Original scientific paper
DOI: /10.5513/JCEA01/27.3.5041
Journal of Central European Agriculture, 2026, 27(3), p.868-880

Strategic liming for sustainable forage production on acidic alluvial soil

Kalcizacija kao strateška mera za održivu proizvodnju krme na kiselom aluvijalnom zemljištu

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Received: October 3, 2025; accepted: January 9, 2026

ABSTRACT

The objective of this long-term field study was to evaluate the impact of soil liming on the species interactions, productivity and ecological stability of a tall fescue (*Festuca arundinacea* Schreb.) and red clover (*Trifolium pratense* L.) mixture, with the aim of supporting the development of sustainable forage management systems. The experiment was conducted from 2014 to 2020 on acidic alluvial soil in Čačak, Serbia, using a randomized block design with three liming treatments: control (A_1), 3 t/ha CaO (A_2), and 6 t/ha CaO (A_3). Results demonstrated that pre-sowing liming significantly improved forage and hay yields, increased the proportion of red clover in the plant community, and reduced weed proportion, particularly under favorable climatic conditions. Liming also mitigated drought-induced adverse effects, with the most pronounced benefits observed during the second and third production years. Residual effects persisted for up to seven years, indicating long-term agronomic value. The crop response was governed by the interaction between lime rate, rainfall distribution, and species developmental stages. The study revealed complex, non-linear responses to liming. Results underscore the role of liming not only as a corrective measure for soil acidity but as a strategic agroecological intervention for establishing stable and low-input forage systems, contributing to the restoration of degraded soils and the advancement of sustainable agriculture.

Keywords: liming, red clover, sustainable management systems, tall fescue

ABSTRAKT

Cilj ove dugoročne terenske studije bio je da se proceni uticaj kalcizacije zemljišta na interakciju vrsta, produktivnost i ekološku stabilnost smeše visokog vijuka (*Festuca arundinacea* Schreb.) i crvene deteline (*Trifolium pratense* L.), sa namerom da se podrži razvoj održivih sistema upravljanja krmnim biljem. Eksperiment je sproveden u periodu od 2014. do 2020. godine na kiselom aluvijalnom zemljištu u Čačku, Srbija, korišćenjem potpuno slučajnog blok sistema sa tri tretmana kalcizacije: kontrola (A_1), 3 t/ha CaO (A_2) i 6 t/ha CaO (A_3). Rezultati su pokazali da je kalcizacija pre setve značajno uticala na povećanje prinosa krme i sena, povećanje udela crvene deteline u biljnoj zajednici i smanjenje prisustva korova, naročito u povoljnim klimatskim uslovima. Kalcizacija je takođe ublažila negativne efekte izazvane sušom, pri čemu su najizraženiji benefiti zabeleženi tokom druge i treće godine proizvodnje. Rezidualni efekti su trajali do sedam godina, što ukazuje na dugoročnu agronomsku vrednost kalcizacije kao mere. Odgovor useva zavisio je od interakcije između količine primenjenog kreča, raspodele padavina i razvojnih faza biljnih vrsta. Studija je otkrila složene, nelinearne odgovore na kalcizaciju. Rezultati naglašavaju ulogu kalcizacije ne samo kao korektivne mere za smanjenje kiselosti zemljišta, već i kao strateške agroekološke intervencije za uspostavljanje stabilnog i niskoinputnog sistema proizvodnje krme, doprinoseći obnovi degradiranih zemljišta i unapređenju održive poljoprivrede.

Ključne reči: crvena detelina, kalcizacija, održivi sistemi upravljanja, visoki vijuk

INTRODUCTION

In recent years, measures for the ecological intensification of agriculture have been increasingly discussed (Reinsch et al., 2021). Agriculture can no longer be managed in the same way as it was two or three decades ago (Ayarza et al., 2022). Sustainable agriculture increasingly relies on soil management practices that enhance productivity while preserving ecological integrity.

One of the major constraints in many agricultural regions is soil acidity, which limits nutrient availability, impairs microbial activity, and reduces crop performance (Yan et al., 2021). In many countries and regions, acid soil management is becoming one of the most important points in the strategy to achieve food security. It is a major challenge that requires investment, analysis, and knowledge to develop and apply practices that are sustainable (Agegnehu et al., 2021). Liming, the application of calcium-containing materials to acidic soils, is a well-established strategy for correcting pH levels, improving soil structure, and creating favorable conditions for plant growth (Rengel, 2011; Bolan et al., 2023; Kharel et al., 2024).

The conservation and introduction of plant diversity today are seen as a key factor for sustainable farming systems (Kremen et al., 2018). Increasing species diversity improves nutrient utilization, stabilizes biomass yield, and controls weeds (Tahir et al., 2022). Mixed forage systems, particularly those combining legumes and grasses such as red clover (*Trifolium pratense* L.) and tall fescue (*Festuca arundinacea* Schreb.), are gaining attention for their ecological and agronomic benefits. These mixtures offer enhanced nitrogen fixation and less nitrogen leaching, improved forage quality, and greater resilience to environmental stressors, making them ideal candidates for sustainable agricultural production systems (Suter et al., 2015; Brink et al., 2021). The grass-legume mixtures contribute to stable biomass production and reduced reliance on synthetic inputs (Tomić et al., 2023).

While the benefits of liming on individual crop species are well documented, its influence on species interactions, forage yield, and botanical composition within mixed stands remains underexplored. Recent studies suggest that optimal soil pH can significantly alter competitive dynamics between legumes, grasses, and weeds, potentially increasing legume dominance and improving overall forage quality (Kopittke et al., 2019; Bi et al., 2024; Tomić et al., 2025). Understanding these interactions is critical for designing agroecological systems that maximize productivity and sustainability.

This study aims to evaluate the impact of pre-sowing soil liming as a soil management strategy on the species interactions in a red clover–tall fescue mixture, focusing on fresh biomass yield, hay yield, and species proportion in certain existing climatic conditions during the entire period of crop utilization. The findings are expected to support sustainable forage production and promote ecological balance in agricultural lands.

MATERIALS AND METHODS

The field trial was conducted over a seven-year period (2014–2020) at the experimental site of the Veterinary Extension Service in Čačak, Serbia (43°54'39.06" N, 20°19'10.21" E; 246 m a.s.l.). The experiment was established on alluvial soil characterized by acidic reaction (Table 1). Prior to the initiation of the trial, the site was under natural meadow vegetation. Soil fertilization was performed in the autumn preceding sowing and at the onset of each growing season, applying 45 kg/ha of nitrogen (N), 45 kg/ha of phosphorus (P_2O_5), and 45 kg/ha of potassium (K_2O).

During the study period, the mean annual air temperature in the investigated area was 12.5 °C. Monthly average temperatures ranged from 2.0 °C in January to 22.6 °C in August (Figure 1). The average annual precipitation amounted to 676 mm, with the highest rainfall typically recorded during the May–June period. Interannual variability was notable, with the highest total precipitation observed in 2014 (exceeding 900 mm), while the lowest was recorded in 2020 (below 500 mm).

Table 1. Physico-chemical properties of the soil

Parameter	Value	Parameter	Value	Parameter	Value
Type of soil	Fluvisol	$CaCO_3$	not detectable	Co	27.2 mg/kg
Soil profile	Ah-Bt-C	P_2O_5	22.1 mg/100 g	Na	278.0 mg/kg
Physical clay	75.1%	K_2O	30.0 mg/100 g	Cr	79.6 mg/kg
Silt content	35.0%	Al	12.0 mg/kg	Ni	113.0 mg/kg
Soil structure	cloddy	Mn	1.1 mg/kg	Pb	30.4 mg/kg
pH(H_2O)	4.8	Zn	82.0 mg/kg	Hg	29.2 µg/kg
pH(KCl)	3.6	Fe	38.9 mg/kg	Cd	141.0 µg/kg
Organic mat.	3.18%	Cu	25.0 mg/kg	As	17.2 µg/kg

The experiment was established as a completely randomized block design with four replications. Each plot measured 5 × 1 m, with a 0.5 m buffer zone between adjacent plots. Three liming treatments were applied: A_1 – control (0,0 t/ha CaO), A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO. Unhydrated lime (CaO) was applied once, by ploughing to a depth of 25 cm, prior to the onset of the growing season in February of the establishment year. The lime material applied was obtained by calcination of natural limestone at a temperature of 900 °C and has the following characteristics: it contains approximately 98% CaO, a neutralisation value of 179%, a pH value of 12.5, and a specific electrical conductivity in the range of 0.02–0.08 S/m (20–25 °C).

Sowing was performed on March 20, 2014, with a row spacing of 20 cm. Tall fescue (*Festuca arundinacea*, cv. K-20) and red clover (*Trifolium pratense*, cv. Kolubara) were sown in mixed rows at a seeding rate of 12 kg/ha for each species. Weed control was conducted mechanically on two occasions. The crop was cultivated under rainfed conditions, without supplemental irrigation. Mowing was performed during the budding stage of red clover. The grassland was mown three times during the years 2014 and 2018, while in the remaining years, only two cuts were performed due to drought-induced limitations. Forage yield (t/ha) was assessed by measuring the total aboveground biomass from each plot immediately following mowing. Subsequently, a subsample of 1000 g was collected to determine forage moisture content.

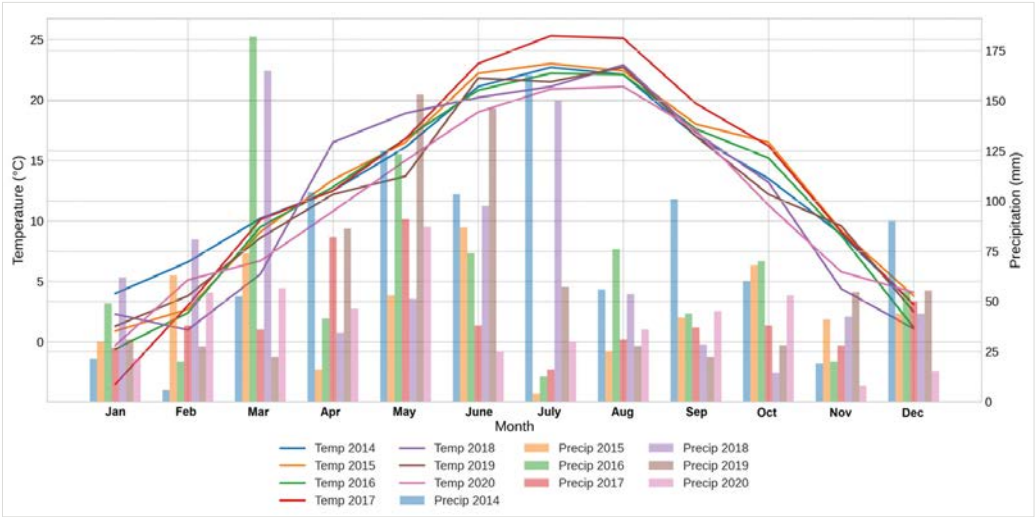


Figure 1. Average monthly temperature and monthly precipitation distribution for the experimental period (Republic Hydrometeorological Service of Serbia)

Plant biomass was classified into three functional groups: tall fescue, red clover, and weeds (other accompanying species). Samples were oven-dried at 65 °C to determine dry matter yield (t/ha). The relative proportion of each plant group within the dry matter was then calculated.

The collected data were analysed using a one-way analysis of variance (ANOVA), with soil liming treatments considered as fixed effects. Statistical analysis was performed using STATISTICA 8 software (StatSoft Inc., 2007), and differences between treatment means were evaluated using the Least Significant Difference (LSD) test.

RESULTS AND DISCUSSION

The application of lime before sowing significantly influenced both forage and hay yields across the study period (Tables 2 and 3; Figure 2).

In the initial years (2014–2017), liming treatments (3 and 6 t/ha CaO) consistently resulted in higher biomass production compared to the control, with the most pronounced effects observed in the first cuts of 2014 and 2016. For instance, in the first cut of 2016, forage yield increased by 36.7% and 47.9% under 3 and 6 t/ha CaO, respectively, compared to the control. According to Rengel (2011) and Fageria and Baligar (2008), liming had a positive effect on hay yield, especially in the first cuts, due to improved soil structure and nutrient availability. Low pH adversely affects all stages of plant development, including disease resistance, cold tolerance, longevity, yield, and forage quality (Jan et al., 2023). Acidic soils are characterised by elevated concentrations of mobile Al (Li et al., 2024), which was also observed in the control treatment of this experiment. At pH levels below 5.0, Al becomes highly soluble and dominates the soil solution, leading to root tip damage and inhibited elongation (Krstić et al., 2015; Grafu et al., 2024).

Table 2. The influence of soil liming treatments (control, 3 t/ha and 6 t/ha CaO) on the productivity of the crop in the period 2014-2017 (n = 9)

Cut	Liming	Forage yield (t/ha)	Hay yield (t/ha)	Grass proportion (%)	Clover proportion (%)	Weed proportion (%)
			2014			
1	Control	22.8 ± 3.40^{b}	5.59 ± 0.64^{b}	5.5 ± 0.17	64.1 ± 3.23	30.4 ± 3.18
	3 t/ha	31.5 ± 0.17^{a}	6.72 ± 0.01^{a}	5.4 ± 0.18	66.1 ± 1.47	28.5 ± 1.45
	6 t/ha	32.4 ± 1.78^{a}	7.26 ± 0.11^{a}	5.4 ± 0.23	56.5 ± 4.92	38.1 ± 3.15
P		*	*	ns	ns	ns
2	Control	26.9 ± 0.58	8.34 ± 0.10^{a}	3.2 ± 0.14	89.0 ± 2.66	7.8 ± 2.58
	3 t/ha	29.2 ± 3.08	8.62 ± 0.04^{a}	3.3 ± 0.17	91.7 ± 2.56	5.1 ± 2.38
	6 t/ha	29.0 ± 0.93	7.67 ± 0.01^{b}	3.5 ± 0.26	88.0 ± 3.43	8.5 ± 2.20
P		ns	*	ns	ns	ns
3	Control	5.46 ± 0.14^{b}	1.13 ± 0.02^{b}	2.0 ± 0.01	97.3 ± 0.23	0.7 ± 0.23
	3 t/ha	7.86 ± 0.48^{a}	1.78 ± 0.02^{a}	2.1 ± 0.03	89.8 ± 3.11	8.1 ± 1.11
	6 t/ha	7.46 ± 0.22^{a}	1.60 ± 0.16^{a}	2.1 ± 0.29	93.0 ± 3.05	4.9 ± 0.89
P		*	*	ns	ns	ns

Continued. Table 2

Cut	Liming	Forage yield (t/ha)	Hay yield (t/ha)	Grass proportion (%)	Clover proportion (%)	Weed proportion (%)
			2015			
1	Control	27.97 ± 1.97	8.62 ± 0.95	78.0 ± 1.22^{a}	21.5 ± 0.95^{c}	0.5 ± 0.03^{b}
	3 t/ha	33.79 ± 0.97	9.29 ± 0.54	42.4 ± 2.33^{b}	53.7 ± 2.43^{b}	3.9 ± 0.12^{a}
	6 t/ha	33.89 ± 1.28	8.79 ± 0.02	20.2 ± 1.97^{b}	79.7 ± 3.38^{a}	0.1 ± 0.01^{b}
	P	ns	ns	*	*	*
2	Control	14.37 ± 1.61^{b}	4.22 ± 0.37^{b}	73.0 ± 2.17^{a}	24.8 ± 2.28^{c}	2.2 ± 0.18
	3 t/ha	17.54 ± 0.91^{a}	4.80 ± 0.20^{a}	50.8 ± 0.68^{b}	48.8 ± 0.89^{b}	0.4 ± 0.21
	6 t/ha	19.09 ± 1.29^{a}	4.96 ± 0.30^{a}	23.6 ± 1.13^{c}	76.4 ± 1.13^{a}	0.1 ± 0.01
	P	*	*	*	*	ns
			2016			
1	Control	49.90 ± 2.00^{b}	12.25 ± 0.21^{b}	98.7 ± 0.15	0.7 ± 0.16	0.6 ± 0.01
	3 t/ha	68.20 ± 4.00^{a}	15.02 ± 0.92^{a}	97.1 ± 0.83	1.1 ± 0.03	1.8 ± 0.11
	6 t/ha	73.80 ± 3.11^{a}	15.61 ± 0.96^{a}	97.0 ± 1.21	2.4 ± 0.17	0.6 ± 0.02
	P	*	*	ns	ns	ns
2	Control	14.57 ± 0.41^{c}	4.5 ± 0.09^{b}	97.6 ± 0.92^{a}	1.4 ± 0.45^{b}	1.0 ± 0.08^{b}
	3 t/ha	17.59 ± 0.87^{b}	5.8 ± 0.14^{a}	83.7 ± 2.47^{ab}	15.0 ± 1.77^{a}	1.3 ± 0.07^{b}
	6 t/ha	19.13 ± 0.96^{a}	5.9 ± 0.23^{a}	78.9 ± 6.62^{b}	18.1 ± 1.79^{a}	3.0 ± 0.40^{a}
	P	*	*	*	*	*
			2017			
1	Control	23.79 ± 0.89^{c}	8.07 ± 0.03^{b}	97.0 ± 1.43^{a}	1.8 ± 0.25^{b}	1.2 ± 0.43^{b}
	3 t/ha	39.16 ± 1.45^{a}	11.80 ± 0.51^{a}	97.5 ± 0.54^{a}	2.4 ± 0.54^{a}	0.1 ± 0.01^{b}
	6 t/ha	29.94 ± 1.61^{b}	8.16 ± 0.45^{b}	91.8 ± 0.55^{b}	5.3 ± 0.18^{a}	2.9 ± 0.62^{a}
	P	*	*	*	*	*
2	Control	6.22 ± 0.31^{b}	2.81 ± 0.04^{b}	86.7 ± 0.57^{a}	10.4 ± 0.18^{c}	2.9 ± 0.75^{a}
	3 t/ha	11.08 ± 0.45^{a}	4.11 ± 0.32^{a}	64.2 ± 2.63^{b}	31.8 ± 1.98^{b}	4.0 ± 0.64^{a}
	6 t/ha	10.46 ± 0.79^{a}	2.98 ± 0.13^{b}	43.3 ± 2.35^{c}	46.7 ± 2.24^{a}	10.0 ± 1.23^{b}
	P	*	*	*	*	*

Data represent mean ± SE. The values denoted with different small letters within columns are significantly different ($P<0.05$) in accordance with the LSD test; *P* indicates the significance of liming effects within the F test, ns – non-significant, * - $P<0.05$

Impaired root growth reduces water and nutrient uptake, diminishing drought tolerance and further suppressing plant growth and yield (Chakraborty et al., 2024). Liming primarily neutralises active acidity, followed by the incorporation of Ca into the soil's adsorptive complex, which mitigates exchangeable acidity and reduces overall metal toxicity (Olego et al., 2021). Calcification in this experiment resulted in an increase in soil pH from 4.8 to 6.1 (A_2) and to 6.3 (A_3), thereby boosting the availability of nutrients (Gurmu et al., 2025a). In acidic soils, elements such as Al, Mn, and Fe are more soluble and potentially toxic, whereas under neutral conditions their solubility decreases, reducing toxicity and improving growth conditions (Ofoe et al., 2022; Gurmu et al., 2025b). Furthermore, in similar types of acidic soils, studies have demonstrated that during pedogenesis, leaching of base cations such as Ca^{2+}, Mg^{2+}, and K^{+} from the surface Ap horizon into deeper soil layers frequently occurs (Agegnehu et al., 2021). Therefore, liming not only optimizes soil pH but also contributes to the replenishment and availability of essential nutrients, thereby supporting improved crop performance (Gurmu et al., 2025a; Gurmu et al., 2025b). This process also enhances microbial activity and nitrogen mineralization (Meena et al., 2021), creating favourable conditions for symbiotic nitrogen fixation. Furthermore, studies indicate that liming decreases the concentration of mobile and toxic forms of Al, Fe, and Mn, while increasing the availability of P_2O_5 (Olego et al., 2021; Chakraborty et al., 2024). In mixed swards of red clover and Italian ryegrass, liming has been shown to significantly improve forage and hay yields (Tomić et al., 2019). Enhanced nitrogen fixation can contribute up to 300 kg/ha N (Kristensen et al., 2022). The abundance and activity of nitrogen-fixing microorganisms in perennial legumes are significantly limited under low pH conditions, impairing nodule formation and reducing legume yield (Burns et al., 2020; Alves et al., 2021). Al toxicity and soil acidity also suppress microbial activity and disrupt nutrient cycling (Kunito et al., 2016). Increasing soil pH creates more favourable conditions for the growth of bacteria and actinomycetes, whereas fungi are generally more tolerant of acidic environments (Cha et al., 2021). Consequently, soil liming has been shown to alter the structure of microbial communities (Silveira et al., 2021). The activity of nitrifying bacteria is enhanced, accelerating the transformation of ammonium into nitrate, although this process may also lead to greater nitrogen losses through leaching (Mitsuta et al., 2025). In addition, liming stimulates enzymes involved in the mineralisation of organic matter, thereby facilitating the release of nutrients and enhancing the biological diversity of agroecosystems (Xiao et al., 2024).

In the other years (2018–2020), and in the second and third cuts, the yield response to liming was more variable, likely due to climatic fluctuations, particularly reduced precipitation (Tables 2 and 3, Figures 1 and 2). The results indicate that the impact of soil liming on forage and hay yield is significantly amplified under conditions of adequate water availability. Conversely, its effect diminishes in harvests characterized by limited precipitation. This pattern underscores the pivotal role of water supply in mediating plant responses to soil amendments. Precipitation serves as a key regulator of species' reactions to shifts in mineral nutrition within semi-arid grasslands (Yadav et al., 2020). Moreover, variations in climate and edaphic conditions can influence how changes in soil pH affect grassland ecosystems (Ma et al., 2017). Both precipitation and soil water balance are critical determinants of plant productivity and pH dynamics in these systems (Slessarev et al., 2016). Ultimately, ecosystem-level responses to altered soil pH in grasslands are largely governed by precipitation patterns (Liu et al., 2022).

These outcomes align with sustainable land management goals, promoting reduced fertilizer dependency and improved resilience of forage systems (FAO, 2020; Lal, 2015). Acidic soil conditions first manifest as root damage due to Al toxicity (Chakraborty et al., 2024). Root impairment in sensitive species typically occurs when Al concentrations in the soil solution exceed 1 mg/kg, and when over 60% of the soil's exchangeable capacity is occupied by Al ions (Agegnehu et al., 2021). Mg toxicity may also arise under low pH conditions (<5.5), further inhibiting root development (Lu et al., 2023).

Table 3. The influence of soil liming treatments (control, 3 t/ha and 6 t/ha CaO) on the productivity of the crop in the period 2018-2020 (n = 9)

Cut	Liming	Forage yield (t/ha)	Hay yield (t/ha)	Grass proportion (%)	Weed proportion (%)
			2018		
1	Control	23.33 ± 1.70^{b}	7.44 ± 0.30^{c}	95.4 ± 0.46	4.6 ± 0.46
	3 t/ha	30.41 ± 0.57^{a}	8.95 ± 0.26^{b}	91.4 ± 2.71	8.6 ± 2.71
	6 t/ha	33.21 ± 1.58^{a}	9.68 ± 0.09^{a}	94.5 ± 1.49	5.5 ± 1.49
	P	*	*	ns	ns
2	Control	11.00 ± 0.98	3.53 ± 0.07	92.9 ± 1.04^{a}	7.1 ± 1.04^{ab}
	3 t/ha	12.55 ± 0.65	3.93 ± 0.12	95.2 ± 0.48^{a}	4.8 ± 0.48^{b}
	6 t/ha	12.22 ± 1.69	3.34 ± 0.23	92.2 ± 0.23^{b}	7.8 ± 0.23^{a}
	P	ns	ns	*	*
3	Control	9.11 ± 0.40	4.26 ± 0.05	83.1 ± 3.22^{b}	16.9 ± 3.22^{a}
	3 t/ha	9.30 ± 1.07	4.21 ± 0.22	96.8 ± 0.49^{a}	3.2 ± 0.49^{b}
	6 t/ha	8.63 ± 0.64	4.13 ± 0.07	98.5 ± 0.42^{a}	1.5 ± 0.42^{b}
	P	ns	ns	*	*
			2019		
1	Control	26.7 ± 1.25	6.88 ± 0.81^{b}	94.0 ± 1.62	6.0 ± 0.62
	3 t/ha	29.4 ± 1.68	9.07 ± 0.11^{a}	95.8 ± 0.07	4.2 ± 0.07
	6 t/ha	26.5 ± 1.29	7.00 ± 0.13^{b}	94.0 ± 0.85	6.0 ± 0.85
	P	ns	*	ns	ns
2	Control	9.53 ± 0.29^{a}	2.99 ± 0.21^{a}	90.8 ± 3.18^{a}	9.2 ± 3.18^{b}
	3 t/ha	8.98 ± 0.59^{ab}	2.86 ± 0.23^{a}	95.2 ± 1.12^{a}	4.8 ± 1.12^{b}
	6 t/ha	7.84 ± 0.32^{b}	2.27 ± 0.04^{b}	83.6 ± 0.09^{b}	16.4 ± 0.09^{a}
	P	*	*	*	*
			2020		
1	Control	15.79 ± 0.97	5.22 ± 0.24^{a}	98.0 ± 0.34^{a}	2.0 ± 0.34^{b}
	3 t/ha	13.56 ± 1.92	3.95 ± 0.05^{b}	96.4 ± 0.96^{ab}	3.6 ± 0.96^{ab}
	6 t/ha	15.04 ± 1.08	5.10 ± 0.05^{a}	94.2 ± 0.25^{b}	5.8 ± 0.25^{a}
	P	ns	*	*	*
2	Control	6.44 ± 0.69	2.77 ± 0.32^{ab}	92.8 ± 0.88^{a}	7.2 ± 0.88^{b}
	3 t/ha	7.68 ± 0.46	2.98 ± 0.07^{a}	81.8 ± 2.28^{b}	18.2 ± 0.28^{a}
	6 t/ha	6.77 ± 0.83	2.31 ± 0.16^{b}	79.3 ± 2.32^{b}	20.7 ± 2.32^{a}
	P	ns	*	*	*

Data represent mean ± SE. The values denoted with different small letters within columns are significantly different ($P<0.05$) in accordance with the LSD test; *P* indicates the significance of liming effects within the F test, ns – non-significant, * - $P<0.05$

Affected root systems become stunted and thorn-like, severely limiting the plant's ability to absorb water and immobile nutrients such as P_2O_5, thereby increasing sensitivity to drought and nutrient deficiencies (Chakraborty et al., 2024).

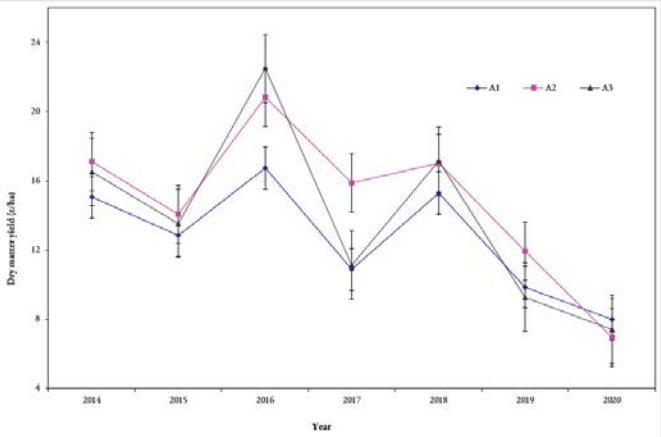


Figure 2. Dry matter yield (mean ± SE) of the grass-clover mixture for all cuts from 2014-2020, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

Soil liming had the most pronounced impact on forage and dry matter yield during the second, third, and fourth years of utilization (2015–2017). However, in the late years of exploitation, following the disappearance of red clover, this positive effect was no longer evident (Tables 2 and 3, Figure 2). In the sixth and seventh years, the influence of liming was minimal, with slight benefits observed primarily in the second cut. These findings support the well-established notion that the residual effects of soil liming typically persist for five to seven years. Agegnehu et al. (2021) similarly reported that barley yields peaked in the third year after liming, suggesting that lime application tends to be more effective in subsequent years than in the initial one or two years. Although lime generally enhances the proportion of clover and promotes nitrogen fixation, responses can vary and are not always linear (Kristensen et al., 2022), a trend also observed in this trial. Over time, precipitation leaches soluble nutrients such as Ca, Mg, and K, which contribute to reduced soil acidity. These nutrients are gradually replaced by Al ions, leading to re-acidification (Yadav et al., 2020).

In the first year of production, the proportion of tall fescue in the total yield was low, ranging from 5.5% in the first cut to 2% in the third cut (Table 2). This was expected, considering that tall fescue is a perennial grass species that reaches its full growth potential only from the second or third year onward. Subsequently, throughout the trial period, tall fescue exhibited a dominant presence in the mixture, particularly in the first cuts (Table 2 and 3, Figures 3 and 4). Liming did not significantly affect its proportion in many cuts, indicating its adaptability to a wide pH range and its competitive growth under improved soil conditions, which is confirmed by the results of Kemp and Michalk (2007). According to Brink et al. (2021), tall fescue exhibits greater tolerance to moderately acidic soils, but its growth and nutritive value are also improved under neutral pH conditions due to better phosphorus and calcium availability.

However, in both cuts of 2015, 2017, and 2020, as well as in the second cuts of 2016, 2018, and 2019, a significant opposite effect was observed: the proportion of tall fescue was significantly decreased under liming (from a few percent to several times), coinciding with a significant increase in red clover biomass (Table 2 and 3). This suggests a temporary competitive advantage for legumes in such conditions. These shifts aligned with the occurrence of drought periods (Figure 1), during which soil liming had a more pronounced effect on red clover. Under such conditions, red clover suppressed tall fescue, whose proportion was partially reduced. Grasses generally tolerate acidic soils better than legumes; a pH value of 5.5 can be sustained without significant yield reduction. In contrast, legumes require higher Ca availability and perform optimally at a pH between 6.5 and 7.5 (Agegnehu et al., 2021). According to Yang et al. (2021), red clover exhibits slightly higher tolerance to acidic soils compared to most other legume species. The findings of Tomić et al. (2019) indicate that in pure red clover stands, soil liming did not significantly alter the proportion of red clover relative to weeds in any cut.

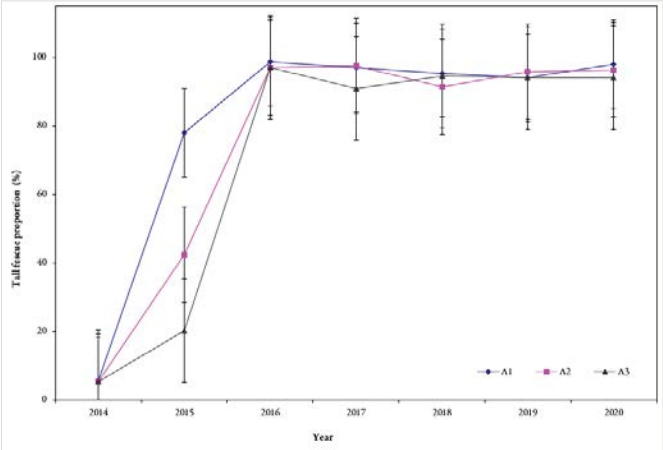


Figure 3. Tall fescue proportion (mean ± SE) in the first cut from 2014-2020, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

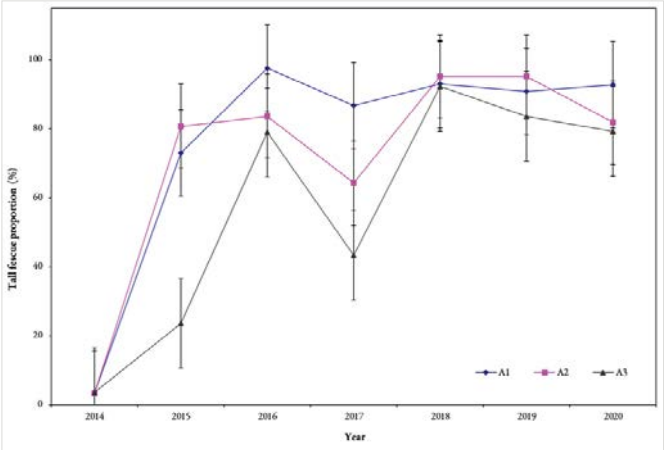


Figure 4. Tall fescue proportion (mean ± SE) in the second cut from 2014-2020, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

However, in mixtures with Italian ryegrass, liming positively influenced red clover's proportion. Quantitatively, nitrogen fixation in grass-clover mixtures depends on two key factors: the proportion of clover and the intensity of symbiotic activity. Both are strongly influenced by interspecies competition - clover content is determined by competition for light above the soil surface, while symbiotic activity is shaped by competition for inorganic nitrogen in the soil (Kristensen et al., 2022). Zhang and Xiao (2024) demonstrated that red clover's physiological response to environmental stress, including light and temperature fluctuations, can significantly influence its competitive behavior and biomass accumulation. Stević et al. (2025) further indicated red clover's contribution to sustainable agricultural systems, particularly its ability to maintain ecological balance and soil fertility under variable soil conditions, including those modified by liming. In the second cut, in general, the proportion of tall fescue was lower compared to the first cut, at the expense of a higher proportion of red clover (Figure 4).

The proportion of red clover in the first cut was highest during the establishment year (56.5-97.3%) (Table 2), and declined progressively in subsequent years (Figures 5 and 6). This trend reflects the increasing dominance of tall fescue, whose competitive advantage becomes more pronounced when it reaches the stage of full plant development, especially under favorable soil and climatic conditions (Castillo et al., 2022).

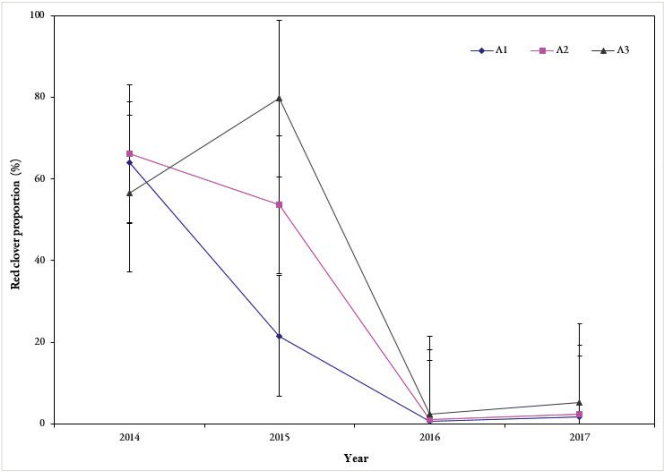


Figure 5. Clover proportion (mean ± se) in the first cut from 2014-2017, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

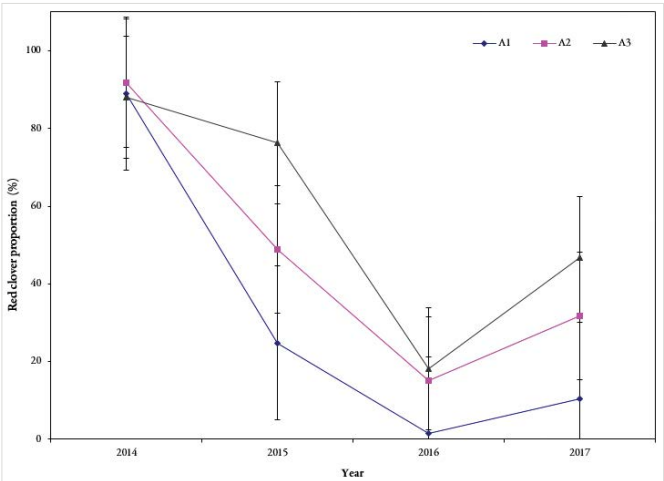


Figure 6. Clover proportion (mean ± SE) in the second cut from 2014-2017, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

In the final year of red clover persistence (2017), a temporary increase in its proportion was observed during the second cut, coinciding with arid weather conditions (Figure 1). Under drought stress, red clover demonstrated greater resilience than tall fescue, contributing more significantly to the biomass. Across all years except 2015, red clover consistently accounted for a higher proportion in the second cut compared to the first (Table 2). This pattern is attributed to its greater drought tolerance during the regrowth phase. Comparable findings were reported by Tomić et al. (2019), who observed significantly higher forage yields in pure red clover stands than in grass–clover mixtures under pronounced drought conditions. Their results underscore red clover's role as the primary yield contributor in water-limited environments, due to its physiological adaptability and sustained productivity, which is confirmed by the results of Jaiswal et al. (2018), Fereira et al. (2020), and Vleugels et al. (2023). In the year of establishment of the crop, in all treatments, a generally high proportion of weeds was recorded in all cuts, and especially on control (28.5-38.1%) (Figures 7 and 8). However, already in the second and third year of production, the weed proportion in both cuts was minimal in all treatments, thanks to the strong competition from tall fescue and red clover. This aligns with findings by Bainard et al. (2020) and Demircan et al. (2025), who demonstrated that diverse forage mixtures with vigorous growth can effectively suppress weed emergence, even under semiarid conditions. After that, in the first cut, the proportion of weeds remained at the same level, while in the second cut, the proportion of weeds gradually increased over the years, thanks to the decreasing competitiveness of tall fescue. The weed proportion did not show a linear dependence on the liming, but their proportion varied depending on the behavior of the forage mixture in appropriate weather conditions. In general, in the last two years, when the crop was thinned, weediness was higher on the liming treatments. Skuodienė et al. (2020) reported that liming can shift weed flora composition, favoring the emergence of nitrophilous and ruderal weeds under reduced crop density. Liu et al. (2021) similarly observed that liming influences the floristic structure of plant communities, not by directly enhancing soil fertility, but by modifying pH and exchangeable Al levels, which in turn affect species richness, biomass distribution, and competitive dynamics. These studies support the conclusion that weed resurgence in limed treatments is closely linked to the ecological behavior of the forage mixture under site-specific conditions. In the eighth year, tall fescue plants were sparse, and the weed proportion was high, indicating the end of the crop's productive lifespan. Consequently, no further measurements were conducted beyond this point.

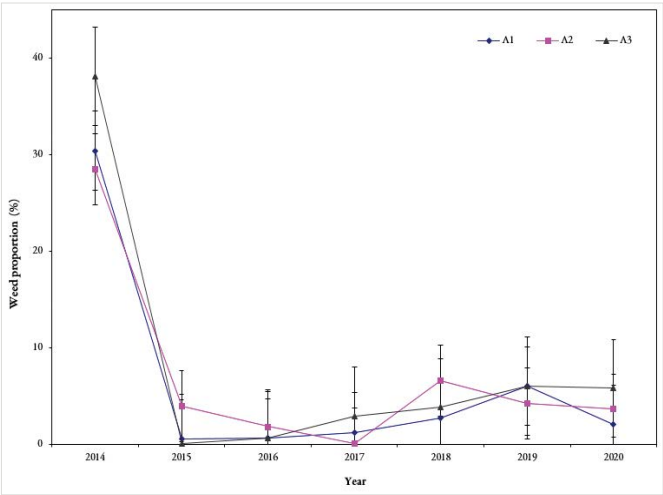


Figure 7. Weed proportion (mean ± SE) in the first cut from 2014-2020, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

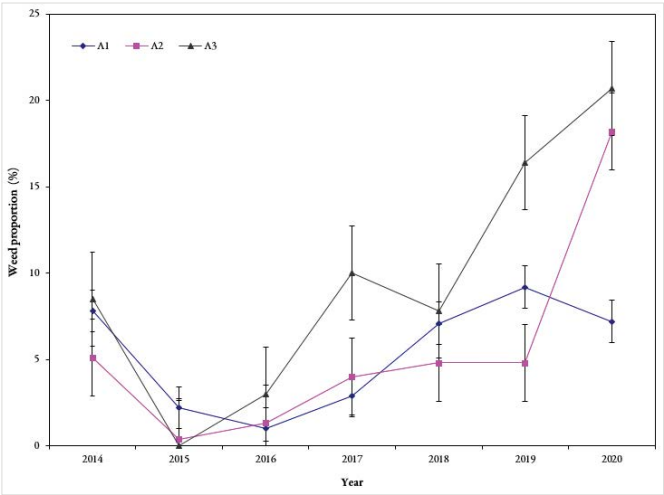


Figure 8. Weed proportion (mean ± SE) in the second cut from 2014-2020, as affected by soil liming (A_1 – control, A_2 – 3 t/ha CaO, and A_3 – 6 t/ha CaO)

CONCLUSIONS

The results of this multi-year study confirm that pre-sowing soil liming is an effective agroecological operation for improving the productivity and stability of grass-legume mixtures. The application of lime (CaO) at rates of 3 and 6 t/ha significantly increased forage and hay yields, enhanced red clover proportion within the plant community, and reduced weed proportion. These effects were most pronounced under favourable climatic conditions, while in dry seasons, liming demonstrated potential to alleviate stress-induced impacts. Crop response to liming was governed by the interaction between lime application rate, rainfall availability, and the developmental stages of tall fescue and red clover. The most substantial positive effects were observed during the second and third years of production, with residual benefits persisting for five to seven years. Although an increase in clover proportion and nitrogen fixation was anticipated, the study revealed that these parameters may respond in complex and non-linear ways to liming. When red clover is cultivated in mixtures with fast-growing grasses such as tall fescue and supported by appropriate agronomic practices, soil liming contributes to the establishment of a stable and productive forage system. Given that such grasslands require minimal fertilisation and aid in the restoration of soils previously subjected to intensive use, they represent a valuable component in the development of sustainable agricultural systems. This research highlights liming not merely as a corrective measure for soil acidity, but as a strategic tool for fostering resilient, productive, and ecologically sound agroecosystems.

ACKNOWLEDGEMENTS

The research presented in this article is part of Project Ref. Nos. 451-03-33/2026-03/200088 and 451-03-33/2026-03/200217 were funded by the Ministry of Science, Technological Development and Innovation, Republic of Serbia.

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