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ROLE OF SILICON IN THE PHOSPHORUS NUTRITION AND GROWTH OF THE OATS (*AVENA SATIVA* L.) AT DIFFERENT PHOSPHORUS LEVELS

R. Bakır[1] and A. Horuz[2,*]

[1]The Ministry of Agriculture, Provincial Directorate of İspir, 25900 Erzurum, Turkey
[2]Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, 55139 Samsun, Turkey
[*]Corresponding author's email: ayhanh@omu.edu.tr

ABSTRACT

In some circumstances, silicon (Si) application is environmentally the most useful way of correcting or alleviating the negative effects of some abiotic stress factors on plant growth, e.g., nutrient element deficiency and toxicity. Therefore, the aim of this study was to investigate the effects of Si and phosphorus (P) levels, and their interaction, on the dry weight (DW) biomass and P concentration of 65 days old oats plants (*Avena sativa* L. cv. Faikbey) in a pot trial. The experiment was conducted with a completely randomized design with full factorial arrangement and three replicates under greenhouse conditions. The factors were Si application rate (0, 50, 100, 200 and 400 mg kg^{-1} soil) and P level (0, 10, 25, 50, 100 and 250 mg kg^{-1} soil). Increasing the P level in the soil from 0 mg kg^{-1} to 100 mg kg^{-1} significantly increased ($P<0.05$) the DW of oats shoots from 3.60 g pot^{-1} to 12.01 g pot^{-1}, respectively, compared to the control, but the DW significantly decreased from 12.01 g pot^{-1} to 8.68 g pot^{-1} at 250 mg kg^{-1} of P, due to P toxicity. In comparison, Si at all application rates significantly increased shoot DW compared to the control. The DW of shoots corresponding to the increasing Si concentrations were 7.06 (control), 7.82, 8.01, 8.55 and 9.08 g pot^{-1}, respectively. The relative DW increases, compared to the control as a function of increasing Si rate, were 10.76, 13.46, 21.10 and 28.61%, for 50, 100, 200 and 400 mg kg-1 of Si, respectively. The lowest shoot P concentration (0.03%) was in the control treatment and the highest was 0.45% at 250 mg P kg^{-1} of soil, without Si application. The P concentration was 0.20% at 200 mg Si kg^{-1}, without P application. Furthermore, P concentrations continuously decreased from 0.45 % to 0.29% as Si concentrations increased from 0 to 400 mg Si kg^{-1} at 250 mg P kg^{-1}. It is concluded that Si application to moderately acidic soils may be an effective method for the reduction of both P deficiency stress and P toxicity in oats, the latter by decreasing excess P absorption.

Keywords: silicon application, phosphorus fertilizer, oat, dry weight, P concentration

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INRODUCTION

There are a number of beneficial effects of silicon (Si) application on phosphorus (P) nutrition for many plant species. in situations where an insufficient level of P is available, including adverse soil conditions, nutrient disorders and plant diseases. An interaction between Si and P may occur in plants, although the partial substitution of Si for P in physiological processes is doubtful (Ma *et al*., 2001). Further research is necessary to determine if the beneficial effects of Si application on P nutrition occur where adequate P is supplied or is limited to situations where nutritional deficiencies affect growth (Tavakkoli *et al*., 2011).

Silicon is the second most plentiful element in the soil (Mitani *et al*., 2008). In agricultural production, Si is a supplementary element in both the plant physiological system and soil (Hou *et al*., 2006). Plants take up Si primarily in the form of monosilicic acid $Si(OH)_4$ and its content in soil solution varies between 0.1 and 0.6 mM (Ma and Takahashi, 2002). Depending primarily on their species and varieties, plants grown in soil incorporate Si in their tissues in various amounts, which range between 0.1 to 10% Si on a dry weight (DW) basis (Ma and Takahashi, 2002; Hodson *et al.*, 2005). Under P-deficiency stress, the positive effects of Si application have been reported in a great number of plants, for example, cereals like rice and barley (Ma, 2004). In addition, there have also been reports of its positive effects on plant growth and development under abiotic stress (salinity, metal toxicity, drought, radiation damage, nutrient imbalances and high temperatures), and in biotic stress situations, for example, in the presence of pests and diseases (Kim *et al.*, 2011; Kaya *et al.*, 2017). Silicon has been shown to be beneficial to higher plants and various cultivated crops such as tomato, cucumber, rice, wheat and oats (Hattori *et al*., 2005; Hamayun *et al*., 2010; Parveen and Ashraf, 2010; Ahmed *et al*., 2011; Chen *et al*., 2011). Its effects, which are attributable to a partial substitution of Si for P, or to the enhancement of P availability in the soil, differ in terms of plant species (Ma *et al*., 2001).

Phosphorus deficiency stress is a global issue because it limits crop yields on approximately half of all agricultural fields (Lynch, 2011). Furthermore, global P reserves are being depleted at a high rate and according to some estimates there will be no soil P reserves by the year 2050 (Balemi and Negisho, 2012). This situation represents an enormous threat to sustainable crop production. However, the presence of Si in the soil solution improved the conditions for the growth of maize, resulting in increased transpiration due to greater P uptake and utilization. The same reasons were given for the increase in DW biomass when both Si and P were applied (Owino-Gerroh and Gascho, 2004).

The oversupply of P causes chlorosis or necrosis in leaves, probably due to the decreased availability of essential minerals such as Fe and Zn. By suppressing excessive P uptake, Si can decrease the tissue levels of inorganic P and consequently can decrease the tissue damage caused by excess P. Decreased P uptake in the case of high soil P concentration can result from the deposition of Si in the roots and an Si-induced decrease in transpiration (Ma *et al*., 2001; Lux *et al*., 2003).

The substitution of silicate anions for phosphate ions at soil binding sites releases tied-up P and increases P availability for plant uptake (Balemi and Negisho, 2012). Silicon also influences the relationship of plants with other nutrient elements, such as Fe, Mn and Al, by reducing toxicity levels through the reduction of shoot transport and partitioning in the plant, or increasing P uptake in soils, in situations the P level is low or deficient in the soil (Ma, 2004). For this reason, the increased level of internal P via a decrease in the excessive uptake of Fe and Mn, due to the presence of Si, is a useful effect of Si on plant development under conditions of P deficiency stress (Sahebi *et al.*, 2015). In addition, Kostic *et al*. (2017) reported a direct increase of P availability due to P displacement from its binding sites on soil minerals by Si, and indirect benefits such as increasing soil pH and decreasing the effects of rhizotoxic Al species (primarily Al^{3+}), which further decreases P acquisition due to root damage.

Guo *et al.* (2006) reported that Si application (0, 25, 50, 100, 200, 300 mg kg^{-1} soil) at the mature stage of alfalfa (*Medicago sativa* L.) increased the leaf area index by the greatest margin in the 50 mg Si kg^{-1} treatment, and the most tillers on alfalfa plants occurred in the 100 mg Si/ kg^{-1}treatment. Silicon application also increased plant growth parameters such as blossoming, shoot dry weight, root number, leaf area, height, forage yield, root volume, secondary rooting, root biomass and shoots per plant, during the reproductive period (Liu *et al*., 2011).

Silicon uptake was also reported to enhance seed germination and seedling growth of soybean (*Glycine max* L.) at soil soluble Si levels of 55.1 to 202.8 mg kg^{-1} (Li *et al.*, 2004). Foliar applications of silicic acid increased pod numbers and grain yields by 14% for soybean, 15% for common bean (*Phaseolus vulgaris* L.) and 9.6% for peanuts (*Arachis hypogaea*) (Crusciol, 2013). Many researchers have reported beneficial effects of Si on plant growth when available P is low or in excess, but the reasons for this are poorly understood (Ma *et al*., 2001; Tavakkoli *et al*., 2011; Meharg and Meharg 2015; Sahebi *et al*., 2015; Kostic *et al.*, 2017)

Against that background, the objective of the present study was to investigate the effects of increasing levels of Si application on the P content and uptake, dry weight (DW) of oat plants at different P levels, especially at deficient or excess levels. A complementary objective of the study was the investigation of the interaction between Si and P on the growth parameters of oats.

MATERIALS AND METHODS

The experimental soil samples were taken at 0-30 cm soil depth from Mescitli village of Terme District in Samsun Province, Turkey (GPS coordinates:330191 E - 4556718 N (WGS84, UTM Zone 37). The air-dried soil sample was passed through a 2 mm sieve to produce homogenous subsamples for physical and chemical characterization. Physico-chemical properties of the soil were determined with standard procedures, as follow:

Soil pH was measured with a pH meter in a 1:2.5 soil:water suspension and soluble salts were measured with an electrical conductivity (EC) meter in a saturated paste (Sağlam, 2006). Organic matter (OM) was analyzed according to a modified Walkley-Black method (Kacar, 2009). Cation exchange capacity (CEC) was determined by using 1 N NH_4OAc (Kacar, 2009) and water holding capacity (WHC) was determined according to the method of Labuschange *et al.* (1995). Available phosphorus (P) was determined with the use of 0.03 N NH_4F+0.06 N H_2SO_4 and a spectrophotometer (Shimadzu UV 1208 model), according to the methodology of Kacar (1994). Exchangeable potassium (K), calcium (Ca) and magnesium (Mg) were extracted with 1 N NH_4COOH at pH 7.0; the Ca and Mg concentrations were determined with 0.01N EDTA adjusted to pH 7.0 and the K concentration was determined with flame photometry, as per the method of Sağlam (2006). Available iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) were extracted with DTPA. Their concentrations were then measured with a PERKIN ELMER AA-200 model Atomic Absorption Spectrophotometer (AAS) (Liang and Karmanos, 1993). The available soil silicon (Si) was extracted as described by Sauer *et al*. (2006). The concentration was then determined by using an Optima 2100 Inductively Coupled Plasma-Mass Spectrometer (ICP-MS Perkin-Elmer, DV). Some chemical and physical properties of the experimental soil are shown in Table 1.

Table 1. The physico-chemical properties of the experimental soil.

Soil properties		Value
pH	(1:2.5)	5.40
EC	dS m^{-1}	0.55
Sand	%	49.97
Silt	%	32.59
Clay	%	17.44
Textural class	-	Loam
OM	%	0.64
CEC	cmol kg^{-1}	37.56
WHC	%	50.42
Available P	mg kg^{-1}	1.42
Exchangeable K	cmol kg^{-1}	0.15
Exchangeable Ca	cmol kg^{-1}	21.64
Exchangeable Mg	cmol kg^{-1}	5.50
Available Fe	mg kg^{-1}	36.50
Available Mn	mg kg^{-1}	39.27
Available Zn	mg kg^{-1}	0.58
Available Cu	mg kg^{-1}	4.22
Available Si	mg kg^{-1}	16.68

The experiment was conducted in a greenhouse at the Agriculture Faculty of Ondokuz Mayıs University in Samsun, Turkey in 2014. It was established as a completely randomized design pot trial, with factorial arrangement and with three replicates. The treatments consisted of 5 silicon application rates (Si_0:0, Si_{50}:50, Si_{100}:100, Si_{200}:200 and Si_{400}:400) mg Si kg^{-1} soil, as pure silicic acid [$Si(OH)_4$], and 6 phosphorus fertilizer application rates (P_0:0, P_{10}:10, P_{25}:25, P_{50}:50, P_{100}:100 and P_{250}:250) mg P kg^{-1} soil, as triple super phosphate (42% P_2O_5). The interaction effects represented the combined effects of Si application and P fertilizer concentration on the dry weight (DW) of oats shoots and their P content. The Faikbey oat cultivar (*Avena sativa* L. cv. Faikbey) was chosen because it is recommended for moderately acid soils, with the soil used having a pH of 5.4. Two kilograms of air-dried soil amended with basic fertilization of 75 mg N kg^{-1} as urea (46% N), and 150 mg K kg^{-1} as potassium sulphate (50% K_2O), was thoroughly mixed and then placed in each plastic pot (16 x 17 x 12.5 cm - height x top diameter x bottom diameter) before the oats seeds were sown. In addition, 75 mg N kg^{-1} in the form of ammonium nitrate (NH_4NO_3; 33% N) was applied to each pot as a top dressing at the tillering stage.

In the three replicates of each treatment, 20 seeds were sowed at even spacing in each pot, and the emerged seedlings were thinned to leave 15 of them. All pots were regularly irrigated to 80% of field capacity with the gravimetric method. At the end of the 65-day development period, the plants were harvested at 1 cm above the soil surface. The labelled plant samples were then oven-dried at 65°C to obtain the DW of the harvested aboveground biomass. The samples were then ground to a particle size below 0.5 mm to have uniform, homogenised aliquots for nutrient analysis. Half a gram (0.5 g) of aliquot was wet-digested with concentrated HNO_3:$HClO_4$ mixture (4:1, V/V). The P concentration of the digested oat shoot material was colourimetrically measured (JENWAY 6320D Model spectrophotometer) by using Barton's reagent (Kacar and İnal, 2008).

Percentage changes in biomass and nutrient concentration relative to the controls were calculated with the equation provided below:

$$\text{Percentage Change (\%)} = \frac{\text{Treatment} - \text{Control}}{\text{Control}} \text{x100} \quad (1)$$

All data were subjected to analysis of variance (ANOVA) in a 5 x 6 factorial arrangement. Treatment means were compared with Duncan's multiple range test, with statistical significance accepted at $P < 0.05$, by using SPSS for Windows, version 17.1 (SPSS Inc., Chicago, USA).

RESULTS

The effect of Si on growth of oats with increasing P levels: In the greenhouse pot experiment, soil amendment with Si at different soil P levels had beneficial effects on the dry weight of oats shoots, ranging from 3.20 to 13.58 g pot^{-1} (**Table** 2). Variance analysis showed a significant effect (P<0.01) of all Si applications and P fertilizer levels on the DW of oats shoots, and on the interaction between Si and P. Increasing P application rates increased the DW of oats shoots, and there was also a significant, positive correlation at 1% between the P application rate and the DW of oats shoots (**Figure 1**).

The 10, 25, 50 and 100 mg kg^{-1} application rates of P increased the mean DW of oats shoots from 3.60 mg kg^{-1} in the control to 7.02, 8.20, 9.12 and 12.01 g pot^{-1}, respectively, when compared to the control, but the DW of oats shoots decreased to 8.68 g pot^{-1} at P_{250} (Table 2).

Increasing Si application rates increased the DW of oats shoots at 50, 100, 200 and 400 mg Si kg^{-1} soil from 7.06 g pot^{-1} (control-Si_0) to 7.82, 8.01, 8.55 and 9.08 g pot^{-1}, respectively (Table 2).

The highest shoot DW of oats shoots was obtained from the Si_{400} application. The effect of Si application rates on the DW of oat shoots was statistically significant (P<0.05) at Si_{200}. The relationship between Si application rate and DW of oats shoots had a high correlation coefficient (Figure 2).

Separately, the mean increase in the DW of oats shoots obtained with increasing Si application rates (50, 100, 200 and 400 mg kg^{-1}) was 10.76, 13.46, 21.10 and 28.61%, respectively (Figure 3).

In terms of the interaction between Si and P, Si application also increased the DW of oats shoots from 3.20 to 4.34 g pot^{-1} in the P_0 (control). As the Si application increased from 50, 100, 200 and 400 mg Si

kg^{-1} soil, the DW increased from 5.35 to 7.57 g pot^{-1} at the P_{10} level, from 7.06 to 8.68 g pot^{-1} at the P_{25} level, from 8.88 to 9.30 g pot^{-1} at the P_{50} level, from 10.61 to 13.58 g pot^{-1} at the P_{100} level, and from 7.26 to 11.06 g pot^{-1} at the P_{250} level, respectively (Table 2). These increases meant that Si amendment significantly increased the DW of oats shoots at all P levels ($P<0.05$).

The highest increases were obtained with Si_{400} at 0, 25, 100 and 250 mg kg^{-1} of P, with the Si_{50} application rate at the P_{10} level, and with the Si_{100} application rate at the P_{50} level (Figure 4).

Furthermore, the optimal application rates of Si at different P levels, according to the statistical analysis, were the combinations of Si_{400} and P_0, Si_{50} and P_{10}, P_{25} and P_{50}, Si_{100} and P_{100}, and Si_{200} and P_{250}. Compared to the controls, the increases obtained at the P_{250} level for the 50, 100, 200 and 400 mg kg^{-1} application rates of Si were 1.38, 2.89, 41.32 and 52.34% respectively (Figure 5).

Table 2. Effect of Si on the dry weight of oats shoots at the different P concentration levels.

P application, mg kg^{-1}	Shoot DW of oat, g pot^{-1}					Mean
	Si application, mg kg^{-1}					
	0	50	100	200	400	
0	3.20k[+]	3.39k	3.28k	3.82k	4.34jk	3.60E
10	5.35j	7.94f-i	6.96i	7.29h-i	7.57g-i	7.02D
25	7.06iı	8.13f-i	8.64e-i	8.50f-i	8.68e-ı	8.20C
50	8.88e-h	9.10d-g	9.38d-f	8.92e-h	9.30d-f	9.12B
100	10.61cd	11.03bc	12.33ab	12.51ab	13.58a	12.01A
250	7.26h-i	7.36h-i	7.47g-i	10.26c-e	11.06bc	8.68BC
Mean, g	7.06D	7.82C	8.01BC	8.55AB	9.08A	-

[+]: There is no significant difference at the 5% level between means with the same letter within each column.
*F: Si**, P**, Si x P***

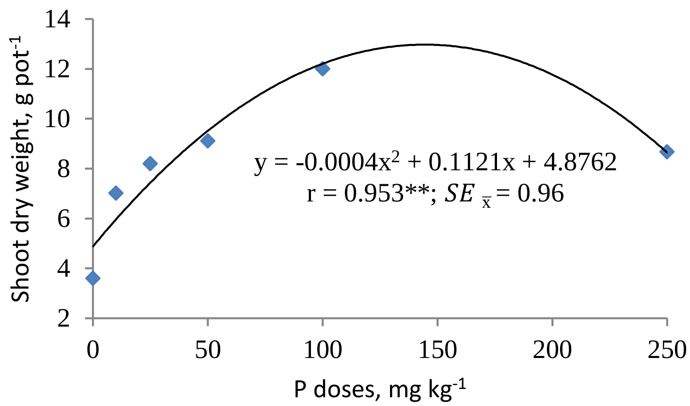

Figure 1. The relationship between P application rate and dry weight of oats shoots

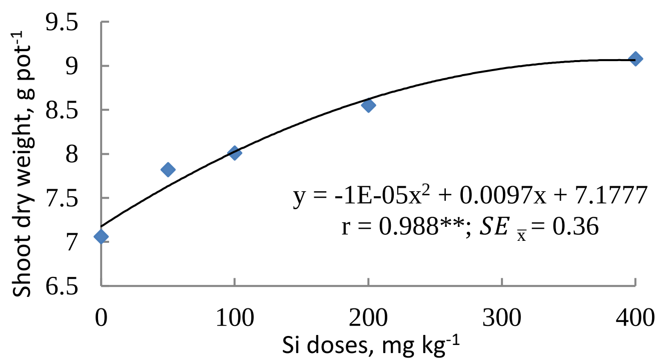

Figure 2. The relationship between Si application rate and dry weight of oats shoots

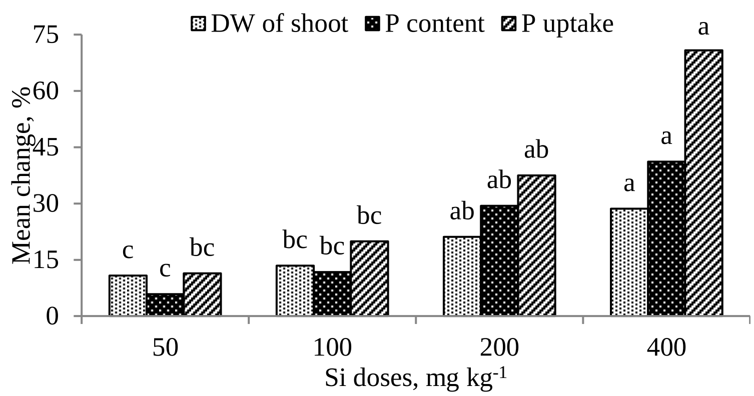

Figure 3. The mean change of dry weight, and P content and uptake by oats shoots for increasing Si application rates.

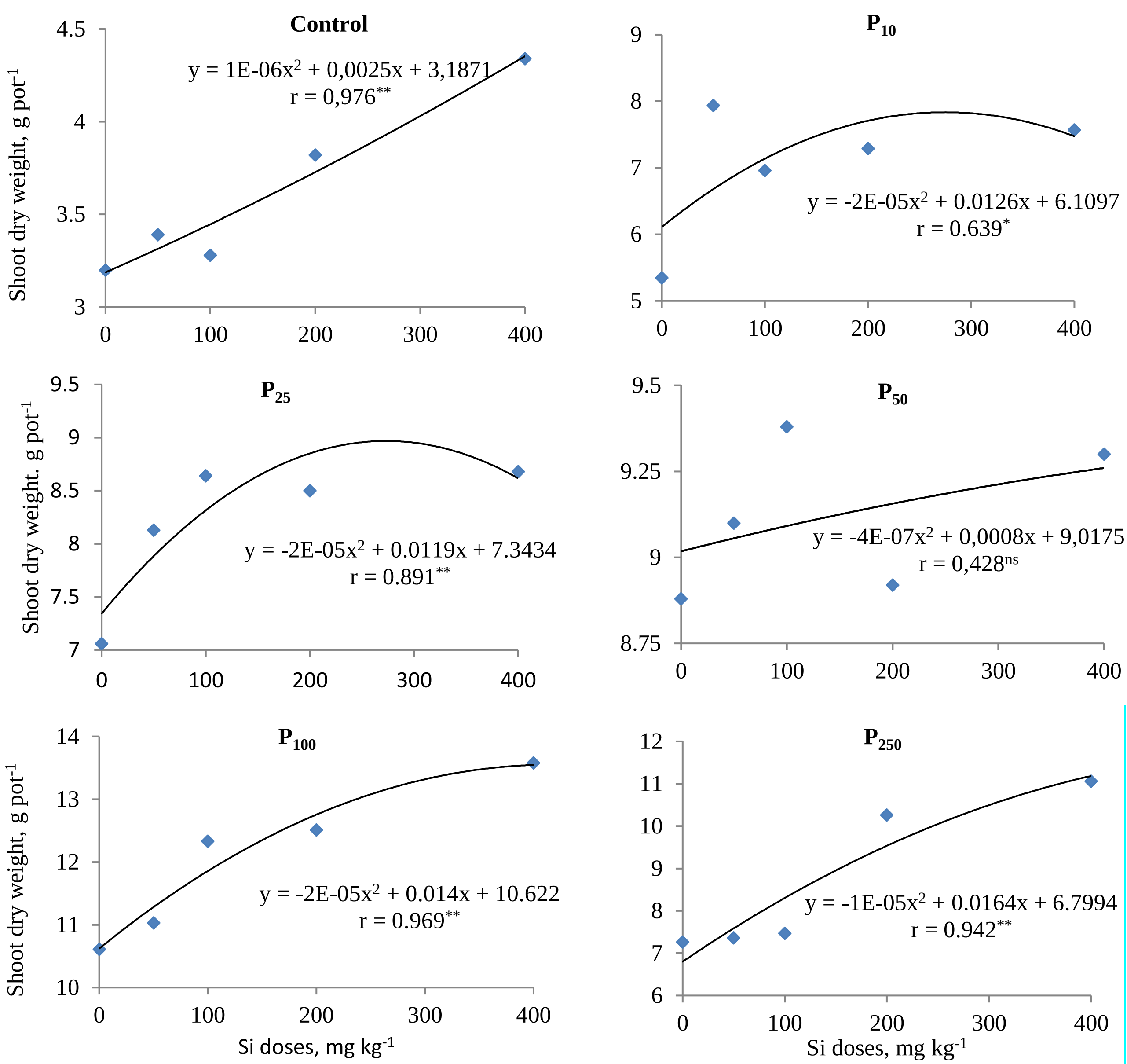

Figure 4. The relationships between Si and dry weight of oats shoots at different P application rates.

The effect of silicon on the phosphorus content of oats shoots at increasing soil P levels: The P content of oats shoots ranged between 0.03 and 0.45 % (**Table 3**). In addition, the P content of the oats shoots generally increased with increasing Si application at all P levels, except for P_{250}. The effects of all Si applications and P levels, and of all Si × P interactions on the P content of oats shoots, were statistically significant (P<0.01).

Phosphorus application at 10, 25, 50, 100 and 250 mg P kg^{-1} soil increased the P content of oats shoots from 0.12 % (control) to 0.14, 0.16, 0.18, 0.25 and 0.36%, respectively. The P content of oats shoots increased significantly (P<0.05) for the 25, 50, 100 and 250 mg kg^{-1} applications of P compared to the control, with the highest P content at P_{250} application level (**Table3**).

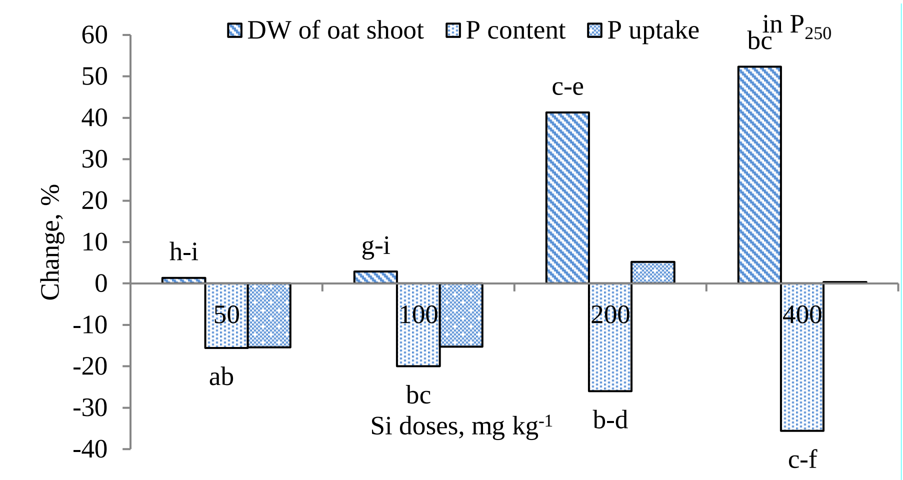

Figure 5. Dry weight, P content and P uptake of oat shoots at increasing Si application rates at the P_{250} level.

The 50, 100, 200 and 400 mg kg^{-1} Si applications increased the P content of oat shoots from 0.17 to 0.18, 0.19, 0.22, 0.24%, respectively, when compared to the control, with a significant effect (P<0.05) at Si_{200} (Table 3). Furthermore, there was a significant positive correlation between Si application and the P content of oats shoots (Figure 6). The mean changes in the P content of oats shoots obtained from the application of 50, 100, 200 and 400 mg Si kg^{-1} were 5.88, 11.76, 29.41 and 41.18 %, respectively, compared to the control (Figure 3).

Regarding the interaction of Si and P, Si applications significantly increased (P<0.05) the P content of oat shoots from 0.03% in the control to 0.20% (Si_{200}) (Table 3). At the P_{10} application rate, the P content increased from 0.07% to 0.20% (Si_{400}), at P_{25} from 0.11% to 0.23 (Si_{200}), at P_{50} from 0.14% to 0.26% (Si_{400}), and at P_{100} from 0.24% to 0.32% (Si400), but at P_{250} the P content of oats shoots decreased significantly (P<0.05) from 0.45% to 0.29% (Si400). Furthermore, at the highest soil P level (P_{250}), the P content of oat shoots decreased at all Si application rates. In other words, the 50, 100, 200 and 400 mg kg^{-1} Si applications all reduced the P content of oats shoots. Specifically, the decreases in P content were 15.56, 20.00, 26.00 and 35.56%, respectively, for the 50, 100, 200 and 400 mg kg^{-1} Si applications (Figure 5).

Table 3. Phosphorus content of oats shoots at different Si application rates.

P application, mg kg^{-1}	Shoot P content, %					Mean
	Si application, mg kg^{-1}					
	0	50	100	200	400	
0	0.03m+	0.07lm	0.10k-m	0.20g-i	0.18g-k	0.12E
10	0.07l-m	0.13i-l	0.16h-l	0.16h-l	0.20g-i	0.14DE
25	0.11j-m	0.10j-m	0.16h-l	0.23f-ı	0.20g-i	0.16CD
50	0.14ı-l	0.17h-k	0.16h-l	0.19g-k	0.26d-g	0.18C
100	0.24e-h	0.25d-h	0.23f-ı	0.19g-k	0.32b-e	0.25B
250	0.45a	0.38ab	0.36bc	0.33b-d	0.29c-f	0.36A
Mean	0.17C	0.18C	0.19BC	0.22AB	0.24A	

+: There is no significant difference at the 5% level between means with the same letter within each column
F: Si^{**}, P^{**}, Si x P^{**}

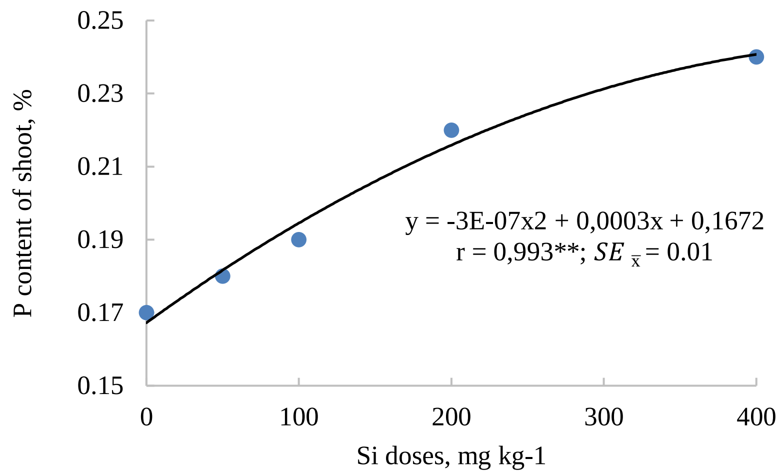

Figure 6. The relationship between Si application rate and P content of oats shoots

The effect of Si on the P uptake of oats shoots at increasing soil P levels: The mean P uptake of oats shoots ranged between 0.97 and 43.87 mg pot^{-1} (Table 4). Variance analysis showed that the P uptake of oat shoots was significantly affected (P<0.01) by some Si and P application rates, but the effects of all of the combinations of Si and P interaction on P uptake were not significant (P>0.05).

Phosphorus uptake at 10, 25, 50, 100 and 250 mg kg^{-1} of P increased from 4.41 mg pot $^{-1}$ to 10.45, 13.17, 16.72, 30.03 and 30.60 mg pot $^{-1}$, respectively, compared to the control (Table 4). From that series of applications, the uptake of P was statistically significant (P<0.01) at 100 mg P kg^{-1} soil.

Also, increasing the Si application rate increased the total P uptake by the oat plants. At 50, 100, 200 and 400 mg Si kg^{-1}, the uptake of P increased from 13.73 mg pot^{-1} (control) to 15.29, 16.46, 18.88 and 23.45 mg pot^{-1}, respectively. The mean changes obtained from 50, 100, 200 and 400 mg kg^{-1} applications of Si were 11.36, 19.88, 37.51 and 70.79%, respectively, compared to the control (Figure 3).

Regarding the interaction of Si and P, Si application significantly increased (P < 0.01) the P uptake of oats shoots from 0.97 mg pot $^{-1}$ in the control to 7.79 mg pot $^{-1}$ (Si_{400}) (Table 4). Phosphorus uptake increased from 3.99 to 15.45 mg pot $^{-1}$ (Si_{400}) at the P_{10} level, from 7.56 to 19.08 mg pot $^{-1}$ (Si_{200}) at the P_{25} level, from 12.42 to 24.13 mg pot $^{-1}$ (Si_{400}) at the P_{50} level, from 25.16 to 43.87 mg pot $^{-1}$ (Si_{400}) at the P_{100} level, and from 32.29 to 33.97 mg pot^{-1} (Si_{200}) at the P_{250} level. Silicon applications at the P_{250} level changed the P uptake of oats shoots by -15.40, -15.30, 5.20 and 0.37% at the 50, 100, 200 and 400 mg kg^{-1} application rates of Si, respectively, compared to the control (Figure 5).

Table 4. Phosphorus uptake by oats shoots at different Si application rates.

P application, mg kg^{-1}	Shoot P uptake, mg pot^{-1} Si application, mg kg^{-1}					Mean
	0	50	100	200	400	
0	0.97	2.35	3.20	7.76	7.79	4.41C^{+}
10	3.99	10.61	10.89	11.32	15.45	10.45B
25	7.56	8.33	13.54	19.08	17.32	13.17BC
50	12.42	15.27	14.74	17.03	24.13	16.72BC
100	25.16	27.95	29.05	24.10	43.87	30.03A
250	32.29	27.25	27.35	33.97	32.17	30.60A
Mean	13.73C	15.29BC	16.46BC	18.88B	23.45A	

$^{+}$: There is no significant difference at the 5% level between means with the same letter within each column.
F: Si**; P**, Si x P^{ns}

DISCUSSION

In this study, at each level of P application up to 100 mg kg^{-1}, the DW of oats shoots significantly increased (P<0.01) but at 250 mg kg-$^{-1}$ the DW decreased due to toxicity (Table 2), with the interpolated maximum beneficial application rate of P obtained from the relationship between the DW of oats shoots and P level being 140 mg kg^{-1} (Figure 1). There was a close proximity between the most appropriate P level found with the experimental values and the value calculated from the equation in Figure 1. Threshold soil P levels are too limiting to be the sole criterion to guide P management (Sharpley and Beegle, 2001). The same research also stated that P application at 75 - 150 mg kg^{-1} of the soil was equal to crop removal and a sufficient level, and if the P level was > 150 mg kg^{-1} in the soil, there was no need to apply P from any source. While sufficient level of P in soil increases plant growth, it could be reduced in situations where there is a lack or excess of P levels (Kacar and Katkat, 2009; Turan and Horuz, 2012).

The increase in DW and P content of oats shoots were both significant (P<0.05) at Si_{200}, and P uptake was significantly higher (P<0.05) at Si_{400}, in comparison to the control. The relationship between Si application and the DW of oats shoots showed that the maximum DW of oats shoots was at 400 mg Si kg^{-1} soil (Figure 2). Furthermore, the correlation coefficient between Si application and the DW of shoots was significant at the 1 % level. Similarly, Horuz and Korkmaz (2014) stated that there was a significant positive relationship at the 1% level between available Si and the grain yield of rice plants. Also, Liang *et al.* (2015) reported that Si fertilization increased spike density during harvest, the number of grains per spike and the weight of 1000 grains, which are all important contributors to maize yield. Separately, Jinger *at al.* (2018) reported that a combination of Si (80 kg Si ha^{-1}) and P (60 kg P_2O_5 ha^{-1}) applications increased the plant growth, yield parameters and economical benefit of aerobic rice (*Oriza sativa* L.).

The highest mean changes in the DW of shoots, and P content of the shoots and total plant P uptake were 28.61, 41.18 and 70.79%, respectively, at the Si_{400} application rate (Figure 3). In addition, the highest increases for all growth parameters were at Si400. Silicon can increase P use efficiency by increasing P availability in the soil and altering P metabolism in the plant, thus resulting in improved yields under low soil P conditions (Rogerio *et al.*, 2019). Especially in acidic soil conditions, Fe, Mn and Al are the metals most often less toxic in the presence of Si, as they can be bound as complexes by Si in the root cell walls and therefore are not transported to the shoots. The mechanism of such protection is due to Si binding with metals and preventing their concentration at toxic levels at localized sites (Meenai, 2014). Hossain *et al.* (2002) reported that the optimal Si concentration to be applied to rice, oats and wheat was 5-10 mM (140-280 mg kg^{-1}). Additionally, Si can enhance growth by increasing leaf erectness, and therefore increasing light acquisition by plants, which facilitates increased photosynthesis, transpiration, water use efficiency, CO_2 and H_2O exchange, and mineral nutrition, all of which collectively translates to increased vegetative growth (Hattori *et al.*, 2005; Savvas *et al.*, 2007; Savvas and Ntatsi, 2015).

For the interaction of P and Si, the maximum DW of oats shoots calculated from the equations for each P level (0, 10, 25, 50, 100 and 250 mg kg^{-1}) were at 400, 315, 298, 100, 350 and 400 mg Si kg^{-1} soil, respectively (Figure 4). The required Si application rates to achieve the maximum DW of oats shoots found both experimentally and calculated from the equations in Figure 4 were similar. These results showed that Si was more efficacious, especially at low and excess P levels, than at the medium P level. However, the grain yield of winter wheat only increased significantly at medium levels of addition of Si, probably due to the increased availability of P to plants (Neu *et al.*, 2017).

Similar to our study results, it has been reported that the Si availability simultaneously prevents P deficiency and toxicity (Ma and Takahashi, 2002). Also, many studies showed having to positive effect of Si on cereal crop yield by increasing photosynthesis, carbon translocation, water-soluble phosphorus levels and water use efficiency, which translate to increased plant growth, including more tillering and leaf area, and ultimately, the number of grains in the spike; in short, it increases plant growth by stimulating vegetative and generative development (Deren, 1994; Singh *et al.*, 2005; Kim *et al.*, 2012; Cuong *et al.*, 2017).

In the interaction between Si and P applications, the highest tissue P content (0.45 %) was at the P_{250} level, without Si application and then decreased up to the Si_{400} application rate (0.29 %). Increasing Si application rates at P_{250} application reduced the negative effects of P toxicity due to the P concentration in oats shoots; Si increased the DW of oats shoots by 52.34 % by reducing the P concentration by 35.56 % at Si_{400}, and also decreased the P uptake of oat shoots by approximately 15.00 % at both 50 and 100 mg Si kg^{-1} soil (Figure 5). The results further demonstrate that Si was more effective in reducing the effects of P on the DW of oats shoots at 200 and 400 mg Si kg than at 50 and 100 mg Si kg^{-1}. The authors of the present study suggest that Si reduced the harmful effects of P by localizing it in the root cells of our experimental oats plants, as reported by Ma *et al.* (2011), and exclusively in the endodermis (Chiba *et al.*, 2009; Mitani *et al.*, 2009). Also, Si can be deposited in hydrated, precipitated silica polymers within the cell wall, the silica-cuticle double layer and in off-shoot cells (Ma and Takahashi, 2002; Prychid *et al.*, 2004). Thus, Si limited P uptake, probably by reducing the transpiration rate, when P was supplied in excess (Ma *et al.*, 2001). Horuz *et al.* (2013) reported that silicon fertilization positively affected the grain yield of the rice plant, with a highest increase of 30.02%, and Wattanapayapkul *et al.* (2011) reported that at 0, 250, 500 and 1000 kg Si ha^{-1} increased the rice yield by 2-43%. Furthermore, Si application increased the yields of rice by 20-30 %

(Singh *et al.*, 2006), sugar beet by up to 40% (Prentice, 2017) and cucumber (*Cucumber sativus* L.) by 46 % by promoting fruit formation and speeding up fruit maturation (Matichenkov and Bocharnikova, 2008).

In the present study, the highest P content in oats shoots was at the maximum application rate of Si (400 mg kg^{-1}) (Figure 6). Silicon increased the plant available portion of P by reducing the level of soil adsorption of P, especially at low pH (Koski-Vähälä *et al*., 2001; Owino-Gerroh and Gascho, 2004). Available P in low soil pH was adsorbed mainly by Fe, Al and Mn hydroxides, but Si increased the available form of P for plant uptake by reducing the pool of hydroxides and by exchange with the available Fe and Mn (Treder and Cieslinski, 2005; Meharg and Meharg, 2015).

In the interaction of Si and P in the present study, Si increased the P uptake of oat shoots, especially at low (0, 10 and 25 mg P kg^{-1} soil), and moderate (50 and 100 mg P kg^{-1} soil) levels, but at the highest level (P_{250}), it reduced the P uptake of oats shoots and consequently the level of P toxicity (Table 4). Similarly, under the stress of low soil pH, a high proportion of soil P was fixed and therefore P availability decreased. In such soils, P uptake in many plants, especially Gramineae, increased with Si application (Ma *et al*., 2001). In contrast, Mali and Aery (2008) reported that the shoot DW of corn plants increased more at a low Si level (100 mg kg^{-1}) than at a high level (800 mg kg^{-1}). However, Eneji *et al.* (2008) reported a positive correlation between Si and P uptake in grasses. Also, P uptake and utilization increased and the Si concentration also increased in the shoots and roots of rice at low soil pH when Si was applied (Owino-Gerroh and Gascho, 2004).

Similarly, under low soil pH conditions, soil P was fixed at high levels and therefore P availability decreased. In such soils, P uptake in many plants, especially Gramineae, increased with Si application to soil with low soil P content by increasing the availability of P to the plant; P formed a complex with Fe, Mn and Al, and also increased the P/Fe, P/Mn and P/Al ratios, and thus increased P uptake by oat shoots (Ma *et al*., 2001). Furthermore, Si can alleviate P deficiency in the soil and can also decrease P toxicity when there is too much P in the plant shoots (Kostic *et al.*, 2017). Also, Owino-Gerroh and Gascho (2004) stated that the reason for the decrease in P concentration was that Si could have been adsorbed primarily at the level of the soil particle since the applied silicate ions were converted into amorphous silicic acid (H_3SO_4) and thus had less negative surface loads than phosphate ions. In addition, they reported that the combination of Si and Ca ions could increase P availability by increasing the pH of soil in acidic conditions.

In the present study, the most beneficial effect of Si was generally seen at 400 mg kg^{-1} application, when P was at low or high levels, i.e. the control and 250 mg kg^{-1} application rate, respectively. Horuz *et al.* (2013) reported that the optimum Si application rate for soils in the Samsun region was 87 mg kg^{-1} of soil for optimum rice yield. Furthermore, extractable Si was correlated with the plant yield (Korndorfer *et al*., 2001). That result is supported by Gong *et al.* who (2003) reported that Si application can increase the DW of wheat under well-watered conditions and enhance plant growth under water shortage conditions by helping maintain high leaf area.

Phosphorus deficiency in soils is a common problem worldwide (Ma, 2004). Silicon does not influence P uptake directly, but it forms a complex in the soil with Fe and Mn, and decreases their available concentration significantly (Kostic *et al*., 2017). Thus, Si promotes the uptake of P by the plant, and increases its concentration, especially in the shoot and spike. Also, Si can alleviate the excessive uptake of P and therefore decrease the inorganic P concentration in the tissues. On the other hand, Si deposition in the root endodermal cells decreased the P uptake by reducing transpiration under the excess P concentrations in soil (Lux *et al*., 2003; Ma *et al*., 2001; Ma *et al.*, 2011).

Conclusions: In the present study, the application of silicon in the form of silicic acid to a moderately acidic soil at differing levels of P-induced abiotic stress had beneficial effects on the DW of oats shoots, and on the P concentration and P uptake, of oat plants. Normally, acidic soils are problematic for the maintenance of adequate amounts of available P. In this study, P fertilization enhanced biomass production in treatments up to 100 mg P kg^{-1} of soil. A possible explanation is that Si treatments were likely to have relieved the stresses induced by both P deficiency (0, 10 and 25 mg kg^{-1}) and a relatively toxic level of P (250 mg kg^{-1}). It is also noteworthy that no harmful effects on the measured plant parameters were evident at adequate levels of P application. Therefore, Si was demonstrated to have reduced the effects of both P deficiency and toxicity in oats plants. It is therefore recommended that 400 and 200 mg Si kg^{-1} of soil be applied at low and high available P levels, respectively, to reduce the harmful effects of P stress on oats plants. On the basis of the current findings, the efficacy of Si in potentially improving P uptake and metabolism should be tested on different combinations of plants, soil types and abiotic stresses.

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