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Effectiveness of different liming materials on some soil properties and yield of crops

Učinkovitost vapnenih materijala na neke značajke tla i prinos usjeva

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ABSTRACT

The stationary field experiment on the application of different types and doses of liming was started in Kupres plateau (1.184 m.a.s.l.), Bosnia and Herzegovina in the summer 2017. The aim of this three-year research was to determine the effectiveness of liming materials on changes in soil chemical properties and yield of cultivated crops. The used treatments were; control, crude dolomite from Rama, crude dolomite from Kupres, and commercial burnt lime; each applied at lower and higher dosages of 7 and 15 t/ha, respectively. Application of lime materials resulted in desirable reduction in soil acidity, and changes in the soil chemical complex with an increase of exchangeable Ca^{2+} after limestone application and increase of exchangeable Mg^{2+} after dolomite application. Commercial burnt lime (BLP) proved to be most effective, followed by crude dolomite Rama (CDR), while crude dolomite Kupres (CDK) proved to be the least effective. All cultivated crops (silage corn > triticale > spring barley) responded positively to the applied lime materials. In terms of investment and yields achieved, silage corn proved to be the most economical.

Keywords: liming, soil, crops, yield, profit

SAŽETAK

Stacionarna terenska istraživanja različitih vrsta i količina vapnenih materijala započela su u ljeto 2017. godine na Kupreškoj visoravni (1.184 m.n.m.), Bosna i Hercegovina. Cilj ovih trogodišnjih istraživanja je utvrditi učinkovitost vapnenih materijala na kemijske promjene u tlu i prinose uzgajanih usjeva. Korišteni tretmani u istraživanju bili su; kontrola, sirovi dolomit iz Rame, sirovi dolomit iz Kupresa i komercijalno trgovačko vapno. Svaki tretman primijenjen je u manjoj i većoj dozi od 7 i 15 t/ha. Primjena vapnenih materijala uzrokovala je poželjno smanjenje kiselosti tla, te promjene u kemijskom kompleksu tla s povećanom koncentracijom dostupnog Ca^{2+} nakon unosa vapnenca i povećanom koncentracijom dostupnog Mg^{2+} nakon unosa dolomita. Trgovački vapneni materijal (BLP) pokazao je se najučinkovitiji, te zatim slijedi sirovi dolomit iz Rame (CDR), dok se sirovi dolomit iz Kupresa (CDK) pokazao najmanje učinkovitim. Uzgajane kulture pozitivno su reagirale na primjenu vapnenih materijala: kukuruz za silažu > tritikale > jari ječam. S obzirom na ulaganje i ostvarene prinose, kukuruz za silažu pokazao se najekonomičnijim usjevom.

Ključne riječi: kalcifikacija, tlo, usjev, prinos, zarada

INTRODUCTION

Soil acidity is a global factor limiting soil fertility. According to von Uexküll and Mutert (1995) acid soils (pH < 4.8) occupy about 30% of the world's ice-free land area (or 3950 Mha) and occur mainly in two global belts where they have developed under udic or ustic moisture regimes. The most effective solution to improve the fertility of acid soils is to carry out liming on acid soils, although this procedure has its advantages and disadvantages (Jawad et al., 2014). Liming and appropriate mineral fertilization, according to the rules of science and profession, are agrotechnical interventions that can significantly affect the quantity (Holland et al., 2018), and in some cases the quality of yields of individual crops (Fageria and Baligar, 2008). Excessive soil acidity is a problem that significantly affects the intensity of plant production in many parts of the world, including in this part of Europe at Balkan Peninsula (Kovačević et al., 2006; Lončarić, et al., 2007). The most common reason for (non) application of lime materials is their price, with transportation of these materials, from the place of production to the place of application, accounting for most of this price (Li et al., 2010). Increased acidity with all its negative consequences (Bolan et al., 2003; Rengel, 2003; Li et al., 2018) limits the growth and development of cultivated plants, very often to the economic limit of justifying the use of these soils (Farhoodi and Coventry, 2008; Holland et al., 2019). Goulding (2015) reported that liming is a common and long-established management practice to maintain optimum soil pH for crop production. In acidic soils, liming can create better environmental conditions for the development of acid-intolerant microorganisms, resulting in higher microbial mass (Neale et al., 1997). Zhao et al. (2015) concluded that soil pH is a key determinant of soil microbial community and activity.

In this part of Bosnia and Herzegovina, liming is a completely unknown agrotechnical intervention, which presents itself as the first and primary problem in improving the fertility of highly acid soils. Due to increased acidity, only triticale and rye are grown in this area, as they can tolerate increased soil acidity (Đekić et al., 2014) and extremely low temperatures (sometimes as low as -30 °C) during winter months (Bašić and Herceg, 2010). As this is a region with predominantly agricultural livestock, with a higher demand for barley and silage corn (as raw materials for animal feed), the emphasis on the implementation of liming is even stressed. These crops are unlikely to produce economically viable yields on acid soils (Tang et al., 2003; von Tucher et al., 2018). Slattery and Coventry (1993), and Liu et al. (2004) found that triticale is the least sensitive crop to pH. Mugwira et al. (1976) and Dolling et al. (1991) reported that barley is very sensitive to soil acidity. Farhoodi and Coventry (2008) and Goulding (2016) state that the soil should have a pH of about 5.9 for optimum barley growth.

Research aimed at finding the most appropriate ways to remove excess acidity is often based on the use of multiple lime materials (Rippy et al., 2007). Lime material is any material added to the soil to neutralize or reduce soil acidity (Rengel, 2003; Li et al., 2018). Some studies have compared burnt lime and unburnt lime materials (Nduwumuremyi et al., 2013; Iren and Uwah, 2018). Numerous authors (Fageria and Baligar, 2008; Ramadas et al., 2011; Goulding, 2016, Demissie et al., 2017; Hale et al., 2020) state that there are materials that are specifically manufactured for use in reducing soil acidity. On the other hand, materials that are manufactured for other purposes (construction) can also serve as liming materials. Some substances are waste in a technological process but have a sufficient content of calcium and magnesium or alkaline reaction (Ondrašek et al., 2020).

One of the most important issues in the selection of liming materials in practice (besides physical and chemical quality) is the price of these materials (Li et al., 2010). Since liming is a very expensive process, the most frequently asked questions in practice are the amount of liming materials to be applied and the durability of this agricultural improvement process (Beukes et al., 2012; Lončarić et al., 2013; Li et al., 2018). Considering all this, two materials from local quarries and one commercial material, primarily intended for liming, were used in this study to reduce the cost of liming.

The research presented in this paper is designed to provide more accurate answers to the questions that arise. The purpose of this three-year-long research is to:

- Determine the effectiveness of lime materials on chemical changes in the soil and yields of crops grown;
- Identify the impact of climatic conditions on the effectiveness and durability of liming;
- Determine the economic feasibility of implementing liming under these agroecological conditions.

MATERIALS AND METHODS

Study area

This three-year experiment was conducted on the arable land of the Kupres d.o.o. farm from Kupres, mountainous part of Bosnia and Herzegovina: 43°55'21.1"N 17°13'26.8"E, 1.184 m.a.s.l. (Figure 1.). The area where the experiment was conducted has been used in arable crop production since 2015, previously it was used as pasture. On the territory of Kupres Plateau there is a total of 43000 ha of agricultural land. Arable land accounts for 9000 ha (21%), meadows for about 13000 ha (30%), and pastures for about 21000 ha (49%). In the 1970s, there were about 12 thousand cattle on the Kupres plateau, today there are no more than a thousand (Bašić and Herceg, 2010). According to Köppen climate classification, the climate is classified as Dfb - Warm summer continental or hemiboreal climates (Kottek et al., 2006). For the research the climatic data of precipitation and temperatures were taken from Federal Hydro-Meteorological Institute of Bosnia and Herzegovina.

Experimental design

The total area of the experimental plot was 0.24 ha (120 m long and 20 m wide), while the size of the primary

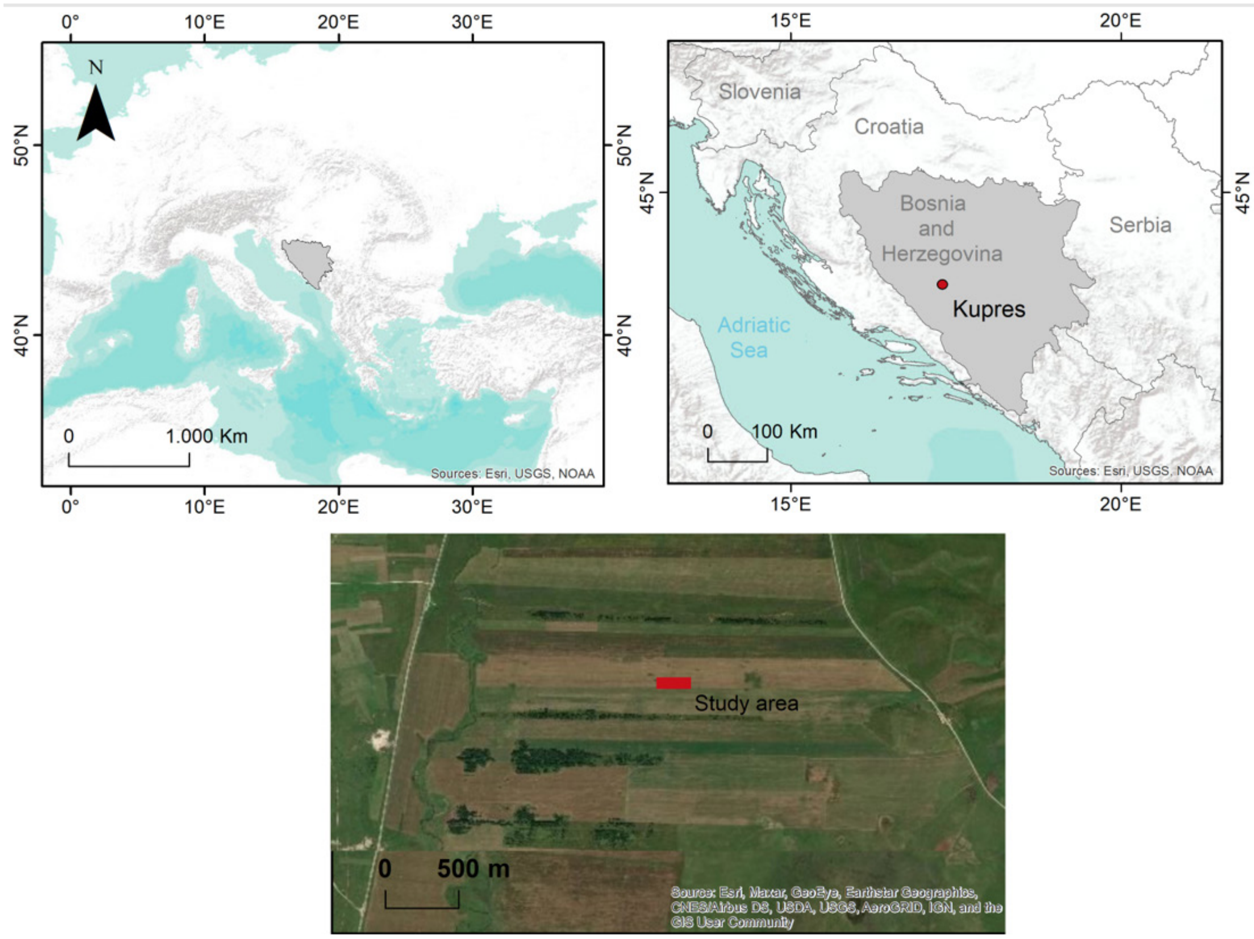

Figure 1. Location of experimental field on Kupres plateau

experimental plot was 30 m^2 (5 m long and 6 m wide). The trial was set up according to the randomized block design with three replications. The agro-technical work on the experimental plot started in summer 2017. Liming material was applied once when the experiment was established in August 2017, and mineral fertilizer was applied for each phenophase of the crops grown per year (Table 1). Three crops were included in the experiment: triticale (*Triticosecale* Wittmack), spring barley (*Hordeum vulgare* L.), and silage corn (*Zea mays* L.). Part of the mineral fertilizers was applied during the preparation of the sowing layer and the other part was applied as a top dressing. Weed protection was carried out according to standard agrotechnics. The only parameter that changed was the type and amount of liming materials.

Two unburned crude dolomitic liming materials in two levels (7.5 and 15 t/ha) from local quarries of Rama and Kupres were used in the study (Table 2). The lime materials were applied manually according to the established methodology and then incorporated into the soil with a rotary harrow to a depth of about 10 – 15 cm. If their effectiveness was shown in agriculture, the local government would allow their favourable use in agriculture. The third material used in this research is commercial burned lime, as well in two levels (7.5 and 15 t/ha), obtained from GIRK Kalun Ltd Company in Drniš, Croatia. The lime requirement of the soils was calculated according to the equation of Bašić and Herceg (2010). All materials used in this research comply with EC Regulation 463/2013.

Tractor John Deere 6610, reversible plough Vogel, power harrow Fradent rotary harrow, the Nodet small grain seed drill, and the MA/AG corn seed drill were used in the experiment. Before applying liming (August 17, 2017), composite soil samples (total 63) were collected from 0 – 20 cm depth from each treatment using soil auger equipment for chemical analysis. Soil sampling in subsequent years was carried out before the basic tillage for the crop which was to be grown that year in the experimental field. The soil samples were air-dried, crushed, and passed through a 2-mm mesh sieve after homogenization.

The following analyses were performed: soil pH (KCl, 1:2,5) method: HRN ISO10390: 2005. Soil organic matter (SOM) is determined according to Kotzman method (JDPZ, 1966), which is based on oxidation of organic matter with 0.1 M $KMnO_4$ and H_2SO_4. Plant-available phosphorus is determined by AL method (Egner et al., 1960). Cation exchange capacity (CEC) and base saturation of CEC after exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+ extracted by neutral mol/L ammonium acetate (Jones, 2001). Liming materials were analysed by measuring Ca^{2+} and Mg^{2+} content to calculate calcium carbonate equivalent (CCE). Relative Neutralizing Value (RNV) was determined by the CCE and particle size distribution expressed as fineness (Yang et al., 2018) to compare the lime materials, used both with each other as well as with pure limestone (CCE = 100) with particles smaller than 0.15 mm (Effective Neutralizing Value (ENV) = 100) (Table 3).

Table 1. Dates of implemented agrotechnical work

Liming & shallow ploughing - August 17, 2017						
Crop	Ploughing	Fertilizing	Preparation of soil and sowing	Top dressing	Weed out by weeders	Harvest
Triticale, type Odisej, 2017/18	October 10	October 10	October 10	April 28 & June 23	June 23	August 18
Barley, type Matej, 2018	April 28	April 28	May 3	June 23	April 28 & June 23	August 25
Maize, type Pioneer 2019	May 18	May 18	May 19	July 25	July 2 & August 4	September 23

Table 2. Variants and quantities of lime materials applied in the research

Treatment	Name of treatment	Doses of liming (t/ha)
- Control, local farmers usual agrotechnics, without liming, only mineral fertilizers	Control	-
- Crude dolomite Rama - lower level	CDR-L	7.5
- Crude dolomite Rama - higher level	CDR-H	15
- Crude dolomite Kupres - lower level	CDK-L	7.5
- Crude dolomite Kupres - higher level	CDK-H	15
- Commercial burnt lime - lower level	BLP-L	7.5
- Commercial burnt lime - higher level	BLP-H	15

Table 3. Calcium and magnesium content, particle size, CCE and ENV of used liming materials

	Crude dolomite Rama (CDR)	Crude dolomite Kupres (CDK)	Commercial burnt lime (BLP)
Ca (g/kg)	211.06	238.93	421.46
Mg (g/kg)	183.22	193.39	3.24
CCE* (%)	98.57	108.08	106.18
Particles < 0.15 (%)	27.92	3.91	5.41
Particles 0.15-0.25 (%)	2.33	8.32	9.79
Particles 0.25-0.84 (%)	20.45	19.24	84.26
Particles > 0.84 (%)	49.31	68.53	0.55
ENV** (%)	37.41	19.73	49.84

* CCE – calcium carbonate equivalent; ** ENV - Effective Neutralizing Value

The soil type on the experimental plot is Ranker or Leptosols on sand (IUSS WRB, 2015). Ranker is an acid soil with pH in KCl less than 4.00, low base status, base saturation is less than 50%, very highly leached. The main reason for these parameters is the pedogenetic development of this soil. These soils are formed in the mountainous part where there is a high amount of precipitation and snow, which causes weathering and leaching processes. It is common for snow to remain on agricultural land from late October to early April. Table 4 shows the texture and chemical properties of this soil.

Table 4. Soil texture and chemical properties*

Depth of soil (cm)	2 – 0.2 mm	0.2 – 0.02 mm		0.02 – 0.002 mm		< 0.002 mm	Texture	Gravel, %
0 - 20	6	13		66		15	Silty loam, gravelly	15
20 - 35	9	15		57		19	Clay loam, gravelly	24
	pH (KCl)	SOM %	S	T-S	T	V %	P_2O_5	K_2O
0 – 20	4.08	10.8	3.25	24.95	28.2	11.52	1.4	3
20 - 35	3.89	2.42	7.60	26.52	34.12	22.27	1.2	7.7

*average of two soil profile (SOM; soil organic matter, Soil adsorption complex; S, T-S, T, V)

Statistical analyses

Prior to analyses, normal distribution for soil parameters (soil pH, SOM and P_2O_5) and yield crops (triticale, barley and silage corn) was tested using the Kolmogorov-Smirnov test (K-S). Data were considered normal at a P>0.05 level. SOM and crop yields follow the Gaussian distribution, pH and P_2O_5 after Box-Cox transformation. However, the results presented here, consider the untransformed values. Comparison of soil parameters and yield crops between sampling dates and treatments were made using the one-way, and two-way ANOVA, respectively. If significant differences were identified at P<0.05, *post hoc* Fisher LSD test was applied, using transformed and untransformed data. Correlations between the crop yields and soil parameters were carried out with the Pearson coefficient of correlation. Significant correlations were considered at a P<0.05. Statistical analyses were carried out with STATISTICA 12.0 for windows (StatSoft Inc., 2013).

RESULTS AND DISCUSSION

Climatic conditions on a multi-year average and in years studied

For a better understanding of the effectiveness of each lime material that were applied in this research, it is important to indicate the climatic conditions in the multi-year average and during the experiments (Figure 2). In some years, climatic parameters can have a decisive influence on the performance of the applied materials and the yield of cultivated crops.

If we look at multi-year average rainfall (1960 – 2019) in the Kupres plateau, the average is 1194 mm of rain per year. The lowest rainfall was in 2003 (863 mm) and the highest in 2017 with 1771 mm (Figure 2a). In the first year of research (2017), 1771 mm of rain fell on the experimental field, which is the rainiest year since measurements began at this station (1947). In 2018, 1375 mm of rain fell, and in 2019 1395 mm of rain fell, which is

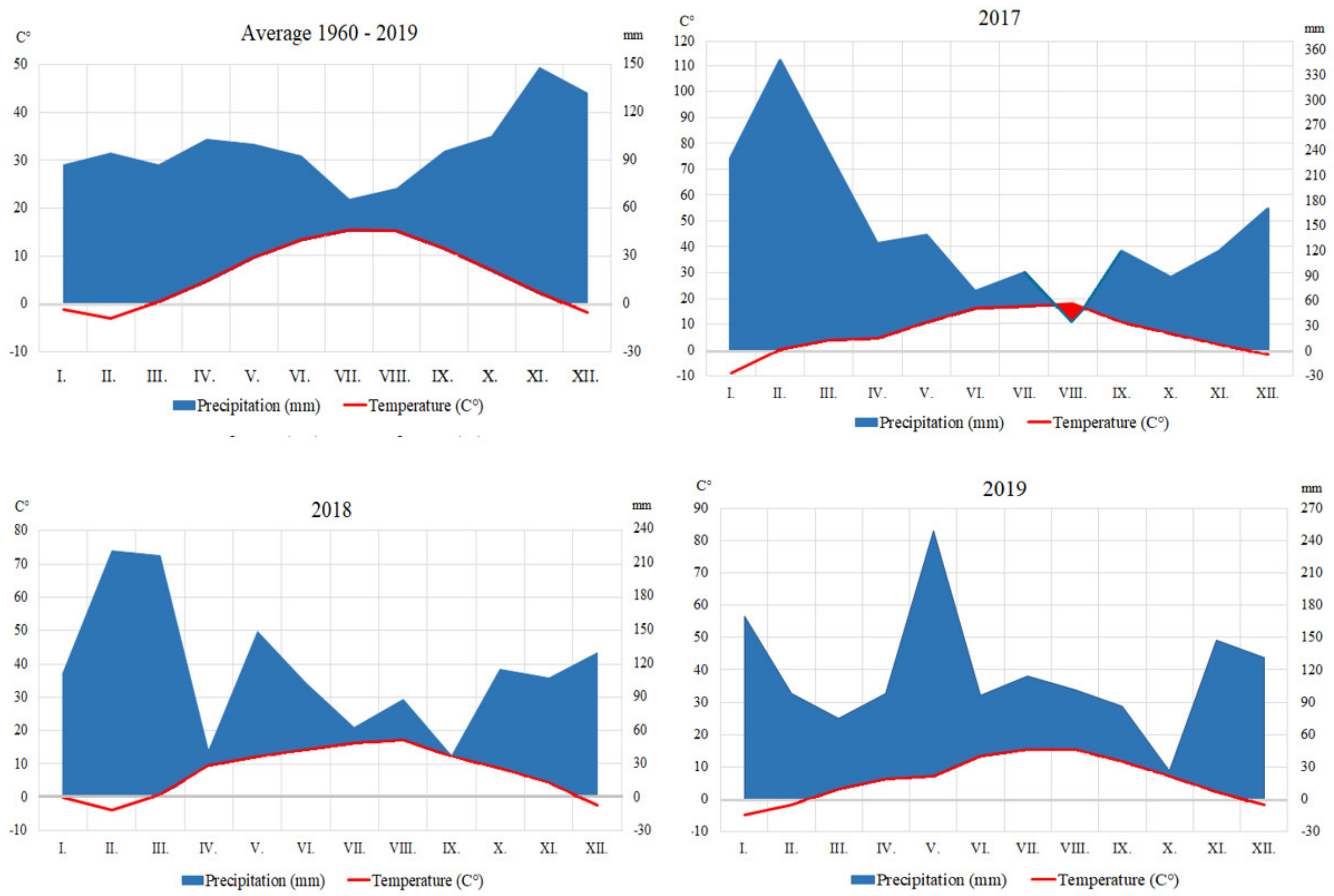

Figure 2. Climate graph according to Walter for 1960 – 2019, 2017, 2018 and 2019

about 200 mm more than the multi-year average. Figures 2a, 2b, and 2c show the climatic conditions during the experiment. From the attached images (Figure 2) it can be concluded that there was no lack of rainfall during the vegetation period (April – October). On average, about 60% of the total annual precipitation falls from April to October (1960 – 2019). However, considering 2017 and 2018, the peak total precipitation was observed in February and March, and in 2019 in May, respectively. As for temperatures, the average for this period is 6.0 °C. The coldest year was 1967 with an average temperature of 5.6 °C and the warmest were 2000 and 2018 with 7.4 °C. Compared to the multi-year average, all three study years were warmer. The average annual temperature was 6.7 °C in 2017; 7.4 °C in 2018 (warmest since measurements began) and 6.1 °C in 2019. The above climate data show that the climatic conditions during the research period were optimal for these studies.

Changes in soil chemical characteristics (soil pH, soil organic matter and plant available phosphorus)

Table 5 shows the changes in soil pH during the study period. In 2018 (one year after the application of lime materials), no significant changes in soil pH were observed in the control and the lower level of lime materials (CDR-L). In the second year of research on variants where burnt lime was applied at both levels (BLP-L and BLP-H), the highest values of soil pH were recorded, i.e. an increase in soil pH of 0.87 at a lower dose (BLP-L) and of 1.33 pH at a higher dose (BLP-H). Significantly less effective was the application of higher dolomite doses (CDR and CDK) which resulted in an increase in pH of only 0.46. The differences in effectiveness almost completely explain the differences in RNV (Relative Neutralizing Value) of lime materials. Namely, the ENV for burnt lime was 49.84%, while lower values were observed for CDR (37.41%), and for CDK (19.73%). At the same time, the differences in the CCE values of the used lime materials didn't showed pronounced variability (98.6 – 108.1, Table 3). The difference in the neutralization effectiveness of the applied liming materials is also visible by comparing the values of hydrolytic acidity (Hy) at the beginning of the experiment (16.58 – 18.16 cmol/kg), and after one year (7.44 – 17.15 cmol/kg). In the first year, BLP-H treatment neutralized 10.32 cmol/kg of Hy (17.76 – 7.44), and the BLP-L treatment 4.07 cmol/kg (18.16 – 14.09). Materials with low RNV neutralized only 0.13 – 2.14 cmol/kg Hy. It is more than surprising that in the third year of the study there were no statistically differences between the soil pH for variants studied. Whether this is due to

Table 5. Mean values of soil pH, SOM (%) and P_2O_5 (mg/kg) in different treatments

Treatment	Soil pH			SOM		P_2O_5	
	2017	2018	2019	2017	2019	2017	2019
Control	3.82Aa	3.81Ba	3.77Aa	8.28Ba	8.33Aa	17.00Aa	6.00Ab
CDR-L	3.77Aa	3.90Ba	3.78Aa	7.99Ba	8.06Aa	15.33Aa	14.30Aa
CDR-H	3.78Ab	4.24Aa	3.83Ab	7.98Ba	8.43Aa	11.33Aa	15.73Aa
CDK-L	3.76Aa	4.04Aa	3.78Aa	8.20Ba	8.06Aa	17.33Aa	9.07Ab
CDK-H	3.71Ab	4.18Aa	3.77Ab	7.95Ba	8.40Aa	16.67Aa	6.00Ab
BLP-L	3.69Ab	4.56Aa	3.84Ab	8.22Ba	8.39Aa	16.00Aa	11.53Aa
BLP-H	3.67Ab	5.00Aa	3.73Ab	8.84Aa	7.98Ab	16.00Aa	12.37Aa

Mean data followed by the different uppercase letters are statistically significant different within the same date. Mean data followed by the different lowercase letters are statistically significant different within the treatment. (CDR-L & CDR-H, crude limestone, lower & higher level; CDK-L & CDK-H crude dolomite, lower level & higher level; BLP-L & BLP-H Commercial lime powder, lower level & higher level; SOM - soil organic matter) the relatively low dose of applied materials (Brown et al., 2008), the high humus content and low clay content, or the influence of climatic conditions is unclear and requires further experimental investigation. Soil organic matter (SOM) content was only significantly higher in BLP-H, in 2017. CDK-H had the lowest SOM content in 2017, although not significantly. Available phosphorus showed significant differences in 2019, with the highest content in both CDR and BLP. By comparing 2017 and 2019, significantly higher P_2O_5 were observed for control, and both CDK in 2017 (Table 5).

The soil cation exchange capacity (CEC) before liming was in the range of 19.93 –21.17 cmol/kg, but the percentage of acid cations was very high (81.20 – 88.91%) as the Hy was in the range of 16.58 – 18.16 cmol/kg. After liming, CEC values (Table 6) remained practically in the same range (18.39 – 22.30 in 2018, and 19.24 – 20.99 in 2019), but there were very significant effects on Hy, Ca^{2+} and Mg^{2+} adsorbed on soil adsorption complex (AC). In 2018, Hy content in the control plot remained at the level > 80% (83.93%), but all liming treatments decreased content of Hy on soil AC to values 40.46 – 78.08%. The lowest Hy percentage (40.46%) on AC was measured after applying a higher dose of commercial lime powder (treatment BLP-H), followed by a lower dose (BLP-L) with a Hy content 71.09 cmol/kg, which was expected considering the values of ENV. On the other hand, both doses of CDR and CDK decreased the Hy content on AC only slightly, from range 81.20 – 88.91% to 72.99 – 78.08%, which was also expected considering the lower ENV of CDR and CDK.

At the same time, liming with lower and higher limestone dose (BLP treatments) increased soil exchangeable Ca^{2+} in soil 2.7 or 6.3 times, from 34.6 and 32.6 to 92.82 (lower dose) and 204.38 mg/kg (higher dose), respectively, with little effect on exchangeable Mg^{2+}. All applications of dolomitic material (CDR and CDK treatments) increased exchangeable Ca^{2+} on soil AC only 1.01 (CDK-L treatment) to 1.48 (CDR-H) times, in 2018. At the same time, the application of dolomitic material increased the exchangeable Mg^{2+} on the soil AC very significantly from 2.6 (CDK-L) to 4.2 (CDR-H) times. Although Hy was again very high in 2019, in all limed treatment, from 15.44 – 17.98 (Table 6), the concentration of exchangeable Ca^{2+} and Mg^{2+} on soil AC remain higher than before liming depending on the type of liming material (limestone or dolomite). Two years after liming application, in 2019, the exchangeable Ca^{2+} on soil AC remains 1.65 – 1.7 times higher than before application. Higher dolomite dose (CDK and CDR) resulted in only 1.02 and 1.16 times higher exchangeable Ca^{2+}, as lower dolomite dose resulted in a decrease in exchangeable Ca^{2+} (85 and 86% of Ca^{2+} concentrations before liming). But the application of dolomite resulted

Table 6. Mean values of Hy (cmol/kg), adsorbed Ca^{2+} and Mg^{2+} (mg/kg) and CEC on treatments

Treatment	Hy			Ca^{2+}			Mg^{2+}			CEC		
	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019
Control	16.58	16.06	18.03	55.52	41.82	30.89	7.27	8.33	5.67	20.16	19.14	20.41
CDR-L	17.28	17.15	17.98	41.16	58.37	35.60	5.74	18.47	9.84	20.47	21.97	20.99
CDR-H	17.72	16.28	15.66	42.52	62.99	49.37	5.15	21.72	17.77	19.93	21.54	20.04
CDK-L	17.19	15.05	16.10	52.36	52.82	44.57	7.59	19.94	14.49	21.17	19.60	19.92
CDK-H	17.72	16.28	16.49	46.36	67.95	47.28	7.08	28.25	15.44	20.83	22.30	20.50
BLP-L	18.16	14.09	15.44	34.57	92.82	59.27	4.91	8.58	10.16	20.50	19.82	19.69
BLP-H	17.76	7.44	15.79	32.63	204.38	53.35	5.36	5.31	5.03	20.03	18.39	19.24

(Hy - hydrolytic acidity, CEC - cation exchange capacity, CDR-L & CDR-H, crude limestone, lower & higher level; CDK-L & CDK-H crude dolomite, lower & higher level; BLP-L & BLP-H Commercial lime powder, lower & higher level) in high increase in exchangeable Mg^{2+} two years after liming. Lower doses of CDK and CDR resulted in 1.7 – 1.9 times higher Mg^{2+} and higher doses resulted in 2.2 – 3.5 times higher exchangeable Mg^{2+} in the soil AC.

Although liming significantly neutralized soil acidity only in the first year after liming, but not two years after liming, the liming effect was maintained in the soil as the increased concentrations of exchangeable Ca^{2+} after limestone application and exchangeable Mg^{2+} after dolomite application (Table 6).

Yields of cultivated crops

Table 7 shows the achieved yields of the cultivated crops (triticale, barley and silage corn) during three-year research. Triticale yield, in 2017, had significant higher values in BLP-H, followed by BLP-L and CDR-H, respectively. Barley yield showed somehow different behaviour, with the significant highest in BLP-H, and the lowest in control. Silage corn showed significantly higher values in BLP-L and BLP-H, while in control lowest. Between other treatments, there were no significant differences for barley yield and silage corn, respectively.

Table 7. Mean values of yield crops in harvested year (t/ha)

Treatment	Triticale 2017	Barley 2018	Silage corn 2019
Control	1.31F	1.33C	6.37C
CDR-L	1.87D	1.89B	15.22B
CDR-H	2.25C	1.76B	16.34B
CDK-L	1.87D	1.67B	16.82B
CDK-H	1.55E	1.92B	15.50B
BLP-L	2.85B	1.67B	19.27A
BLP-H	3.58A	2.23A	18.52A
CV%	34.71	17.16	27.30
SD	0.76	0.31	4.21

Mean data followed by the different uppercase letters are statistically significant different within the same date. (CDR-L & CDR-H, crude dolomite, lower & higher level; CDK-L & CDK-H crude dolomite, lower & higher level; BLP-L & BLP-H Commercial lime powder, lower & higher level)

In the context of correlations between soil parameters and obtained yields, in 2017, the significant correlation was only observed between triticale yield and soil pH (r=–0.46), while in 2019, significant correlation was observed between silage corn and soil pH (r=0.50). In 2018, no significant correlation between barley yield and soil pH was observed.

Table 8 shows the cost of production, and the economics of the liming procedure. The presented data show that the studied cultures reacted very differently to the applied materials. Triticale yields were nearly constant to the amounts of liming material applied. BLP proved to be the most effective material with the highest earnings at both levels. The same results were seen in the year when corn for silage was in the experimental field. The highest earnings were obtained in variants where BLP was applied at any level. When spring barley was sown in the experimental field, the effectiveness of applied lime, expressed by yield, proved to be unsatisfactory. Spring barley responded most poorly worst to the applied lime materials.

The application of lime materials caused desirable changes in the chemical complex of the soil. This was most evident in the reduction of excess soil acidity and the increase in the content of P_2O_5. Similar conclusions, but in four years of research were reached by Kisić et al. (2004), Lončarić et al. (2007), Rastija et al. (2008) and Jaskulska et al. (2014). Surprisingly, already in the third year the effectiveness of the lime materials was lost, i.e. the soil pH returned to the values that we had before the experiment set up. More so, the P_2O_5 content dropped below the values we had at the beginning of the study. Rippy et al. (2007) and Woodard and Bly (2010) found that the optimal liming period should be about three years. The short-term acidity neutralization effectiveness of the lime materials was possible due to a much higher relative proportion of humus particles than clay particles (70:30) in the total CEC since the SOM content was in the range of 7.95 – 8.84% and clay particles were only about 15%.

Table 8. Costs of production

	Profit, €/ha				Costs, €/ha						
Treatment/crop	Yield	Profit yield	Subsidy	Total profit	Crop management	Fertilizing	Machinery amortization	Land tenancy	Liming	Total costs	Earn
Triticale: 2018											
Control	1.31	209	200	409	150	100	50	40	0	340	69
CDR – L	1.87	299	200	499	150	100	50	40	40	380	119
CDR – H	2.25	360	200	560	150	100	50	40	80	420	140
CDK – L	1.87	298	200	498	150	100	50	40	40	380	118
CDK – H	1.55	247	200	447	150	100	50	40	80	420	27
BLP – L	2.85	455	200	655	150	100	50	40	115	455	200
BLP – H	3.58	572	200	772	150	100	50	40	230	570	202
Spring barley: 2018											
Control	1.33	238	200	438	200	100	50	40	0	390	48
CDR – L	1.89	341	200	541	200	100	50	40	40	430	111
CDR – H	1.76	317	200	517	200	100	50	40	80	470	47
CDK – L	1.67	300	200	500	200	100	50	40	40	430	70
CDK – H	1.92	346	200	546	200	100	50	40	80	470	76
BLP – L	1.67	301	200	501	200	100	50	40	115	505	-4
BLP – H	2.23	402	200	602	200	100	50	40	230	620	-18
Silage corn: 2019											
Control	6.37	1.593	200	1.793	250	150	500	40	0	940	853
CDR – L	15.22	3.805	200	4.005	250	150	500	40	40	980	3.025
CDR – H	16.34	4.085	200	4.285	250	150	500	40	80	1.020	3.265
CDK – L	16.82	4.205	200	4.405	250	150	500	40	40	980	3.425
CDK – H	15.50	3.875	200	4.075	250	150	500	40	80	1.020	3.055
BLP – L	19.27	4.818	200	5.018	250	150	500	40	115	1.055	3.963
BLP – H	18.52	4.630	200	4.830	250	150	500	40	230	1.170	3.660

Of the materials used, commercial burnt lime (BLP) proved to be the most effective, followed by crude dolomite Rama (CDR), while crude dolomite Kupres (CDK) proved to be the least effective. This is in complete agreement with the determined ENV which was significantly highest (49.84%) for commercial burnt lime (BLP), lower (37.41%) for crude dolomite Rama (CDR), and lowest (19.73%) for crude dolomites Kupres (CDK). However, no expressed variability was found in CCE (CDR 98.57; CDK 108.08 and BLP 106.18, respectively) between the lime materials used, suggesting that the better fineness of BLP (only 0.55% particles > 0.84 mm) compared to CDR (49.31% particles > 0.84 mm) and CDK (68.53% particles > 0.84 mm) probably contributed, as indicated in numerous studies (Haby et al., 1979; Rippy et al., 2007; Alvarez et al., 2009; Pagani and Mallarino, 2012). In addition to the differences in fineness, calcite carbonates are softer in chemical composition compared to calcium magnesium carbonates. For this reason, they melt faster and act more quickly on chemical changes in the soil (Oates, 1998; Rippy et al., 2007). This means that burnt lime (BLP) also acts faster because it contains 42% Ca^{2+} and only 3% Mg^{2+}, while CDRs and CDKs contain less Ca^{2+} (21 – 24%) and more Mg^{2+} (18 – 19%) (Table 3).

When calculating the required liming dose to neutralize the acidity using the determined ENV and 20 cm application depth, 7.5 and 15 t/ha of CDR should neutralize only 0.8 and 1.6 cmol of Hy. According to the analysis after the first year, 7.5 and 15 t/ha of CDR neutralized 0.13 and 1.44 cmol of Hy, which was consistent with the expected effect for the higher dose. Furthermore, 7.5 and 15 t/ha of CDK should have neutralized only 1.5 and 3.0 cmol of Hy, and this material neutralized 1.44 and 2.14. Finally, 7.5 and 15 t/ha of BLP should neutralize 2.0 and 4.0 cmol of Hy. However, BLP neutralized significantly more acidity, a lower dose of 4.5 and a higher dose of 10.32 cmol of Hy. These differences in the effectiveness of BLP compared to CDR and CDK can be explained by the fact that BLD is a limestone with a high Ca^{2+} and a very low Mg^{2+} content, whereas in CDR and CDK the Ca^{2+} and Mg^{2+} contents are practically equal. This fact is not taken into account in CCE or ENV.

Although, triticale is a crop that tolerates low soil pH, it has been shown that as soil pH increases – higher yield are also obtained. Similar conclusions were reached by Mugwira et al. (1976), Slattery and Coventry (1993), and Liu et al. (2004). Spring barley responded very poorly to all applied materials. Similar conclusions were reached by Haynes and Mokolobate (2001) and Brown et al. (2008). According to them, the probable reason for the ineffectiveness of lime in barley cultivation is the increased organic matter content in these soils. From an economic point of view, the greatest effectiveness of liming was shown in silage corn. The positive effect of liming on corn grain yield was determined by Kisić et al. (2002), Kovačević and Rastija (2010), Opala et al. (2018), and Hale et al. (2020). In terms of materials invested and realized yields of silage corn, this crop proved to be the most economical. However, it is a crop that local farmers from this area rarely grow for several reasons. First, this is an area where the probability of frost in late June and early September is very high. Trends over the last 60 years show that temperatures are rising in the winter and spring months and that the time with snow cover is getting shorter. For this reason, it is almost impossible to grow corn for grain in this area, only corn for silage. Climate change in recent decades indicates that more and more corn will be grown for silage in this area, but with the condition of liming. In 60 years, average monthly and annual precipitation has not changed in this area. But temperatures increased by almost 2 °C, especially in the summer months. At the same time, the number of days without frost increased. This indicates that in the future, the optimal growing season for growing silage corn will be longer and that this crop will be easier to grow. Another reason why this economically highly profitable crop is not grown in this area is the lack of appropriate mechanization (silage corn harvester). However, even with its acquisition, which is calculated in the costs in the Table 7, this culture is still worth cultivating.

Based on the conducted three-year research, we try to clarify the reasons for the return of the chemical changes (soil pH) to the initial state, two years after the application of lime materials. Climatic conditions, especially the amount of precipitation (peak rainfall observed in February and March, 2017 and 2018), and increased content of organic matter, as well as texturally lighter soils are considered to be the main reasons for the very rapid leaching of lime materials. In addition, increased macro-porosity and the content of gravel (15%) in the soil support this observation. What we would like to emphasize is that the main reason for the increased acidity of these soils are natural processes (Fageria and Nascente, 2014; Holland et al., 2018). The increased organic matter content and silty loam, gravelly texture of these soils do not allow them to bind the applied amounts of lime materials to the adsorption complex of the soil. Some part of the applied lime materials was probably washed out into deeper layers during the first winter after their application. This observation is support by high precipitation observed in February and March in 2017 and 2018, respectively. Therefore, it did not even succeed in reacting chemically to bring about desirable changes in the soil pH. In the pedological profiles that we opened in this area on the soils formed on solid clays at a depth of 40 – 50 cm, we found limestone dolls up to 30 cm in diameter. At the same depth, at the contact of the surface and groundwater, a limestone horizon up to several centimetres thick was found. This indicates increased leaching of lime materials.

All this indicates that, in this area, it is very difficult to determine the optimum amount of lime materials by applying criteria for soils that have up to 3% organic matter and are formed in a different climate (Liu et al., 2004; Fageria and Baligar, 2008). The increased content of organic matter in these soils has a great influence on the activity and effectiveness of the performed calcification procedure (Briedis et al., 2012). Based on the conducted research it is undeniable that all cultivated crops (silage corn > triticale > spring barley) responded positively to the applied lime materials. For spring barley, which responds the worst to the application of lime materials, it would be best if it were grown as the first crop after application, as this is when the effectiveness of the applied materials is highest. If larger amounts of lime material were applied, the effectiveness would not be higher. What would happen is that much lime material would be displaced to the deeper layers of the soil by leaching, and would not cause chemical changes in the soil.

Commercial burnt lime had the highest effectiveness in the research. It is a commercial material that must be purchased, for which local farmers either justifiably or unjustifiably do not have the resources. Another option is to use lime materials from local quarries. The advantage of these materials is that they are more environmentally friendly as they do not require energy for combustion and produce hardly any CO_2 emissions (Oates, 1998). de Lespinay (2006) states that the production of one ton of lime emits about 0.785 tons of CO_2 into the air.

If farmers were being able to buy cheaper lime materials with even better granulation preparation, we believe this would be a good way to improve the soil response, i.e. increase fertility and achieve higher yields and therefore higher income. Table 7 shows the achieved yields of the cultivated crops (triticale, barley and silage corn) during three-year research. Triticale yield, in 2017, had significant higher values in BLP-H, followed by BLP-L and CDR-H, respectively. Barley yield showed somehow different behaviour, with the significant highest in BLP-H, and the lowest in control. Silage corn showed significant higher values in BLP-L and BLP-H, while in control lowest. Between other treatments, there was no significant differences for barley yield and silage corn, respectively.

CONCLUSIONS

The application of lime materials caused desirable changes in the soil chemical complex. The application of small doses of liming materials resulted in a short-term neutralization of the excessive soil acidity, but with a more permanent effect on increase of exchangeable Ca^{2+} after limestone application and increase of exchangeable Mg^{2+} after dolomite application. However, in this mountainous area, it is very difficult to determine the optimal amount of lime materials based on criteria for soils that have up to 3% organic matter and were formed in a different climate. The observed climate data show that the average annual temperatures were optimal for this study, however, content of gravel (15%) in soil and observed high amount of precipitation contributed to the higher leaching of liming materials. In the context of archived crop yields, commercial burnt lime (BLP) proved to be most effective, followed by crude dolomite Rama (CDR), while crude dolomite Kupres (CDK) proved to be the least effective. All cultivated crops reacted positively (silage corn > triticale > spring barley) to the applied lime materials. Regarding the investment and the yields achieved, silage corn proved to be the most economical crop, while highest economic feasibility was observed for BLP for the agro-ecological conditions of our research.

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