ONLINE JOURNAL OF BIOLOGICAL SCIENCES

RESEARCH ARTICLE

Productivity and Energy Efficiency of Hybrid Sorrel (*Rumex tianschanicus* × *Rumex patientia*) Under Various Mowing and Fertilization Regimes

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Abstract: Hybrid sorrel (*Rumex patientia* × *Rumex tianschanicus*) is a multi-purpose crop that serves as both a fodder source and a potential biofuel feedstock. Despite growing interest in perennial forage and energy crops, limited information is available on the performance of hybrid sorrel (Rumex tianschanicus × Rumex patientia) under varying mowing and fertilization regimes, particularly in continental climates. This study aimed to evaluate the green mass yield, forage quality, and total energy output of hybrid sorrel under different mowing phases and mineral fertilization levels in the southern forest-steppe of Western Siberia. It is characterized by good winter hardiness, unpretentiousness to growing conditions, a long period of use of seven years or more, an 18% increase in green mass yield, and a 29% increase in total energy output under balanced compound fertilization compared to the unfertilized control. To maintain the long-term productivity of sorrel, research was conducted to determine the optimal mowing regimes with and without the use of balanced compound fertilizer. The study established that annual mowing in the flowering phase or alternating first mowing stages (budding, fruiting, flowering) over the years optimizes productivity; with these modes of use, the green mass of the crop is obtained up to 34.5-37.2 t ha^{-1}, the total energy output 76.6-89.4 GJ ha^{-1}. The use of mineral fertilizers ($N_{90}P_{90}K_{90}$) in sorrel crops enables the production of up to 40.4-44.6 t ha^{-1} of green mass under these regimes, resulting in a 13-18% increase in productivity. It is more effectiveness to apply the fertilizer rate in two steps: annually in the spring before the grass grows back (45 kg a.i. ha^{-1}) and after the first mowing (45 kg a.i. ha^{-1}).

Keywords: *Rumex patientia* × *Rumex tianschanicus*, Mowing Season, Mineral Fertilizers, Grass Stand, Productivity

Received: 03-02-2025 | **Revised:** 25-07-2025 | **Accepted:** 31-10-2025 | **DOI:** 10.3844/ojbsci.2026.26.01.007

Introduction

In recent years, issues of climate change and its impact on plant communities have become topical, as this process leads to increased temperatures and drier conditions during the growing season (Malhi, Kaur and Kaushik, 2021; Chaudhry and

DOI: 10.3844/ojbsci.2026.26.01.007

Sidhu, 2022). The negative impact of drought can have different effects on the formation of above-ground biomass depending on the soil type, weather conditions before the drought, and the intensity of grass use (Yang et al., 2021; dos Santos et al., 2022).

According to forecasts, increasing climate aridity will gradually lead to a decrease in the productivity of forage lands and the quality of harvested green fodder. The resistance of agrocenoses to extreme climatic events can be increased by selecting forage plant species with functional characteristics that allow them to cope with abiotic stress. For example, plant species with deep root systems have demonstrated increased drought tolerance, which is associated with their ability to obtain water from deeper layers of the soil, and are therefore often discussed as drought adaptation options (Zhang et al., 2024).

Therefore, in addition to traditional forage crops, introduced plant species can be used as a supplement to solve this problem. An interesting culture in this regard may be hybrid sorrel (*Rumex patientia* × *Rumex tianschanicus*) or shhavnat (Rakhmetov, 2018).

As the results of research by various authors show, hybrid sorrel is a promising crop for fodder production; it can be used both in its green form and for the preparation of succulent fodder, biologically active additives for various types of farm animals and birds, in addition, it is possible to use it in leather production, for soil phytomelioration and biofuel production (Ustak and Vana, 1998; Hujerova et al., 2013; Slesaka et al., 2014; Hedeneca et al., 2014; Hedeneca et al., 2015; Rakhmetov, 2018).

Sorrel is a versatile plant that can be used as a food, medicine, technical material, and fodder. It is particularly valuable as a perennial plant, as it provides a vitamin-rich green mass in the early spring. The leaves of sorrel contain various vitamins such as C, A, B1, B2, and PP, as well as organic acids and mineral salts. It has a positive effect on digestion and can be used for stomach disorders, jaundice, and liver diseases. Additionally, sorrel has phytomeliorative properties, protecting soils from heavy metal pollution, and acts as a disinfectant. It also has high fodder value with a high protein content and metabolizable energy. (Kukusheva and Stepanov, 2019).

The advantages of hybrid sorrel are good winter hardiness, unpretentiousness to growing conditions, the ability for early regrowth in the spring, immediately after the snow melts, while the regrown plants can withstand low air temperatures down to minus 3-5ºC, in the fall up to minus 4-6ºC (Rakhmetov, 2018). It is distinguished by a long period of use, from 7 years or more, high yield of green mass and energy output (Stepanov et al., 2015; Kukusheva and Stepanov, 2016). According to Ustak et al. (2020), the average yield usually ranges from 4 to 10 t ha^{-1} of Dry Matter (DM) per year. Sorrel is capable of leaving up to 60 t ha^{-1} of weakly mineralizable organic matter in the soil. The root of the crop is formed, powerful, taprooted, branched, and deepens in the first year to 80 cm, subsequently up to 1.5-2.0 m. The accumulation of root mass increases over the years: in the fourth year, compared to the second - 2.2, in the sixth - 3.7 times (Uteush, 1991; Stepanov et al., 2015).

Thanks to early-spring regrowth and a short growing season, hybrid sorrel in areas with insufficient moisture makes maximum use of the moisture of autumn-winter precipitation and early forms a large above-ground biomass for mowing (second to third ten days of May), which is important for regions with a short growing season. At the same time, dry and hot weather leads to the premature aging of leaves and the rapid formation of flowering shoots. Sorrel can withstand short-term summer droughts, but with a longer absence of moisture, it sheds some of its lower leaves and loses turgor; however, when moistened, it resumes growing (Stepanov et al., 2015).

In addition, the crop forms a well-developed leaf apparatus; the net productivity of photosynthesis in the spring is 12-13 g m^{-2} of leaf surface per day, which is several times higher than this figure for other forage crops (Uteush, 1991). Sorrel forms a leaf area of 80.6 thousand m^2 ha^{-1}, photosynthetic potential - 2.27 million m^2 ha^{-1}, dry weight up to 8.2 t/ ha^{-1} (Kshnikatkina and Moskvin, 2016).

Research conducted in the Altai Krai on the comparative analysis of the chemical composition and nutritional value of green forage from Hybrid Sorrel and perennial grasses (smooth brome and alfalfa) has shown that sorrel contains 39 % more carotene and significantly less fiber (almost 2-4 times lower) Yevtefeev and Zykovich, 2011; Shchkis, 2001) (Table 1).

Table 1: Chemical composition and nutritional value of green forage from Hybrid Sorrel at the budding stage and perennial grasses

Parameter	Indicator values per 1 kg			Per 1 feed unit	Deviation from the zootechnical feeding norm for dairy cows (regarding hybrid sorrel)
	Alfalfa	Smooth brome	Hybrid sorrel		
Feed units	0.25	0.25	0.22	-	norm
DM	250.0	377	140	-	-
Crude protein (CP), %	50.0	43.0	2.67	-	-
Digestible protein, g/kg	38.0	26.0	21.0	105.0	norm
Crude fat, %	7.0	10.0	0.6	30.0	norm
Crude fiber, %	68.0	116.0	2.8	140.0	norm
Starch, g	3.0	4.4	4.1	20.5	-100
Sugar, g	14.0	19.0	18.3	91.5	norm
Calcium, g	4.5	1.7	1.8	9.0	+2
Phosphorus, g	0.7	0.9	0.4	2.0	- 2.5
Magnesium, g	0.6	0.42	0.7	3.5	norm
Potassium, g	5.3	5.34	3.7	18.5	+10.5
Iron, mg	34.0	40.0	9.8	49.0	+40.0
Copper, mg	2.6	1.3	0.61	3.0	- 6.0
Zinc, mg	6.1	3.0	3.0	15.0	- 45.0
Manganese, mg	8.3	8.0	4.5	22.5	- 37.5
Sulfur, mg	1.0	0.32	336.0	1680.0	- 320.0
Iodine, mg	0.02	0.026	0.025	0.13	- 0.67
Carotene, mg	44.0	65.0	71.0	305.0	+ 260.0
Vitamin A, IU	-	-	< 1.0	-	-
Vitamin D, Vitamin	2.5	3.7	< 6.0	-	-
Vitamin E, mg	50.0	45.0	15.0	75.0	+ 35.0

Consequently, its palatability for animals is expected to be higher. According to the comparison of the chemical composition and nutritional value of Hybrid Sorrel at the budding stage with zootechnical feeding norms for dairy cows producing 11-20 kg of milk per day, it was found that the nutritional value of sorrel aligns with feeding standards in terms of digestible protein, fat, fiber, sugar, calcium, magnesium and vitamins. However, a deficiency in starch, phosphorus, copper, zinc, manganese, and sulfur was observed, along with an excess of potassium and iron. Considering that no single forage crop fully meets the nutritional requirements of dairy cows, a combination of different feed sources is used to balance rations. Thus, Hybrid Sorrel can be included in livestock diets, including as a supplement to balance concentrated feeds by enriching them with vitamins.

In addition to developing technology for cultivating it for fodder, an important point is to establish effectiveness methods for using its grass. Thus, Vogel et al. (2012) found that in arid conditions with intensive use of pastures due to frequent mowing, there is a sharp decrease in biomass yield.

The mowing regimes tested in this study were selected based on prior agronomic recommendations and practical applications in forage crop management. Several studies emphasize the importance of selecting the optimal efficiency of forage production. Research has shown that optimizing mowing frequency and height can significantly increase the yield and nutritional value of the crop (Yang et al., 2020; Wang et al., 2025; Zhang et al., 2020).

Early mowing of the above-ground mass leads to weakening of plants, which negatively affects the accumulation of reserve nutrients, the greatest accumulation of which is observed in grasses during the period of full flowering - seed ripening. In addition, with the frequent alienation of grass shoots, the possibility of their use of solar energy is limited, since a significant period of the growing season is spent on regrowth, when the grasses do not yet have the optimal leaf surface for maximum photosynthesis. The negative impact of frequent and early mowing on plants and maintaining their productive longevity can be reduced by alternating the harvesting of grasses at different stages of development over the years. Alternating the regimes of using grass stands from year to year significantly increases the vitality of plants, their longevity during intensive use, and high productivity (Nadezhkin and Satarov, 2011; Shpakov and Volovik, 2012). When systematically carrying out two mowings, the crop yield in subsequent years is significantly reduced and for its formation, the plants need additional provision of nutrients. Taking this into account, it is necessary to systematically apply fertilizers with a double-cutting system and alternate with single-cutting late mowing of grasses (Stepanov et al., 2015). In bluegrass crops, mineral fertilizers ensure an increase in the productivity of grass stands by up to 40-65 %, primarily due to nitrogen fertilizers (Harkevich et al., 2017).

Numerous studies with mineral fertilizers indicate that enhancing crop yields and improving their chemical composition, a balance between sufficient and excessive application is necessary, taking into account the nutrient content of soil components and the requirements of plants. The role of essential nutrients in increasing plant resistance to abiotic stresses is emphasized (Niu et al.,2024; Noulas, Torabian and Qin, 2023; Luo et al., 2023).

Although hybrid sorrel (Rumex tianschanicus × Rumex patientia) has shown promise as a multipurpose perennial crop in previous trials, limited data are available on its biomass productivity, fodder quality, and energy output under different mowing and fertilization regimes in continental climates such as that of Western Siberia. This study is the first to comprehensively evaluate the agronomic and energy performance of hybrid sorrel in the southern forest-steppe zone, providing valuable insights for optimizing its management and expanding its use in sustainable forage and bioenergy systems.

The aim of this study was to evaluate the green mass productivity, forage quality, and total energy output of hybrid sorrel (Rumex tianschanicus × Rumex patientia) under different mowing phases and fertilizer regimes. The research seeks to determine optimal management strategies that enhance both fodder and bioenergy value of this crop in the conditions of the southern forest-steppe of Western Siberia. Given the increasing interest in multipurpose perennial crops, the results contribute to the development of sustainable agroecosystems in continental climates.

Thus, in the conditions of a changing climate and the negative impact of abiotic factors affecting perennial grasses during mowing, the issue of studying the optimal harvesting regime of sorrel green mass with the use of mineral fertilizers, which will ensure the growth of productivity and nutritional content of fodder mass, deserves attention. To address this issue, we have established a field experiment where mowing sorrel annually in one phase and with alternation of phases by years on two backgrounds.

Materials and Methods

The experimental site is located at 52.31°N latitude and 77.01°E longitude, in the southern forest-steppe zone of Western Siberia. The soil is classified as meadow-chernozem with a pH of 6.3 and humus content of 3.8 %. The field experiment was carried out on established sorrel crops in their third year of growth and continued for three consecutive years (2012-2014), allowing the assessment of interannual yield variability.

The soil of the experimental plot is meadow-chernozem. The content of nutrients is: N-NO_3 - 7.7 mg kg^{-1} of soil, P_2O_5 and K_2O - 75 and 118 mg kg^{-1} of soil, respectively. Weather conditions during the years of research were different, but quite typical for the climate of this region.

Experiment Arrangement

1- Annual mowing of sorrel grass in the phase: stemming, budding, flowering, and fruiting

2- Mowing the grass stand with alternating harvesting periods (development phase) by year:

- Stemming - flowering - budding
- Stemming - fruiting - budding
- Stemming - fruiting - flowering
- Budding - fruiting - flowering

Establishment was carried out on sorrel crops of the Rumex K-1 variety of the third year of life on two backgrounds: without fertilizers (control) and $N_{90}P_{90}K_{90}$. Fertilizers were applied annually, superficially, in fractions - 45 kg of the active substance of the elements per 1 ha in the spring and after the first mowing. The recording area of the plots in the experiments was 25 m^2, with a 4-fold repetition, and the location of the plots was systematic. The mowing height in all variants was 10 cm. The research used a methodology developed by the All-Russian Research Institute of Feeds named after. V.R. Williams (Methodological instructions for conducting field experiments with forage crops, 1997).

During the growing season of the crop, the phenological phases of sorrel development were recorded. Determination of plant height was realised using a measuring ruler before mowing according to the experimental scheme. The number of plants per unit area was determined on stationary plots by counting them before mowing. The mass of the whole plant and the percentage of leaf content were also determined. The yield of green mass was taken into account by weighing on a laboratory scale VM-153M. The content of absolutely DM was determined on the day of harvesting by drying the plant sample in a SESH-3M drying cabinet at a temperature of 105°C to constant weight. The total energy output was determined according to the recommendation (Sheljuto, 2011).

Statistical data processing was performed using Microsoft Excel 2010. Correlation analysis was carried out by calculating the Pearson correlation coefficient, errors and criteria for the significance of the correlation coefficient were determined to assess the relationship between sorrel yield and grass stand indicators.

Results

Our research has shown that in the conditions of the southern forest-steppe in the fourth and subsequent years of life, the resumption of the growing of hybrid sorrel is observed in the first - second ten days of April, stemming - from May 16 to 25, budding - from May 22 to June 8, flowering - from 4 to June 25, fruiting - from June 18 to July 7 (Fig. 1). When mowing the grass stand in all variants, sorrel formed only a rosette of leaves in the second mowing.

Fig. 1: Hybrid sorrel grass stand under different mowing regimes 1 − stemming phase; 2 − flowering phase (photo by A.N. Kukusheva)

The mowing regime and fertilization influenced the growth and development of hybrid sorrel plants. For example, in the variant without applying fertilizers and with annual mowing in the stemming phase, the height of plants in the first mowing was on average 49 cm, but when alternating harvesting times with this phase over the years, it was 31-41 cm higher.

In the flowering-fruiting phases, the height of sorrel was maximum - 103-108 cm in the first, and the second - 37-42 cm with annual mowing in the stemming and budding phase (Fig. 2). In years with good moisture supply in the spring, sorrel regrowth is observed earlier, on average by 4-6 days. In years with higher spring precipitation, plant regrowth began earlier (by 4-6 days) and biomass accumulation was greater. However, drought stress reduced yields, particularly in plots subjected to early mowing (stemming phase). This suggests that mowing timing should be adjusted based on annual rainfall conditions. These interannual differences highlight the sensitivity of hybrid sorrel productivity to climatic variability and underscore the importance of precipitation in determining optimal mowing schedules. Such findings are essential for evaluating the stability and adaptability of the mowing-fertilization model under changing environmental conditions.

The average daily increase in height of sorrel varied by development phases. In the initial growing, the growth rate of plants was slow and amounted to only 1.3-1.8 cm per day. With the beginning of budding, it increased (up to 2.3 cm per day), but then with the onset of full flowering it decreased to 1.4-1.5 cm, and by the fruiting phase, the growth of plants in height practically stopped. The height of sorrel plants in the second mowing depended on the phase of mowing in the first mowing.

DOI: 10.3844/ojbsci.2026.26.01.007

When the crop was mowed annually in the first mowing, in the stemming phase, on average, the height of the regrowth was 42 cm, in the budding phase - 37, and flowering - only 32 cm; in the fruiting phase, a rosette of leaves 26 cm high was formed. In all phases of development, sorrel regrowth occurred only from buds located on the root collar. At the same time, the earlier the first mowing was carried out, the faster the plants grew, so when the first mowing was carried out in the early phases of development (stemming, budding), the regrowth of the regrowth began on the 4th-6th day, and in the later phases (flowering, fruiting) - only on 8-10 days.

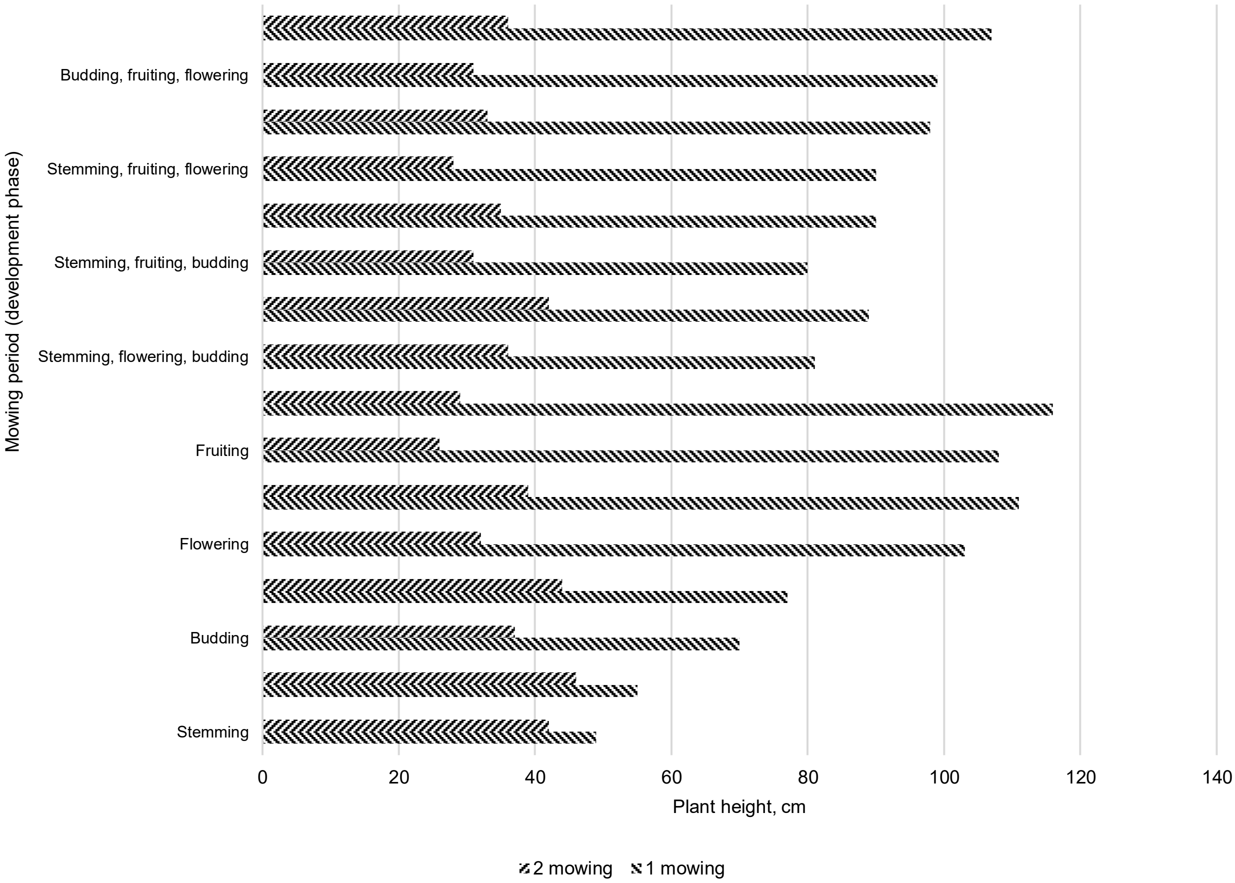

Fig. 2: Height of hybrid sorrel grass before harvesting, depending on the mode of use and fertilizers, source: own study: x-axis - plant height, cm, y-axis - moving period (development phase)

Under the influence of $N_{90}P_{90}K_{90}$, the height of sorrel, both in the first and second cuttings, increased by 3-8 cm (Fig. 2). Sorrel showed the highest responsiveness to fertilizers when the soil had a good moisture supply. Research conducted by Zuo et al. (2022) showed that the post-mowing treatment of 5 mM nitrate on chlorophyll content was also observed, which enhanced photosynthetic capacity of plants, accelerated their regrowth and increased resistance against mowing stress. Therefore, nitrogen is necessary for the growth and development of perennial grasses after mowing, especially in areas with nitrogen deficiency in soils.

According to our research, the least thinning of the sorrel herbage was observed when it was mowed annually in the flowering and fruiting phases and when these harvesting phases alternated with the budding and stemming phases over the years. At the same time, the density of the herbage in the first mowing during the control was 45-46 shoots m^{-2}, in the second - 33-37 pieces m^{-2}, exceeding by 7-28% with annual mowing of sorrel in the stemming phase. According to Paušič et al. (2017), earlier mowing negatively affects the density of flowering plants and their performance in general. Whereas with later mowing, an increase in plant viability and population density was noted. Under the influence of fertilizers, the density of the herbage increased by 5-24 %, and with the annual alienation of the sorrel herbage in the flowering phase, when applied fractionally in the fertilizer $N_{90}P_{90}K_{90}$, in the first mowing it reached 50 pieces m^{-2}, in the second - 42 pieces m^{-2} (Table 2).

Table 2: Characteristics of hybrid sorrel herbage before harvesting, depending on the mode of use and fertilizers, source: own study

Mowing period (development phase)	Background power supply	The number of plants per unit area (rosette of leaves) (pieces m^{-2})		Weight of shoot (rosette of leaves) (g)		Total green mass (t ha^{-1})
		mowing				
		1	2	1	2	
Annual mowing of sorrel grass in the phase						
Stemming	without fertilizer	42	29	36.5	32.3	22.1
	$N_{90}P_{90}K_{90}$	45	31	42.4	36.9	29.6
Budding	without fertilizer	44	31	55.1	27.7	27.1
	$N_{90}P_{90}K_{90}$	47	36	61.8	35.2	34.0
Flowering	without fertilizer	45	37	83.9	21.0	37.2
	$N_{90}P_{90}K_{90}$	50	42	91.2	28.6	44.6
Fruiting	without fertilizer	45	33	85.9	17.5	33.9
	$N_{90}P_{90}K_{90}$	49	37	94.1	20.8	39.9
Mowing the grass stand with alternating harvesting periods (development phase) by year						
Stemming, flowering, budding	without fertilizer	44	31	57.3	21.7	27.2
	$N_{90}P_{90}K_{90}$	47	34	63.2	28.9	33.9
Stemming, fruiting, budding	without fertilizer	44	29	59.5	21.3	27.2
	$N_{90}P_{90}K_{90}$	46	36	66.9	26.4	33.4
Stemming, fruiting, flowering	without fertilizer	46	35	68.4	19.5	29.5
	$N_{90}P_{90}K_{90}$	50	41	76.3	24.7	35.3
Budding, fruiting, flowering	without fertilizer	46	36	75.5	21.9	34.5
	$N_{90}P_{90}K_{90}$	50	42	84.2	27.7	40.4

At the same time, however, some authors note a decrease in stem growth by 70 % with an increase in nitrogen nutrition (Klimeš and Klimešová, 2002). This is associated with a change in soil pH towards acidification, since large doses of fertilizers such as urea and nitrates change the composition of alkaline cations in the soil, and ammonium salts strongly acidify the soil during the process of nitrification. When soil pH decreases, this can disrupt the functioning of plant roots and cause chemical stress in plants (Li et al., 2023). However, according to Eek and Zobel (2001), the use of fertilizers and mowing did not affect plant diversity and density, but in fertilized areas, additional lighting led to significantly denser grass.

The timing of mowing sorrel also affected the mass of plants. The maximum weight of one shoot in the control in the first mowing was observed when harvesting the grass stand in the flowering and fruiting phase - 83.9-85.9 g, exceeding 2.3-2.4 times compared with annual mowing in the stemming phase (Table 1). In the second cutting, the largest mass of sorrel shoots was observed during annual mowing of the grass stand in the stemming and budding phase - 27.7-32.3 g. This is explained by the fact that the first cutting, harvested in the early phases of crop development, has more time for the formation of the second cutting. When applying mineral fertilizers, there is an increase in the weight of each sorrel plant in the first mowing by 5.9-8.7 g (9-16 %), and in the second by 3.3-7.6 g (14-36 %) compared with the control.

According to our data, the yield of sorrel biomass varied across different growth stages. During the annual harvesting of grass in the stemming phase, the yield of green mass for two cuttings in the control averaged 22.1 t ha^{-1}, while in the budding phase it was higher by 5.0 t ha^{-1} (23 %), and flowering - by 15.1 t ha^{-1} or 68 % (Table 1). It was found that with later mowing of the grass stand, the yield of sorrel green mass decreased. When mowing the grass in the fruiting phase in the control, the yield was 33.9 t ha^{-1}, which was lower by 3.3 t (9 %) with annual mowing in the flowering phase. This is explained by the fact that the harvesting of the first mowing was carried out during the period of moisture outflow from the plants; in addition, drying of the basal and stem leaves in the lower tier of the grass stand was observed, which also affected the decrease in sorrel yield. According to Melnikov (2008), the annual harvesting of perennial forage crops during the flowering phase also contributed to an increase in the yield of green mass to 45.6-46.8 t ha^{-1}. When alternating harvesting periods over the years, the yield of green mass in the control was 27.2-34.5 t ha^{-1} and was 5.1-12.4 t ha^{-1} more (23-56%) than with annual mowing of the grass in the phase stemming. Uteush (1991) also proposed to reduce the negative impact of frequent mowing of sorrel and thinning of the grass, leaving areas for fruiting and seed ripening every three years. Repeated mowing can lead to lower yields in subsequent years due to irreversible tissue damage. Consequently, it was determined that the yield of a single mowing in the second year is 22-51% higher than that of mowing three times per season in the first year (Temu, Rutto and Kering, 2022).

An increase in yield was also obtained in variants with the application of fertilizers from 5.8 to 7.5 t ha^{-1} of green mass or 20-34 % (Table 1). Studies have shown that the increase in green mass of sorrel from fertilizers will be more significant with the early use of grass. If, during the annual harvesting of the crop in the stemming and budding phase, fractional application of $N_{90}P_{90}K_{90}$ in the fertilizing increased the yield of green mass in total for two cuttings by 6.9-7.5 t ha^{-1} (25-34 %) compared to the control, then in the fruiting phase only by 18 %. Qi et al. (2024) also found that mowing fodder rice (ratun) in the phases of formation of generative organs and milky ripeness with the introduction of nitrogen at a dose of 270 kg ha^{-1} N increased the stubble biomass (up to 73 %) and non-structural carbohydrates (up to 198 %) compared with mowing in later dates.

In the study by de Souza et al. (2023), application of nitrogen fertiliser at a dose of 80 kg ha^{-1} increased maize grain yield by 2988 kg ha^{-1} compared to the control, while application of 160 and 240 kg ha^{-1} resulted in an increase of 5104 kg ha^{-1}. According to Kotas et al. (2017), the combination of grass mowing with fertiliser maintains high species diversity only for a short period, as regular application of mineral fertiliser acidifies the soil and suppresses soil microorganisms.

With early mowing and application of fertilizers, sorrel had better regrowth. Thus, the share of the second cutting of the total harvest during the growing season during the annual harvesting of grass in the stem phase in the control was 39 %, in the budding phase - 29 %, and in the flowering phase - only 18 %. When applying fertilizers, the collection of green mass for the second cutting of the total during the growing season in these phases increased to 21-43 %.

An increase in the proportion of leaves in the total mass of plants was also noted. Thus, on average over the years, with the annual mowing of sorrel grass in the flowering phase in the first mowing, it was 36 % in the control, and when $N_{90}P_{90}K_{90}$ was applied, it was 41 %. In Klimeš and Klimešová (2002) studies, the application of fertilizers increased the foliage of the studied plants by 8-12 %, and the leaf area by 1.5-2.0 m^2 m^{-2}. When mowing the grass in the early phases, the percentage of leaves was higher: on average, in the first cutting in the stemming phase - 55 %, budding - 48 %, and flowering - only 36 %.

The importance of nitrogen is that it is a part of the most important compounds (protein, enzymes, vitamins, etc.), which play a major role in the metabolic processes in plants. Nitrogen fertilisers promote enhanced growth of vegetative mass, but delay ripening. Phosphorus plays an extremely important role in energy metabolism, participates in a variety of metabolic processes, division, and reproduction. Especially great is the role of this element in carbohydrate metabolism, in the processes of photosynthesis, respiration, and fermentation. In case of phosphorus deficiency, growth slows down and delays plant maturation, reduces yield, and deteriorates its quality. Potassium is one of the main, along with nitrogen and phosphorus, necessary elements of mineral nutrition. In case of potassium deficiency and increased transpiration, plants lose turgor and wilt more quickly. Potassium has a positive effect on the intensity of photosynthesis, oxidative processes and the formation of organic acids in the plant, it is involved in carbohydrate and nitrogen metabolism.

The greatest zootechnical efficiency is achieved when using complex fertilizers, taking into account both excess and insufficient nutrient content in the grass (Kulakov and Sedova, 2012). Some authors suggest using high doses of mineral fertilizers when repeatedly mowing the grass. For example, according to Kadzhyulis (1977), on bluegrass grass stands, in order to obtain three cuttings during the growing season, it is necessary to introduce nitrogen at a dose of more than 200 kg a.i. ha^{-1}. Plants need nitrogen for the synthesis of amino acids, proteins, chlorophyll, and metabolites that support photosynthetic carbon assimilation and carbohydrate synthesis (Flexas and Carriquí, 2020). Application of nitrogen increases CP levels and increases metabolic rate, but the effect on crude fiber and DM digestibility is variable. Higher nitrogen rates ensure an increase in the amount of fiber in plants in wetter years as a result of a change in the ratio of leaves to stems in favor of less digestible stems (Coleman et al*.,* 2004; Gong et al*.,* 2022).

Kharkevich et al. (2017) in experiments with perennial grasses established that the use of mineral fertilizers at a dose of $N_{180}P_{120}K_{180}$ contributed to an increase in the yield of green mass by 6 times in comparison with the option without their application. In addition, nitrogen at a dose of N_{180} increases the carotene content, but at the same time, the collection of feed units decreases due to a decrease in the yield of absolute DM. Parakhin (1997) recommends applying high rates of nitrogen in fractions after each mowing, due to the fact that nitrogen fertilizers are quickly absorbed by plants and have a weak aftereffect; this technique will ensure their more complete use; it also contributes to a significant increase in the leaf surface of grasses. However, high doses can cause a delay in plant maturation, increasing the ripening period and overall biomass digestibility (Coleman et al., 2004). According to Kazantsev (2001), who studied the effect of mineral fertilizers on the productivity of plants of the cabbage family, a high background of nitrogen nutrition delays their aging and maturation by an average of 2-4 days. From a physiological point of view, he explains this by the fact that in the hormonal system of plants from nitrogen fertilizers, phytohormones - growth stimulants are suppressed by growth inhibitors (abscisic acid, ethylene). An increase in nitrogen nutrition in wet years ensures the growth of fungal and bacterial communities due to acidification of the pH of the environment and imbalance of nutrients, while mowing reduces the negative effect of high doses of nitrogen by removing part of it with the mowed mass (Cui et al., 2020).

Annual application of phosphorus (10 g P m^{-2} $year^{-1}$) and nitrogen fertilizers (15 g N m^{-2} $year^{-1}$) to low-productivity upland meadows of northern Greece contributed to an increase in their productivity due to changes in environmental pH and increased species diversity (Veresoglou et al., 2011). Stepanov et al. (2015) note that the application of $N_{90}P_{90}K_{90}$ helps to increase the carbohydrate content in bluegrass grasses, which is associated with their intensive regrowth after cutting due to the use of nitrogen fertilizers and, thus, the rapid replenishment of reserve nutrients in plants. At the same time, nutritious Fertilizer substances in the early phases are used by the plant mainly for growth processes, and in the later phases they have a greater influence on the chemical composition (Tjul'djukov and Mihalev, 1986). To provide plants with nutrition during all periods of their growth and development, it is necessary to know the dynamics of nutrient consumption during the growing season of the crop.

Full mineral fertilizer, applied in the spring and after the first mowing, had a positive effect on increasing the nutritional value of the green mass of sorrel due to greater foliage of plants by 4-6%, and reduced the negative consequences of annual frequent and early mowing of the grass stand. For example, fractional application of nitrogen fertilizer during the growing season reduced NO_3^--N leaching without affecting wheat yield (Torabian et al., 2023).

During the years of research with acute drought and lack of precipitation, the effectiveness of mineral fertilizers was lower; the highest level of yield was achieved with the annual application of $N_{90}P_{90}K_{90}$ only when mowing in the flowering and fruiting phases. Terminal stress reduces nitrogen metabolism by decreasing photosynthesis, which is reflected in the loss of nutrients, reduced plant development and worse product quality. However, increased nitrogen application helps to reduce the damage caused by temperature effects (Hammer et al*.,* 2018; James et al*.*, 2018; Ru et al., 2022). Thus, in studies by Luo et al. (2023), it was found that at high temperatures, nitrogen doses of 230.23 kg hm^2, 230.02 kg hm^2 and 115.32 kg hm^2 had a positive effect on plant growth and yield.

The establishment of correlations showed that the yield of green mass of hybrid sorrel in the first cutting is in close direct dependence on the density of the grass stand (r = 0.83±0.15), weight (r = 0.79±0.17) and plant height (r = 0.70±0.19). In the second mowing, the relationship between these indicators weakens, between the yield of green mass and shoot mass (r = 0.65±0.21), grass density (r = 0.56±0.23) and plant height (r = 0.47 ±0.24). At the same time, a close relationship was revealed between the yield of green mass and the collection of DM: in the first mowing r = 0.99 ± 0.04, in the second mowing r = 0.99±0.01.

The minimum amount of DM (1.60 t ha^{-1}) was observed during annual mowing of the crop in the stemming phase, which is associated with a smaller amount of green mass per hectare with such use of grass and its low DM content - 7.8-8.5 % (Table 2). As the plants further developed, the DM content in them increased: in the budding phase to 10.2 %, flowering - 15.7 % and fruiting - 16.4 %.

When harvesting sorrel annually in the budding phase, its harvest was 49% more than in the stemming phase. With annual mowing in the flowering and fruiting phase, the DM collection increased to 4.97-5.14 t ha^{-1}, which is 3.1-3.2 times more than in the stemming phase. When alternating the timing of sorrel harvesting from year to year in different phases, compared with annual mowing in the stemming phase, there was an increase in the collection of DM by 1.41-2.83 tons (88-177%), CP by 218-446 kg (60-122%) (Table 2).

The greatest productivity was observed when harvesting sorrel grass annually in the flowering phase - DM collection - 5.14 t ha^{-1} and CP - 907 kg ha^{-1}, and when applying $N_{90}P_{90}K_{90}$ respectively - 5.94 t ha^{-1} and 1067 kg ha^{-1} or 16-18% more than without the use of fertilizers. In the variants with alternating harvesting times over the years, the highest productivity indicators were when mowing sorrel during budding - fruiting - flowering: DM collection was 4.43 t ha^{-1}, CP 812 kg ha^{-1}.

However, with earlier mowing of the first mowing, a higher content of CP is noted, and with later mowing, an increase in fiber is noted (Holman et al., 2018; Zhao et al., 2021). According to Stepanov et al. (2015) the percentage of DM content in the stemming phase of CP is 29.2 %, fiber - 25.1 %, and in the flowering phase - 23.3 % and 28.4 %, respectively. At the same time, when harvesting grass at the end of the growing season, the authors note a decrease in the quality of feed, which may affect the productivity of animals. This is largely due to the increase in the proportion of stems in the total mass and their maturation. Tanaka et al. (2016) suggest that different timing of harvesting crop biomass affect the seasonal dynamics of non-structural carbohydrates between shoots and rhizomes, and subsequently affects the nutritional value of roughage. Harvesting plants early, during the period of active growth, leads to higher losses of nutrients (Petrov et al., 2020).

Discussion

Extreme heat or cold can kill farm animals, making climate stress one of the most significant elements affecting their metabolism and productivity (Marai et al., 2007). The hot, arid savannah regions of Nigeria are ideal for Sokoto red goats. Approximately 70% of Nigeria's sheep and goat populations are concentrated in the dry savannah zone or northern region since they frequently die from pneumonia or the cold when raised in the country's humid southern and sub-humid zones (Adedeji et al., 2006; Anoh et al., 2021). Despite the fact that the majority of these native goats are not seasonal breeds, they frequently show signs of prolonged anoestrus, reduced ovulation rates, anovulation, high embryonic and foetal losses, and poor sperm production due to inadequate nutrition and occasionally environmental factors (Oni, 2002; Rojero et al., 2005; Bushara et al., 2016). The distribution and productivity of ruminants in Nigeria are significantly influenced by seasonal and climatic changes (Marai et al., 2007). Selection for genetically superior people as parent stock for subsequent generations is typically impeded by non-genetic factors that obscure the true breeding values of the selected individuals (Dadiet al., 2008).

Numerous authors have reported that vitamin E improves animals' immune responses and reduces their susceptibility to common infections, which supports the observed significant effect of vitamin E on the majority of the physiological stress parameters studied (Cusack et al., 2009; Chandra et al., 2013; Idamokoro et al., 2020). Vitamin E incorporation in feed has been linked to improved hatchability, growth rates, and egg production in chicken (Rengaraj and Hong, 2015). In addition, pigs develop faster, experience less stress, and have better-quality meat (Shastaket al., 2023). The notable rise in body weight supports Lu et al. (2014)'s finding that vitamin E administration enhances growth performance. Though it was within the typical range for goats, it also markedly raised the rectal temperature. Given that vitamin E is a potent chain-breaking antioxidant that prevents lipid peroxidation, the rise in rectal temperature may be the consequence of increased cellular activity (Burton et al., 1982; Traber and Atkinson, 2007). Altesman and Cole (1983) reported that vitamin E has an antidepressant-like effect by lowering oxidant alterations brought on by stress in a secondary role with antioxidants such glutathione peroxidase and superoxide dismutase. Vitamin E has antioxidant qualities that assist reduce stress, just like vitamin C. The body uses a lot of nutrients when under stress, which leads to oxidative stress and free radicals (Wang et al., 2003). This is why animals' development and body weights have been shown to increase. It stops lipid peroxidation, which is its antioxidant mechanism (Lee et al., 2022).

According to Lu et al. (2014) and Al-Sowayan and Almarzougi (2024), the effective use of nutrients in the cell membranes by averting free radical reactions may be the cause of the noted notable decrease in total cholesterol, low density lipoprotein, and triglycerides. Okosun and Adu (2015) found that oral vitamin E intake had no discernible impact on a human subject's serum cholesterol profile, which runs counter to the current observation. Additionally, it has been shown to raise serum HDL cholesterol (Yoon et al., 1984) but shield low-density lipoprotein cholesterol from lipid peroxidation (Princenet al., 1995), which was not the case in this investigation.

Vitamin E was found to have a major impact on male sex hormones, increasing levels of testosterone and oestrogen while decreasing concentrations of prolactin and luteinizing hormone. According to Yin et al. (2011), oral vitamin E supplementation reverses the effects of dioxin on testosterone, sperm concentration, and testis structure in rats that have been harmed by the toxin. Vitamin E counteracts the reproductive endocrine toxicity and mitigates the structural alterations in the testicles brought on by polychlorinated biphenyl (Aroclor 1254) and dioxin (2, 3, 7, 8-tetrachlorodibenzo-p-dioxin) (Moore and Wray, 2000). Since vitamin E has been shown to modulate its release from the anterior pituitary in male rats, the increased supplementation may be the cause of the lower levels of prolactin and luteinizing hormone (Karanth et al., 2003). It has been observed that giving Boer goats an 80 IU daily vitamin E supplement improves their reproductive health by increasing the quantity of epithelium, seminiferous tubule diameter, and Sertoli and Leydig cells (Zhu et al., 2009). The Leydig cells produce androgen (testosterone), and the Sertoli cells are crucial for both the transit and maintenance of androgens in the testes (Cooper et al., 1987; Zubair, 2017).

Additionally, it was shown that vitamin E treatment significantly increased sperm motility and acrosome integrity while decreasing progressive motility, sperm abnormalities (tail to tail and head to head attachment), and dead spermatozoa. According to earlier research, vitamin E's ability to stop free radical reactions in cells may improve sperm performance and activity (Tengerdy et al., 1984; Yousef et al., 2003; Li et al., 2006; Palaniappan et al., 2007). Its application increases sperm motility and fertilizing capacity in hamster egg penetration, according to in vitro research (Plante et al., 1994; Zubair, 2017). Additionally, it was found to be successful in mitigating the detrimental effects of reactive oxygen species (ROS) on sperm concentration and motility in in-vivo experiments (Keskes-Ammar et al., 2003). Through the decrease of malondealdehyde (MDA), the byproduct of lipid peroxidation, oral gavage significantly improved sperm motility (Suleiman et al., 1996). An imbalance between the body's capacity to detoxify or repair the damage caused by reactive oxygen species (ROS) and ROS generation results in oxidative stress (Makpol et al., 2010). According to reports, ROS can harm DNA, proteins, and cell membranes, impairing cellular function and making a person more vulnerable to a number of illnesses (Li et al., 2006). According to reports, vitamin E deficiency alters the structure of spermatozoa, which increases abnormalities, testicular dysfunction, and seminiferous tubule shrinkage (Suleiman et al., 1996; Todorovic et al., 2004). In addition to its antioxidant properties, vitamin E improves the activity of antioxidant enzymes in animals, including glutathione peroxidase and superoxide dismutase (SOD) (Wilson et al., 2003; Wang et al., 2007).

Table 3: Influence of the regime of use of grass and fertilizers on the collection of DM, CP and total energy output of hybrid sorrel, source: own study

Mowing period (development phase)	Background power supply	DM (t ha^{-1})	CP (kg ha^{-1})	Gross energy yield (GJ ha^{-1})
Annual mowing of sorrel grass in the phase				
Stemming	without fertilizer	1.60	366	27.7
	$N_{90}P_{90}K_{90}$	2.07	478	35.8
Budding	without fertilizer	2.38	515	41.4
	$N_{90}P_{90}K_{90}$	2.85	623	49.6
Flowering	without fertilizer	5.14	907	89.4
	$N_{90}P_{90}K_{90}$	5.94	1067	103.4
Fruiting	without fertilizer	4.97	839	83.5
	$N_{90}P_{90}K_{90}$	5.67	974	95.8
Mowing the grass stand with alternating harvesting periods (development phase) by year				
Stemming, flowering, budding	without fertilizer	3.01	585	42.1
	$N_{90}P_{90}K_{90}$	3.57	706	51.8
Stemming, fruiting, budding	without fertilizer	3.10	584	43.6
	$N_{90}P_{90}K_{90}$	3.65	703	53.2
Stemming, fruiting, flowering	without fertilizer	3.81	686	49.9
	$N_{90}P_{90}K_{90}$	4.40	804	60.1
Budding, fruiting, flowering	without fertilizer	4.43	812	76.6
	$N_{90}P_{90}K_{90}$	5.01	930	86.7

When assessing the energy use regime of hybrid sorrel herbage, it was found that with annual early mowing (stemming), the gross energy output is 1.5 times less in comparison with annual harvesting in the budding phase, and 3.2 times in the flowering phase (Table 3). When alternating harvesting dates over the years in comparison with annual early mowing (stemming phase), an increase in gross energy output by 1.5-2.8 times was noted. When applying fertilizers, the amount of energy obtained from the crop increased by 13-29%, compared to the option without application. The total energy output of hybrid sorrel ranges from 76.6 to 89.4 GJ ha-1. In comparison, the total energy output per hectare is 33.8 GJ ha-1 for spring rapeseed and 85.6 GJ ha-1 for winter rapeseed (Isaeva, 2022). For maize, the energy yield reaches 93.88 GJ ha-1 when harvesting cobs and 66.32 GJ ha-1 when harvesting grain (Zudilin, 2006). This indicates its energy efficiency as a raw material for biofuel. According to Ust'ak (2021), hybrid sorrel can generate a methane yield ranging from 2500 to 3000 m3 per hectare. Additionally, as a biofuel, its DM exhibits a calorific value of up to 18 MJ/kg.

To evaluate the relative performance of hybrid sorrel, we compared its productivity and energy efficiency with other commonly cultivated forage and energy crops such as alfalfa, smooth brome, maize, and rapeseed. The total energy output of hybrid sorrel (up to 89.4 GJ ha^{-1}) was comparable to winter rapeseed (85.6 GJ ha^{-1}) and maize (93.88 GJ ha^{-1}), while exceeding that of spring rapeseed (33.8 GJ ha^{-1}). In terms of fodder quality, sorrel showed higher carotene levels and lower fiber content than alfalfa and smooth brome, making it a competitive alternative in forage systems.

Study Limitations and Future Directions

This study was conducted within a single agro-climatic zone - the southern forest-steppe of Western Siberia. As such, the findings may not be directly generalizable to other ecological regions with different soil and climate conditions. Additionally, the methane yield and calorific value were derived from literature sources and not measured experimentally, which limits the precision of energy potential estimates. Future studies should aim to validate the results under diverse environmental conditions and include direct measurements of biochemical energy indicators to strengthen the conclusions.

Although this study primarily focused on biomass yield and energy output, the perennial nature of hybrid sorrel allows for reduced annual input costs, such as replanting and tillage. Moreover, the crop's positive response to moderate levels of mineral fertilizers indicates potential for optimizing nutrient input while maintaining high productivity. These factors suggest that hybrid sorrel may be economically viable under low-input farming systems. However, a full economic feasibility assessment - considering costs of cultivation, energy conversion, and market demand - should be addressed in future studies.

Conclusion

To obtain maximum productivity and reduce the negative impact of early mowing on the herbage of hybrid sorrel, it is better to mow it annually in the flowering phase or alternate the timing of harvesting the first mowing over the years (budding - fruiting - flowering), with these modes of use it is possible to obtain green mass of the crop up to 34,5-37.2 t ha-1, gross energy output 76.6-89.4 GJ ha-1. The use of mineral fertilizers (N90P90K90) in sorrel crops makes it possible to obtain up to 40.4-44.6 t ha-1 of green mass under these regimes, and increases its productivity by 13-18 %. It is more effectiveness to apply a dose of fertilizer in two steps: annually in the spring before the grass grows back (45 kg a.i. ha-1) and after the first mowing (45 kg a.i. ha-1).

Although this study was conducted within a single agro-climatic zone, future research should aim to test hybrid sorrel under varying ecological conditions (e.g., arid, humid regions) to assess its regional adaptability and verify the robustness of the observed results.

Acknowledgment

We thank the editor and the reviewers for their suggestions for revising our manuscript.

Funding Information

The authors have no support or funding to report.

Authors Contributions

Altinay Naziulovna Kukusheva: Supervised the study, conducted the literature review and drafted the manuscript.
Ainagul Balgauovna Kaliyeva and Zarina Mukhtarovna Sergazinova: Conducted fieldwork and also contributed to manuscript writing.
Aliya Toleuzhanovna Toleuzhanova and Madiana Orazbaikyzy Kabdolla: Developed a research plan and participated in all the experiments.
Irina Yurievna Chidunchi: Visualization, writing-final draft.
Shynar Zhanybekovna Arynova: Conceptualization, writing – final draft, review and editing, correspondence with the journal.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

References

Chaudhry, S., & Sidhu, G. P. S. (2022). Climate change regulated abiotic stress mechanisms in plants: A comprehensive review. *Plant Cell Reports, 41*(1), 1–31. https://doi.org/10.1007/s00299-021-02759-5

Coleman, D. C., Crossley, D. A., & Hendrix, P. F. (2004). *Fundamentals of soil ecology.*

Cui, H., Sun, W., Delgado-Baquerizo, M., Song, W., Ma, J.-Y., Wang, K., & Ling, X. (2020). The effects of mowing and multi-level N fertilization on soil bacterial and fungal communities in a semiarid grassland are year-dependent. *Soil Biology and Biochemistry, 151*, 108040. https://doi.org/10.1016/j.soilbio.2020.108040

De Souza, M., Barcelos, J. P. de Q., & Rosolem, C. A. (2023). Synergistic effects of subsoil calcium in conjunction with nitrogen on the root growth and yields of maize and soybeans in a tropical cropping system. *Agronomy, 13*(6), 1547. https://doi.org/10.3390/agronomy13061547

dos Santos, T. B., Ribas, A. F., de Souza, S. G. H., Budzinski, I. G. F., & Domingues, D. S. (2022). Physiological responses to drought, salinity, and heat stress in plants: A review. *Stresses, 2*(1), 113–135. https://doi.org/10.3390/stresses2010009

Eek, L., & Zobel, K. (2001). Structure and diversity of a species-rich grassland community treated with additional illumination, fertilization, and mowing. *Ecography, 24*(2), 157–164. https://doi.org/10.1034/j.1600-0587.2001.240206.x

Flexas, J., & Carriquí, M. (2020). Photosynthesis and photosynthetic efficiencies along the terrestrial plant's phylogeny: Lessons for improving crop photosynthesis. *The Plant Journal, 101*(4), 964–978. https://doi.org/10.1111/tpj.14651

Gong, J., Zhang, Z., Wang, B., Shi, J., Zhang, W., Dong, Q., Song, L., Li, Y., & Liu, Y. (2022). N addition rebalances the carbon and nitrogen metabolisms of *Leymus chinensis* through leaf N investment. *Plant Physiology and Biochemistry, 185*, 221–232. https://doi.org/10.1016/j.plaphy.2022.06.001

Hammer, K. J., Borum, J., Hasler-Sheetal, H., Shields, E. C., Sand-Jensen, K., & Moore, K. A. (2018). High temperatures cause reduced growth, plant death, and metabolic changes in eelgrass *Zostera marina*. *Marine Ecology Progress Series, 604*, 121–132. https://doi.org/10.3354/meps12740

Harkevich, L., Shapovalov, V. F., Smolsky, E. V., Zholudeva, N. K., & Serdyukova, K. A. (2017). Influence of fertilisers and agro-technological measures in production of hay of perennial grasses on floodplain meadow in conditions of radioactive contamination. *Agrohimicheskij Vestnik, 3*, 15–18.

Heděnec, P., Novotný, D., Ust'ak, S., Honzík, R., Kovářová, M., Šimáčková, H., & Frouz, J. (2014). Allelopathic effect of newly introduced biofuel crops on soil biota: A comparative study. *European Journal of Soil Biology, 63*, 14–20. https://doi.org/10.1016/j.ejsobi.2014.05.002

Heděnec, P., Novotný, D., Ust'ak, S., Honzík, R., Váňa, V., Petříková, V., & Frouz, J. (2015). Effect of long-term cropping of hybrid sorrel (*Rumex patientia* × *Rumex tianshanicus*) on soil biota. *Biomass and Bioenergy, 78*, 92–98. https://doi.org/10.1016/j.biombioe.2015.04.016

Holman, J. D., Obour, A., Roberts, T., & Maxwell, S. (2018). Forage type and maturity effects on yield and nutritive value. *Kansas Agricultural Experiment Station Research Reports, 4*(8), 1–6. https://doi.org/10.4148/2378-5977.7636

Hujerová, R., & Gaisler, L. (2017). Hybrid of *Rumex patientia* × *Rumex tianschanicus* (Rumex OK-2) as a potentially new invasive weed in Central Europe. *Weed Research*, 313–315.

Isaeva, E. I. (2022). The influence of technologies with different levels of chemicalization on the yield and feed characteristics of spring and winter rapeseed in the conditions of the Bryansk region. *Multifunctional Adaptive Fodder Production, 28*(76), 129–133.

James, D., Borphukan, B., Fartyal, D., Ram, B., Singh, J., Manna, M., Sheri, V., Panditi, V., Yadav, R., Achary, V. M. M., & Reddy, M. K. (2018). Concurrent overexpression of *OsGS1;1* and *OsGS2* genes in transgenic rice (*Oryza sativa* L.): Impact on tolerance to abiotic stresses. *Frontiers in Plant Science, 9*, 786. https://doi.org/10.3389/fpls.2018.00786

Kadzhjulis, L. (1977). *Growing perennial grasses for fodder.*

Kazancev, V. (2001). *Rapeseed, oilseed rape and oilseed radish in Siberia.*

Klimeš, L., & Klimešová, J. (2001). The effects of mowing and fertilization on carbohydrate reserves and regrowth of grasses: Do they promote plant coexistence in species-rich meadows? *Evolutionary Ecology, 15*(4–6), 363–382. https://doi.org/10.1023/a:1016041100087

Kotas, P., Choma, M., Šantrůčková, H., Lepš, J., Tříska, J., & Kaštovská, E. (2017). Linking above- and belowground responses to 16 years of fertilization, mowing, and removal of the dominant species in a temperate grassland. *Ecosystems, 20*(2), 354–367. https://doi.org/10.1007/s10021-016-0031-x

Kshnikatkina, A., & Moskvin, A. (2016). Diversification of non-traditional plants as an important factor in sustainable development of fodder production. *Niva Povolzhye, 3*, 49–60.

Kukusheva, A., & Stepanov, A. (2019). Hybrid sorrel: A multipurpose crop. *Internauka, 32*(114), 31–32.

Kulakov, V., & Sedova, E. (2012). Productivity of pastures of different floristic composition and forage quality depending on the level of application of mineral, organic and microfertilisers. *Adaptive Fodder Production, 3*, 20–25.

Li, F., Minggagud, H., Jarvie, S., Wang, Y., Yan, Y., Gong, X., Han, P., & Zhang, Q. (2023). Effects of fertilization on plant diversity and changes in soil bacterial and fungal community structure in the Inner Mongolia grassland. *Agriculture, Ecosystems & Environment, 346*, 108358. https://doi.org/10.1016/j.agee.2023.108358

Luo, J., Yang, Z., Zhang, F., & Li, C. (2023). Effect of nitrogen application on enhancing high-temperature stress tolerance of tomato plants during the flowering and fruiting stage. *Frontiers in Plant Science, 14*, 1172078. https://doi.org/10.3389/fpls.2023.1172078

Malhi, G. S., Kaur, M., & Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability, 13*(3), 1318. https://doi.org/10.3390/su13031318

Mel'nikov, V. (2008). Oriental goatgrass in the Non-Black Earth zone.

Nadezhkin, S., & Satarov, M. (2011). Optimal utilisation regimes of oriental goatgrass (*Galega orientalis* L.). *Kormoproizvodstvo, 7*, 9–10.

Niu, H., Wang, T., Dai, Y., Yao, M., Li, B., Zheng, J., Mao, L., Zhao, M., Xu, Z., & Zhang, F. (2024). Optimal irrigation and fertilization enhanced tomato yield and water and nitrogen productivities by increasing rhizosphere microbial nitrogen fixation. *Agronomy, 14*(9), 2111. https://doi.org/10.3390/agronomy14092111

Noulas, C., Torabian, S., & Qin, R. (2023). Crop nutrient requirements and advanced fertilizer management strategies. *Agronomy, 13*(8), 2017. https://doi.org/10.3390/agronomy13082017

Parahin, N. (1997). Ecological and stabilising importance of forage crops in crop production.

Paušič, I., Kaligarič, M., & Bakan, B. (2017). Late seasonal mowing enhances Central European *Spiranthes spiralis* population viability. *Botany Letters, 164*(4), 401–412. https://doi.org/10.1080/23818107.2017.1396495

Petrov, K. A., Dudareva, L. V., Nokhsorov, V. V., Stoyanov, K. N., & Makhutova, O. N. (2020). Fatty acid content and composition of the Yakutian horses and their main food source: Living in extreme winter conditions. *Biomolecules, 10*(2), 315. https://doi.org/10.3390/biom10020315

Qi, D., Chen, Y., Harrison, M. T., Liu, K., He, H., Ji, C., Du, K., Wang, J., Sun, Y., Yu, G., Liu, Y., Zhao, Y., Zhang, J., Zhao, Q., & Peng, T. (2024). Mowing and nitrogen management guidelines for superior rice ratoon yields. *Field Crops Research, 308*, 109302. https://doi.org/10.1016/j.fcr.2024.109302

Rakhmetov, D. (2018). *Non-traditional plant species for bioenergetics.* https://doi.org/10.15414/2018.fe-9788055218557

Rolinec, M., Rakhmetov, D., Bíro, D., Juráček, M., Šimko, M., Gálik, B., & Hanušovský, O. (2018). Nutritional value of hybrid *Rumex patientia* × *Rumex tianschanicus* in different periods. *Acta Fytotechnica et Zootechnica, 21*(4), 197–200. https://doi.org/10.15414/afz.2018.21.04.197-200

Ru, C., Hu, X., Chen, D., Song, T., Wang, W., Lv, M., & Hansen, N. C. (2022). Nitrogen modulates the effects of short-term heat, drought, and combined stresses after anthesis on photosynthesis, nitrogen metabolism, yield, and water and nitrogen use efficiency of wheat. *Water, 14*(9), 1407. https://doi.org/10.3390/w14091407

Ślesak, H., Liszniańska, M., Popielarska-Konieczna, M., Góralski, G., Sliwinska, E., & Joachimiak, A. J. (2014). Micropropagation protocol for hybrid sorrel (*Rumex tianschanicus* × *Rumex patientia*). *Industrial Crops and Products, 62*, 156–165. https://doi.org/10.1016/j.indcrop.2014.08.031

Tanaka, T. S. T., Irbis, C., Kumagai, H., & Inamura, T. (2016). Timing of harvest of *Phragmites australis* affects canopy structure and nutritive value of roughage. *Journal of Environmental Management, 166*, 420–428. https://doi.org/10.1016/j.jenvman.2015.10.055

Temu, V. W., Rutto, L. K., & Kering, M. K. (2022). Compensatory yield responses of young native warm-season grass stands to seasonal changes in harvest frequencies. *Agronomy, 12*(11), 2761. https://doi.org/10.3390/agronomy12112761

Torabian, S., Farhangi-Abriz, S., Qin, R., Noulas, C., & Wang, G. (2023). Performance of nitrogen fertilization and nitrification inhibitors in irrigated wheat fields. *Agronomy, 13*(2), 366. https://doi.org/10.3390/agronomy13020366

Usťak, S., Šinko, J., & Muňoz, J. (2021). Hybrid sorrel: Cultivation potential and use as a novel non-food multipurpose crop. *Biofuels, Bioproducts and Biorefining, 15*(1), 131–149. https://doi.org/10.1002/bbb.2157

Veresoglou, S. D., Voulgar, O. K., Sen, R., Mamolos, A. P., & Veresoglou, D. S. (2011). Effects of nitrogen and phosphorus fertilization on soil pH–plant productivity relationships in upland grasslands of Northern Greece. *Pedosphere, 21*(6), 750–752. https://doi.org/10.1016/s1002-0160(11)60178-1

Vogel, A., Scherer-Lorenzen, M., & Weigelt, A. (2012). Grassland resistance and resilience after drought depends on management intensity and species richness. *PLoS ONE, 7*(5), e36992. https://doi.org/10.1371/journal.pone.0036992

Wang, Y., Zhang, J., He, C., Meng, P., Wang, J., Gao, J., & Xue, P. (2025). Effects of intercropping and mowing frequency on biological nitrogen fixation capacity, nutritive value, and yield in alfalfa (*Medicago sativa* L.). *Plants, 14*(2), 240. https://doi.org/10.3390/plants14020240

Yang, X., Lu, M., Wang, Y., Wang, Y., Liu, Z., & Chen, S. (2021). Response mechanism of plants to drought stress. *Horticulturae, 7*(3), 50. https://doi.org/10.3390/horticulturae7030050

Yang, Z., Minggagud, H., Baoyin, T., & Li, F. Y. (2020). Plant production decreases whereas nutrient concentration increases in response to the decrease of mowing stubble height. *Journal of Environmental Management, 253*, 109745. https://doi.org/10.1016/j.jenvman.2019.109745

Zhang, Y., Yin, Y., Amombo, E., Li, X., & Fu, J. (2020). Different mowing frequencies affect nutritive value and recovery potential of forage bermudagrass. *Crop and Pasture Science, 71*(6), 610–619. https://doi.org/10.1071/cp19369

Zhang, Y., Wu, X., Wang, X., Dai, M., & Peng, Y. (2025). Crop root system architecture in drought response. *Journal of Genetics and Genomics, 52*(1), 4–13. https://doi.org/10.1016/j.jgg.2024.05.001

Zhao, C., Li, Q., Cheng, L., & Zhong, R. (2021). Effects of mowing regimes on forage yield and crude protein of *Leymus chinensis* in Songnen grassland. *Grassland Science, 67*(4), 275–284. https://doi.org/10.1111/grs.12314

Zuo, H., Yin, S., Wang, T., Xiong, X., Shi, M., & Guo, Q. (2022). Nitrogen application alleviates the adverse effects of defoliation stress on *Lolium perenne* by enhancing the antioxidant system and promoting photosynthesis. *Agronomy, 12*(11), 2902. https://doi.org/10.3390/agronomy12112902