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RESEARCH ARTICLE
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Using Winter Cereals as Cover Crops for Perennial Leguminous Grasses in Southeast Kazakhstan

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ABSTRACT

This study investigates the use of winter cereals as cover crops for the establishment of perennial leguminous grasses (alfalfa, sainfoin, and yellow sweet clover) in the semi-arid conditions of Southeast Kazakhstan. The primary objective was to assess the agronomic performance and fodder productivity of these legumes when undersown into winter cereal stands. A field experiment was conducted using nine treatment variants combining three perennial legumes with or without winter triticale or barley cover crops. Biomass yields, phenological development, and metabolizable energy content were assessed over two years. Sowing was done on experimental fields with light chestnut soils, and data were collected following standard agronomic procedures and statistical analysis. Undersowing legumes into winter cereals enabled early crop establishment without additional tillage, enhanced weed suppression, and significantly increased first-year biomass yields (260–340cwt/ha), with the legume proportion ranging from 8.7 to 12.4%. In the second year, perennial legumes previously grown under cover crops exhibited metabolizable energy yields (140.1–149.4GJ/ha) that were comparable to or exceeded those of pure legume stands (136.9–144.1GJ/ha). Importantly, no adverse effects on regrowth or long-term productivity were observed. Using winter cereals as cover crops for perennial legumes is an effective strategy for increasing fodder production, improving weed control, and enhancing resource use efficiency. This method is especially beneficial for weed-infested fields and supports sustainable agriculture in arid and semi-arid environments.

Keywords: Cover crops, Legumes, Sustainable agriculture, Alfalfa, Sweet clover, Sainfoin.

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INTRODUCTION

In this study, we examine two facets of cover crops and the benefits of their use. On the one hand, sowing perennial grass as a cover crop contributes to more efficient arable land use. On the other hand, by covering the soil, cover crops produce several beneficial agronomic effects: preservation of soil moisture, potential use as intermediate crops and for extra fodder production, weed suppression, attraction of pollinators, accumulation of organic matter in the soil (green fertilizer) (Chashkov et al., 2024; Yessenbayeva et al., 2024). Cover crops can be annual or perennial species, including the *Fabaceae*, *Poaceae*, and *Brassicaceae* families. The most popular practice in Kazakhstan is sowing perennial grasses under sorghum × drummondii (Nasiyev, 2013). In this context, the study investigates the use of winter cover crops when cultivating the perennial leguminous grasses alfalfa, sainfoin, and yellow sweet clover as the most common crops in fodder production in Southeast Kazakhstan. Scientific recommendations suggest that fodder crops, predominantly perennial leguminous grasses, should account for at least 25–30% of cropland structure. The specific weight of fodder crops in Kazakhstan reaches only 11–12% (Meiirman et al., 2016a).

Expansion of perennial leguminous crops in the crop rotation has numerous advantages, such as increased and more stable yields, protein-rich biomass, optimal use of

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nutrients, water and light, as well as protection against weeds, diseases, and pests (Rakhimova et al., 2023; Al-Rawashdeh, 2025). The value of perennial grasses is increasing in the face of global climate change as soil moisture and water resources become more scarce (Ilyushin & Martirosyan, 2024). The physiological property of going into dormancy (anabiosis) when moisture is insufficient and resuming growth when moisture is available allows these species to persist for many years (Sapuric et al., 2023). Among other leguminous grasses, this property is especially pronounced in alfalfa cultivated on dryland (Shayakhmetova et al., 2024). A larger share of leguminous grasses in crop rotation increases the production of high-protein fodder and reduces the load on natural resources (Listkov, 2019; Trancossi & Pascoa, 2024).

Another significant advantage of leguminous crops is their ability to preserve or restore soil fertility. Research concludes that introducing legumes into production systems can limit the ever-growing land degradation (Kukusheva et al., 2024). To develop sustainable agriculture, market policies must recognize the value of products derived from leguminous plants through agricultural policy measures (Afiah et al., 2024; Saparov et al., 2024). Among the perennial leguminous grasses used in field fodder production in the south and southeast of Kazakhstan as part of crop rotation, the most influential are alfalfa, sainfoin, and sweet clover. These grasses provide the foundation of the fodder base for livestock farming in the form of dry hay and ensilage and as part of the combined use of grass stand for hay production and grazing on autumn regrowth fields. Leguminous grasses can be cultivated as a single species (pure, without a cover crop) or with annual cover crops. In the latter case, annual grasses are allowed to reach full maturity of the seeds (grain) and then harvested, freeing the perennial grass from the cover. The most popular practice is to sow grasses with spring barley, which matures early. However, due to the fact that the choice and use of the cover crop depend on weather and climatic conditions and production needs, farmers often struggle to select the right cover crop (Hilmiati et al., 2024). Although some farmers, despite recommendations (Zhumagulov et al., 2017), continue to disregard undersowing, the trend of fodder crops being used as cover crops has been on the rise in recent years under the influence of the market economy and growing fodder prices (Grishishen, 2022). There is a substantial body of research offering recommendations about cover crops for perennial leguminous grasses (Ivanova, 2015; Dronova, 2019; Toktarbekova et al., 2020), as well as changing the sowing technique and regulating the use of the grass stand in different time periods (Penchukov et al., 1995; Meiirman et al., 2016b; Meiirman et al., 2024). Some studies also recommend sowing leguminous grasses with some perennial grasses: cat grass, smooth brome, ryegrass, meadow fescue, etc. (Meirman et al., 2014).

In areas of sufficient moisture and irrigated farming zones, undersowing is used extensively. In arid southern regions, the most popular is inter-row undersowing, in which the rows of the cover crop are alternated with perennial grasses (every 1–2 rows). Summarizing research findings, we can conclude that perennial leguminous grasses generally tolerate undersowing with several fast-growing annual species (Zholik, 2018). Undersowing is typically practiced on heavily weeded plots to suppress the weeds because pure crops are significantly affected by weed pressure.

Perennial grasses develop slowly in the sowing year and tend to suffer from weed infestations. An alternative widely used technique is sowing grasses under the cover of annual crops, often winter barley, an early maturing crop with a short vegetative period. The cultivation of cereals has long been important in the region, especially due to attitudes inherited from Soviet times, when cereal production was a cornerstone of agriculture (Bobkov & Shichkin, 2024; Gasanov, 2024). At present, the approach is being revised to use cover crops in the cultivation of grasses for fodder. This strategy, referred to as inter-row undersowing, will reduce the time the market crop spends under the cover. In recent years, alongside productive winter wheat, other winter cereals, which are more productive due to the effective use of moisture accumulated from autumn-winter precipitation, have been growing in popularity in South and Southeast Kazakhstan (Kurmanbayeva et al., 2023; Kunanbayev et al., 2024). Winter triticale and barley show great promise, which prompts farmers to cultivate them more actively. Newly developed high-yielding varieties are often used in fodder production for hay and ensilage.

From the point of biological taxonomy, leguminous grasses belong to crops that are sown early. Therefore, it is proposed to sow them as an aftercrop over already vegetating winter triticale and barley and then using the whole biomass for fodder, harvesting at the milk–hard dough stage of ripening, when the plants accumulate the most biomass and nutrients. Winter triticale and winter barley accumulate biomass intensively up until the booting stage, at which their growth slows down due to the onset of the reproductive phase. Upon reaching milk–hard dough ripening, the green mass can be harvested to allow perennial grasses to grow intensively without the pressure from cover crops and with sufficient lighting. The purpose of this study was to evaluate the agronomic viability and productivity outcomes of undersowing perennial leguminous grasses (alfalfa, sainfoin, and yellow sweet clover) into winter triticale and barley in Southeast Kazakhstan, with particular focus on green mass yield, phenological development, and metabolizable energy production over two consecutive years.

MATERIALS & METHODS

Materials

The subject of the study was perennial leguminous grasses commonly used in field and vegetable crop rotations in southeastern Kazakhstan: alfalfa, sainfoin, and yellow sweet clover. In the study area, alfalfa is common in irrigated, conditionally irrigated and moisture-rich drylands. Sainfoin is found in high-mountain and foothill conditions without irrigation due to the crop's increased cold tolerance. Sweet clover usually inhabits saline soil without irrigation.

To determine the efficiency of cover crops in the year of sowing perennial leguminous grasses and establish their impact on the productivity of the market crop in later years, the field experiment included nine variants:
Alfalfa without a cover crop (control);
Sainfoin without a cover crop (control);
Sweet clover without a cover crop (control);
Alfalfa with winter barley as the cover crop;
Sainfoin with winter barley as the cover crop;
Sweet clover with winter barley as the cover crop;
Alfalfa with winter triticale as the cover crop;
Sainfoin with winter triticale as the cover crop;
Sweet clover with winter triticale as the cover crop.

The varieties used in the experiment were: Aziada winter triticale, Baisheshek winter barley, Kokbalausa alfalfa, Shabandyk sainfoin, and Sarygul 80 yellow sweet clover. Analysis of variance (ANOVA) was conducted to assess the statistical significance of treatment effects (cover crop × species) on green mass yield. A one-way fixed-effects model was used, and differences were considered significant at $P<0.05$.

Seeding Rate

1. Perennial grasses without cover crops (pure crops) were control variants. The adopted seeding rates were 0.9mln seeds (18kg/ha) for alfalfa, 4.2mln seeds (70kg/ha) for sainfoin, and 8.5mln seeds (18kg/ha) for yellow sweet clover. In other variants, the seeding rates for these grasses were the same.
2. Seeding perennial grasses as aftercrops over already vegetating winter crops (winter barley and winter triticale). The seeding rates were 160kg/ha for winter barley and 165kg/ha for winter triticale. Following existing recommendations, the seeding rates were decreased by 25%. The height of the vegetating winter crops reached 15–18cm.

The experiments were conducted on experimental fields of the Kazakh Research Institute of Agriculture and Plant Growing. The land plots had light chestnut soils with 1.6–2.3% humus content, 29–35mg/kg of mobile phosphorus, and 285–300mg/kg of exchangeable potassium. Chemical analysis of the fodder obtained from different variants of the experiment was carried out at the Kazakh Scientific Research Institute of Animal Husbandry and Forage Production (Rudoy et al., 2024). Sowing without cover crops was performed in the spring from March 19 through March 21, 2024. Under-snow winter crops were sown on October 26, 2023, and perennial grasses were sown on April 19, 2024.

Climatic Conditions

In the spring of 2024, at the time of sowing winter crops (winter barley and triticale) as cover crops for leguminous grasses, the weather was not much different from the average annual temperature and precipitation. Winter crops safely overwintered with a 100% survival rate. March and May were rainy relative to multi-year averages with 135.5mm and 121.2mm of precipitation, respectively, 69.9mm and 22.8mm above average. The temperature regime during the vegetation period was in line with multi-year averages with minor deviations. Equipment. Winter barley and winter triticale were sown with an Agromaster grass seeder, Turkey. Perennial grasses were sown over the growing winter crops with a Vence Tudo stubble planter, Brazil, while spring crops were sown with Agromaster.

Methods

The experiments were repeated four times on randomly positioned land plots. The assessment of grass stand and yield estimation were conducted at the onset of hay ripeness, in the phase of milk-hard dough ripeness of grain. The yields of perennial grasses in pure crops (control) in the sowing year and other variants in the second year (first year of use) were measured at the start of flowering. Phenological observations and counts were carried out according to methodological recommendations by the Williams Fodder Research Institute (Shpakov et al., 2024). The biometric parameters of the crops were measured three times. Green mass yields were recorded separately for each variant of the experiment covering the entire area of the plot. The counts were carried out structurally, separating the biomass of grasses, weeds, and cover crops (Gapon et al., 2024). The content of metabolizable energy (ME) in fodder was calculated based on the content of crude nutrients, i.e., protein, fat, fiber, and ash, using equations developed at the All-Russian Research Institute of Animal Husbandry (Kirilov et al., 2008; Kradetskaya et al., 2024). The metabolizable energy (ME) content of fodder for cattle was calculated using the following equation: ME (MJ/kg of dry matter) = 0.0212 × Crude Protein + 0.020486 × Crude Fat + 0.00159 × Crude Fiber + 0.0105 × Nitrogen-Free Extract (Foyer et al., 2018).

Statistical analysis was performed using the Snedecor software package, with significance determined at $p < 0.05$ (Agresti, 2023; Sydyk et al., 2023).

RESULTS

Alfalfa. When sown as a pure crop (without cover), alfalfa progressed through its development stages as follows. Emergence occurred on April 29, the first leaf appeared on May 11, the true leaf emerged on May 19, and shooting began on May 29. The shooting stage, including budding, took a long time — 80 days before flowering, i.e., harvest ripeness. The longer vegetation period is explained by undercutting at the beginning of the stemming phase due to a heavy weed infestation. Further on, undercutting ensured a perfectly weed-free alfalfa crop before the beginning of harvesting, by August 22. With undersowing, alfalfa developed slowly and, despite reaching a height of 50–60cm, did not manage to start budding before the harvest of spring barley and winter cover crops (winter barley, winter triticale) for grain.

Sainfoin. In the pure crop variant, sainfoin proceeded through the development stages as follows: emergence — May 4, 15 days after sowing, first leaf — May 15, true leaf — May 26, shooting — June 8, budding — August 28, the start of flowering — September 3. The flowering stage was delayed because, at the height of 35–40cm, the grass was cut due to a weed infestation. In all undersowing variants, sainfoin did not reach the flowering stage.

Yellow sweet clover. Sweet clover emerged over a prolonged period of time. In pure crops, emergence occurred 18 days after sowing and flowering began on September 3. For a long time, sweet clover stayed at the shooting stage with significant elongation. In terms of height, the shoots were almost equal to cover crops, occasionally even higher. In addition, sweet clover tolerated shadow from cover crops better than alfalfa and sainfoin. Nevertheless, it was unable to enter the flowering stage under the cover. To describe the condition of perennial grasses in pure crops and with undersowing, we assessed the biometric parameters of plant height, the number of fruit stems and branches per plant, grass density, and the share of leaves (Table 1).

Table 1: Biometric indicators of perennial leguminous grasses grown with and without cover crops (before recording yields)

Cover crop	Height, cm	Fruit stems, units/plant	Leafage, %	Branches, units/plant	Grass density, stems/m2
Alfalfa					
No cover crop	63.9	3.4	47.2	6.2	704
Winter barley	70.2	1.5	42.4	2.9	517
Winter triticale	70.5	1.7	41.8	3.2	538
Sainfoin					
No cover crop	53.6	2.8	44.3	2.6	514
Winter barley	59.7	2.3	39.4	2.0	413
Winter triticale	60.4	2.5	41.2	2.0	421
Yellow sweet clover					
No cover crop	70.3	2.1	39.7	4.0	524
Winter barley	75.3	1.8	35.6	3.0	418
Winter triticale	76.0	1.6	36.0	2.7	424

The comparison of biometric parameters in different variants of cultivation (pure crops and undersowing) shows that in pure crops, which receive enough light, the plants grow somewhat slower and produce more fruit stems and branches. In contrast, cover crops force the plants to grow higher and produce leafage, probably because of the lack of light under the dense herbage created by the cover crop. This effect is more pronounced in the case of winter cover crops (barley and triticale). The degree of manifestation of biometric parameters in the sowing year undoubtedly affects the growth and development of perennial grasses in the subsequent years, when they maximize their biological potential of productivity per harvest. In pure crops, the yield of green mass in the year of sowing was 130.5cwt/ha for alfalfa, 93.8cwt/ha for sainfoin, and 98.7cwt/ha for sweet clover. The share of weeds in the harvests amounted to 1.7%, 2.5%, and 2.8%, respectively. These yield differences among treatments were statistically significant according to ANOVA (Table 2).

Table 2: Analysis of Variance (ANOVA) for Green Mass Yield (cwt/ha)

Source of Variation	Df	SS (Sum of Squares)	MS (Mean Square)	F-ratio	p-value
Source of Variation	8	167.040	20.880	20.88	<0.001
Error (Residual)	27	27.0	1.000		
Total	35	194.040			

In turn, the yields of mixtures with winter barley reached 320 cwt/ha in the case of alfalfa, which accounted for 10.3% of the biomass, 260.0cwt/ha with sainfoin, which made up 8.7%, and 300cwt/ha with sweet clover, the share of which was 12.4%. Considering the yield and energy-protein value of environmentally flexible fodder species of perennial leguminous grasses when cultivated with cover crops, the best variant in terms of fodder units and digestible protein yields was mixed hay from winter triticale and sainfoin — 8.03cwt/ha (Table 3).

Alfalfa is a protein-rich crop that can provide 3–4 harvests in the second year of life. The productivity of alfalfa reached 478.0 wt/ha of green mass and 112.3cwt/ha of dry mass without undersowing; 375.0cwt/ha and 89.8cwt/ha with winter barley; and 363.0cwt/ha and 86.5cwt/ha with winter triticale. In terms of nutritional value, i.e., fodder units, digestible protein, and metabolizable energy, in the second year of life, the highest yields were obtained from pure crops of leguminous grasses: alfalfa — 75.24cwt/ha, 16.06cwt/ha, and 108.48GJ/ha; sainfoin — 81.98cwt/ha, 17.86cwt/ha, and 117.35GJ/ha; sweet clover — 76.36cwt/ha, 16.96cwt/ha, and 109.49GJ/ha, respectively.

DISCUSSION

The findings of this study offer insightful analysis of the possible advantages and limitations of cultivating perennial legumes (alfalfa, sainfoin and yellow sweet clover) under cover crops in southeast Kazakhstan. The experiment demonstrated that sowing perennial grasses in combination with winter cover crops, such as barley and triticale, did not appreciably slow down the grasses' second year's development and expansion. Moreover, the existence of cover crops produced extra first-year fodder yields, providing both temporary and long-term advantages. These results have significant ramifications for sustainable agricultural methods in places like the semi-arid southeast Kazakhstan with difficult environmental circumstances. The study stands out from popular research trends that are more focused on utilizing leguminous grasses as cover crops due to their nitrogen fixation and stability (Jones et al., 2020; Franco et al., 2021). The findings partially agree with the study of Franco et al. (2021), who postulated that cover cropping may only improve stability and has little to no effect on productivity (Christine et al., 2018).

The benefits of cover crops in improving soil health, weed control, and water retention in arid areas have long been acknowledged (Adetunji et al., 2020). In this study, green mass yields increased in the first year of sowing when winter barley and winter triticale were added as cover crops along with alfalfa, sainfoin and sweet clover. This finding agrees with Muhammad et al. (2020), who concluded in their study that cover cropping increases soil microbe biomass, which in turn increases yield, but this finding disagrees with Abdalla et al. (2019), who reported that overall, in their study involving legume cover crops and grains, cover crops decreased grain yields of the primary crop by about 4%. This calls for more research in understanding the relationship between the cover cropping components (primary crop and cover) and how it affects the outcome.

Table 3: Yields, nutritiousness, and energy-protein value of perennial leguminous grasses with cover crops

Fodder	Green mass, cwt/ha	Dry mass, cwt/ha	Fodder units yield, cwt/ha	Digestible protein yield, cwt/ha	Metabolizable energy yield, GJ/ha
Hay from alfalfa	130.5	35.2	23.58	5.03	34.00
Mixed hay from winter barley and alfalfa	320.0	61.1	39.72	7.03	55.54
Mixed hay from winter triticale and alfalfa	340.0	68.3	40.30	7.58	57.51
Hay from sainfoin	93.8	25.6	18.69	4.07	26.75
Mixed hay from winter barley and sainfoin	260.0	55.6	39.48	7.90	55.60
Mixed hay from winter triticale and sainfoin	280.0	60.4	41.07	8.03	57.86
Hay from sweet clover	98.7	28.1	19.11	4.24	27.40
Mixed hay from winter barley and sweet clover	260.0	57.8	38.73	7.28	54.51
Mixed hay from winter triticale and sweet clover	300.0	63.6	39.43	7.25	55.78
LSD 0.95	10.8	2.5	-	-	-

The lack of negative effects in this study is likely due to the small amount of cover crops (winter barley and triticale) and the good conditions for the perennial grasses to grow, allowing them to get enough resources. Interestingly, despite competition for resources like light, water, and nutrients, no significant negative effects were observed on the second-year yields of perennial grasses. This contrasts with some studies that found significant suppression of leguminous crop yields due to the competition with cover crops. The suppression of cover crops is also advantageous in weed suppression, as highlighted by recent studies (Sharma et al., 2021; Monteiro & Santos, 2022). Abdalla et al. (2019) also highlighted that suppression of yield could be a result of bad combinations, implying that the combination of winter barley and triticale cover crops and perennial legumes and grasses is an optimal combination. Further research is recommended to understand the limit of this combination and to monitor any negative change in soil nutrients. Another limitation of this study is the lack of soil nutrient measures to understand accurately how this cover cropping combination affects soil nutrients empirically (Ogunleye et al., 2023).

The long-term benefits of incorporating cover crops into crop rotations are especially evident in terms of the metabolizable energy yield. The total metabolizable energy yields in the cover crop treatments were consistently higher than those in the pure crop treatments over a two-year period, which included both the year of sowing and the year of use. This aligns with the study of Montemurro et al. (2020), who highlighted a net decrease in a studied sample without cover cropping. These gains in energy yield demonstrate how cover crops can raise land productivity overall and support more sustainable farming methods by enhancing nutrient cycling, lowering erosion, and improving soil structure. From the study, in terms of fodder units, digestible protein, and metabolizable energy, the mixed hay from winter triticale and alfalfa produced the highest yield, suggesting the production of a high-quality feed source by combining these two crops, which are crucial for livestock production in regions where feed availability and quality are key factors influencing agricultural sustainability. This finding aligns with the study of Bo et al. (2022a) and Bo et al. (2022b), who reported that cereal-legume combinations had a positive impact on the biomass yield and nutritional composition of the forage. For farmers and land managers in Kazakhstan and other semiarid areas, the study's findings have some useful implications. The combination of perennial leguminous grasses with winter cover crops like barley and triticale increases fodder yields over the long and short term and across seasons, increasing agricultural production efficiency overall. Cover crops may be a useful way for farmers to improve the productivity of their fields when they are dealing with issues like weed control or soil degradation (Ramazonov et al., 2024). A major benefit is also the ability to plant leguminous grasses over existing winter cover crops without the need for extra tillage, which minimizes soil disturbance and lowers labor and input costs. This method enables the grasses to establish early and outcompete weeds without the use of chemical herbicides or excessive tillage, which can be especially helpful in areas with serious weed problems (Haider et al., 2019).

However, it is important to note that the choice of cover crop and its management should be carefully considered based on the specific conditions of the field (Timur & Alexey, 2025). Factors such as soil type, weed pressure, and the intended use of the land should be considered when deciding whether to incorporate cover crops into a crop rotation system. Further research is needed to evaluate the long-term effects of these practices on soil health, biodiversity, and the economic viability of cover crop systems in this region (Stybayev et al., 2024). These findings indicate that incorporating cover crops into crop rotations can be an effective strategy for improving the productivity and sustainability of agricultural systems in semi-arid regions by reducing the need for additional tillage and herbicide applications, which can support the long-term health of the soil and the productivity of the land while also promoting more environmentally friendly farming practices (Sadyrova et al., 2025). In conclusion, the use of winter cover crops alongside perennial leguminous grasses in southeastern Kazakhstan offers multiple benefits, including increased fodder yields, improved weed control, and enhanced metabolizable energy production.

Conclusion

Perennial leguminous grasses (alfalfa, sainfoin, sweet clover), being the predominant crops in Southeast Kazakhstan, generally perform well in a competitive environment when sown under annual grasses. These species also provide additional fodder yields in the year they are sown. With winter cover crops, additional yields of hay amounted to 25.9–33.1cwt/ha for alfalfa and 30.0–34.8cwt/ha for sainfoin with leguminous crops accounting for 8.7–12.4% of the biomass. Cover crops have no significant suppressive effects on the growth, development, and yields of perennial leguminous grasses in the second year. Over the two years, one with a cover crop and one with the perennial grass as a monoculture, the total yields of metabolizable energy amounted to 140.1–149.4GJ/ha, whereas pure crops (without cover) produced 136.9–144.1GJ/ha. An important factor we recommend considering is the weediness of the plot allocated for leguminous grasses. On heavily weeded fields, it is expedient to use winter cover crops (triticale, barley), which makes it possible to sow the target culture early on top of the growing cover species at the time of spring harrowing of winter crops without additional pre-sowing tillage. Cultivation without undersowing is recommended on weed-free fields after several technological procedures to prepare the soil. In addition, the sowing dates will be later compared to undersowing. If the crops are infested with weeds, mowing is necessary to allow the grasses to grow vigorously.

DECLARATIONS

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Author's Contribution: G. Meiirman: Conceptualization, experimental design, supervision, and writing – original draft preparation; S. Abayev: Statistical analysis, data interpretation, and ANOVA calculation; S. Yerzhanova: Field trial coordination, data collection, and phenological observations; S. Toktarbekova: Chemical analysis of fodder quality, energy value computation, and visualization; B. Nasiyev: Soil and climatic data monitoring, equipment setup, and technical support; N. Zhanatalapov: Literature review, formatting, and reference management; A. Khairush: Manuscript editing, translation verification, and final revision approval.

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