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Maintenance of phosphorus fertilizer and residual phosphorus effect on corn production

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Abstract

Phosphorus (P) deficiency is invariably a common crop growth and yield-limiting factor in unfertilized soils, especially soils high in calcium carbonate, which reduces P solubility. Even when such soils are fertilized, adsorption and desorption lead towards a reversion to stable and less soluble P forms, thus reducing fertilizer use efficiency. Field trials that examine the implications of such P reactions and residual fertilizer P responses in the field are relatively rare in Mediterranean environments. A 5-year field experiment in southern Turkey examined the residual effects of repeated P fertilizer applications for corn production in a calcareous soil Typic Xerofluvent. Following the initial year's fertilization (0, 33, 66 and 99 kg P ha^{-1}) to establish a range of soil P levels in subsequent years, the main plots received 0, 9, 18, 27 and 36 kg P ha^{-1} annually. Grain P uptake was calculated for each year and used in the prediction of P recovery. All plots were sampled and analyzed for available P prior to planting with a local corn hybrid. Soil P values increased with the initial P levels (8–24 mg kg^{-1}) but declined after 3 years (6–10 mg kg^{-1}). Only the lowest annual P application rate (9 kg P ha^{-1}) produced an available P level that was not in the sufficiency range. Grain yields across the main and subplots and years ranged from 6.6 to 13.2 t ha^{-1}. Overall corn yield averaged over the years increased by 8–33% compared to the control as the rates of applied P increased. However, P application had no effect in a year when below-average rainfall restricted crop growth. A residual P effect on grain yield occurred with higher P application levels in the last year. Leaf and grain P concentrations were in the sufficiency range in general. Grain P uptake was calculated for each year and used in the prediction of P recovery. Actual recovery was higher with low P application rates and ranged between 10.8 and 46.4%. The study indicated that under irrigated conditions, corn is likely to respond to P fertilization, but that buildup of available P can occur within a few years and adequate plant available P levels can be maintained by modest P fertilizer application rates.

Introduction

Phosphorus is one of the essential nutrients affecting crop production and quality (Khasawneh et al. 1980). For decades, most agricultural soils have been fertilized with P for optimum crop production, especially in Europe and the Western world. Even in lesser developed countries such as the Mediterranean area, crop fertilization is now a common practice (Ryan 1997). Upon application, fertilizer P undergoes several initial and longer-term chemical reactions that potentially influence its availability to plants (Ryan et al. 1985a, b). Plant availability of P in soils is closely related to soil, plant and climatic factors, which make P chemistry very complex (Kamprath 1967). In such locations with high clay, calcium carbonate and iron oxide contents, plant P availability and fertilizer P use efficiency is restricted (Afif et al. 1993). Therefore, P fertilizer and nutrition studies need to be considered locally.

Phosphorus deficiency is common in calcareous soils and can be a major obstacle to crop growth and yield production. Calcareous soils may contain considerable amounts of total P, but only small fraction of it is plant available (Matar et al. 1992). Calcium carbonate can immobilize substantial amounts of P by both adsorption and precipitation of various forms of calcium phosphates (Freeman and Rowell 1981). Iron oxides can also contribute a large proportion of the sorption of P by calcareous soils (Ryan et al. 1985a, b; Matar et al. 1992). Solis and Torrent (1989) found P-sorption capacity of soil to be highly correlated with Fe oxide and clay content. Afif et al. (1993) showed that the ratio of Olsen-P to applied P is negatively correlated to Fe oxide content at low P application rates and to $CaCO_3$ content at high P application rates. Both Fe oxides and calcium carbonate react with soluble P, but the influence of Fe_2O_3 is disproportional to its content in the soil.

Asher and Loneragan (1967) showed 5 μM soil solution P phosphate (about 0.16 μg ml^{-1}) is generally satisfactory for the plants. However, for most plants as much as 25 μM P (0.8 μM ml^{-1}) is required (Kamprath and Watson 1980 and Olsen and Khasawneh 1980). Soluble P in extracted soil solutions ranges from 0.02 to >200 μM in heavily fertilized soils. Soils containing less than 10 mg P kg^{-1} ($NaHCO_3$ extract) do not provide the 0.2 mg P in soil solution which is necessary for maximum plant growth (Asher and Loneragan 1967). Phosphorus concentration in soil solutions may not be sufficient for optimal plant growth. In many cases, Matar et al. (1992) suggested that 10 mg kg^{-1} Olsen P is threshold value for cereals and legumes grown in West Asia and North Africa region, and 17 mg kg^{-1} Olsen P for potato (Maier et al. 1989). However, crop response to P is closely related to rainfall (Matar 1977).

While the response to applied P in any 1 year is a major concern to farmers, what also has to be considered is the influence of previous fertilizer applications, i.e. residual P or carryover effect, which has implications for agronomic efficiency of fertilizer use and economic returns (Bolland 1994; Bolland and Gilkes 1995; Barrow et al. 1998 and Bolland 1999). Crops use only 10–30% of fertilizer P in the year of application (Manske et al. 2000). The remaining P often stays in less soluble forms such as Al–P and Fe–P in acidic soils, and Ca–P complexes in alkaline soils (Samadi and Gilkes 1999). Residual effects from large P applications (685 kg P ha^{-1}) were also observed on high P-fixing soils, in which sufficient amount of P was supplied for corn 7–9 yr after application (Kamprath 1967). Ryan et al. (1997) showed that under rainfed conditions in Syria regular application of 15 kg P ha^{-1} or more, available P levels build up with time. In a long-term P fertilization study of corn sequences, Aulakh et al. (2003) showed that residual P, in labile or moderately labile forms, was adequate to meet the needs of the second crop of groundnuts and increased fertilizer-use efficiency compared to fertilizing both crops in the same year. Raun and Barreto (1995) reported that the consistent response to applied P across a wide range of environments demonstrated that P is a limiting element for maize production on marginal lands and that the probability for economic response to applied P is high. Plant composition and nutrient absorption by grain may be influenced by many genetic and environmental factors. Of the environmental factors, nutrient availability and temperature are of prime importance because they affect physiological and developmental processes determining plant growth, nutrient uptake and grain yield.

Most soils in the Mediterranean region are inherently low in P and respond to applied P (Matar et al. 1992; Afif et al. 1993; Ryan 2003). Therefore, in order to ensure adequate P nutrition of crops, soils have to have a sufficient pool of plant available P. However, any fertilization program has to consider the crop response to P in the first year and the influence of residual or carryover P on subsequent crops. Under commercial farming conditions, this problem is solved by the regular use of fertilizers. In this research, we evaluated both the initial year's response to P fertilization of corn in southeastern Turkey as well as its residual effect over a number of years.

Materials and methods

Field-location

Multiple year, field corn experiments as a second rotation-crop were conducted at the Research Station of Cukurova University in Adana, Turkey. The soil was a loamy, smectitic, calcareous, thermic Vertic Xerofluvent. Selected physical and chemical properties of soil that might influence P use and crop growth were: clay loam texture, pH 7.6 (1:5 soil:water), low organic matter content (0.74%), high $CaCO_3$ (29%), high cation exchange capacity (29 Cmol kg^{-1}) and marginal levels of plant available P, i.e., 10 mg kg^{-1} $NaHCO_3$-extractable P (Olsen).

Treatments and growth conditions

A corn genotype (Hybrid XL72AA) was planted manually in late June to early July, based on the weather conditions of that specific year. In the first year (1998), the main plots were fertilized with 0, 33, 66 and 99 kg P ha^{-1} (as triple superphosphate) prior to the experiment in order to establish a range of soil test values for the following years. Nitrogen (250 kg N ha^{-1}) and potassium (80 kg K ha^{-1}) fertilizers were applied to all plots as basal rates every year. During the second and following years, the main plots were divided into subplots, each receiving 0, 9, 18, 27 and 36 kg P ha^{-1}.

The first-year experiment was arranged in a randomized complete block design, and then became a split-plot design having 0, 33, 66 and 99 kg P ha^{-1} rates as main plots and 0, 9, 18, 27 and 36 kg P ha^{-1} rates as subplots with four replications in 1999, 2000, 2001 and 2002. Phosphorus, K and half of the N were applied as a band at planting, and the other half of the N was added when the plants were about 50-cm high. The plot dimensions was 5×2.8 m^2, having inter-row and row spacings of 20 and 70 cm, respectively. Plants were irrigated periodically as needed, approximately every 10–15 d. The average rainfall of the specific years was 647 mm (1998), 511 mm (1999), 706 mm (2000), 327 mm (2001) and 683 mm (2002) with the long-term average of 575 cm.

Soil, leaf and grain sampling and analysis

Prior to the experiment, soil samples were taken from 0 to 30, 30 to 60 and 60 to 90 cm depths, and analyzed for the selected physical and chemical soil properties using standard procedures. Extractable soil P was determined by Olsen procedure and the concentration of P in the extract was measured as described by Murphy and Riley (1962).

Representative leaf samples from 10 randomly selected plants in each plot were collected at silking stage (Jones and Steyn 1973). The samples were washed with deionized water, dried at 60 °C for 72 h, and ground using a silica grinder to pass a 0.5-mm sieve. The samples were dry-ashed and extracted with 0.3 N HCl solution to determine selected nutrients (Walsh and Beaton 1973).

Plants were harvested about 125 d after planting. Ears from each plot were manually harvested for determination of grain yield. Representative grain subsamples were dried at 60 °C for dry matter determination and then ground to pass a 0.5-mm sieve. Phosphorus analysis of grain was done in the same manner as the leaf samples. Phosphorus recovery percentage was calculated as fertilized – nonfertilized P uptake by grain/fertilizer P added. Soil, plant and grain data were statistically analyzed using the MSTAT computer program.

Results

Yield

Grain yield of corn following the initial heavy P application of the main plots in 1998 and sub-plots in the subsequent 4 years (1999–2002) is presented in Table 1. In the initial establishment season, there was a significant effect (5%) of adding P at the 33 kg ha^{-1} rate; however, there was no further increase in yield with the 66 and 99 kg ha^{-1} application rates.

In subsequent years in which each of the main plots received incremental amounts of P fertilizers (0, 9, 18, 27, 36 kg P ha^{-1}), the effects were consistent each year except in 2001, a season that

Table 1. Initial (main-plot) and currently applied (sub-plot) fertilizer P in relation to yield and increment.

Main-plot kg P ha^{-1}	Yield 1998 t ha^{-1}	Sub-plot[a] kg P ha^{-1}	Yield t ha^{-1}				Average t ha^{-1}	Increment[b] %	
			1999	2000	2001	2002		A	B
0	9.0	0	8.5	8.3	6.6	8.6	8.0	–	–
		9	9.6	9.8	7.1	9.3	8.9	11	–
		18	9.9	9.9	8.5	12.2	10.2	26	–
		27	10.4	10.1	8.5	12.3	10.3	29	–
		36	10.5	10.3	9.5	12.6	10.7	34	–
33	10.5	0	8.7	8.9	8.2	9.1	8.7	–	9
		9	9.9	10.5	7.6	9.8	9.4	8	18
		18	10.4	10.6	7.9	12.5	10.4	19	29
		27	10.8	11.2	9.2	12.9	11.0	26	37
		36	11.6	11.9	10.0	12.7	11.5	33	44
66	10.2	0	8.8	9.0	7.6	9.0	8.6	–	7
		9	10.1	10.1	7.5	9.3	9.3	8	15
		18	10.8	10.5	8.2	12.7	10.5	23	32
		27	11.5	11.5	8.1	13.0	11.0	29	38
		36	11.8	12.6	8.5	12.9	11.4	33	43
99	10.2	0	10.2	9.3	9.0	8.9	9.3	–	16
		9	10.5	10.6	10.0	9.5	10.2	9	27
		18	11.7	11.1	9.2	12.8	11.2	20	40
		27	11.7	12.2	8.9	12.9	11.4	22	42
		36	11.7	12.8	10.1	13.2	12.0	28	49
F Test									
A(Main-plots)	*		***	***	NS	NS			
B (Sub-plots)	–		NS	***	NS	***			
AB	–		NS	***	NS	NS			

[a] phosphorus was applied at the same rates between 1999 and 2002.

[b] percentage increment (A) based on the subplot 0–P level, (B) based on the mainplot 0–P level.

*, ***, significance at 0.05 probability and 0.001 level; NS = non significance.

was characterized by lower than normal rainfall. Apparently the fixed time irrigation schedule was not sufficient to compensate for the lack of rainfall, and thus the crop growth was probably restricted due to moisture stress.

While the zero-fertilized plots, where the initial P applications were made (33, 66, 99 kg P ha^{-1}), were consistently higher than the absolute control, where no P was applied, yearly increments of P tended to increase grain yield. This indicated that while the initial heavy P applications produced a residual P effect, it did not provide adequate P for grain yield of corn. There was little influence of residual P beyond the 33 kg ha^{-1} rate on overall crop responses in absolute or relative response terms.

Relative yield of corn is reported in Table 3. Average relative yield was 120, 124, 112 and 134 for the years of 1999, 2000, 2001 and 2002, respectively. Disregarding the anomolous data of the erratic 2001 year, there was only 14% yield difference between the initial year and the last year of the currently applied P.

Plant P uptake

Phosphorus uptake data for corn for initial (and therefore residual) and yearly P applications are presented in Table 2. As with yield, there was a significant effect of the initially applied P only at the 33 kg P ha^{-1} rate; there was no further increases with 66 and 99 kg ha^{-1}. As with yield data, there were significant effects of both residual and currently applied P in all except 1 year. Total P recovery in sub-plots reflected a residual effect of initially applied P. At any level of residual P, recoveries tended to increase with P application rates. Relative recovery percentages tended to

Table 2. Initial (main-plot) and currently applied (sub-plot) fertilizer P in relation to grain P uptake, total plant P uptake and P recovery.

Main-plot kg P ha^{-1}	Grain P uptake 1998 kg P ha^{-1}	Sub-plot[a] kg P ha^{-1}	Grain P uptake kg P ha^{-1}				Total grain P Uptake kg P ha^{-1}	Total applied P kg P ha^{-1}	P recovery %
			1999	2000	2001	2002			
0	24	0	9	23	8	9	73	0	–
		9	19	25	9	11	88	36	42.5
		18	16	26	10	12	88	72	21.4
		27	13	26	10	11	85	108	10.8
		36	27	28	12	8	98	144	17.6
33	31	0	12	24	10	10	87	33	39.3
		9	20	34	10	11	106	69	46.4
		18	9	30	10	14	94	105	19.7
		27	20	31	11	15	107	141	24.0
		36	18	37	11	14	112	177	22.0
66	30	0	10	27	9	9	86	66	17.7
		9	13	31	11	11	96	102	21.9
		18	18	30	11	15	103	138	21.4
		27	18	36	10	15	109	174	20.4
		36	24	38	11	14	118	210	21.1
99	30	0	14	26	11	11	91	99	18.2
		9	23	30	13	10	106	135	24.6
		18	21	35	10	15	111	171	22.6
		27	21	35	11	17	114	207	20.2
		36	19	40	12	16	117	243	18.1
F Test									
A(Main-plots)	**		***	***	NS	***	***	–	–
B (Sub-plots)	–		***	***	NS	***	***	–	–
AB	–		***	NS	NS	***	NS	–	–

[a]phosphorus was applied at the same rates between 1999 and 2002.

, * significance at 0.01 and 0.001 probability levels; NS = non significance.

Table 3. Relative corn yield to currently applied P for 4 years after the initial P application[a].

Main plots P rates kg P ha^{-1}	Relative yield			
	1999	2000	2001	2002
0	119	121	128	135
33	123	124	106	132
66	126	124	107	133
99	112	126	106	136
Average	120	124	112	134

[a]Mean response of the 9, 18, 27 and 36 kg P ha^{-1} rates relative to the control for each initial level of P.

decrease as the P application rate increased, though with some inconsistencies.

Total P uptake by grain from the control plots – the amount that comes solely from the soil – was 73 kg P ha^{-1} in 5 years; however, uptake distribution varied with the year. Previous studies suggest that about 80% of total crop P uptake is found in the grain. Therefore, the approximate total plant P uptake, calculated based on this assumption, was 92 kg P ha^{-1} for the unfertilized control treatment. Total grain P uptake increased by main plot P rates by an average of 86, 100, 101 and 108 kg P ha^{-1}, respectively. Since plant residues are incorporated into the soil after harvest, part of the P taken up (about 20% of total uptake) is returned back to the surface horizon. However, this amount is not readily available for plant use, as it takes some time for mineralization of P to occur.

Phosphorus recovery calculated based on the grain P uptake ranged between 10.8 and 42.5%, which are within the limits of literature values. Higher recovery was found with the lower P application rates, especially in plots receiving smaller applications in the 0 and 75 kg P main plots. The total P offtake depends on the quantity of crop residue left in the field.

Leaf tissue and grain P concentrations are not only a basis for calculating P uptake, but also an indication in themselves of P sufficiency. However, the main plot and sub-plot P applications did not statistically increase tissue P concentrations. Overall tissue P concentrations were in the sufficiency level (Bergmann 1992), ranging between 0.14 and 0.41%. Even though the P values were relatively low in 2000, no deficiency symptoms were observed; in fact, these low P values had no negative effect on grain P and grain yield.

Grain P concentrations were not statistically influenced by either main and sub-plot P applications, and ranged between 0.27 and 0.30% in 1998, 0.09 and 0.25% in 1999, 0.27 and 0.32% in 2000, 0.11 and 0.14% in 2001, and 0.07 and 0.13% in 2002; P concentration was relatively higher in 2000. Based on variety, climate and soil nutrient levels, a wide range of P concentration ranges are found in the literature (Walsh and Beaton 1973; Khasawneh et al. 1980).

Soil analysis

Soil P values are given in Figure 1. The initial soil test values of the profile in 1998 were 10, 5 and 6 ppm P for 0–30, 30–60 and 60–90-cm soil depths, respectively. These values are typical for the most cultivated soils in the region (Ryan et al. 1997). After the first year's growing season, the P values in the surface horizon (0–30 cm) were 8, 20, 24 and 26 ppm for 0, 33, 66 and 99 kg P ha^{-1} applied main plots, respectively. Except for the unfertilized plots, surface P values increased 2, 2.4 and 2.6 fold with increasing P rates, respectively. After 33 kg P ha^{-1} application, extractable P was not proportionally increased; most of the P was evidently retained at the surface horizon.

Following sub-plotting, the main plots in 1999, and with additional P rates each year as treatments prior to the planting, the P values of the control (−P) treatments were 10 (1998), 8 (1999), 6 (2000), 8 (2001) and 7 (2002) mg P kg^{-1}, indicating that a considerable amount of plant available P was being supplied to the soil solution by the solid phase. On the other hand, added annual P rates (9, 18, 27 and 36 kg P ha^{-1}) increased P test values in the sub-plots. In 2000, P values ranged between 6 and 10 mg P kg^{-1}, the numbers were slightly higher in the 66 and 99 kg P plots than those of the 0 and 33 kg P treatments. In the control nil-P main plots, the trend for soil test P to increase with increasing P rates was lower than that of 33, 66 and 99 P ha^{-1} main plots. The following year, in 2001, the P values stayed similar to those of 2000, and increased in 2002, ranging between 6 and 18 mg P kg^{-1}, which indicates that amount of plant available P in the soil solution had begun to increase after subsequent P applications.

Discussion

The literature on P fertilization of crops in various parts of the world generally shows varying degrees of responses where the soil has been originally low in available P or has not been intensively fertilized. However, there is always a degree of site specificity reflecting the influence of the soil. The trial reported here on corn in southeastern Turkey is no exception to this generalization. What is unique about it is the extent to which available P can buildup with modest P applications, thus eliminating P deficiency on a growth-limiting factor

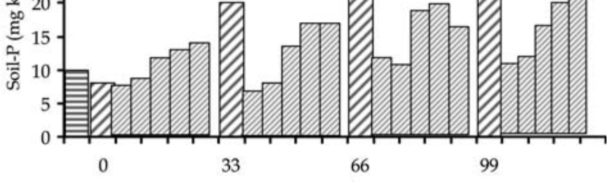

Figure 1. Extractable P status in 2002 after 5 years of P fertilization. Initial main-plots received 0, 33, 66 and 99 kg P ha^{-1} in 1998 and sub-plots 0, 9, 18, 27, 36 kg P ha^{-1} annually from 1999–2002.

despite the dominance of soil factors that would dictate otherwise.

The literature is replete with evidence, mainly from laboratory studies of the negative effect of calcium carbonate on P availability (Ryan et al. 1985a, b; Solis and Torrent 1989; Afif et al. 1993; Samadi and Gilkes 1999) and its association with P deficiency. As soils in the Mediterranean area are invariably high in $CaCO_3$, solid-phase carbonate, contributing one-third of the soil volume in our study, would be expected to have a major negative influence on P availability. Regardless of the factors that influence soil P chemistry, with the inevitable shift of applied P fertilizer to more stable and less soluble forms, the practical concerns hinge around how effective is P fertilization and how long will it persist. Thus, numerous studies have considered P release dynamics following fertilization (Steffens 1994; Selles et al. 1995; Amrani et al. 1999). Thus, efficiency of P fertilization is determined by the residual value in soils (Sander et al. 1990; Harmsen and Jasem El-Mahmoud 2004), an aspect that can be reflected by changing P availability tests (Esilaba et al. 1992).

In similar, though more extensive studies from Australia, the value of residual P for succeeding crops grown on acid duplex soils was shown to decline rapidly, causing a proportionally greater response in the current year fertilizer application (Bolland 1994, 1995). Our study from the coastal lowlands of southern Turkey-examined an applied aspect of P fertilization over a 5-year period. Though Fe oxides were not measured in the soil, an additional negative effect on solubility would be expected. The available soil P data and crop responses over the four subsequent growing seasons after the initial year fertilization suggest that the adverse effect of soil properties under field conditions is less than expected. Factors that contribute to this disparity include differences in the extent of mixing P fertilizer with the soil, temporal changes due to mineralization, specific effects of the crop on P solubility, and the extent of root exploitation.

While this field was irrigated, the patterns of rapid buildup of available P was similar to observations from rainfed trials in the Mediterranean region. Thus, Orphanos (1996) showed that within five growing seasons in a long-term trial in Cyprus annual applications of P at 30 and 60 kg P ha^{-1} resulted in elevated residual P levels. A similar type of long-term rotation trial at three sites in northern Syria indicated a buildup of residual P in the same time period (Ryan et al. 1997). Conversely, these studies have shown that where no P fertilizer was added, yields declined within a year or two, as did chemical measurements of available P to an extent that depended on the initial soil P level and the soil type, i.e., its capacity to release soluble P for plant uptake.

While the field responses to applied P were moderate, it is likely that these would have been accentuated if the initial soil test levels were lower. The trial illustrates the difficulty of finding suitable sites for long-term P experiments where soil P levels are low and no fertilizer has been added. This effectively rules out most experimental stations. On-farm sites where low P levels can be found are preferable, but these pose drawbacks in terms of supervision and management. Nevertheless, this on-station study showed that residual P from fertilizer application does accumulate rapidly for the benefit of succeeding crop. The phenomenon occurs in calcareous Mediterranean soils which “fix” applied P fertilizer, as has been shown in other areas of the world. Based on research in the Mediterranean region, and data from our study, the fertilizing value of P fertilizer residues can easily be assessed and monitored by soil testing.

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