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Soil Depth and Moisture in Relation to Barley and Chickpea Growth and Uptake Responses to Applied Phosphorus

J. Ryan[1], H. Ibrikci[2], S. Masri[1], K. Korkmaz[3], G. Buyuk[4] & E. Karnez[2]

[1] *International Center for Agricultural Research in the Dry Areas (ICARDA), P.O. Box 5466, Aleppo, Syria*
[2] *Soil Sci. Dept., Faculty of Agriculture, Cukurova University, Adana 01330, Turkey*
[3] *Ordu University, Soil Science Dept. Ordu, Turkey*
[4] *Adiyaman University, Kahta Meslek Yuksek Okulu, Kahta-Adiyaman, Turkey*

Email: hibrikci@cu.edu.tr

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Abstract

While drought is the major crop-limiting factor in Middle Eastern agriculture, nutrients for such as phosphorus (P) are inherently deficient and need to be added as fertilizers; the amounts of P required are theoretically related to critical soil test values derived from field calibration studies. Soil test values for P recommendations are based on shallow sampling (e.g., 0-20 cm) and do not consider profile or rooting depth, an important factor in rainfed cropping where soil moisture is invariably limited. Under field conditions, soil depth controls the soil's water-holding capacity and the potential of plant roots to exploit soil moisture and available nutrients such as P. While field crop responses to applied P have been observed to vary with soil depth and available moisture, the interaction between these variables can only be assessed under a controlled environment. Two successive crops, barley (*Hordeum vulgare*) and chickpea (*Cicer arietinum*), were grown to maturity in a greenhouse in a P-deficient (3.2 mg kg^{-1} Olsen P) clay soil (Chromic Calcixerert) in tubes (15-cm internal diameter) of variable depth (15, 30, 45 cm) and moisture (33, 66 and 100% of the water required for field capacity), with applied P (0, 30, 150 mg kg^{-1}) as monocalcium phosphate. In most cases, the response was highly significant at 30 mg kg^{-1}, with relatively smaller increases thereafter. While growth responses increased with increasing soil moisture, soil depth had a major influence, with growth directly related to rooting depth. For chickpea, relative responses to P increased with soil depth and with soil moisture at any depth. Barley showed less consistent trends, but the relative increase was inversely related to depth, especially at low soil moisture. Thus, in addition to crop variation, both soil depth and moisture, which controls rooting depth, are also important considerations in the interpretation of critical test values and thus P fertilizer response.

Keywords: Soil moisture, rooting depth, P application rates, soil P test values, dryland agriculture.

Introduction

Globally, dryland or rainfed agriculture is attracting increasing attention from the agricultural research community and policymakers at large. This concern is driven by increasing population growth, especially in the developing world and consequently increasing land use pressure (Peterson et al., 2006). Concerns about the sustainability of cropping environmentally fragile arid and semi-arid ecosystems are likely to be exacerbated by climate change (Lal, 2002). Despite being the site of settled agriculture and the center of origin of many of the world's major crops, especially cereals and pulses (Damania, 2008), and being cultivated for millennia, the Middle East region optimizes such concerns. This largely semi-arid, vast land mass is characterized by a Mediterranean climate in coastal areas merging to a continental one inland, and agricultural output is largely constrained by climate, primarily limited rainfall, allied to cold and heat stress (Kassam, 1981). The region's farming system, mainly cereals and legumes and associated sheep production, is constrained by many socio-economic factors, being traditional and low-input with small fragmented holdings and weak infrastructural support (Cooper et al., 1987a). However, in the past two decades, irrigation has increased (Oweis et al., 1998), as has mechanization and cropping intensification (Ryan, 2002).

Notwithstanding the prevalence of drought in the Mediterranean region's semi-arid rainfed agriculture, fertilizer use, mainly supplying nitrogen (N) and phosphorus (P), is now common practice (Ryan, 2002). While useful information on P reactions has been gained with soils under controlled laboratory conditions (Afif et al., 1993; Ryan et al., 1985), the key issue is how it behaves in the field where moisture is the major variable due to the xeric moisture regime characteristics of the Mediterranean climate. Recent work by He et al. (2002) showed that P uptake in unfertilized soil in a pot study increased threefold as available moisture increased from 30% to 75% of water holding capacity. Not surprisingly, the role of fertilizer P in relation to crop production under drought-stressed conditions has been the subject of much research (Matar et al., 1992; Bolland, 1992; Ryan, 2003). Soil moisture mediates the reactions of fertilizer P with soil components, leading to lower availability due to precipitation, as well as controlling P diffusion to root surfaces and at the same time supporting plant growth (Braschi et al., 2003).

Most field studies have shown relatively higher responses to N under favorable rainfall conditions, but relatively higher response to P in the lower rainfall range (Keatinge et al., 1986; Krentos & Orphanos, 1979; Harmsen et al., 1983; Pala et al., 1996). The differential effect of P on crop growth, such as cereals and food legumes under Mediterranean conditions, leads to increased water-use efficiency (Brown et al., 1987; Cooper et al., 1987b; Gregory et al., 1984). The response is attributed to increased concentration of P in contact with the plant roots, whose growth is limited by soil moisture, and by a stimulating effect on roots to exploit deeper layers of soil and thus obtain more moisture when subsoil moisture is available (Matar & Brown, 1989a, 1989b).

This raises the issue of soil depth and its interaction with soil moisture in relation to available soil P and response to P fertilization. Critical levels and ranges of available P have been developed for rainfed agriculture in the West Asia and North Africa region without regard to these factors (Ryan and Matar, 1992) and are generally in the range of 5-7 mg P kg^{-1} soil. However, observations from Syria (Matar et al., 1992) and Cyprus (Krentos & Orphanos, 1979) suggested higher critical values for drier conditions and shallow soils, both factors related to soil moisture. Predicting crop yields based on soil test P can only provide a general guideline since yield depends on both P and water supply, which obviously vary under fields conditions depending on seasonal rainfall (Bolland, 1992). The influence of soil type, specifically soil depth, has not been identified directly, and then only by inference. Therefore, in order to quantify the interaction of soil depth – and thus the soil's capacity to hold water and be exploited by roots – and available moisture, a controlled study is necessary, whereby only these parameters are varied, and the soil type and level of soil P are kept constant. Responses were assessed in terms of growth and P uptake of barley and chickpea representing the major crop groups adapted to the dryland semiarid Mediterranean environment.

Materials and Methods

Soils

The soil used in this greenhouse study was a thermic, montmorillonitic, Calcixerollic Xerochrept (Ryan et al., 1997), the dominant soil type at the main research station of the Center for the International Agriculture Research in the Dry Areas (ICARDA) at Tel Hadya, near Aleppo, Syria. Relevant characteristics are clay 50%, calcium carbonate 25%, organic matter 1.2%, effective depth to parent rock 1 - 2 m in most places, and 3.2 mg kg^{-1} Olsen available P. Following the 5-month dry summer season, the top 20 cm of soil was dug up in air-dry condition and put through a 5-mm screen in the field and then taken to the greenhouse for potting.

Treatments

Individual soil batches of over 300 kg were prepared, with one batch to serve as an unfertilized control; the other two batches were mixed uniformly with P fertilizer, monocalcium phosphate, at the P equivalent of 30 and 150 mg kg^{-1}. Nitrogen was added as a basal dressing as ammonium sulfate at 300 mg kg^{-1} to all columns. Neither potassium nor micronutrients were added as the soil at the station is adequate in these elements according to conventional tests (Ryan et al., 1997). Subsequently, the respective soil batches were distributed in plastic columns (15-cm internal diameter) of variable length (15, 30 and 45 cm) to simulate differences in soil depth.

The respective soil weights were 3.35, 6.70, and 10.05 kg for the 15, 30, and 45-cm columns. Following potting, the individual columns were weighed and water added from the soil surface to give three moisture levels: 33, 66, and 100% of the amount of water required to bring the soil to field capacity (previously determined in the laboratory). For example, the amounts of water added for field capacity for the three column depths were 0.9, 1.8 and 2.7 L pot^{-1}; the amounts for the 66 and 33% were correspondingly reduced. This provided a moisture range from adequate to stressed conditions. The soil columns were arranged on the greenhouse bench in a randomized complete block design in three replications. Soil moisture levels were adjusted by weighing once per week during the growing season and adding the required amounts of water.

Subsequently, the surface of each set column was sown with seven seeds of a local barley cultivar “Rihane” to a depth of 1 cm. Upon emergence, the seedlings were thinned to three per column. The plants were grown to maturity and harvested after a total growing period of 136 days. This coincided with the winter-late spring (January-April) season of the Mediterranean cropping system, with minimum temperature and light intensity in the early growth stages to near optimum ambient conditions at the end of the growing period. Measurements of total dry matter yield were recorded following oven-drying. Dry plant samples were ground to pass 0.5-mm sieve for P analysis. The samples were dry-ashed, and P was brought into solution using 0.1 *N* HCl and determined colorimetrically by spectrophotometer. Phosphorus was determined by development of a blue color using ammonium molybdate-ascorbic acid method of Murphy and Riley (1962) with color intensity measured on a spectrometer at 882-nm wavelength. Phosphorus analysis procedure was the same for chickpea as for barley. Plant P concentration and uptake were calculated, as was relative yield and uptake.

The same experimental treatment was repeated for a second growing season under similar conditions, this time using chickpea as the test crop, and all other treatments (P, moisture, depth) were similar to the first trial except that no N fertilizer was added since chickpea is an N-fixing crop. In this case, three seeds were sown and the crop was grown for 109 days and harvested at flowering. The data recorded were subjected to standard analysis of variance (ANOVA) and treatment differences interpreted in terms of Least Significant Differences (LSD).

Results

Barley: Yields and P Uptake

Soil depth, P application rates and field moisture capacities had significant influences on total dry matter (TDM), grain yield and straw of barley (Table 1). TDM across the treatments ranged between 1.8 to 60.6 g pot^{-1}. The overall effect of each parameter can be seen by comparing TDM means; depth -12.9, 29.2, and 35.8 g pot^{-1}; P level - 17.5, 33.1, and 34.9 g pot^{-1}; and moisture - 16.5, 28.9, and 36.9 g pot^{-1}. The increase was linear and essentially proportional to the treatment increments. Similarly, both grain and straw yields increased by increasing soil depth, P application rate, and available moisture. Ranges of grain and straw yields were 0.4 to 28.8 and 1.4 to 36.0 g/pot, respectively. Yields were almost negligible where no P was applied in the shallow (15 cm) tubes. It is noteworthy that at any one potting depth the mean effect of increasing moisture levels was similar to P fertilization. Depth had a major influence on yield component values; at any one P and moisture level, values increased consistently with depth.

The main treatments were similarly effective on P uptake in total biomass and grain and straw (Table 2) as was the case with yield components. The lowest moisture level (33% field capacity) limited the uptake values of all three components at each depth and P application rate, especially at the shallowest depth. However, depth had a sig-

Table 1: *Soil depth, P- rates and field moisture capacity in relation to barley yield components*

Depth	P	Available moisture (%)											
		33	66	100		33	66	100		33	66	100	
		Total dry matter			Average	Grain			Average	Straw			Average
Cm	mg kg^{-1}	g pot^{-1}											
	0	1.8	9.6	9.9	7.1	0.4	4.3	5.3	3.3	1.4	5.3	4.6	3.8
15	30	8.0	15.7	19.2	14.3	4.2	9.0	6.7	6.6	3.9	6.7	9.5	6.7
	150	9.1	20.5	22.4	17.3	4.9	9.4	8.9	7.7	4.2	11.0	13.6	9.6
	Average	6.3	15.3	17.2	12.9	3.2	7.6	7.0	5.9	3.2	7.7	9.2	6.7
	0	8.5	18.2	27.1	17.9	2.5	8.1	12.1	7.6	6.0	10.1	15.0	10.4
30	30	14.7	36.5	45.0	32.1	6.6	14.8	20.1	13.8	8.0	21.7	24.9	18.2
	150	25.5	40.0	47.8	37.8	12.1	17.9	20.0	16.7	13.4	22.1	27.8	21.1
	Average	16.2	31.6	40.0	29.3	7.1	13.6	17.4	12.7	9.1	18.0	22.6	16.6
	0	16.5	26.6	39.3	27.5	6.9	14.1	15.3	12.1	9.6	12.5	23.9	15.3
45	30	30.6	40.0	60.5	37.1	15.9	25.3	28.2	23.1	14.7	24.9	32.3	24.0
	150	33.8	54.4	60.6	49.6	17.5	28.8	24.6	23.6	16.3	25.6	36.0	26.0
	Average	27.0	33.7	53.5	38.1	13.4	22.7	22.7	19.6	13.5	21.0	30.7	21.8

Total dry matter LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=1.6; interactions of D x P, D x FC, and P x FC=2.7

Grain LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=0.7; interactions of D x P, D x FC, and P x FC=1.2

Straw LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=1.6; interactions of D x P, D x FC, and P x FC=2.7

nificant effect even at the limited moisture level. Thus, without added P, uptake values increased from 1.6 mg kg^{-1} at 15 cm to 6.8 mg kg^{-1} at 30 cm, and 15 mg kg^{-1} at 45 cm. The corresponding values at the first P level (30 mg kg^{-1}) were 9.5, 23.2 and 52.1 mg kg^{-1}, respectively. While uptake values, from both fertilized and unfertilized pots, were significantly increased with increasing soil moisture, the effect of depth was even more pronounced, and even more so when both moisture and depth were increased together.

Chickpea: Yields and P Uptake

All treatments had a significant influence on TDM and total P uptake of chickpea (Table 3). TDM response was most restricted at 33% available moisture, especially at the shallowest depth (15 cm), and increased with increasing moisture and P application levels, with values ranging between 1.7 to 62.3 g pot^{-1}. The highest chickpea TDM yield was recorded at 100% field capacity across the P rates and soil depths. As observed for barley, without P fertilization, increasing depth had a disproportionate effect on dry matter yield than did increasing moisture; when both depth and moisture were increased with applied P, the effect of each variable was additive. For chickpea, total P uptake followed a similar pattern as with TDM yield, except for the fact that differences between the low and high P rates was reflected in uptake but not in yield. While biomass yield increased, with the second increment of P had less of an effect than in the case of P uptake; even at maximum yield, crop uptake would be expected to continue.

Table 2: *Soil depth, P-rates and field moisture capacity in relation to P uptake of barley*

Depth	P	**Available moisture (%)**													
		33	66	100		33	66	100		33	66	100	
		Total dry matter			Average	Grain			Average	Straw			Average
Cm	mg kg^{-1}	mg pot^{-1}											
	0	1.6	9.5	11.0	7.4	0.9	7.8	9.5	6.1	0.7	1.7	1.5	1.3
15	30	9.5	30.0	40.6	26.7	8.7	28.1	36.5	24.4	0.9	1.9	4.1	2.3
	150	20.3	49.3	53.7	41.1	17.7	38.2	36.3	30.7	2.7	11.1	17.3	10.4
	Average	10.5	29.6	35.1	25.1	9.1	24.7	27.4	20.4	1.4	4.9	7.6	4.7
	0	6.8	17.0	28.7	17.5	5.3	13.2	23.8	14.1	1.5	3.9	5.0	3.5
30	30	23.2	56.7	87.2	55.7	17.5	50.4	76.5	48.1	5.7	6.5	10.7	7.6
	150	59.4	98.6	121.6	93.2	48.8	72.5	80.9	67.4	10.6	26.1	40.7	25.8
	Average	29.8	57.4	79.2	55.5	23.9	45.4	60.4	43.2	5.9	12.2	18.8	12.3
	0	15.0	27.3	42.8	28.4	12.8	23.0	35.1	23.6	2.2	4.3	7.7	4.7
45	30	52.1	97.6	123.3	91.0	44.8	89.6	112.1	82.2	7.3	8.0	11.3	8.9
	150	79.5	141.0	158.0	126.2	68.9	119.7	101.8	96.8	10.5	21.3	56.2	29.3
	Average	48.9	88.6	108	81.9	42.2	77.4	83.0	67.5	6.7	11.2	25.1	14.3

Total dry matter P uptake LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=2.8; interactions of D x P, D x FC, and P x FC=4.9

Grain P uptake LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=2.3; interactions of D x P, D x FC, and P x FC=4.0

Straw LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=3.5; interactions of D x P, D x FC, and P x FC=6.0

Given that all parameters increased consistently, of the magnitute of the effect of any one factor can be seen by its mean effect across the other two factors. Thus, for optimum biomass or TDM yields, the increases were of a similar order of magnitude, e.g., overall means for depth (15, 30, 45 cm) were 8.2, 20.4, and 28.4 g/pot; overall means for moisture level (33, 66, 100%) were 9.5, 20.3 and 27.9 g pot^{-1}; and overall means for P (0, 30, 150 mg kg^{-1}) were 5.6, 23.5, and 28.7 g pot^{-1}. Mean values for uptake followed a similar pattern, except for accentuated differences between P levels

Relative Responses of Barley and Chickpea

While individual effects of treatments are shown for barley (Tables 1, 2) and chickpea (Table 3) and mean effects of each parameter presented in numbers, a comparison between the responses for the two crops is possible by considering relative yields (all reponses are relative to the control) (Fig. 1) and uptake (Fig. 2) for both crops. While depth and moisture showed a consistent pattern for chickpea for P responses, the pattern for barley was different. Thus, the relative re-

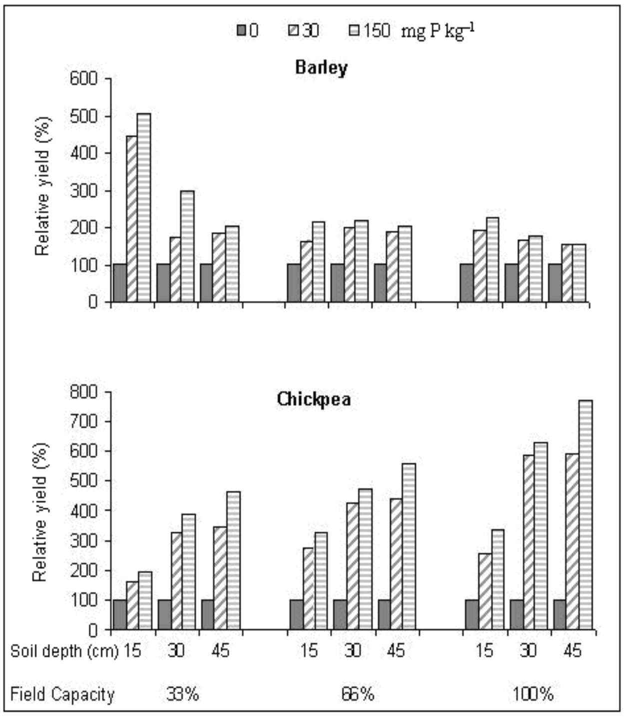

Figure 1: *Relative total dry matter yield of barley and chickpea in relation to P application levels, soil depth, and available moisture*

sponse of chickpea to applied P at any moisture level consistently increased with depth (15, 30, 45 cm), but no such pattern was evident for barley; relative increases showed the opposite trend, with a particularly pronounced increase at the low moisture level.

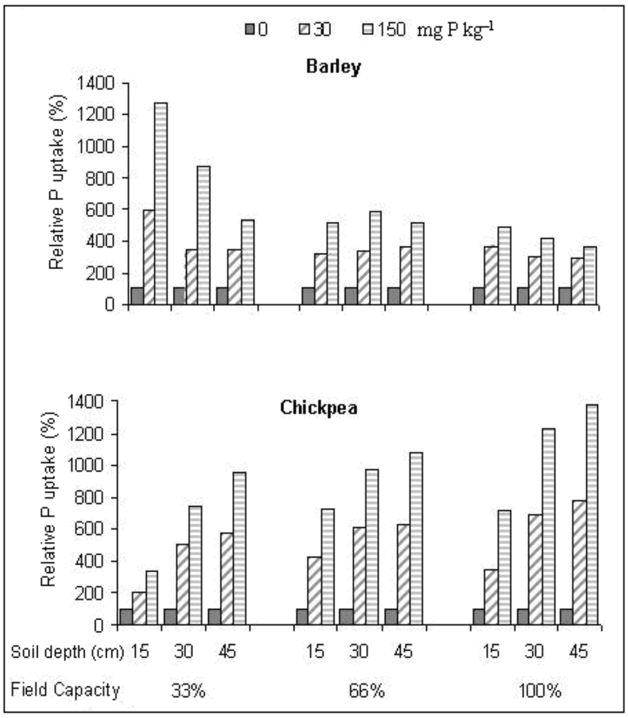

Figure 2: *Relative P uptake of barley and chickpea in relation to P application levels, soil depth, and available moisture.*

Discussion

Despite the fact that no greenhouse or controlled environment study can adequately reflect the variable and constantly changing environmental conditions that growing crops encounter in the field, this study reasonably simulated two major factors that influence P fertilizer use under field conditions. As soil moisture is the controlling factor in crop growth in dryland agriculture (Smith & Harris, 1981), a range of soil moisture from growth-limiting to adequate was adopted. Soil depth is the second major factor influencing growth as it directly controls the soil's capacity to store moisture and as well as the potential of plant roots to exploit stored soil moisture. Under field conditions normally encountered in the Mediterranean area (Kassam, 1981), cultivated soils range from "shallow" i.e., 0-30 cm, where the soil moisture storage capacity is limited and thus crop growth is limited, to "deep", i.e., > 100 cm or more which is adequate to store the excess moisture from rainfall that normally falls (200–500 mm yr^{-1}) in the cool months of (Dec.– Feb.) when precipitation usually exceeds evaporation (Cooper et al., 1987a).

Given what is known about the restrictive role of soil moisture on crop growth in Mediterranean-type conditions (Cooper et al., 1987a, 1987b), it was hardly surprising that a substantial reduction in available soil moisture, i.e., 33% of field capacity, had a major effect in reducing growth. However, at two-thirds of field capacity, yields were close to those obtained with maximum available moisture. As such, our study showed a similar effect of increasing soil moisture on yield as He et al. (2002) in their pot trial. Under conditions where irrigation was scheduled to deliver 1/3, 2/3 and full field capacity, Oweis et al. (1998) found a similar range of effectiveness, with the lower level severely curtailing growth and the intermediate level giving near optimum growth.

Of particular interest in this study was how P fertilizer use was influenced by moisture. While several studies from the region had dealt with P in relation to root growth under stressed conditions (Keatinge et al., 1987; Gregory et al., 1984; Matar & Brown, 1989a, 1989b), there was little indication that P had a proportionately greater effect in increasing crop yields under less favor-

***Table 3:** Soil depth, P application rates and available soil moisture in relation to total dry matter and P uptake of chickpea*

Depth	P	Available moisture (%)							
		33	66	100		33	66	100	
		Total dry matter			Average	Total P uptake			Average
Cm	mg kg^{-1}	------------- g pot^{-1} -------------				--------------- mg pot^{-1} -----------			
	0	1.7	3.9	6.6	4.1	1.2	2.5	4.2	2.6
15	30	2.7	10.7	16.7	10.0	2.4	10.6	14.7	9.2
	150	3.3	12.7	22.3	12.8	4.1	18.2	30.3	17.5
	Average	2.6	9.1	15.2	9.0	2.6	10.4	16.4	9.8
	0	3.8	6.5	6.7	5.7	2.6	4.7	5.5	4.3
30	30	12.4	27.9	39.2	26.5	13.2	28.7	37.6	26.5
	150	14.6	30.8	42.0	29.1	19.5	45.8	67.8	44.4
	Average	10.3	21.7	29.3	20.4	11.8	26.4	37.0	25.1
	0	5.2	8.2	8.1	7.2	3.6	6.5	7.2	5.8
45	30	18.0	36.0	47.9	34.0	20.9	40.8	56.3	39.3
	150	24.2	45.9	62.3	44.1	34.4	70.2	98.9	67.8
	Average	15.8	30	39,4	28.4	19.6	39.2	54.1	37.6

Total dry matter LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=0.7; interactions of D x P, D x FC, and P x FC=1.3

Total P uptake LSD values for Depth (D), P-applied (P), and Field Capacity (FC)=1.3; interactions of D x P, D x FC, and P x FC=2.3

able rainfall conditions as had been suggested by Harmsen et al, (1983) and Krentos & Orphanos (1979). While added P did increase TDM and P uptake under the most moisture-stressed conditions, the increases were consistently higher at the more favorable moisture levels.

The differential response in terms of relative yields between the crops in relation to moisture status may reflect differences in root systems and barley being better adapted to dry conditions than chickpea. (However, circumstances did not permit an examination of the root mass within the sectional soil columns). As with the study of He et al. (2002), while the relative increases may have been greater at the lower moisture range, the actual increases due to P were greater at the higher moisture level. Similarly, Bolland (1992) showed that relative P responses were higher under moisture-stressed conditions but absolute responses were higher without moisture stress. The apparent discrepancy between field observations on P response under stressed conditions and the results reported here probably is related to soil depth. Under stressed conditions, where rainfall is erratic and in small showers, effective soil depth is the limited extent of movement of the wetting front. Where this is limited by rainfall, any effect of P is probably due to a stimulating effect on tillering and root growth and thus allows the crop to make maximum use of what little rain that falls. Regardless of the mechanisms involved for any given level of rainfall, yield increases due to P always lead to better water use efficiency, which is defined as dry matter yields per unit of rain or soil moisture.

Our study demonstrated how important soil depth is in governing the plant's response to both P and moisture; with the limited P in each column size, increasing the column depth three-fold increased yields by a similar magnitude. Even with added P, the yield increases paralleled the increases in depth. The only explanation is that as the P concentrations were similar in each column size; as column size increased so too did the volume of soil to be exploited by roots which were exposed to the same P concentration. These results might account for observations that for any critical level of P, responses are higher in deeper soils, which might explain the observations of Sahrawat et al. (1996) that Vertisols, usually deep soils have lower critical P levels than Alfisols. These results might explain the broad range of critical P values reported by Ryan & Matar (1992) for a variety of soil types, including deep Vertisols. Clearly, soil depth to bedrock or the limit of the soil, or imposed "depth" due to limited soil moisture storage capacity, should be considered in the interpretation of critical P levels and corresponding fertilizer application rates.

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