

Article

Effects of Liming and Nutrient Management on Yield and Other Parameters of Potato Productivity on Acid Soils in Montenegro

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Abstract: This study was conducted to evaluate the effect of liming (CaCO_3 1000 kg ha⁻¹) and application of organic fertilizers (rotted farmyard manure 40 t ha⁻¹) and six different combination of mineral fertilizers: NPK 15:15:15 800 kg ha⁻¹ + KAN (calcium ammonium nitrate) 240 kg ha⁻¹; NPK 15:15:15 400 kg ha⁻¹ + MCB (water-soluble mineral fertilizer NPK 13:11:20 + 2MgO + microelements + humic acid) 300 kg ha⁻¹ + KAN 125 kg ha⁻¹; MCB 400 kg ha⁻¹; MCB 400 kg ha⁻¹ + KMg (water-soluble mineral fertilizer Multi KMg 13:0:43 + 2MgO) 100 kg ha⁻¹; MCB 600 kg ha⁻¹ + KMg 100 kg ha⁻¹ and MCB 800 kg ha⁻¹ + KMg 100 kg ha⁻¹ on yield and other productivity parameters of potato (Kennebec variety). The aim of the research was to optimize the system of potato plant nutrition for maximum profitability in the future potato production on acid soils of mountainous region of Montenegro. The experiments were carried out during 2015 and 2016, on Dystric Cambisols. The results obtained suggested that in both years, the highest values for all studied parameters were measured on plots with combined application of liming, organic and mineral fertilizers. In addition, a significant influence on the increase in the number of tubers per plant, the average tuber weight and the total yield was also demonstrated in all individual trials of potato nutrition, and the interaction of organic manure and mineral fertilizer. Fertilizing with rotted farmyard manure had significantly increased potato productivity, with the effect more pronounced in treatments with liming. The highest number of tubers (6.2 and 7.2), average tuber weight (93.5 g and 101.0 g) and yield (27.6 t ha⁻¹ in 2015 and 34.8 t ha⁻¹ in 2016, respectively) were obtained using combinations of MCB 800 kg ha⁻¹ + KMg 100 kg ha⁻¹ on variants fertilized with rotted farmyard manure and liming. This research is a valuable source of information for potato growers and scientists from this region as the results have shown how fertilization is raising productivity in this environment and its importance in the future potato growing on acid soils in mountainous regions of Montenegro and Western Balkans.

Keywords: potato; liming; nutrient management; potato productivity; soils; Montenegro

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important agricultural crops in the world and the seventh most important food source in Europe. Global potato production is estimated at 370.4 million tons in about 17.34 million hectares and the production in Asia 189.81 million tons in 9.30 million hectares, in Europe 107.26 million tons in 4.7 million

hectares, the Americas was 45.1 million tons in about 1.54 million hectares; in Africa 26.53 million tons in 1.76 million hectares in 2019 and in Oceania 1.74 million tons in 43,303 ha [1–3]. It is the most widely grown tuber crop and the primary source of calories from starch in many underdeveloped and developing countries around the world. Its nutritional value is determined by the nutrients contained in the tubers such as protein, starch, fat, vitamins, polyphenols, macroelements and microelements. In addition, it is relatively low in calories, and antinutritional substances are found in tubers in very small amounts [4–8]. Potatoes are of great importance for the Montenegrin economy and, according to the planted areas, represent the leading agricultural crop. It accounts for about 25% of the production on arable land [9]. The main regions intended for potato production for storage and consumption during the autumn and winter are located in the central and mountainous regions of the country. Potato yields in Montenegro are very low (about 15 t ha^{-1}) and highly dependent on weather conditions. In addition to the direct effects of climate change (high temperatures, droughts and excessive rainfall during the growing season), there are number of other factors that are affecting such productivity state, of which, in importance, stand out: relatively small use of certified planting material, limited use of irrigation, potato cultivation in long-term monoculture, diseases and pests and poor agronomic practices, especially poor nutrient management. In order to improve the situation in this production, besides favorable agroecological conditions, more intensive application of agrotechnical measures will be necessary, especially irrigation and fertilization [10].

Due to its short life cycle and high yield, potato has a pronounced need for nutrients [11]. In addition, it requires a regular supply of nutrients because their deficiency causes decreased quality of the tubers [12]. In the short growing season and in early varieties, the greatest need for nutrients is, in principle, in the phase of vegetative growth and tuber initiation. In late varieties, the period of mineral nutrition is much longer.

Of all the essential nutrition elements, N is one of the most restrictive nutrients affecting potato growth and development. Profitable potato production is only possible with adequate application of nitrogen fertilizers because most of the nitrogen found in soil is in the organic form (soil organic matter and plant residues) and is not readily available to plants [13]. Amounts of mineral nitrogen in the soil are essential for yield formation and an increase in dry matter yield [14]. Inadequate nutrition with N causes poor potato plant development and low yields, while overfertilization results in leaching, prolonged vegetation, poor tuber quality and sometimes reduced yields. Poor mineral nutrition with N not only leads to a decrease in yield but also to a decrease in the number of tubers as a result of reduced leaf area and early defoliation [15]. Phosphorus is a very important element in the many processes that take place in the plant organism (energy transfer in cells, respiration and photosynthesis) [16], which make it an essential element for the growth and development of potato plants [17]. In addition to increasing yields, it has a very beneficial effect on the development of the root system, promotes better uptake of nitrogen, promotes early and better formation of tubers and their development and increases the resistance of plants to low temperatures and diseases [18]. Potatoes have high needs for potassium because it promotes root and leaf development, regulates water balance, reduces susceptibility to damage, protects the plant from disease and the negative effects of adverse weather conditions and affects the quality and length of tuber storage [19]. The lack of potassium is manifested by lower yields and quality of the tubers produced. Poor potassium nutrition also causes a decrease in specific gravity [20,21].

Potatoes respond well to fertilization with organic fertilizers because they contain almost all the necessary macro (nitrogen, phosphorus and potassium) and trace elements (copper, zinc, manganese, etc.). The positive effect of manure is also reflected in the increase of the humus component of the soil and the faster warming of the soil in early spring, when higher temperatures are needed for the growth and development of the tuber sprouts. Through its mineralization, plant nutrients and carbon dioxide are released, essential substances in the process of photosynthesis [21,22]. In addition, the released CO_2

contributes to the activation of nutrients from the existing land reservoir, increasing their accessibility to plants [23].

Acidification of soil is caused by a number of factors (precipitation and the deposition from the atmosphere of acidifying gases or particles), but fertilizers based on ammonium and urea, elemental S fertilizer and cultivation of leguminous plants are certainly the largest causes of acidification. Acidic soil repair is performed through liming or other acid-neutral materials [24]. Potatoes tolerate well the low pH of the soil, which is why it is often grown in very acidic soils, even when the pH is below 5 [25]. Regardless of the fact that liming has a beneficial effect on increasing the yield of potatoes, many growers are avoiding it due to fear that increased pH of the soil, could cause intensive development of common scab (*Streptomyces* spp.) [26].

As a consequence of climate change, the number of very hot days and the duration of heat waves in Montenegro are continuously increasing, while on the other hand, the deficit of precipitation during the potato vegetation period is becoming more frequent. From current perspective, increasingly pronounced changes in the summer precipitation regime will pose the greatest threat to potato production in the mountainous areas, especially where possibility for irrigation is very modest or completely limited [9].

The market-oriented production of potatoes in this area is based exclusively on the application of mineral fertilizers. Due to very scarce information on fertilizing potatoes grown on acidic and very acidic soils that are prevailing in the mountainous area of Montenegro, the aim of the study was to investigate the influence of the effects of new nutrient systems on yield and other parameters of potato productivity on acid soils based on use of water-soluble fertilizers, manure and liming.

2. Materials and Methods

2.1. Location

The trial was set up as three-factorial in a randomized block design in four replications during 2015 and 2016, in the mountainous area of Montenegro, at an elevation 900 ASL ($42^{\circ}50'51.7''$ N; $19^{\circ}31'10.7''$ E), on acid-brown soil (Dystric Cambisols) (Figure 1).

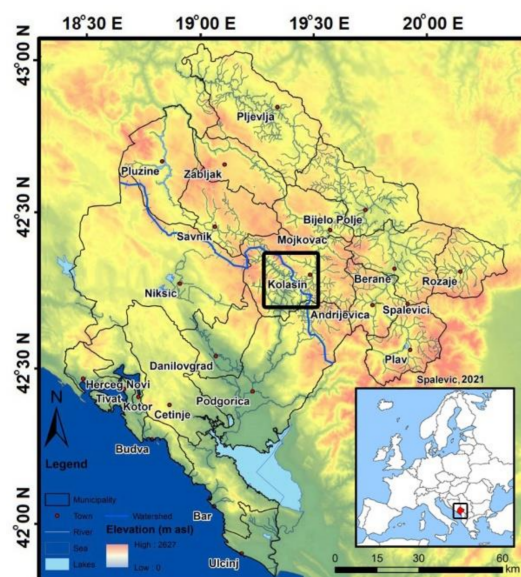


Figure 1. Study area: Kolasin, Montenegro, Europe.

2.2. Climatic Characteristics

The impacts of climate have the high impacts on this type of potato production. Global warming is driving a dynamic hydrological cycle with higher total precipitation and more frequent high intensity rainfall events. Rainfall amounts and intensities expanded around the world and according to the various models it is expected to increase furthermore

during the 21st century. Rainfall and temperature changes have noteworthy impacts on potato production in Montenegro, where we are experiencing increasing temperatures and evapotranspiration, most notably in the northern mountainous region of the studied area. The first two decades of the 21st century was recorded as the warmest since records started, with the most prominent changes within the northern hilly region of +1.4 °C and with a decrease in the number of frost days and exceptionally cold days and evenings. Changing precipitation pattern is also forecasted in the near future (less precipitations in summer, more in winter), increasing land degradation and erosion processes, water stress (summer) and flood risk (winter). Regarding rainfall there has been no critical decreasing within the normal annual rainfall: precipitation has increased in autumn whereas it has decreased from springtime to wintertime. There has been a significant increase in the number of extreme weather events.

Furthermore, storms have become more frequent and more intense as of the beginning of the 21st century, resulting in huge amounts of precipitation and high flooding. Flooding, droughts and heatwaves are progressively impacting natural assets. Flash floods and heavy snowfalls are becoming more common. For this research we used the data provided by the Institute of Hydrometeorology of Montenegro, where the studied region was considered to be with the continental climate, with rainy autumns and springs and cold winters [27–29].

Some basic data on meteorological conditions in the course of experiment are presented in the Table 1.

Table 1. Meteorological conditions in the course of experiment.

Year	Month					Average
	May	June	July	August	September	
Air temperature (°C)						
2015	13.2	15.5	19.8	18.8	14.4	16.3
2016	10.2	16.4	18.0	16.4	12.6	14.7
Amount of precipitation (mm)						
2015	65.4	93.8	31.1	94.4	109.4	394.1
2016	268.1	109.1	76.0	43.8	92.6	589.6

2.3. Soils of the Area

Mountains region in this part of Montenegro is part of the Dinaric Alps. The wider area of the studied region consists of various types of sedimentary, magmatic and metamorphic rocks, ranging in age from Paleozoic to Quaternary. Soils of the wider region of the studied are characterized by limited to low fertility, skeletal and shallow, with acid reaction (naturally acidic) and small retention capacity for moisture and nutrients. The most important types of soil in the region are: Dystric Cambisols (more than 80%), Eutric Cambisols (about 15%), Kalkomelanosols (4%) and some of fluvisols and colluvial fluvisols (1%), [29,30].

The experiment was set up at the Cambisol Dystric soil, in Kolašin, in Montenegro. Agrochemical analysis of the soil was done according to standard methods for soil analysis. This type of soil is characterized by unfavorable physical and chemical properties. Table 2 shows the soil properties until depth of 30 cm of typical Cambisol Dystric, from which soil samples were taken to establish the experiment. Agrochemical analysis of the soil in the determined that it is acidic soil that has a poor concentration of phosphorus and potassium, but rich in humus.

Table 2. Chemical composition of Cambisol Dystric soil.

Parameter	pH	CaCO ₃	Humus	P ₂ O ₅	K ₂ O
Depth (cm)	KCl	H ₂ O	(%)	mg/100g soil	
1–30	4.68	5.77	2.35	4.88	2.70 4.30

The Cambisol Dystric type of soil is unsuitable for agricultural production due to the poor water and air regime, the possibility of stagnation and compaction during dry periods. The Cambisol Dystric in the experimental field are poorly supplied with plant nutrition elements. The content of soluble P_2O_5 and K_2O is low: 2.7 and 4.3 mg/100 g of soil respectively and is insufficient to achieve high yields, and their deficiency must be compensated by fertilization. The soils are acidic (pH in water is 5.77 and in nKCl 4.68), and weakly carbonated (2.35% $CaCO_3$). The humus content is high (4.88%), which means that the soils are well supplied with organic matter. The availability of the most important plant nutrients in such soils, primarily phosphorus and calcium, is significantly reduced, which results in a reduction in potato yield, but also other cultivated crops. Potato is a crop that prefers moderately acidic soils for its development (pH in nKCl 5.5–6.5). Since the pH values are lower in the experimental field, in order to successfully grow potatoes and achieve higher yields and better quality of tubers, it is necessary to improve this condition with liming.

2.4. Experimental Design

The preceding crop in both years was a natural meadow. Ploughing was done in the fall, along with the application of rotted farmyard manure and liming. The manual planting of potatoes (Kennebec variety) was carried out at a distance of 70 cm \times 30 cm, achieving the density of 43,300 plants per hectare. The size of the elementary plot was 21 m². The previous crop for potatoes in both studied years was a natural meadow. During the growing season, standard agrotechnical measures for potatoes were applied. The trial was conducted in rainfed conditions.

Factor A (mineral fertilizer) consisted of six treatments: (a₁) NPK 15:15:15 800 kg ha⁻¹ + KAN 240 kg ha⁻¹; (a₂) NPK 15:15:15 400 kg ha⁻¹ + MCB (water-soluble mineral fertilizer NPK 13:11:20 + 2MgO + microelements + humic acid) 300 kg ha⁻¹ + KAN 125 kg ha⁻¹; (a₃) MCB 400 kg ha⁻¹; (a₄) MCB 400 kg ha⁻¹ + KMg (water-soluble mineral fertilizer NPK 13:0:43 + 2MgO) 100 kg ha⁻¹; (a₅) MCB 600 kg ha⁻¹ + KMg 100 kg ha⁻¹ and (a₆) MCB 800 kg ha⁻¹ + KMg 100 kg ha⁻¹. The combination of mineral fertilizers NPK 15:15:15 800 kg ha⁻¹ + KAN 240 kg ha⁻¹ (a₁) is the dominant type of fertilization in this production area and it was used as a control treatment in the experiments. Factor B (rotted farmyard manure) involved two types of application: (b₁) non-fertilized variant and (b₂) 40 t ha⁻¹. Data on the content of organic matter, nitrogen, phosphorus and potassium in the rotted farmyard manure are given in Table 3. Factor C (liming) was examined in two variants: (c₁) without liming and (c₂) 1000 kg ha⁻¹. Hydrated lime fertilizer with 46% of calcium oxide was used. Rotted farmyard manure and lime fertilizer were applied in the fall before ploughing. The application of mineral fertilizers was done in the spring together with seedbed preparation.

Table 3. Chemical composition of farmyard rotted manure used in the experiment.

Year	Organic Matter (%)	N (%)	P (%)	K (%)
2015	10.3	1.87	0.47	1.90
2016	11.1	2.03	0.54	2.71

The average value of agrochemical properties of soil is in Table 2. The chemical analyses of the soil were performed by the methods described by Bogdanović et al. [31]. The farmyard rotted manure composition is presented in the Table 3. using the following methods: organic matter according to Turin [32]. Corg was calculated from organic matter using a factor of 1.724 [33]. N total content was determined by Kjeldal (SPRS ISO 13878-2005) and P_2O_5 and K_2O content by the Egner-Riehm AL method [34].

2.5. Data Collection

A few days before harvesting, sampling was performed by taking all the potato plants from two middle rows on each variant (50 plants per plot) studied followed by analysis

of number and weight of tubers. Harvest of potato was carried out after the maturation of potato vine. The yield was determined by measuring all the tubers at each elementary plot and the total yield per hectare was calculated according to theoretical categories for crop density.

2.6. Statistical Analysis

Statistical analysis was done using factorial analysis of variance (Statistica for Windows 5.5), and significant differences among the means were evaluated according to the least significant difference (LSD) test. The degree and type of the dependence of potato yield on the simultaneous influence of tuber mass and number of tubers per plant were tested using multiple regression and correlation models.

The obtained data were processed using a three-way factorial analysis of variance, ANOVA (F test), tailored into completely randomized block system with four replicates; $p < 0.05$ were set as a significance level. Statistical analysis was performed by SPSS 15.0 (IBM Corporation, Armonk, New York, NY, USA) for Windows Evaluation version. The data were statistically processed by the multiple regression analysis and the correlation analysis using the equation ($\hat{y}_i = \alpha + \beta_1 \times X_1 + \beta_2 \times X_2$), which shows the average change (increase or decrease) in potato yield was established in dependence on tuber weight (β_1) and number of tubers (β_2). Difference testing of partial regression coefficients by the t test (b_1 and b_2 : $H_0: \beta_1 = 0$ vs. $H_a: \beta_1 \neq 0$ and $H_0: \beta_2 = 0$ vs. $H_a: \beta_2 \neq 0$). The significance of the linear regression model was tested by the F test ($H_0: \beta_1 = \beta_2 = 0$ vs. $H_a: \beta_1 \neq 0 \vee \beta_2 \neq 0$) and the simultaneous effect of the tubers weight and number of tubers on potato yield was established. The correlation dependence between variables was tested by the coefficient of multiple correlation (dependence of yield on the simultaneous effects of tubers weight and number of tubers) and by the coefficient of partial correlation (dependence of yield on the effect of one factor whereby the effect of the second factor is not considered). Testing of significance of correlation coefficients was done by the F and t tests.

3. Results

The results of the influence of the applied fertilizers on average tuber number per plant, the influence of the applied fertilizers on average tuber weight and the tuber yield are presented at the Tables 4–7. The largest number of tubers was determined in 2015 in the variants a_5 , a_6 and a_2 —6.18, 6.18 and 6.10—and lowest in treatment a_3 —5.8 (Table 4). The number of tubers in variants a_5 and a_6 was statistically significantly higher compared to all mineral fertilizer treatments, except for the combination applied in variant a_2 . In 2016, the highest number of tubers per potato plant was found in treatments a_6 , a_2 and a_1 —7.20, 7.12 and 7.0, respectively. The increase in the average number of tubers in the plots fertilized with these fertilizers compared to all other variants, except variant a_1 (7.00) was statistically justified.

The largest tubers in 2015 were measured in the variant a_6 , 90 g, while the tubers with the lowest average weight had plants grown in the variant a_3 , 79 g (Table 5). The increase in the average weight of tubers in the a_6 treatment in comparison with all other methods of fertilization was marked as statistically significant. In 2016, as in the previous year, the highest average weight of tubers was measured in the treatment a_6 , 101.0 g, while the smallest tubers had plants grown in the variant a_3 , 79.7 g. In both research years, the a_6 variant (27.6 t ha⁻¹ in 2015 and 34.8 t ha⁻¹ in 2016) yielded significantly higher tuber yields compared to all other mineral fertilizer variants (Table 6). At the same time, the lowest yields were in potato plants grown on treatment a_3 (22.0 t ha⁻¹ in 2015 and 24.8 t ha⁻¹ in 2016).

Table 4. The influence of the applied fertilizers on average tuber number per plant.

Year	Factor A (Mineral Fertilizer)	Factor C (Liming)						Average AB		Average A
		c ₁			c ₂			Factor B (Manure)		
		b ₁ ABC	b ₂ ABC	Average AC	b ₁ ABC	b ₂ ABC	Average AC	b ₁	b ₂	
2015	a ₁	5.8 ^a	6 ^b	5.9 ^b	5.9 ^{bc}	6.3 ^a	6.1 ^a	5.85 ^b	6.15 ^{bc}	6.0 ^b
	a ₂	5.9 ^a	6.3 ^a	6.1 ^a	5.7 ^c	6.5 ^a	6.1 ^a	5.8 ^b	6.4 ^{ab}	6.1 ^{ab}
	a ₃	5.8 ^a	5.7 ^c	5.75 ^b	5.8 ^{bc}	5.9 ^b	5.85 ^b	5.8 ^b	5.8 ^d	5.8 ^{bc}
	a ₄	5.7 ^a	6.0 ^b	5.85 ^b	5.8 ^{bc}	6.0 ^b	5.9 ^b	5.75 ^b	6.0 ^c	5.88 ^b
	a ₅	5.9 ^a	6.3 ^a	6.1 ^a	6.2 ^a	6.3 ^a	6.25 ^a	6.05 ^a	6.3 ^b	6.18 ^a
	a ₆	5.7 ^a	6.5 ^a	6.1 ^a	6.0 ^{ab}	6.5 ^a	6.25 ^a	5.85 ^b	6.5 ^a	6.18 ^a
	Average	5.8 ^c	6.1 ^b	5.95 ^b	5.9 ^c	6.3 ^a	6.1 ^a	5.85 ^b	6.2 ^a	6.03
2016	a ₁	6.5 ^a	7.3 ^{ab}	6.90 ^{ab}	6.8 ^a	7.4 ^{ab}	7.10 ^{ab}	6.65 ^a	7.35 ^a	7.00 ^{ab}
	a ₂	6.8 ^a	7.4 ^a	7.10 ^a	6.7 ^a	7.6 ^a	7.15 ^a	6.75 ^a	7.50 ^a	7.12 ^a
	a ₃	6.5 ^a	6.5 ^c	6.50 ^c	6.8 ^a	6.5 ^d	6.65 ^c	6.65 ^a	6.50 ^c	6.58 ^{bc}
	a ₄	6.6 ^a	6.8 ^c	6.70 ^{bc}	6.8 ^a	6.8 ^{cd}	6.80 ^{bc}	6.70 ^a	6.80 ^{bc}	6.75 ^b
	a ₅	6.5 ^a	6.9 ^{bc}	6.70 ^{bc}	6.6 ^a	7.0 ^{bc}	6.80 ^{bc}	6.55 ^a	6.95 ^b	6.75 ^b
	a ₆	6.6 ^a	7.5 ^a	7.05 ^a	6.9 ^a	7.8 ^a	7.35 ^a	6.75 ^a	7.65 ^a	7.20 ^a
	Average	6.60 ^b	7.10 ^a	6.85 ^a	6.77 ^b	7.18 ^a	6.98 ^a	6.68 ^b	7.14 ^a	6.92
Parameter		2015			Lsd		2016		Lsd	
Source	d.f.	MS	<i>p</i>	0.05	0.01	MS	<i>p</i>	0.05	0.01	
Mineral fertilizers (A)	5	0.409	0.000000 **	0.141	0.241	1.003	0.000003 **	0.242	0.414	
Manure (B)	1	2.600	0.000000 ***	0.081	0.139	4.905	0.000000 ***	0.140	0.239	
Liming (C)	1	0.260	0.013225 **	0.081	0.139	0.650	0.022429 **	0.140	0.239	
A × B	5	0.232	0.000163 **	0.199	0.340	0.645	0.000283 **	0.342	0.586	
A × C	5	0.112	0.924425 nsd	0.199	0.340	0.014	0.988939 nsd	0.342	0.586	
B × C	1	0.007	0.685590 nsd	0.115	0.196	0.013	0.746206 nsd	0.198	0.338	
A × B × C	5	0.055	0.249133 nsd	0.281	0.481	0.036	0.909934 nsd	0.484	0.828	

A-mineral fertilizers (a₁; a₂; a₃; a₄; a₅; a₆); B-rotted farmyard manure (b₁ without; b₂ with); C-liming (c₁ without; c₂ with); nsd = no significant difference, $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. ^{a,b,c,d,e} Means that columns followed by the same letter are not significantly different according to Fisher's protected LSD values ($p = 0.05$).

Table 5. The influence of the applied fertilizers on average tuber weight (g).

Year	Factor A (Mineral Fertilizer)	Factor C (Liming)						Average AB		Average A
		c ₁			c ₂			Factor B (Manure)		
		b ₁ ABC	b ₂ ABC	Average AC	b ₁ ABC	b ₂ ABC	Average AC	b ₁	b ₂	
2015	a ₁	76 ^d	88 ^{ab}	82.0 ^c	78 ^{cd}	93 ^b	85.5 ^c	79 ^c	85 ^{bc}	82 ^d
	a ₂	78 ^{cd}	92 ^a	85.0 ^b	84 ^b	94 ^b	89.0 ^b	81.5 ^{bc}	88.5 ^{ab}	85 ^b
	a ₃	74 ^d	84 ^c	79.0 ^d	76 ^d	86 ^d	81.0 ^d	76.5 ^c	81.5 ^d	79 ^e
	a ₄	83 ^b	86 ^{bc}	84.5 ^{bc}	81 ^{bc}	88 ^{cd}	84.5 ^c	83.7 ^b	85.3 ^{bc}	84.5 ^{bc}
	a ₅	76 ^d	89 ^{ab}	82.5 ^c	81 ^{bc}	92 ^{bc}	86.5 ^{bc}	79.3 ^c	85.8 ^b	82.5 ^{cd}
	a ₆	88 ^a	92 ^a	90.0 ^a	92 ^a	102 ^a	97.0 ^a	89 ^a	91 ^a	90 ^a
	Average	79.2 ^d	88.5 ^b	83.8 ^b	82.0 ^c	92.5 ^a	87.2 ^a	81.5 ^b	86.2 ^a	83.8
2016	a ₁	85 ^b	96 ^b	90.5 ^b	87 ^b	99 ^b	93.0 ^b	86 ^b	97 ^{bc}	91.8 ^b
	a ₂	83 ^b	95 ^{bc}	87.0 ^c	89 ^b	101 ^{ab}	95.0 ^b	86 ^b	98 ^b	91.0 ^b
	a ₃	72 ^d	81 ^e	77.5 ^e	76 ^{cd}	88 ^d	82.0 ^d	74 ^d	84 ^e	79.7 ^d
	a ₄	81 ^{bc}	86 ^d	83.5 ^d	79 ^c	94 ^c	86.5 ^c	80 ^c	90 ^d	85.0 ^c
	a ₅	77 ^c	91 ^c	84.0 ^{cd}	74 ^d	98 ^{bc}	86.0 ^c	75 ^d	94 ^c	85.0 ^c
	a ₆	92 ^a	105 ^a	98.5 ^a	102 ^a	105 ^a	103.5 ^a	97 ^a	105 ^a	101.0 ^a

Table 5. Cont.

Average	81.7 ^d	92.3 ^b	87.0 ^b	84.5 ^c	97.5 ^a	91.0 ^a	83.1 ^b	94.9 ^a	88.9
Average tuber weight	2015				2016				
Source	d.f.	MS	<i>p</i>	0.05	0.01	MS	<i>p</i>	0.05	0.01
Mineral fertilizers (A)	5	333.569	0.000000 ***	2.036	3.482	946.067	0.000000 ***	2.433	4.161
Manure (B)	1	2370.094	0.000000 ***	1.175	2.010	3243.375	0.000000 ***	1.405	2.403
Liming (C)	1	270.010	0.000000 **	1.175	2.010	416.667	0.000000 **	1.405	2.403
A × B	5	45.969	0.000264 **	2.879	4.924	60.025	0.000568 *	3.441	5.885
A × C	5	19.985	0.047856 *	2.879	4.924	11.217	0.466532 nsd	3.441	5.885
B × C	1	14.260	0.197822 nsd	1.662	2.843	35.042	0.092525 nsd	1.987	3.398
A × B × C	5	14.285	0.147409 nsd	4.072	6.964	57.642	0.000789 *	4.866	8.323

Table 6. The influence of the applied fertilizers on average tuber yield (t ha⁻¹).

Year	Factor A (Mineral Fertilizer)	Factor C (Liming)						Average AB		Average A
		c ₁			c ₂			Factor B (Manure)		
		b ₁ ABC	b ₂ ABC	Average AC	b ₁ ABC	b ₂ ABC	Average AC	b ₁	b ₂	
2015	a ₁	20.9 ^c	25.3 ^c	23.1 ^c	21.9 ^{cd}	27.6 ^c	24.8 ^c	21.4 ^c	26.4 ^c	24.0 ^c
	a ₂	21.9 ^{bc}	27.7 ^{ab}	24.8 ^b	22.9 ^{bc}	29.2 ^b	26.1 ^b	22.4 ^{bc}	28.5 ^b	25.5 ^b
	a ₃	20.4 ^c	22.8 ^d	21.6 ^d	21.0 ^{cd}	24.2 ^d	22.6 ^e	20.7 ^c	23.5 ^e	22.0 ^d
	a ₄	22.7 ^{ab}	24.2 ^{cd}	23.4 ^c	22.3 ^{bcd}	25.1 ^d	23.7 ^d	22.5 ^b	24.6 ^d	23.5 ^c
	a ₅	21.6 ^{bc}	26.5 ^{bc}	24.1 ^{bc}	23.8 ^b	27.7 ^{bc}	25.8 ^{bc}	22.7 ^b	27.1 ^c	25.0 ^b
	a ₆	24.0 ^a	28.5 ^a	26.3 ^a	26.0 ^a	31.5 ^a	28.8 ^a	25.0 ^a	30.0 ^a	27.6 ^a
Average	21.9 ^d	25.8 ^b	23.8 ^b	23.0 ^c	27.6 ^a	25.3 ^a	22.5 ^b	26.7 ^a	24.6	
2016	a ₁	26.5 ^b	33.0 ^b	29.8 ^b	27.9 ^b	34.7 ^{bc}	31.3 ^b	27.2 ^b	33.9 ^b	30.6 ^b
	a ₂	26.8 ^b	33.5 ^b	30.2 ^b	28.6 ^b	36.6 ^b	32.6 ^b	27.7 ^b	35.0 ^b	31.4 ^b
	a ₃	22.2 ^c	25.1 ^e	23.7 ^d	24.5 ^{cd}	27.1 ^e	25.8 ^d	23.4 ^d	26.1 ^e	24.8 ^d
	a ₄	25.2 ^{bc}	27.5 ^d	26.4 ^c	25.5 ^c	30.3 ^d	27.9 ^c	25.3 ^c	28.9 ^d	27.2 ^c
	a ₅	23.5 ^c	29.7 ^c	26.6 ^c	23.4 ^d	32.8 ^c	28.1 ^c	23.4 ^d	31.2 ^c	27.4 ^c
	a ₆	29.0 ^a	37.4 ^a	33.2 ^a	33.5 ^a	39.1 ^a	36.3 ^a	31.2 ^a	38.2 ^a	34.8 ^a
Average	25.5 ^d	31.0 ^b	28.3 ^b	27.2 ^c	33.4 ^a	30.3 ^a	26.3 ^b	32.2 ^a	29.3	
Tuber yield	2015				2016					
Source	d.f.	MS	<i>p</i>	0.05	0.01	MS	<i>p</i>	0.05	0.01	
Mineral fertilizers (A)	5	54.330	0.000000 ***	0.763	1.304	207.122	0.000000 ***	0.954	1.631	
Manure (B)	1	433.500	0.000000 ***	0.440	0.753	820.755	0.000000 ***	0.551	0.942	
Liming (C)	1	45.927	0.000000 **	0.440	0.753	100.655	0.000000 **	0.551	0.942	
A × B	5	8.865	0.000011 *	1.078	1.845	18.399	0.000000 **	1.349	2.307	
A × C	5	2.245	0.105631 nsd	1.078	1.845	1.725	0.466023 nsd	1.349	2.307	
B × C	1	2.470	0.153008 nsd	0.623	1.065	3.118	0.198616 nsd	0.779	1.332	
A × B × C	5	0.703	0.704786 nsd	1.525	2.609	4.825	0.031938 *	1.907	3.262	

Fertilization with rotted farmyard manure had a very positive effect on the potato crop. In both studied years, significantly higher values were achieved for all studied parameters of potato productivity in variants fertilized with organic fertilizer (average number of tubers 6.2 in 2015 and 7.14 in 2016, average tuber weight 86.2 in 2015 and 94.9 g in 2016 and tuber yield 26.7 in 2015 and 32.2 t ha⁻¹ in 2016) compared to plots without its application (average number of tubers 5.85 in 2015 and 6.68 in 2016, average tuber weight 81.5 in 2015 and 83.1 g in 2016 and tuber yield 22.5 in 2015 and 26.3 t ha⁻¹ in 2016).

Table 7. Regression–correlation analysis of parameters tested.

Year	Tabular values: $F_{0.05;2;93} = 3.15$ and $F_{0.01;2;93} = 4.98$; $t_{0.025;93} = 1.990$ and $t_{0.005;93} = 2.639$		Evaluation of significance
2015	Equation of multiple linear regression	$Y = -25.228 + 0.427 * X_1 + 0.700 * X_2$	$F = 26,187.24^{**}$
	Regression coefficient	$b_1 = 0.427$; $b_2 = 0.700$	$t_{b_1} = 81.87^{**}$; $t_{b_2} = 134.26^{**}$
	Coefficient of multiple linear correlation and coefficient of determination	$R_{0.12} = 0.99911$ $d = 0.18\%$	$F = 26,187.24^{**}$
2016	Equation of multiple linear regression	$Y = -30.382 + 0.448 * X_1 + 0.693 * X_2$	$F = 24,269.64^{**}$
	Regression coefficient	$b_1 = 0.448$; $b_2 = 0.693$	$t_{b_1} = 84.97^{**}$; $t_{b_2} = 131.52^{**}$
	Coefficient of multiple linear correlation and coefficient of determination	$R_{0.12} = 0.99904$ $d = 0.19\%$	$F = 24,269.64^{**}$

*, ** significantly different at $p \leq 0.05$ and $p \leq 0.01$.

The application of liming significantly increased the average tuber weight and yield in both studied years. The average weight of tubers in limed plots was 82.0 g in 2015 and 84.5 g in 2016, and in non-limed variants 79.2 and 81.7 g, respectively. This caused the yield of tubers in lime plots (23.0 t ha^{-1} in 2015 and 27.2 t ha^{-1} in 2016) to be significantly higher compared to plots where this agricultural measure was not applied (21.9 t ha^{-1} in 2015 and 25.5 t ha^{-1} in 2016). Differences in the average number of tubers per plant between limed (5.9 in 2015 and 6.77 in 2016) and non-limed plots (5.8 in 2015 and 6.6 in 2016) were without statistical significance.

The interaction of the mineral fertilizer \times manure \times liming had the highest influence on the studied potato productivity parameters. Plants grown in plots with the combined application of the studied factors had the highest number of tubers (6.3 in 2015 and 7.18 in 2016), the highest average tuber weight (92.5 g in 2015 and 97.5 g in 2016) and the highest average tuber yield (27.6 t ha^{-1} in 2015 and 33.4 t ha^{-1} in 2016), while the lowest number of tubers (5.8 in 2015 and 6.6 in 2016), the average weight of tubers (79.2 g in 2015 and 81.7 g in 2016) and the total yield of tubers (21.9 t ha^{-1} in 2015 and 25.5 t ha^{-1} in 2016) determined in variants without the application of rotted farmyard manure and liming. Fertilization with rotted farmyard manure without liming resulted in larger tubers (88.5 g in 2015 and 92.3 g in 2016) and higher yield (25.8 t ha^{-1} in 2015 and 31.0 t ha^{-1} in 2016) compared to limed variants without the use of organic fertilizer (average tuber weight 82.0 g in 2015 and 84.5 g in 2016 and tuber yield 23.0 t ha^{-1} in 2015 and 27.2 t ha^{-1} in 2016). This trend was not found in the case of the average number of tubers.

Based on data of the equation of multiple linear regression (Table 7), a statistically significant or a very significant simultaneous effect of average tuber weight and tuber number in both studied years was determined. The increase of 1 g of average tuber weight resulted in potato yields higher by 0.427 and 0.448 t ha^{-1} with an unchanged number of tubers. Considering the effects of the number of tubers, statistical significance was obtained, when a tuber number increase of one yield higher by 0.700 and 0.693 t ha^{-1} , with unchanged tuber weight per surface unit. All these changes were statistically significant but, according to stated values, the changes in yields in relation to observed productive characteristic are more affected by tuber number.

Dependence of the potato yield on both observed factors, average weight and tuber number, analyzed by the coefficient of multiple correlation, was very significant. Values of obtained coefficients of multiple linear determinations were very similar: $d = 0.18\%$ (percentile dependence of yields on average weight and tuber number in 2015) and $d = 0.19\%$ (percentile dependence of yields on average weight and tuber number in 2016).

4. Discussion

Liming in combination with organic and mineral fertilizers, through soil pH optimization and neutralization of soil acidity, and better availability of nutrients, has a positive impact on potato yield [35,36]. The results of these studies confirm these findings. Higher values for all studied potato productivity parameters were determined in 2016, which is a consequence of better meteorological conditions.

The average air temperature in the period May–September in 2015 was 16.3 °C and was 1.6 °C higher compared to 2016 (14.7 °C). In 2016, 589.6 mm of water deposition during the potato vegetation period, 195.5 mm more compared to the same period in 2015 (391.1 mm). In addition to a larger amount, 2016 also had a better precipitation distribution, especially in the phenophases of intensive potato plant growth and tuberization.

The highest average number of tubers in the experiments in both years studied was obtained under the influence of the A × B × C interaction. The variation of the average number of tubers per plant was significantly influenced by agroecological conditions, so in 2016, due to the higher amount of precipitation in the period of tuber set, higher average values were determined. These results are in agreement with those found by Jovovic et al. [37] and Postic et al. [38]. According to these authors, the number of tubers per plant is a varietal trait, which significantly depends on a number of other factors: the number of primary shoots, the size of the tuber, agroecological conditions and applied agrotechnical measures.

The combined application of mineral fertilizers, rotted farmyard manure and liming significantly affected the increase in average tuber weight. In addition, all treatments with the application of manure significantly contributed to the increase in tuber size compared to treatments that were not fertilized with manure, but also those with the independent application of liming. Increase of average tuber weight, but also of total tuber yield is a consequence of the fact that manure, in addition to its nutritional value, has a very positive effect on soil structure, air, water and temperature regime, but also on increasing microbiological activity and soil pH [39]. With the improvement of the physical and chemical properties of the soil, the potato productivity also significantly increases.

The results of this study have undoubtedly shown that potatoes grown on soils with low phosphorus and potassium content respond well to the application of mineral fertilizers. The highest values in all tested parameters of potato productivity were obtained by applying optimal amounts of water-soluble fertilizers containing humic acids, either alone or in combination with standard NPK or KMg fertilizers, which is in accordance with the results reported by Pack et al. [40].

Profitable potato production, based on high tuber yields, is impossible without the application of high doses of mineral or organic fertilizers [41]. These studies have shown that the combined application of liming, rotted farmyard manure and mineral fertilizers on acidic soils can achieve satisfactory potato yields, especially in meteorologically favorable years. Integrated use of organic fertilizers with optimal doses of NPK fertilizers will not only lead to the improvement of soil nutritional status but also to the stabilization of potato yield over a longer period. These findings correspond to the results of Mărghitaș et al. [42], which state that the combined application of organic and mineral fertilizers significantly increases the fertility of these soils, and is very compatible with the biological and nutritional requirements of potatoes. Studies led by Heitkamp et al. [41] and Jovovic et al. [43] also indicate a positive influence of organic-mineral nutrition of potatoes in the mountain climate.

Acidic and very acidic soils are characteristic of the mountainous area of Montenegro, by active acidity forms (H^+ , Al^{3+} and Mn^{2+}), block the activity of soil microorganisms involved in the processes of mineralization of organic matter, which makes these soils less suitable for potato growth. The systematic fertilization with organic fertilizers on these soils neutralizes their acidity, increases the nutrient content and improves the adsorptive properties. All of this together affects the improvement of the physical and chemical properties of these soils [43–48]. The main conclusion of this research is that the integrated use of liming,

farmyard manure and mineral fertilizers can provide economical and environmentally friendly production of potatoes on a significant part of acidic soils in the mountainous regions of Montenegro. The application of appropriate nutrition systems significantly neutralizes the negative impact of factors that predominantly determine the yield of tubers.

Further studies of bigger number of different soil types and in irrigation conditions, the results on the impact of the combined application of liming, manure and mineral fertilizers will provide comparable results in different potato growing conditions and long-term improvement of soil characteristics.

5. Conclusions

The study presents detailed investigations related to defining the optimal fertilization system and finding possibilities for better adaptation of potato crop on acid soils of the mountainous regions of Montenegro. The fertilization system proposed by the present study had a significant effect on all studied parameters of potato productivity. The potato crop had favorable thermal conditions in both studied years, higher amount and better distribution of rainfall in 2016. The effect of environmental factors on potato yield was clearly evident.

The results of this research indicates that fertilization of potatoes with water-soluble mineral fertilizers significantly increases productivity of potatoes compared to the application of standard mineral fertilizers, which has been the dominant method of potato fertilization in the mountainous area of Montenegro. A significant increase in the average number of tubers, average tuber weight and total tuber yield was achieved on variants fertilized with water-soluble fertilizers (a_5 and a_6) compared to the control treatment (a_1).

Fertilizing with rotted farmyard manure had significantly increased potato productivity, with the effect more pronounced in treatments with liming. Fertilization with rotted farmyard manure caused a significant increase in all studied parameters compared to the variants without the application of organic fertilizer. Total potato yield in variants without the use of organic fertilizer ranged between 20.7 (a_3) and 25.0 t ha⁻¹ (a_6) in 2015 and from 23.4 (a_3 and a_5) to 31.2 t ha⁻¹ (a_6) in 2016, while in fertilized variants varied from 23.5 (a_3) to 30.0 t ha⁻¹ (a_6) in 2015 and from 26.1 (a_3) to 38.2 t ha⁻¹ (a_6) in 2016.

The application of lime fertilizer also had a positive effect on the productivity of potatoes. On calcified plots, significantly higher tuber yield was achieved (25.3 t ha⁻¹ in 2015 and 30.3 t ha⁻¹ in 2016), compared to non-limed plots (23.8 t ha⁻¹ in 2015 and 28.3 t ha⁻¹ in 2016).

The highest average number of tubers, tuber weight and tuber yield in the experiments in both years studied was obtained under the influence of the A × B × C interaction. The highest number of tubers (6.2 and 7.2), average tuber weight (93.5 g and 101.0 g) and yield (27.6 t ha⁻¹ in 2015 and 34.8 t ha⁻¹ in 2016, respectively) were obtained in variant a_6 (combinations of MCB 800 kg ha⁻¹ + KMg 100 kg ha⁻¹) fertilized with rotted farmyard manure and liming. The positive effect of the applied potato fertilization systems is the result of low pH value of soil but also insufficient soil supply with available phosphorus and potassium.

Optimizing fertilization for maximum productivity is of great importance in the future potato growing on acid soils in mountainous regions of Montenegro.

The approach proposed in this study proved to be successful for the central mountainous region of Montenegro; other studies on the other parts of the north mountainous region are necessary to define the environmental constraints of the described application.

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