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Phosphorus Fertilization Impacts on Corn Yield and Soil Fertility

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ABSTRACT

Optimization of phosphorus (P) fertilization is important for balancing soil fertility especially in vertisol to support economic crop production. The objective of the study was to determine the impact of P fertilization (1998 to 2014) on crop yield and nutrient uptake, and soil fertility under continuous annually tilled corn (*Zea mays* L.)-wheat (*Triticum aestivum* L.) system in semi-arid Mediterranean conditions. The study was conducted on Arik clay (isohyperthermic, fine clay Typic Haploxerert) using randomized complete block design with four replications for each treatment at the research farm of the Dept. of Soil Science and Plant Nutrition, Çukurova University, Adana, Turkey. P fertilizer at 0, 50, 100, 200 kg P_2O_5 ha^{-1} as triple superphosphate (TSP), respectively was applied a week before planting corn. Results showed that increasing P fertilization rates significantly decreased the number of mycorrhizal spores associated with corn roots. Similarly, a 10% decrease in corn root mycorrhizal colonization was observed with 200 kg P_2O_5 ha^{-1} fertilization. In the control treatment, corn yield was 4.3 Mg ha^{-1} as compared to 5.6, 5.7 and 6.1 Mg ha^{-1} in 50, 100 and 200 kg of P_2O_5/ha, respectively. The relationship between P fertilization and relative yield showed that more than 95% of the corn yield was produced when P applied at 100 kg P_2O_5 ha^{-1}. While P fertilization significantly increased the leaf N, P, and K contents but decreased the leaf Zn, Fe and Mn contents, as compared with the control. However, P fertilization did not consistently affect the grain N and P contents. Both physiological efficiency- and agronomic efficiency of P fertilization have shown a significant non-linear increase than that of the control. Total organic C (TOC) and total N (TN) concentrations were more than 34 and 26% higher in 100 and 200 kg P_2O_5 ha^{-1}rates as compared with the control. Likewise, available P (AP), manganese (Mn) and zinc (Zn) concentrations increased with an increase in P fertilization rates. The AP, Mn and Zn contents significantly stratified by P fertilization. Our results suggested that 100 kg P_2O_5 ha^{-1} is optimum to sustain Vertisol fertility for supporting economic corn production in the Mediterranean climates of Turkey.

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Economic yield; micronutrients; mycorrhizal infection; organic C; total N; vertisol

Introduction

Sustainable P fertilization is one of the economically and ecologically important agricultural management strategies for crop production worldwide. However, a low plant availability of P in soil is one of the limiting factors to support economic crop production (Lynch and Brown 2001; Khan and Jorgensen 2009; Malik et al. 2013; Johnston et al. 2014). While most of the soils contain substantial amounts of total P, yet plant available P contents are generally low due to rapid precipitation and sorption of soluble P with reactive soil components (Hinsinger 2001, Alam and Ladha 2004; Brady

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and Weil 2008; Khan and Joergensen 2009; Richardson et al. 2011). Owing to the very low efficiency of P, a large amount of chemical P fertilization is required for optimizing P availability to sustain economic crop productivity, especially in vertisol (Syers et al., 2008, Zhang et al. 2010; Shen, Christie, and Li 2016; Bai et al. 2013).

Vertisols surface depth has a natural tendency to granulate, which generally prevents soil drying at sub-surface depths (Coulombe, Dixon, and Wilding 1996). This process often causes the vertisols to be tilled at higher antecedent moisture contents, resulting in poor workable field conditions that may adversely affect soil fertility, root growth and crop growth (Porter, Sullivan, and Harvey 1996). Moreover, P fertilizers are expensive and their accessible natural sources are diminishing fast worldwide (Cordell, Drangert, and White 2009). Therefore, it is important to focus on optimization of P management strategies that are novel and holistic, economic and sustainable in vertisol (Harvey, Warren, and Wakelin 2009; Sánchez 2010). Several studies have reported that crops that are more productive in soils with low available P contents have the inherent capacity of effective P foraging or P mobilizing via biochemically-driven rhizosphere mechanisms with mycorrhizal inoculations (Ciampitti et al. 2011; Ortas 2012).

However, higher P fertilization rates are often affect or suppress soil biological activity, such as mycorrhizae development (Gollner et al. 2011; Ortas 2003). Several studies have reported that at low P levels, plant root colonization and tissue P content are high; however, with increasing P levels the plant root colonization and tissue P content are low (Ortas 2012).

An optimization of chemical fertilization often leads to high recovery of the applied nutrients for economic crop yields and balanced soil fertility or vice-versa. It is reported that an increase in crop yields and biomass returns with optimum P fertilization resulted in a higher SOC and TN contents, as compared with the control (Ortas, Akpinar, and Lal 2013; Ortas and Lal 2012). However, there is a lack of science-based information available related to the impact of limited or excessive P fertilization on mycorrhizal colonization, SOC, TN and micronutrient contents in soils under semiarid Mediterranean regions (Ortas and Lal 2012). The objective of our study was to determine the long-term effects of P fertilization on mycorrhizal root infections, crop yield, nutrient uptake and P-use efficiency, and soil fertility in Ca-enriched vertisols under conventionally tilled corn-wheat system in the semi-arid Mediterranean conditions of Turkey.

Materials and methods

Location and experimental layout

The field study was established at the Cukurova University Agricultural Experimental Research Center in Adana, Turkey (37°0°.47.75N and 35°21′.31.92E at 33-m mean sea level) in 1998. The climate is a typical Mediterranean with long-term average annual air temperature of 19.2°C (varying from 14.2°C in January and February to 25.5°C in July and August) and precipitation of 671-mm. About 80% of the annual total precipitation is received between November and May, with a mean annual humidity of 66% (Anonymous 2008).

Soil belongs to Arık clay (isohyperthermic, fine clay typic Haploxererts) and contains clay 535 to 580 g ha^{-1}, silt 291 to 270 g ha^{-1}, and sand 174 to 150 g ha^{-1}, respectively, pH 7.6 to 7.8, cation exchange capacity 47 to 38 $Cmol_+$ kg^{-1}, salt 0.03 to 0.04% at the surface (0–20 cm) and sub-surface (20–40 cm) depth, respectively. Initial soil organic carbon 0.88 g kg^{-1} soil, zinc (Zn) cocntration is 0.52 mg kg^{-1} soil (Ortas 2012 #11562).

A randomized complete block design using control (P0), 50, 100, and 200 kg P_2O_5/ha treatments, respectively was established with three replicated plots (10 m x 20 m) for each P treatment. The P_2O_5 as 3Ca $(H_2PO_4)_2.H_2O$ with 160 kg N ha^{-1} as $(NH_4)_2SO_4$ for wheat and 200 kg N ha^{-1}as $(NH_4)_2NO_3$ for corn were applied along with a basal dose of 50 kg K ha^{-1} as K_2SO_4. Fertilizers were broadcasted before planting crop and incorporated into the soil with a disc harrow. Corn was planted during the spring-summer growing while wheat was planted during the winter-spring growing season in rotations. Immediately after harvest, the crop residues were incorporated into the soil by moldboard plowing.

Soil sampling, processing and analyses

Composite soil samples were randomly collected from each replicated plot at 0–20 and 20–40 cm depth, respectively after harvesting corn in September 2013 in sealable plastic bags. After air-drying at room temperature (~25°C), a portion of the soil sample was ground and sieved through a 2-mm mesh before analysis.

Soil sieved through a 2-mm mesh was ball-milled and passed again through a 0.25 mm mesh prior to determination of total organic C content using modified Walkley and Black wet oxidation method after treating the soil with HCL solution {Page, 1982 #15288}{Page, 1982 #9847}. Available P concentration was determined spectrophotometrically by following Murphy and Riley (1962). Cation exchange capacity was determined by using 1M neutral NH_4-acetate extraction and followed by distillation method (Bates and Richards 1993). Exchangeable K concentration in NH_4-acetate extraction was determined by a flame photometer. Diethylene triamine pentaacetic acid (DTPA) solution was used to extract micronutrients including Zn, Fe, Cu, and Mn and their concentrations were determined (Lindsay and Norvell 1978) by the Inductively Coupled Plasma (ICP) spectrophotometry. The pH of the soil paste was determined by a glass electrode pH meter. Electrical conductivity (ECe) was determined by using an EC electrode.

Mycorrhizal spores and root infection

Immediately after corn harvest, roots were randomly collected followed by washing with distilled deionized water to remove soil particles. The roots were then treated in 10% KOH solution (w/v) and stained by using trypan blue (Phillips and Hayman 1970). Mycorrhizal colonization was determined by the grid-line intersection method (Giovannetti and Mosse 1980). Rhizosphere soil fungal spores were also isolated by using the wet sieving technique (Gerdemann and Nicolson 1963).

Plant sampling, processing, analyses

At flowering stage, composite leaf samples of corn were randomly collected, oven-dried at 65°C until a constant weight was obtained, ground, and burned the samples at 550°C for 2 hr. Ashes were dissolved in 3.3% HCl acid, filtered and P in the solution was determined spectrophotometrically Murphy and Riley (1962). Total K concentration was determined by using a flame photometer. Micronutrient concentration, such as Zn, Fe, Cu, and Mn was analyzed by the Inductively Coupled Plasma spectrophotometry.

Nutrient uptake and phosphorus-use efficiency

Randomly selected corn grain samples were washed with distilled deionized water and oven-dried at 65°C for 24-hr., ground with a porcelain mortar and pestle, and passed through a 0.125-mm sieve prior to chemical analysis. Grain N content was determined by the micro-kjeldahl digestion and distillation method (Chapman and Pratt 1982). Grain P was determined by following Murphy and Riley (1962). Grain K was determined in diluted acid digestate by using the flame photometry.

P-use efficiency was determined as apparent recovery efficiency of P (AREP), physiological efficiency of P (PEP), and agronomic efficiency of P (AEP) by following Dilz (1988), Isfan (1990) and Novoa and Loomis (1981), respectively.

AREP = [Corn grain P uptake at P plot - corn grain P uptake at P_0 plot]/[P applied]*100.

PEP = (Corn yield at P plot – corn yield at P_0 plot)/(P uptake at P plot - P uptake at P_0 plot).

AEP = (Corn yield at P plot – corn yield at P_0 plot)/(P applied).

Soil phosphorus stratification

Stratification of P was calculated by dividing the P concentration at different depths of soil with the concentration of the respective P concentration at 40 cm depth under the control treatment.

Data analysis

Data were statistically analyzed by using the analysis of variance (ANOVA) procedure of the SAS program (SAS 2009). P levels and soil depth were considered as fixed variables and the block was considered as a random variable. Treatment means were separated by using the least significant difference (LSD) test, when the ANOVA showed significant effects ($P \leq 0.05$) independent variables on dependent variables. Relative yield of corn was regressed on P levels using the boundary line technique to calculate optimum P fertilization to achieve at-least 95% of the corn yield in vertisol (Webb 1972).

RESULTS and DISCUSSION

Effects of p fertilization on mycorrhizal spores and root colonization

Results of the year of 2015 showed that under long-term P fertilization, soil biology such as number of mycorrhizal spores and the consequent root colonization has changed (Figures 1 and 2). Averaged across depth, increased P fertilization significantly decreased the number of indigenous mycorrhizae spores' distribution in soil. While the control soil has the highest spore numbers, the P fertilized soils have the lowest spore numbers (Figure 1). Neither depth nor P fertilization x depth has any significant effects on the number of mycorrhizal spores.

From 1998 to 2015, the post-harvest corn root mycorrhizal colonization decreased non-linearly with increasing levels of P fertilization (Figure 2). In control, corn root mycorrhizal colonization was 27% as compared to only 17% with the highest level of P fertilization. In other words, after 16 years later a 10% decrease in corn root mycorrhizal colonization was observed with higher P fertilization.

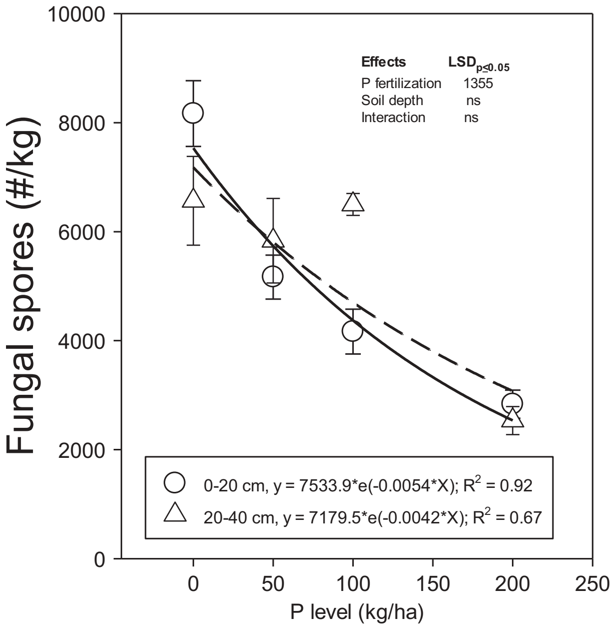

Figure 1. Long-term effects of P fertilization on mycorrhizal spore numbers.

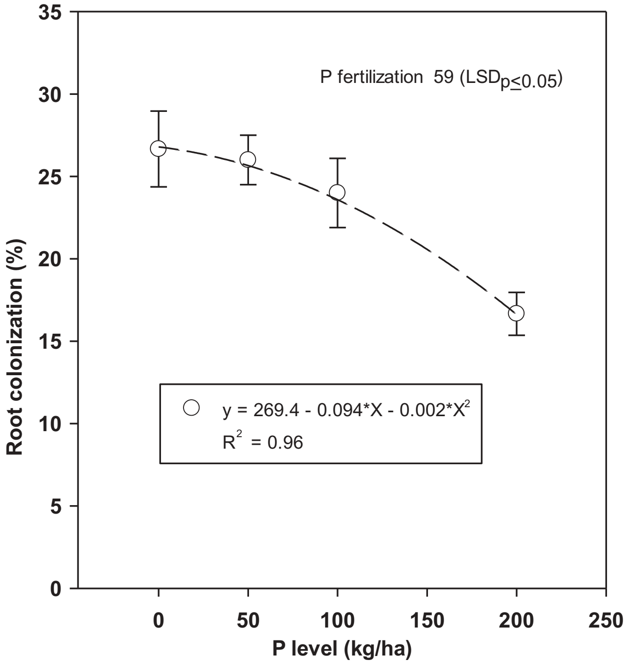

Figure 2. Long-term effects of P fertilization on mycorrhizal root colonization.

Several other studies have reported that plant root colonization is significantly higher when the concentration of soil AP is low and a reverse situation is observed when the soil has higher AP concentrations (Ryan 2008; Wang, White, and Li 2017).

Our results well collaborated with the results of other studies and suggested that long-term P fertilization was responsible for decreased mycorrhizal colonization of corn roots in Ca-enriched vertisol.

Effects of p fertilization on corn yield, nutrient contents and p-use efficiency

Higher rates of P fertilization significantly and non-linearly increased corn yields (Figure 3). Results showed that corn yields were only 4.3 Mg ha^{-1} in the control as compared to 5.6, 5.7 and 6.1 Mg ha^{-1} in 50, 100 and 200 kg of P_2O_5/ha, respectively.

When the relative corn yield was plotted over P levels, P fertilization showed a variable but non-linear significant response (Figure 3). The extrapolation of the relationship suggested that 100 kg P_2O_5 ha^{-1} is optimum for obtaining a near maximum corn production (~95%). Likewise, the relationship between P fertilization and relative yield suggested that 90% of the corn yield was produced when P was applied at 50 kg P_2O_5 ha^{-1}.

P fertilization significantly increased the corn leaf N, P, and K concentrations (Table 1). N content was 1.45% in the control as compared to 1.57, 1.61 and 1.6% when P was applied at 50, 100 and 200 kg P_2O_5/ha, respectively. A higher P content in tissues was also recorded with highest rates of P application. As tissue K concentration is over the critical limit (1.2%), increasing rates of P fertilization did not exert any significant effects on K concentration. However, increasing rates of P fertilization significantly and variably affected the Cu, Mn, Zn, and Fe contents (Table 1).

Corn grain N and P contents did not influence consistently by P fertilization (Table 2). Corn fertilized with 200 kg P_2O_5 ha^{-1} had a significantly higher grain N and P contents as compared with the N and P contents in the control. Corn P-use efficiency showed a similar response by long-term P

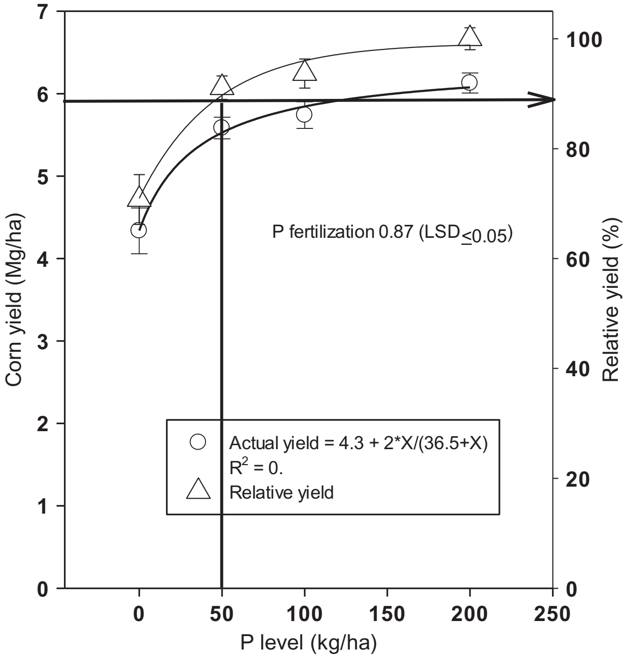

Figure 3. Effects of long-term P fertilization on actual- and relative corn yields.

Table 1. Effects of long-term P fertilization on leaf nitrogen, phosphorus, potassium, iron, and manganese, copper and zinc concentration (for year 2014).

P level	N	P	K	Fe	Mn	Cu	Zn
(kg ha^{-1})	(%)			(mg kg^{-1})			
P_0	1.45b	0.13b	2.6a	56a	73a	7a	36a
P_{50}	1.57a	0.16ab	2.4a	45b	64b	5b	25b
P_{100}	1.61a	0.22a	2.9a	47b	65b	5b	27b
P_{200}	1.6a	0.22a	3.1a	48b	62b	7a	18c

TN = Total nitrogen, AP = Total phosphorus, K = Total potassium, Fe = Total iron, Zn = Total zinc, Cu = Total copper, and Mn = Total manganese.

¥Means separated by same lower case letter in each column are not significantly different at $p < 0.05$ among P fertilization levels.

Table 2. Effects of long-term P fertilization on corn phosphorus-use efficiency.

P level	N	P	K	AREP	PEP	AEP
(kg ha^{-1})	(%)					
P_0	0.07b	0.01b	0.25a	0	0	0
P_{50}	0.13a	0.02ab	0.24a	7a	576a	25a
P_{100}	0.12a	0.02ab	0.22a	7a	198b	14ab
P_{200}	0.13a	0.03a	0.12b	4a	237b	9b

TN = Total nitrogen, AP = Total phosphorus, K = Total potassium, AREP = Apparent recovery efficiency of P, PEP = Physiological efficiency of P, and AEP = Agronomic efficiency of P.

¥Means separated by same lower case letter in each column are not significantly different at $p < 0.05$ among P fertilization levels.

fertilization (Table 2). Both PEP and AEP have shown a significant non-linear change by the impact of 50 to 200 kg P_2O_5 ha^{-1}, as compared to the control. Increasing P fertilizer rates decreased physiological and agronomic P-use efficiency. This is very important to define the economic and agronomic P level application.

Increased corn yield with 50 to 100 kg P_2O_5 ha^{-1} was probably due to higher availability of P in soil by the synergistic influence of greater and effective mycorrhizal root colonizations. Moreover, the mineralization of native SOM and crop residues by annual and moldborad plowing may have increased P availability to corn. It is reported that higher P fertilization is often associated with increased N uptake by plants due to maintaining a balance in N:P stoichiometry (Ma et al. 2016; Tao et al. 2016). Ortas (2006) reported that a significant P x Zn interaction decreased or inhibited the plant's uptake of Zn under excessive P fertilization. Similarly, the higher rates of P fertilization decreased mycorrhizal root colonization and consequently, plant uptake of Zn (Ryan et al. 2008). This is critical for maintaining optimum Zn concentration in high clay vertisol.

P, as one of the most essential macronutrients, is associated with plant growth and consequently, increased the demand for other nutrients. Several studies have reported that both N and P fertilization increased TN and P contents in grain or vice-versa (Ma et al. 2016; Reddy, Ghosh, and Panda 1986). However, increased P application may decrease the plant K contents, which may be attributed to the dilution effect in response to higher plant growth. A significantly higher PEP and AEP of corn was most probably related to higher crop yields in response to long-term P fertilization.

Effects of p fertilization on soil organic carbon and nutreints

After 16 years of P fertilization, both TOC and TN concentrations increased significantly with an increase in the P fertilization rates, as compared with the control (Table 3). The TOC and TN concentrations were more than 34% and 26% higher in 200 kg P_2O_5 ha^{-1} treatment as compared with the control. The AP concentration was by 2 to 3 times higher in 100 and 200 kg P_2O_5 treatments with respect to the control. The extractable Fe and Cu concentration increased with P fertilization upto 100 kg P_2O_5 ha^{-1} and then decreased, as compared with the control. However, the Mn and Zn concentration increased with an increase in P fertilization rates. Generally, P fertilizers contain cadmium (Cd). In soil, Cd with its similar chemical charge and properties acts like Zn ions and exchanged for Zn on the surface and in between the clay layers. In consequence, more Zn is released from the exchange sites into available form (Zhao et al. 2011). As our soils (in Çukurova region of Turkey) are critically low in DTPA extractable Fe and Zn levels, the impact of P fertilization may have

Table 3. Long-term P fertilization effects on organic carbon and nitrogen, and extractable nutrients at different soil depths.

P level	Depth	TOC	TN	AP	K	Fe	Mn	Cu	Zn
(kg ha^{-1})	(cm)	(g ha^{-1})	(mg ha^{-1})						
P_0	7.1b[¥]	0.70b	4.5c	668.5a	7.5b	12.4b	1.49a	0.18b	
P_{50}		9.1a	0.70b	5.8c	645.8a	7.5b	15.7a	1.55a	0.26ab
P_{100}		9.0a	0.86a	10.0b	736.9a	8.1a	16.0a	1.50a	0.39a
P_{200}		9.4a	0.88a	15.1a	635.7a	6.6c	15.1a	1.28b	0.41a
P level x depth interaction									
P_0	20	7.7	0.74	6.6	684.9	7.5	12.6	1.56	0.17
	40	6.5	0.66	2.4	652.1	7.4	12.2	1.41	0.18
P_{50}	20	9.9	0.69	7.4	681.9	7.3	14.8	1.47	0.25
	40	8.3	0.70	4.2	609.7	7.8	16.7	1.64	0.26
P_{100}	20	10.7	0.85	13.9	793.9	8.1	16.7	1.54	0.46
	40	7.3	0.87	6.0	679.9	8.1	15.4	1.47	0.31
P_{200}	20	9.9	1.01	17.9	667.0	6.5	16.1	1.33	0.44
	40	9.0	0.75	12.3	604.5	6.7	14.2	1.24	0.38
$LSD_{\leq 0.05}$									
	Depth	0.52	ns	ns	2.8	ns	ns	ns	ns
	P x depth	0.19	ns	ns	ns	ns	ns	0.14	ns

TOC = Total organic carbon, TN = Total nitrogen, AP = available phosphorus, K = Extractable potassium, Fe = Extractable iron, Mn = Extractable manganese, Cu = Extractable copper, and Zn = Extractable zinc.

[¥] Means separated by same lower case letter in each column are not significantly different at $p < 0.05$ among P fertilization levels.

exerted indirect effects on Cd-Zn exchange reactions to improve Zn availability for plant growth. There is a need to investigate further on the Cd-Zn exchange by the impact of P fertilization.

Averaged across P treatments, the TOC and K concentration significantly infleunced by depth. Moreover, the TOC and Cu concentration significantly influenced by P fertilization x depth. Other nutrients did not vary significantly by P fertilization x depth. It seems that there is elucidation to investigate further on change in the micronutrient concentration by the impact of P fertilization during 16 years.

Effects of chemical fertilization on nutrient concentrations have been widely studied (Banger et al. 2009; Follett, Castellanos, and Buenger 2005; Hati et al. 2008; Hernanz et al. 2002; Huang et al. 2010; Nardi et al. 2004). Several studies have reported that chemical fertilization increased the TOC and other nutrients contents (Ding et al. 2007). Both TOC and TN concentration was significantly increased with P application, which produced higher crop residues and root biomass, and consequently contributed to the higher TOC and TN concentrations (Masto et al. 2007). Ghani, Dexter, and Perrott (2003) observed a positive impact of P fertilization on soil organic C pools. Gregorich et al. (1996) also indicated that adequate P fertilization increased crop yields and TOC storage. The results on most notable increase in TN concentration occurred in 100 kg P_2O_5 ha^{-1} treatment which were also reported in other studies ((Brye et al. 2002), (Ortas and Lal 2012). Similar results on AP concentration at higher rates of P fertilization, as compared with the control, were also reported (Ortas and Lal 2012). Ma et al. (2014) reported that AP contents strongly associated to both TOC and TN concentrations in soil.

Effects of p fertilization on nutreint stratification

P fertilization significantly impacted TOC, TN and other nutrients stratification (Table 4). The TOC, TN and AP contents stratified with increasing rates of P fertilization. A highest stratification was observed for AP contents. Moreover, TOC stratification was significantly influenced by P x depth. Also, Mn and Zn significantly stratified in response to P fertilization. Cu, Fe and K contents increased upto 100 kg P_2O_5 ha^{-1} (Table 4). Under higher P fertilization nutrient avalability to corn have restricted or nutreints were more immobile at the suarface.

Table 4. Effects of different rates of P fertilization on stratification of carbon, nitrogen, potassium, iron, manganese, copper and zinc concentration at different soil depths.

P level	Depth	TOC	TN	AP	K	Fe	Mn	Cu	Zn
(kg ha^{-1})	(cm)	(values were divided by the values of subsurface depth of control soil)							
P_0		1.10b[¥]	1.06b	1.88c	1.02a	1.01b	1.02b	1.07b	0.98c
P_{50}		1.63a	1.23b	2.74bc	0.99a	1.17a	1.48a	1.28a	1.61bc
P_{100}		1.58a	1.48a	4.73b	1.13a	1.23a	1.48a	1.22a	2.39b
P_{200}		1.69a	1.53a	7.31a	0.97a	1.01b	1.42a	1.05b	2.58a
P level x depth interaction									
P_0	20	1.21	1.11	2.75	1.05	1.01	1.03	1.13	0.95
	40	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01
P_{50}	20	1.76	1.21	3.50	1.05	1.12	1.38	1.21	1.57
	40	1.50	1.24	1.98	0.93	1.21	1.57	1.35	1.65
P_{100}	20	1.85	1.45	6.58	1.22	1.22	1.53	1.24	2.81
	40	1.30	1.50	2.87	1.04	1.24	1.44	1.21	1.96
P_{200}	20	1.76	1.74	8.67	1.03	0.99	1.49	1.08	2.77
	40	1.62	1.32	5.95	0.92	1.04	1.34	1.02	2.38
$LSD_{\leq 0.05}$									
	Depth	0.32	ns	ns	ns	ns	ns	ns	ns
	P x depth	0.20	ns	ns	ns	ns	ns	ns	ns

TOC = Total organic carbon, TN = Total nitrogen, AP = available phosphorus, K = Extractable potassium, Fe = Extractable iron, Mn = Extractable manganese, Cu = Extractable copper, and Zn = Extractable zinc.

[¥] Means separated by same lower case letter in each column are not significantly different at $p < 0.05$ among P fertilization levels.

Conclusions

Long-term P fertilization significantly influenced the root colonization and number of fungal spores, crop yield, and nutrient contents in both corn and soil relative to the control. A higher rate of P fertilization may have hindered the mycorrhizal fungi development and consequently, corn root colonization. Boundary line technique showed that P fertilization at 50 and 100 kg P_2O_5 ha^{-1} is optimum for obtaining a near maximum crop production (~90 to 95%). However, physiological and agronomic P-use efficiency by corn decreased with higher rates of P fertilization. Soil TOC and TN contents were higher when receiving higher rates of P fertilizer than that of the unfertilized control. As compared to initial soil TOC contents, increasing rates of P fertilization increased TOC contents. The extractable Zn concentration in soil has decreased over a 16 years period of P fertilization. It can be concluded that 50 to 100 kg P_2O_5 ha^{-1} is optimum to maintain vertisol fertility for corn production in the Mediterranean climates of Turkey.

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