (Table 6).

Table 5
Yield of the absolute dry matter, nitrogen content, and nitrogen uptake by the crops (average for three years of the study, n = 4)

Types of crops	Year of usage								
	1st			2nd			3rd		
	yield, t/ha	nitrogen content, %	nitrogen uptake, kg/ha	yield, t/ha	nitrogen content, %	nitrogen uptake, kg/ha	yield, t/ha	nitrogen content, %	nitrogen uptake, kg/ha
Alfalfa	5.36 ± 0.56[a]	3.76 ± 0.05[a]	201 ± 47[a]	4.90 ± 0.34[ab]	3.75 ± 0.33[a]	184 ± 9[a]	4.15 ± 0.29[b]	3.62 ± 0.24[a]	150 ± 31[a]
Smooth brome	4.47 ± 0.48[b]	2.81 ± 0.02[c]	126 ± 33[b]	4.36 ± 0.31[b]	2.66 ± 0.28[c]	116 ± 8[b]	3.61 ± 0.15[b]	2.75 ± 0.18[b]	99 ± 25[b]
Alfalfa + smooth brome	5.52 ± 0.62[a]	3.68 ± 0.04[ab]	203 ± 48[a]	5.22 ± 3.40[a]	3.23 ± 0.32[b]	169 ± 9[a]	4.61 ± 0.32[a]	3.23 ± 0.20[ab]	149 ± 32[a]

Note. See Table 1.

Table 6
Symbiotic nitrogen accumulation by alfalfa in the monoculture and alfalfa-brome mixture (average for three years of the study, n = 4)

Year of usage	Types of grasses	Nitrogen uptake		Symbiotic nitrogen, kg/ha	Nitrogen-fixing coefficient, %	Mineral nitrogen equivalent	
		kg/ha	%			kg/ha	GJ/ha
1st	smooth brome	126 ± 39[b]	100 ± 29[b]	–	–	–	–
	alfalfa	201 ± 47[a]	159 ± 37[a]	75.1 ± 0.4[a]	37.3 ± 0.2[a]	217.3 ± 3.8[a]	18.9 ± 0.3[a]
	alfalfa + smooth brome	203 ± 48[a]	161 ± 38[a]	77.3 ± 0.4[a]	37.9 ± 0.2[a]	223.1 ± 3.7[a]	19.4 ± 0.4[a]
2nd	smooth brome	116 ± 9[b]	100 ± 7[b]	–	–	–	–
	alfalfa	184 ± 10[a]	159 ± 9[a]	67.8 ± 3.5[a]	37.0 ± 0.2[a]	197.4 ± 27.0[a]	17.1 ± 2.3[a]
	alfalfa + smooth brome	169 ± 9[a]	146 ± 8[a]	52.6 ± 2.9[a]	31.4 ± 0.1[a]	154.0 ± 20.1[b]	13.4 ± 1.2[b]
3rd	smooth brome	99 ± 22[b]	100 ± 22[b]	–	–	–	–
	alfalfa	150 ± 32[a]	151 ± 31[a]	51.4 ± 0.3[a]	34.0 ± 0.2[a]	147.8 ± 1.9[a]	12.9 ± 0.2[a]
	alfalfa + smooth brome	149 ± 31[a]	150 ± 31[a]	50.2 ± 0.3[a]	33.5 ± 0.2[a]	145.1 ± 2.1[a]	12.6 ± 0.1[a]

Note. See Table 1.

In the third year of cultivation, the symbiotic accumulation of nitrogen by the alfalfa monoculture decreased to 50–51 kg/ha. This reduction is attributed to a significant change in the botanical species composition. Due to the marked decrease in alfalfa's contribution to the botanical composition in both monoculture and mixtures, the extent of symbiotic nitrogen fixation by alfalfa at the aforementioned levels was equivalent to 145–148 kg/ha of mineral nitrogen in the form of ammonium nitrate, or 12.6–12.9 GJ/ha of total energy.

Discussion

Cultivation of forage crops in the rainfed conditions of semiarid climate zone is a difficult task, as most forage crops decrease their productivity significantly when facing water supply deficit. However, our study supports the theory that in case of drought-tolerant cultivars of alfalfa and smooth brome, it is possible not only to achieve the desired level of feed productivity but also contribute to soil fertility preservation through nitrogen-fixing activity of legume component.

As most studies report, dry matter yield of perennial grasses like alfalfa usually rises in the first years after establishment, and general longevity of sward depends on cultivation technology and environmental conditions, but it is rare that it exceeds six or eight years in semiarid climate, especially without irrigation (Horvat et al., 2023). After reaching the peak, yields decrease due to factors such as depletion of soil moisture and stand thinning, as well as mixing up with ruderal plant species, as was mentioned in our study. Besides, gradual decrease in yields observed over the years of cultivation is also attributed to stresses, to which alfalfa and smooth brome crops are subjected, and these decreases are especially prominent in dry years (Ünlükara et al., 2024; Wang et al., 2025). Also, it should be noted that some cultivars and local genotypes of perennial grasses maintain higher yields and quality over multiple years, especially those bred for drought resistance (Tyshchenko et al., 2020).

As for smooth brome, the crop usually demonstrates stable yield and high forage quality in semiarid climates, especially when managed with optimal seeding rates, row spacing, and grazing. Its adaptability and drought resistance make it a valuable forage crop for these challenging environments. For example, in semiarid regions of Turkey, the herbage yields of smooth brome ranged approximately 499 to 512 kg/da of dry matter, with hay yields around 146 kg/da. These yields were consistent across different genotypes, indicating good adaptation and stable performance in semiarid environments (Ünal & Mutlu, 2015). It has to be pointed out that the reported yields are significantly lower than those recorded in our study.

The studies on using smooth brome in crop mixtures in rainfed semiarid areas reported that the crop in mixed legume/grass systems showed variable yield of dry matter across years, with higher yields in wetter years and under grazing management. Smooth brome often became dominant over time, especially when paired with sainfoin (He et al., 2025). In our study it was also the case, as the proportion of smooth brome was higher over the years of the study than the share of alfalfa in the crop mixture. Another important evidence is that in mixed crops, nitrogen transfer from legumes to smooth brome increases over time but remains relatively low (<10%), suggesting that while legumes contribute to soil fertility, smooth brome's yield is not heavily dependent on this nitrogen transfer (He et al., 2025). In our study, we also did not observe any negative effect of smooth brome on nitrogen fixation and accumulation by alfalfa. It should be noted that in mixtures, alfalfa dominates early (first year), but the grass component (smooth brome) increases over time, often reaching about 50% of the biomass by the third year, as it was in our study, when the share of alfalfa decreased from 64.2% to 11.1%, while the proportion of smooth brome increased up to 78.6% from 30.7% (Hall et al., 2017). Also, it should be noted that smooth brome performance is strongly dependent on cultivation technology, especially nutrition, as was reported by Vasylenko et al. (2020), who found significant difference in the crop seed yield with different rates of mineral fertilization and using fertilizers in different stages of the crop growth and development.

As for specifically alfalfa-brome mixtures, this solution is not the most popular, but at the same time is widely used in semiarid environments to enhance forage productivity and quality. Alfalfa-brome mixtures consistently produce higher or comparable dry matter yields to the monocultures, with some studies showing mixtures nearly matching the highest-yielding alfalfa and outperforming cereal grass monocultures (Baral et al., 2021; Ahmad et al., 2022). In our study, the yields of dry matter from the crop mixture were also usually higher than those of the monocultures, but the difference was not always statistically significant. Apart from yielding improvements, crop mixture provides better seasonal distribution of forage, providing more consistent yields throughout the growing season (Moore et al., 2000).

Regarding forage quality and nutritive value, it should be noted that alfalfa contributes higher crude protein, while smooth brome increases fiber digestibility. Mixtures balance these traits, resulting in improved overall forage quality compared with grass monocultures (Aponte et al., 2019; Balabanlı & Yüksel, 2021). Including alfalfa in smooth brome pastures increases weight gains in the livestock, though alfalfa persistence may decline over time under continuous grazing (Russell & Barnhart, 2002). As for the part of affecting soil erosion, structure and fertility, smooth brome contributes little, but its introduction to alfalfa monocultures also does not lead to decreased efficiency of phytomeliorative properties of legume component (Zemenchik et al., 1996). In general, alfalfa-brome mixtures offer significant advantages in forage yield, quality, and environmental sustainability over monocultures. These mixtures balance protein and fiber, improve seasonal yield distribution, and enhance soil and nitrogen management, making them a valuable option for sustainable forage production. Optimal results are achieved with moderate nitrogen fertilization and appropriate mixture ratios.

Conclusions

Growing alfalfa in monoculture and as part of a binary grass mixture with smooth brome, with different durations of their use over the years, along with increasing the fertility of dark-chestnut soil, made it possible to obtain green fodder balanced in digestible protein, without the application of mineral nitrogen fertilizers. Also, this approach improved the quality of precursor crops for subsequent cereal crops within the crop rotation. The main benefits of grass mixture include increased yields of dry matter and feed units (by 23.5–27.7%), higher competitiveness with rogue ruderal species, higher contents of crude protein and fat in the forage. Notwithstanding the fact that coefficient of nitrogen fixation was somewhat lower in case of the crop mixture than in the alfalfa monoculture, the difference was statistically insignificant, and did not have a pronounced effect on nitrogen accumulation and beneficial effects on the fertility of the studied dark-chestnut soil.

Further research will be directed on studying various combinations of alfalfa with cereal grass and their efficiency in terms of obtaining high-quality forages and providing benefits for soil fertility. Also, it is planned to study whether irrigation changes the peculiarities of productivity formation of grass mixtures and shifts the balance in favor of less drought-tolerant species of perennial grasses, e.g., clover.

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