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Yield response to phosphorus fertilizer in a wheat-lentil rotation in a Mediterranean environment

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Abstract

The effect of a single application of phosphorus (P) fertilizer on yields of wheat and a following lentil crop was studied in two-course rotational trials under rainfed conditions in a Mediterranean-type environment. Wheat was grown during the 1984/85 and 1985/86 growing seasons at three sites in north-west Syria, with P applied at rates of 0, 17.5, 35.0 and 52.5 kg ha^{-1}. Lentil (*Lens culinaris* Med.) was grown during the 1985/86 and 1986/87 seasons at the same sites, following the wheat crops. During the 1985/86 season, no additional P was applied to the lentil crop. During the 1986/87 season, additional P was applied to the lentil crops grown at two of the three sites, in order to compare the residual and direct effects of P fertilizer application. Initial contents of extractable soil P (P-Olsen) were low at all sites: in the range of 2–5 ppm. The response of wheat to direct application of P and of lentil to residual P were described by a modified Mitscherlich equation accounting for the effect of rainfall on potential yield (under rainfed conditions) and on the availability of P to the crop. Under the conditions of the experiments, lentil benefited significantly from P fertilizer applied to the preceding wheat crop. It was concluded that a single application of P to the wheat crop in a wheat-lentil rotation would reduce the cost of lentil production without significantly reducing lentil yields.

Keywords: direct P, Mitscherlich equation, P-moisture interactions, P uptake, residual P, *Triticum vulgare, Lens culinaris.*

Introduction

Lentil (*Lens culinaris* Med.) is an important crop in rainfed farming systems in the Mediterranean environment of West Asia and North Africa (WANA). The grain is a valuable source of good-quality protein in the human diet and lentil straw is a highly valued animal feed (Nygaard & Hawtin, 1981). Under rainfed conditions, lentil is generally grown in rotation after cereals, as is the case with other grain and forage legumes.

Many of the soils in the Mediterranean environment of the WANA region are calcareous and low in native soil phosphorus (P). Significant responses of lentil to P application have been reported in Syria (Loizides, 1970; Matar, 1976, 1977; Harmsen *et al.*, 1983; Matar *et al.*, 1987a; Matar & Brown, 1989) and in other countries of the WANA region (Badawy, 1976; Sharar *et al.*, 1976). In studies on the response of lentil to P fertilizer in southern Syria, it was observed that available soil moisture (i.e., rainfall) affected the availability of soil P. In medium- to high-rainfall seasons near-maximum yields were obtained at levels of extractable soil P (P-Olsen) that gave yields well below maximum yields in low-rainfall seasons. In other words, the same level of soil P appeared to be more effective in supplying the crop with P under medium- to high-rainfall conditions than under low-rainfall conditions (Matar, 1976). This confirmed earlier research on cereals and legume crops, which showed that the response to P fertilizer was greater under dry conditions than when crops were amply supplied with moisture (Marais & Wiersma, 1975; Matar, 1977). Similarly, at the same level of available soil phosphorus, P uptake by crops has been reported to increase with increasing annual rainfall (Olsen *et al.*, 1961; Marais & Wiersma, 1975).

In the rainfed farming systems of the Mediterranean region, the area under lentil is declining because of the relatively high cost of production (Khayrallah, 1981; Papazian, 1983). One way of reducing the cost of lentil production in a cereal-lentil rotation would be to apply P fertilizer to the cereal crop only. The success of this practice would depend on the ability of the lentil crop to benefit from the residual P from fertilizer applied to the preceding wheat crop.

The experiments reported in the present paper were aimed at studying the yield response of lentil to residual P. The results should help to design strategies for the efficient use of P fertilizers in rainfed farming systems in the Mediterranean environment.

Theory

Yield responses to fertilizer application and nutrient uptake by crops can be described by a Mitscherlich equation (Mitscherlich, 1909, 1913) of the following form:

$$Y = Y_x - (Y_x - Y_o)\exp{-\varepsilon_f N_f} \qquad (1)$$

where

Y = the total dry matter (DM) yield of a particular crop (kg DM ha^{-1}),

Y_x = the maximum, or potential yield of that crop under the climatic and soil conditions of the experiment,

Y_o = the yield when no fertilizer is applied (N_f=0),

exp = the exponential function,

ε_f = an 'activity' coefficient (kg^{-1} nutrient ha), which is a measure for the availability of the fertilizer nutrient to the crop, and
N_f = the rate of the fertilizer nutrient applied to the crop (kg nutrient ha^{-1}).

The Mitscherlich equation assumes that only the nutrient under consideration is limiting crop yield, and predicts that yields increase with increasing fertilizer rates until they asymptotically reach a maximum.

Although the Mitscherlich equation is usually applied to describe the yield response to fertilizer application, nutrient uptake by the crop can also be taken as the dependent variable:

$$L = L_x - (L_x - L_o)\exp - \varepsilon_{fl} N_f \qquad (2)$$

where
L = crop nutrient uptake (kg nutrient ha^{-1}),
L_x = the maximum nutrient uptake under the edaphic and climatic conditions of the experiment,
L_o = the nutrient uptake at $N_f=0$,
ε_{fl} = an 'activity' coefficient (kg^{-1} nutrient ha), which is a measure for the availability of the fertilizer nutrient to the crop, and
N_f = the rate of the fertilizer nutrient applied to the crop (kg nutrient ha^{-1}).

Under rainfed conditions in Syria, potential yields of field crops vary from virtually zero under very low rainfall conditions (100–150 mm $year^{-1}$), to 13–15 tons of DM per hectare for cereal crops and 8–9 tons for lentil under high-rainfall conditions (500–600 mm $year^{-1}$). This implies that for a particular crop, Y_x in Equation 1 varies among sites as a result of variation in annual rainfall. In the present study, the water-limited potential yield was estimated in two steps. First, the maximum yields (Y_x) were estimated separately for each trial, from a regression analysis of the plot yields of each trial on a modified Mitscherlich equation. Next, the set of Y_x values thus obtained was used for a regression on annual rainfall. From here onwards, the notation Y_x will be used for the maximum yields in the modified Mitscherlich equation obtained separately for each trial, and the notation Y_θ for the water-limited potential yield estimated from annual rainfall.

It may be noted that sometimes the term 'seasonal rainfall' is used as an equivalent for 'annual rainfall'. In practice, 80–90% of the annual amount of rainfall falls during the growing season, i.e., from November/December to May/June, and many agricultural experiment stations do not measure rainfall during the dry summer months. Moreover, rainfall during the summer months is lost for the crop and does not contribute to stored soil moisture. In the present paper, however, the term 'annual rainfall' is used throughout the text, since the length of the growing season can differ among locations and seasons, and is not therefore an exact term. It should be remembered, however, that the 'annual rainfall' for a growing season is taken from 1 July in the year of sowing until 30 June in the year of harvest. Over some length of time, both ways of expressing 'annual rainfall' obviously give the same result.

In the case of Y_x, i.e., maximum yields estimated for individual trials, the yield response to P can be described by a 'modified' Mitscherlich equation of the following form (Harmsen, 2000a):

$$Y = Y_x - Y_x \exp-(\varepsilon_{ns}P_s + \varepsilon_{nr}P_r + \varepsilon_{nf}P_f)\sqrt{Y_x} \tag{3}$$

where

Y_x = the maximum yield (kg DM ha^{-1}) estimated from the individual trials,
P_s = the initial P-Olsen content (ppm P) of the soil (0–20 cm depth),
P_r = the rate of residual P from fertilizer (kg P ha^{-1}) applied to a preceding crop during the previous season,
P_f = the rate of directly applied P fertilizer (kg P ha^{-1}), and
ε_{ns}, ε_{nr} and ε_{nf} are activity coefficients associated with P_s, P_r and P_f, respectively.

The dimensions of ε_{ns} (ppm^{-1} P $kg^{-1/2}$ DM $ha^{1/2}$) and of ε_{nr} and ε_{nf} (kg^{-1} P ha $kg^{-1/2}$ DM $ha^{1/2}$) are such that the expression to the right of the exponential function becomes dimensionless. Because all available nutrients are included in Equation 3, Y_o is set equal to zero, i.e., if no nutrients are available at all the yield is assumed to be zero.

The expression $\sqrt{Y_x}$ is assumed to account for the water-dependency of the 'activity' coefficients, i.e., the availability of P from different sources. At the same time, it accounts for the increasing demand for P by the crop with increasing Y_x, i.e., increasing annual rainfall. In Harmsen (2000a) the moisture dependency of the exponent of the modified Mitscherlich equation is expressed by Y_θ^n rather than by $\sqrt{Y_\theta}$ and values reported for n were in the range of 0.4 to 0.9. In the present treatment, the value of n is put at 0.5, as was done in a study reported earlier (Harmsen, 1995).

Crop P uptake can be dealt with in a way similar to what was discussed for yield. Hence:

$$L = L_x - L_x \exp-(\varepsilon_{nls}P_s + \varepsilon_{nlr}P_r + \varepsilon_{nlf}P_f)\sqrt{L_x} \tag{4}$$

where L_x is determined in a way similar to Y_x and where the activity coefficients, ε_{nls}, ε_{nlr} and ε_{nlf}, are defined in ways similar to the activity coefficients in Equation 3.

The relation between water-limited potential yield Y_θ and seasonal or annual rainfall may be approximated by the following equation:

$$Y_\theta = Y_p \varepsilon_{\theta r}(r - r_o) \tag{5}$$

where

Y_p = the potential yield (kg DM ha^{-1}) as determined by crop genetic and climatic factors other than rainfall,
$\varepsilon_{\theta r}$ = an 'activity' coefficient (kg^{-1} DM ha mm^{-1} year), which is related to the water-use efficiency of the crop,
r = annual rainfall (mm $year^{-1}$), and

r_o = a constant (mm year^{-1}) that represents the amount of rainfall below which biomass production is zero.

The expression $Y_x\varepsilon_{\theta r}$ could be referred to as the water-use efficiency (kg DM ha^{-1} mm^{-1} year). Equation 5 would apply to the range of about 200–600 mm of annual rainfall, and to deep soils (1–2 m depth) on flat land, where leaching losses and surface runoff would be limited.

Similarly, water-limited potential P uptake L_θ can be approximated as a function of annual rainfall by the following equation:

$$L_\theta = L_p\varepsilon_{\theta lr}(r - r_o) \tag{6}$$

where

L_p = the potential P uptake (kg ha^{-1}) as determined by crop genetic and climatic factors other than rainfall, and

$\varepsilon_{\theta lr}$ = 'activity' coefficient (kg^{-1} P ha mm^{-1} year).

If the water-limited potential yield Y_θ (kg DM ha^{-1}) is estimated from annual rainfall across sites, the crop response to P can be described by the following 'modified' Mitscherlich equation (Harmsen, 2000a):

$$Y = Y_\theta - Y_\theta \exp-(\varepsilon_{ns}P_s + \varepsilon_{nr}P_r + \varepsilon_{nf}P_f)\sqrt{Y_\theta} \tag{7}$$

where symbols have the same meaning as in Equations 3 and 5.

Similarly, if water-limited potential P uptake is estimated from annual rainfall, crop uptake of P can be estimated from the equation:

$$L = L_\theta - L_\theta \exp-(\varepsilon_{nls}P_s + \varepsilon_{nlr}P_r + \varepsilon_{nlf}P_f)\sqrt{L_\theta} \tag{8}$$

where symbols have the same meaning as in Equations 4 and 6.

Finally it may be noted that the P-use efficiencies for each of the P-sources can be derived from the modified Mitscherlich equation by taking the partial derivative of yield with regard to the relevant P-variable, i.e., P_f, P_r or P_s:

$$\partial Y/\partial P_k = \varepsilon_{nk}(Y_{x,\theta} - Y)\sqrt{Y_{x,\theta}} \tag{9}$$

where

k = an index referring to either one of the sources (fertilizer-, residual- or soil-P), and

$Y_{x,\theta}$ = either Y_x or Y_θ.

It follows that the P-use efficiency (kg DM per kg P) increases with increasing $Y_{x,\theta}$. The P-uptake efficiency can be defined in a similar way by the equation:

$$\partial L/\partial P_k = \varepsilon_{nlk}(L_{x,\theta}-L)\surd L_{x,\theta} \qquad (10)$$

where the P-uptake efficiency is in kg P per kg P, which is essentially dimensionless.

The term 'nutrient-use efficiency' could also be referred to as 'agronomic efficiency', and 'nutrient-uptake efficiency' could be referred to as 'nutrient recovery fraction' (e.g. Harmsen, 1984). Similarly, the derivative $\partial Y/\partial L$ may be referred to as 'physiological efficiency'. However, the terminology used here is not universally accepted and it therefore should be emphasized that Equations 9 and 10 also serve as the definitions of P-use efficiency and P-uptake efficiency, respectively, as used in the present paper.

Materials and methods

Field trials were conducted during three growing seasons at three experimental sites of the International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. The experimental sites differed in soil conditions (Table 1) and in long-term annual rainfall: Breda (281 mm year^{-1}), Tel Hadya (332 mm year^{-1}) and Jindiress (471 mm year^{-1}) (Anon., 1987). Prior to sowing, soils at all sites were sampled (0–20 cm depth) and analysed for $NaHCO_3$-extractable P (P-Olsen) (Table 1).

During the 1984/85 growing season, durum wheat (cv. Sham 1) was grown at Breda, Tel Hadya and Jindiress at P application rates of 0, 17.5, 35.0 or 52.5 kg P ha^{-1}. The fertilizer was either banded with the seed or broadcast and incorporated at soil preparation prior to sowing. Plot size was 30 m^2. The entire trial (7 treatments) was replicated three times at each site. Triple superphosphate (19% P) was used and all plots received 60 kg of nitrogen per hectare (urea, 46% N), of which 20 kg at sowing and 40 kg top-dressed in early February. Total DM (straw plus grain) was determined at harvest and analysed for total P.

During the 1985/86 growing season, the durum wheat trial was repeated at the three sites, but in different fields. In the fields that had been under durum wheat during the previous season, lentil crops were grown in the 1985/86 season. At all sites, the lentil (cv. Syrian Local Small) was sown in the first week of December 1985 at a rate of 100 kg seeds ha^{-1}, using a seed drill. No P was applied to any of the lentil crops. The lentil plots were hand-weeded and total DM yields were determined (hand-harvested) at the flowering stage and at harvest, and analysed for total P.

During the 1986/87 growing season, lentil was grown at two of the three sites – Breda and Tel Hadya – following a durum wheat crop. Each main plot (30 m^2) was split into four subplots of 7.5 m^2 each, where P was applied at rates of 0, 17.5, 35.0 or 52.5 kg ha^{-1}, banded with the lentil seed. Total DM yield was determined at early vegetative growth, at flowering and at harvest. Harvesting was done by hand. Only the central plot areas were harvested. The plants were air-dried and threshed to determine the grain yields. Sub-samples of the plants were oven-dried at 80 °C to constant weight (for at least 24 hours). All yield estimates and nutrient contents are expressed on a dry-weight basis. All plant material was analysed for total P. For further details on soil and plant sampling, and analytical procedures, see Harmsen (2000b).

Table 1. Geography, annual rainfall, and some characteristics of the soils (0–20 cm layer) at the three experimental sites. Mechanical analysis was done in soil materials without the removal (dissolution) of lime (Matar *et al.*, 1987b; Ryan *et al.*, 1996). Organic carbon (C) contents are taken from Harmsen *et al.* (1983).

	Experimental site		
	Breda	Tel Hadya	Jindiress
Latitude	35° 56′ N	36° 01′ N	36° 24′ N
Longitude	37° 10′ E	36° 56′ E	36° 44′ E
Altitude	300 m	284 m	210 m
Annual rainfall (mm)			
1984/85	277	373	409
1985/86	218	316	409
1986/87	245	358	601
Soil type	Calciorthid	Rhodoxeralf	Chromoxerert
Clay (% w/w)	28.8	55.5	60.8
Silt (% w/w)	42.4	37.3	32.5
Sand (% w/w)	24.5	6.5	3.8
Lime (% w/w)	33.7	24.9	20.2
Organic C (% w/w)	0.63	0.39	0.65
pH (1:1 w/v)	8.3	8.1	8.0
P-Olsen (ppm)			
1984/85 (wheat)	3.9	3.8	2.4
1985/86 (wheat)	3.5	3.5	1.8
1985/86 (lentil)	3.0	3.2	2.5
1986/87 (lentil)	4.8	3.4	–

Results

Data on yield of durum wheat and P uptake are summarized in Table 2. The effect of the method of fertilizer application, i.e., banding versus broadcast-incorporated, turned out to be statistically not significant (Matar & Brown, 1989). So the yields in Table 2 are averaged over the methods of P application. Initial P-Olsen contents were low at all experimental sites (Table 1).

Results for lentil are summarized in Table 3 (residual P) and Table 4 (direct application of P). The yield responses of wheat and lentil to P application in a wheat-lentil rotation will be discussed on the basis of a modified Mitscherlich equation (Equations 3 and 7). This allows for a regression analysis of pooled data on yield and P uptake across sites and seasons, and thus provides a basis for comparison between different crops.

The results of regression analysis of yield and P uptake on different forms of P, and on rainfall, are summarized in Table 5.

Table 2. Total biological yield and total P uptake by wheat grown at three experimental sites during two growing seasons, and fertilized at rates of 0 (P0dir), 17.5 (P1dir), 35.0 (P2dir) and 52.5 (P3dir) kg P ha^{-1}. All data refer to measurements taken at harvest. The P fertilizer was either banded with the seed or broadcast-incorporated at soil preparation prior to sowing.

Site	Treatment	Total biological yield (kg DM ha^{-1})		Total P uptake (kg P ha^{-1})	
		1984/85	1985/86	1984/85	1985/86
Breda	P0dir	3817	3238	4.04	2.46
	P1dir	4586	3845	4.77	2.87
	P2dir	4966	4022	5.58	3.19
	P3dir	5349	4007	5.81	3.75
Tel Hadya	P0dir	7585	6557	10.86	6.43
	P1dir	9102	6784	13.40	6.66
	P2dir	9113	6950	13.60	6.20
	P3dir	9897	7156	14.63	6.55
Jindiress	P0dir	6787	5673	8.15	5.11
	P1dir	8446	8013	10.24	7.63
	P2dir	8967	8750	11.60	7.71
	P3dir	9837	9006	11.99	9.23

Durum wheat

The yield response of durum wheat to directly applied P fertilizer (Table 2) could be described well (R^2=0.983) by the modified Mitscherlich Equation 3 where the term $\varepsilon_{nr}P_r$ was omitted, as no P fertilizer was applied to the preceding crop (Figure 1).

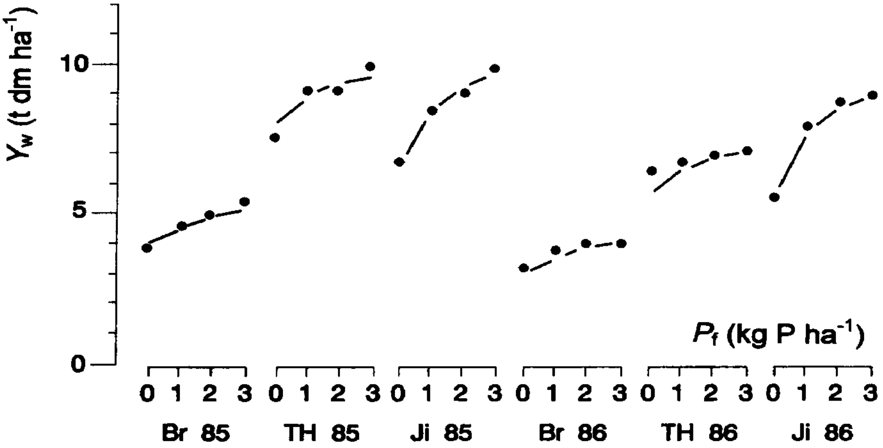

Figure 1. Yield response of durum wheat Y_w (t DM ha^{-1}) to directly applied P fertilizer (P_f) at rates of 0 (0), 17.5 (1), 35.0 (2) and 52.5 (3) kg P ha^{-1}, at Breda (Br), Tel Hadya (TH) and Jindiress (Ji) for harvests 1985 (85) and 1986 (86). Dots denote actual yields (Table 2) and drawn lines represent yields estimated according to Equation 3, with ε_{ns} = 0.00475 and ε_{nf} = 0.000381 (Table 5) and with values of Y_x estimated for each individual trial separately.

Table 3. Initial P-Olsen content of the 0–20 cm soil layer, total biological yield (Y_ℓ), total P uptake (L_ℓ), grain yield (GY_ℓ), and P uptake by the grain (GL_ℓ) for an unfertilized lentil crop at Breda and Tel Hadya during the 1985/86 and 1986/87 growing seasons, and at Jindiress during the1985/86 growing season. The P fertilizer had been applied to the preceding wheat crop at rates of 0 (P0res), 17.5 (P1res), 35.0 (P2res) and 52.5 (P3res) kg P ha^{-1}. Sowing was around mid-November. The data refer to measurements taken at flowering and harvest (maturity).

Treatment	P-Olsen	Flowering		Harvest			
		Y_ℓ	L_ℓ	Y_ℓ	L_ℓ	GY_ℓ	GL_ℓ
	(ppm)	(kg ha^{-1})					
Breda 1985/86							
P0res	3.0	1429	1.74	1429[1]	1.60[1]	488	0.96
P1res	4.4	1610	1.96	1610	1.79	584	1.23
P2res	9.4	1956	2.55	1956	2.33	564	1.26
P3res	9.1	2077	3.00	2077	2.74	536	1.18
Breda 1986/87							
P0res	4.8	1534	1.99	1542	1.88	623	1.46
P1res	8.0	1701	2.23	1718	2.10	664	1.58
P2res	10.0	1792	2.48	1818	2.30	721	1.74
P3res	15.6	1796	2.75	1796	2.38	715	1.87
Tel Hadya 1985/86							
P0res	3.2	2465	4.62	3166	4.24	1476	3.85
P1res	5.0	2365	4.68	3601	4.56	1545	3.99
P2res	7.6	2612	5.41	3250	5.09	1547	4.51
P3res	9.0	2795	6.16	3265	4.90	1544	4.32
Tel Hadya 1986/87							
P0res	3.4	3760	6.79	4757	6.58	1798	4.98
P1res	6.6	4680	8.52	5078	7.09	1861	5.39
P2res	11.2	5286	9.89	5399	9.16	2074	7.09
P3res	15.3	4339	8.23	5422	8.01	1878	5.74
Jindiress 1985/86							
P0res	2.5	2877	4.17	3582	4.27	1631	3.30
P1res	3.5	4014	6.21	4488	5.76	2079	4.53
P2res	4.6	3902	5.88	5412	6.87	2408	5.29
P3res	7.1	4608	7.41	5475	7.68	2453	5.81

[1] Harvest samples of straw were lost in 1985/86. Total yields at harvest were set equal to those at flowering; total P uptake was estimated from the total yields at flowering and the ratio of the crop P contents at flowering and harvest in 1987 at Breda.

A linear regression of the estimated values for the potential yield (Y_x) on total annual rainfall accounted for nearly 96% of the variation in Y_x ($n = 6$). In other words, under the conditions of the experiments, rainfall appeared to be the single variable determining most of the variation in yield, as would be expected when nutrients are not limiting yield, and soil and climatic factors other than annual rainfall do not differ among sites. A regression analysis of durum wheat yield on P_s and P_f according to Equation 7 resulted in a coefficient of variation for the pooled regression analysis

Table 4. Total biological yield (Y_ℓ), total P uptake (L_ℓ), grain yield (GY_ℓ) and P uptake by the grain (GL_ℓ) for a fertilized lentil crop at Breda and Tel Hadya during the 1986/87 growing season following a fertilized wheat crop. The P fertilizer was applied to the lentil crop at rates of 0 (P0dir), 17.5 (P1dir), 35.0 (P2dir) and 52.5 (P3dir) kg P ha^{-1}, banded with the seed. The P fertilizer to the preceding wheat crop had been applied at rates of 0 (P0res), 17.5 (P1res), 35.0 (P2res) and 52.5 (P3res) kg P ha^{-1}. Measurements were taken at early vegetative growth, flowering and harvest (maturity).

Treatment	Vegetative		Flowering		Harvest			
Residual P Fertilizer P	Y_ℓ	L_ℓ	Y_ℓ	L_ℓ	Y_ℓ	L_ℓ	GY_ℓ	GL_ℓ
	(kg ha^{-1})							
Breda								
P0res								
P0dir	260	0.50	1534	1.99	1542	1.88	623	1.46
P1dir	318	0.59	1919	2.56	1735	2.15	688	1.68
P2dir	378	0.74	2208	2.92	1857	2.44	734	1.92
P3dir	402	0.81	2370	3.26	1866	2.48	721	1.94
P1res								
P0dir	282	0.56	1701	2.23	1717	2.10	664	1.58
P1dir	339	0.67	2042	2.85	1783	2.21	666	1.71
P2dir	373	0.75	2244	3.08	1939	2.54	737	1.98
P3dir	430	0.88	2462	3.54	2001	2.69	772	2.13
P2res								
P0dir	258	0.51	1792	2.48	1817	2.30	721	1.74
P1dir	250	0.72	2082	2.82	1891	2.41	733	1.85
P2dir	391	0.72	2351	3.39	1982	2.72	787	2.05
P3dir	473	1.02	2553	3.86	2111	2.83	778	2.10
P3res								
P0dir	307	0.61	1796	2.75	1796	2.38	715	1.87
P1dir	359	0.75	2128	3.12	1883	2.41	713	1.89
P2dir	418	0.90	2466	3.66	1908	2.67	735	2.07
P3dir	483	1.06	2535	3.80	2017	2.89	767	2.22
Tel Hadya								
P0res								
P0dir	382	1.08	3760	6.79	4757	6.58	1798	4.98
P1dir	468	1.26	4821	8.14	5649	7.77	1937	6.06
P2dir	591	1.75	4728	9.81	5232	7.45	1908	5.74
P3dir	642	1.96	4898	9.30	5336	8.13	1862	6.07
P1res								
P0dir	378	1.10	4680	8.52	5078	7.09	1861	5.39
P1dir	508	1.50	5214	9.63	5619	7.61	1955	5.68
P2dir	557	1.66	4881	9.14	5083	7.81	1732	5.58
P3dir	757	2.31	4263	8.31	5415	8.44	1820	5.98
P2res								
P0dir	455	1.27	5286	9.89	5399	9.16	2074	7.09
P1dir	518	1.54	5128	10.01	5667	8.27	2091	6.35
P2dir	686	2.05	4909	9.58	5334	8.11	1786	5.92
P3dir	737	2.21	5105	10.44	5578	8.55	1918	6.42
P3res								
P0dir	431	1.31	4339	8.23	5421	8.01	1877	5.74
P1dir	610	1.88	4990	10.07	5029	8.22	1666	5.79
P2dir	605	1.93	5309	11.90	5353	8.90	1822	6.33
P3dir	718	2.34	5272	11.39	5496	8.88	1777	6.33

of 0.940, i.e., the regression was highly significant. Also the estimates for the activity coefficients in Equations 3 and 7 were very similar. The values of the coefficients ε_{ns} and ε_{nf} cannot be directly compared, as one is in ppm and the other in kg P ha^{-1}. However, for a 20-cm soil layer with a bulk density of 1.25 g cm^{-3}, 1 ppm P would be equal to 2.5 kg P ha^{-1}. So it follows from Table 5 that in terms of P-use efficiency by the crop, soil P as measured by P-Olsen is significantly more efficient than fertilizer P (by a factor of 20–30). Results for P uptake by the crop, according to Equations 4 and 8, show a similar trend.

Lentil

The ratio of grain to total above-ground biomass (harvest index; w/w) for lentil ranged from 0.35 to 0.48, averaging 0.42 over the four trials (excluding Breda 1985/86). Variations in harvest index are likely to be caused by factors like rainfall distribution, moisture stress and temperature, rather than the availability of soil P. So total biological DM yield was taken as the relevant yield parameter in the analysis.

Equation 3 was used for the analysis of the yield responses of lentil to residual P (Table 3), omitting $\varepsilon_{nf}P_f$ because the rate of directly applied P fertilizer was zero in all treatments. Except for Tel Hadya at harvest 1986 – where some scatter occurred in the data points – Figure 2 shows that the trends in the yield data are described well by Equation 3. P uptake by lentil showed similar trends as yield (Table 5).

The effect of directly applied and residual P on lentil yield was compared in two trials only (Tel Hadya and Breda, 1986/87; Table 4). This is not sufficient to obtain a reliable estimate of ε_{nf} for lentil (Equation 3). Moreover, at Tel Hadya, 1986/87,

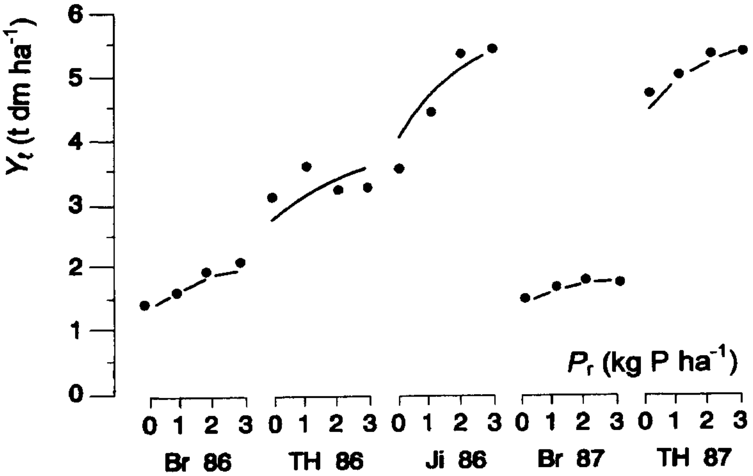

Figure 2. Yield response of lentil Y_ℓ (t DM ha^{-1}) to residual P from fertilizer (P_r) applied at rates of 0 (0), 17.5 (2), 35.0 (2) and 52.5 (3) kg P ha^{-1} to the preceding wheat crop, at Breda (Br), Tel Hadya (TH) Jindiress (Ji) for harvests 1986 (86) and 1987 (87). Dots denote actual yields (Table 3) and drawn lines represent yields estimated according to Equation 3, with ε_{ns} = 0.00600 and ε_{nf} = 0.000350 (Table 5) and with values of Y_x estimated for each individual trial separately.

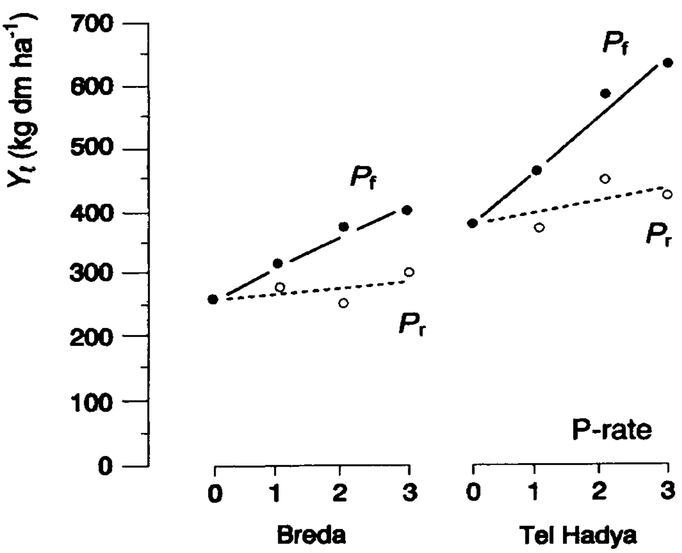

Figure 3. Yield response of lentil at early vegetative stage Y_ℓ (kg DM ha^{-1}) to directly applied (P_f) and residual P (P_r) from fertilizer at rates of 0 (0), 17.5 (1), 35.0 (2) and 52.5 (3) kg P ha^{-1} at Breda and Tel Hadya during the 1986/87 growing season (Table 4). Open circles refer to the P0res-P3res at P0dir treatments, and dots to P0dir-P3dir at P0res treatments (Table 4). Solid and broken lines represent simple linear regression equations.

there was little response to applied P. Lentil responded significantly to directly applied P in the early vegetative stage of crop development (Table 4), but not to residual P (Figure 3). At harvest time, however, this difference in response had largely disappeared, suggesting that ε_{nr} and ε_{nf} in Equation 3 eventually were of the same order of magnitude (Figure 4). The lines in Figure 4 represent Equation 3 with ε_{ns}=0.00600 and ε_{nr}=ε_{nf}=0.000350 for lentil yield, and Equation 4 with ε_{nls}=0.0634 and ε_{nlr}=ε_{nlf}=0.00285 for P uptake by lentil (Table 5).

Lentil responded significantly to P applied to the preceding wheat crop (Figure 5). The predicted yield responses increase with increasing annual rainfall, and in case of lentil are more pronounced for P uptake than for yields (Figure 6).

P requirements and P-use efficiencies

Equations 5 and 7 can be used to estimate the P-Olsen content required to obtain a certain target yield, for instance, 80% or 90% of the water-limited potential yield, expressed as a function of annual rainfall. From Figure 7 it follows that if P_f=P_r=0, this P-Olsen content decreases with increasing rainfall.

The P-use efficiencies of durum wheat and lentil can be compared using Equations 9 and 10. The results suggest that durum wheat would be more efficient in using native soil P than lentil. Furthermore, in the range of 200–400 mm of annual rainfall, durum wheat would be 2–4 times more efficient in using directly applied fertilizer P than lentil in using residual P.

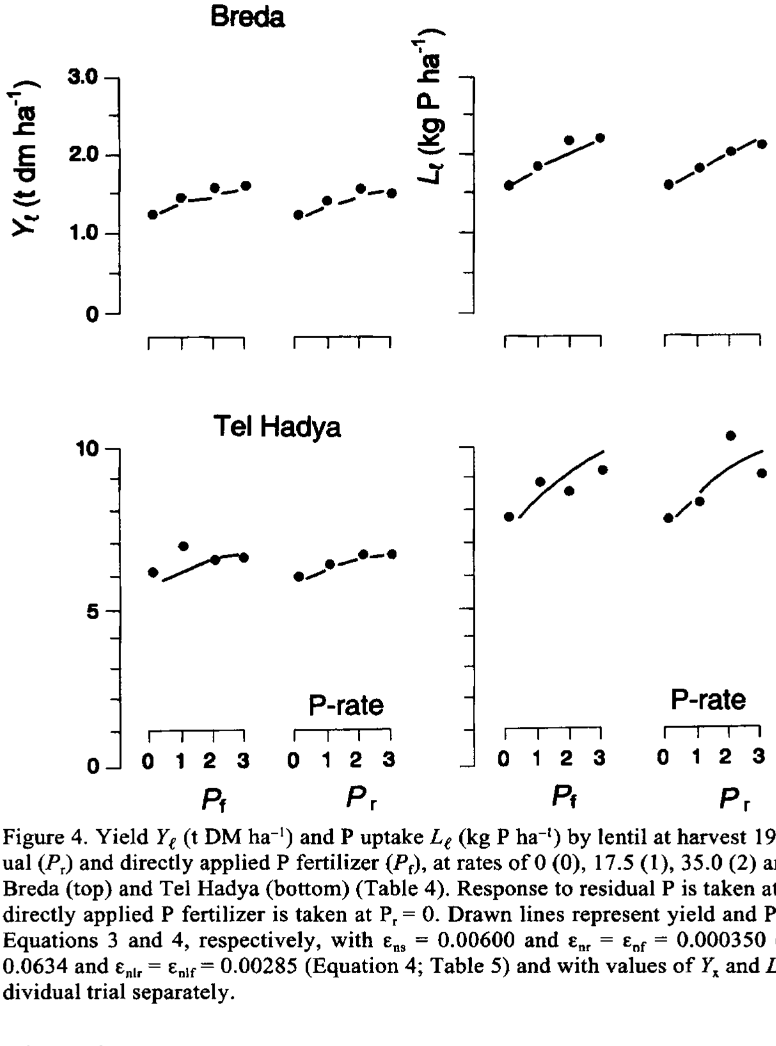

Figure 4. Yield Y_ℓ (t DM ha^{-1}) and P uptake L_ℓ (kg P ha^{-1}) by lentil at harvest 1987 in response to residual (P_r) and directly applied P fertilizer (P_f), at rates of 0 (0), 17.5 (1), 35.0 (2) and 52.5 (3) kg P ha^{-1}, at Breda (top) and Tel Hadya (bottom) (Table 4). Response to residual P is taken at $P_f = 0$, and response to directly applied P fertilizer is taken at $P_r = 0$. Drawn lines represent yield and P-uptake estimated from Equations 3 and 4, respectively, with $\varepsilon_{ns} = 0.00600$ and $\varepsilon_{nr} = \varepsilon_{nf} = 0.000350$ (Equation 3) and $\varepsilon_{nls} = 0.0634$ and $\varepsilon_{nlr} = \varepsilon_{nlf} = 0.00285$ (Equation 4; Table 5) and with values of Y_x and L_x estimated for each individual trial separately.

Discussion

Under the conditions of the experiments, the response of durum wheat and lentil to P as measured at harvest, was described well by a modified Mitscherlich equation (Equation 3; Figures 1 and 2). Equation 7 indicates that the availability of soil P increases with increasing Y_θ. It follows from Equation 5 that $\sqrt{Y_\theta}$ can be used as a measure for the 'effective' annual rainfall (r-r_0) and thus is related to the available moisture in the soil during the growing season. As the availability of native and applied P in the soil is determined, amongst other things, by the soil moisture content, it can be assumed that the factor $\sqrt{Y_\theta}$ in Equation 7 accounts for the effect of soil moisture on the availability of P. However, the actual effect of soil moisture on the availability of P to a crop may be more complex than would follow from the modified Mitscherlich

Table 5: Results of regression analysis of yield and P uptake; R^2 is coefficient of variation and n is the number of observations in the dataset. The dataset for wheat dealt only with direct response to fertilizer P (hence $P_r = 0$); the dataset for lentil dealt only with residual P (hence $P_f = 0$).

Regression eqn.	Crop	ε_{ns}, ε_{nls}	ε_{nr}, ε_{nlr}	ε_{nf}, ε_{nlf}	R^2	n
Equation (3)	wheat	0.00475	–	0.000381	0.983	24
Equation (7)	wheat	0.00485	–	0.000341	0.940	24
Equation (3)	lentil	0.00600	0.000350	–	0.981	20
Equation (7)	lentil	0.00600	0.000342	–	0.880	20
Equation (4)	wheat	0.1310	–	0.0146	0.982	24
Equation (8)	wheat	0.1554	–	0.0071	0.741	24
Equation (4)	lentil	0.0634	0.00285	–	0.975	20
Equation (8)	lentil	0.0650	0.00270	–	0.830	20

Regression eqn.	Crop	Y_p $\varepsilon_{\theta r}$, $\varepsilon_{\theta lr}$	r_o	R^2	n
Equation (5)	wheat	30.68	75.6	0.957	6
Equation (5)	lentil	21.97	125.3	0.916	5
Equation (6)	wheat	0.0425	127.6	0.691	6
Equation (6)	lentil	0.0443	123.7	0.874	5

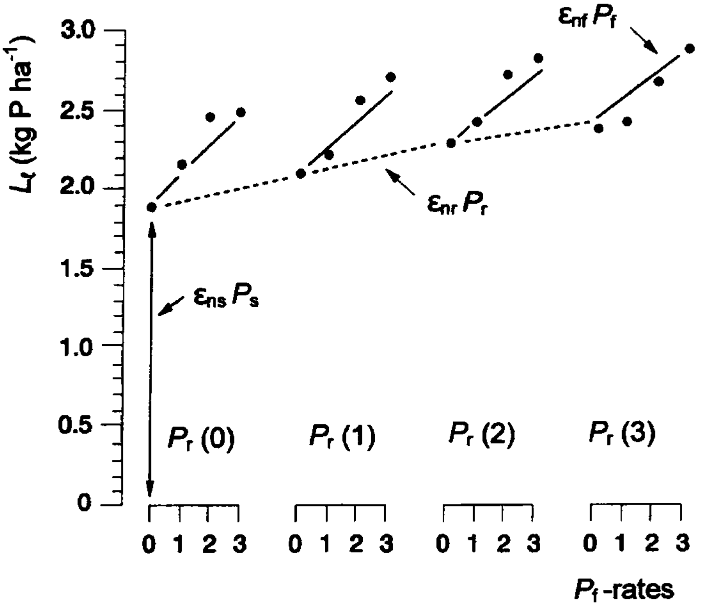

Figure 5. P uptake by lentil L_ℓ (kg P ha^{-1}) in response to residual (P_r) and directly applied P fertilizer (P_f), both at rates of 0 (0), 17.5 (1), 35.0 (2) and 52.5 (3) kg P ha^{-1}, at Breda for harvest 1987. Actual P-uptake is denoted by solid dots (Table 4). The intersect with the y-axis represents Equation 4 with $\varepsilon_{nls} = 0.0634$ and $P_s = 4.8$, at $P_r = P_f = 0$. The broken line represents Equation 4 for $\varepsilon_{nr} = 0.00035$ and P_r rates from (0) to (3), at $P_f = 0$. The solid lines represent Equation 4 for $\varepsilon_{nf} = 0.00035$ and P_f rates from (0) to (3).

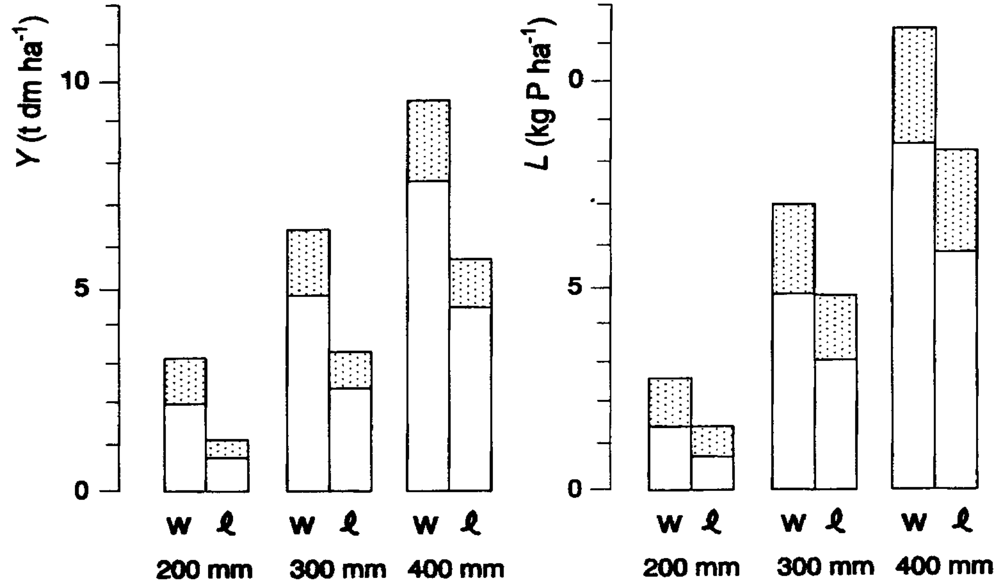

Figure 6. Predicted responses of yield Y (t DM ha^{-1}) and P uptake L (kg P ha^{-1}) by wheat (w) and lentil (ℓ) to 50 kg P ha^{-1} applied to the wheat crop in a wheat-lentil rotation, at $P_s = 3$ ppm and three different rainfall regimes, 200 mm, 300 mm and 400 mm year^{-1}. Water-limited potential yield Y_θ and P uptake L_θ are estimated from Equations 5 and 6, respectively (Table 5). Yield is estimated from Equation (7) and P uptake from Equation 8 (Table 5). The open bars represent yield and P-uptake values at $P_f = 0$ and the dotted part of the bars represents the yield or P-uptake response to an application of 50 kg P ha^{-1}.

equation in the form of Equation 7. This is because the availability of soil P increases with increasing rainfall, but so does the P requirement by the crop. The result of these two effects is the factor $\sqrt{Y_\theta}$ in the modified Mitscherlich equation for P (Harmsen, 1995, 2000a,b).

From Equations 5 and 7 it follows that the total DM yield is assumed to be a function of r, P_s, P_r and P_f, whereas Y_θ would be a function of rainfall only. It should be emphasized that the linear relation between water-limited potential yield and rainfall only holds if there is a simple, direct relation between annual rainfall and crop-available moisture. As all experiments reported here were conducted on deep soils (1 to 1.5 m, or deeper) and on flat land, losses of rainwater owing to deep percolation or surface runoff were limited (Cooper, 1983). However, on shallow soils or sloping land, the linear relationship between water-limited potential yield and annual rainfall would not be valid, and the values of Y_x would have to be estimated separately for each trial (Equation 3). Equations 5 and 7 serve to illustrate, however, that in principle the potential yield in a Mediterranean environment is limited by crop-available moisture, provided other environmental and soil conditions are held constant.

Compared with the classical Mitscherlich equation (Equation 1), the modified Mitscherlich equation in the form of Equations 3 and 7 has some conceptual advantages. In the first place, a single equation is used to describe the yield response of rainfed crops to P fertilizer application across sites and seasons. Secondly, the effect

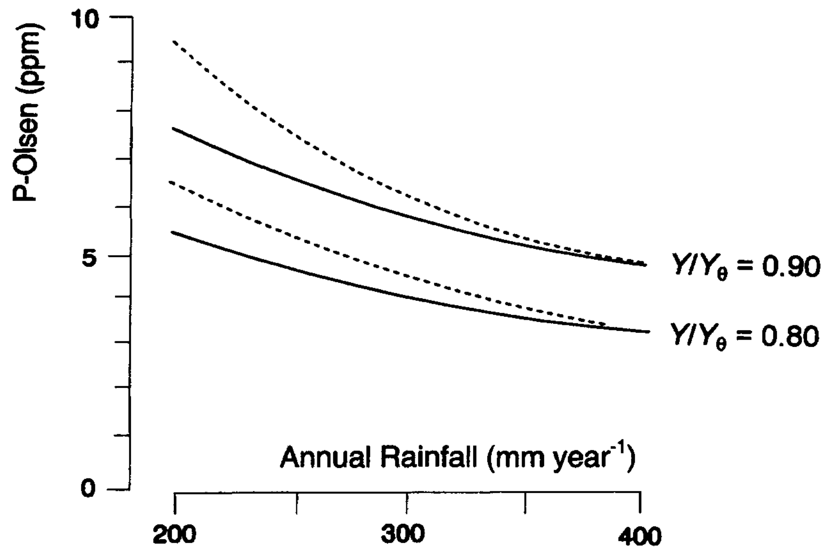

Figure 7. The predicted soil P levels (P-Olsen; ppm) for which the ratio of Y/Y_θ equals 0.90 or 0.80, for wheat (solid lines) and lentil (broken lines), as a function of annual rainfall (mm year^{-1}). Water-limited potential yields Y_θ of wheat and lentil are estimated from Equation 5 (Table 5). P-Olsen contents (i.e., P_s) are estimated from Equation 7 at $P_r = P_f = 0$ (Table 5).

of rainfall on maximum yield is explicitly considered, and estimated independently. Thirdly, the effects of initial soil P (P-Olsen), residual P and directly applied P fertilizer are considered separately. Finally, the effect of Y_θ, i.e., annual rainfall, on the crop-availability of P in soil is explicitly considered (Harmsen, 2000a).

The soil P data in Table 3 show that the P-Olsen values measured one year after the application of P fertilizer increased with increasing residual-P levels at all sites. There were, however, differences among sites and seasons. At the same level of directly applied P fertilizer, the rate of decrease of P-Olsen with time ('P-fixation') tended to increase with increasing rainfall. For example, at r = 200 mm year^{-1} it would take about 12 months for half of the initially extractable fertilizer P to become 'fixed' in the soil, whereas at r = 400 mm year^{-1} this would take about 6 months. Hence, the 'half-life' of the 'fixation' reaction tended to decrease with increasing rainfall, confirming earlier reports on the same sites (Anon., 1986). So one could expect fertilizer P to be relatively more available at the drier sites (lower rate of 'fixation') than at the wetter sites (higher rate of 'fixation'). However, it should be noted that although extraction by a $NaHCO_3$-solution (P-Olsen) recovers dissolved and some of the adsorbed and easily soluble forms of P in the soil, this chemical extraction does not necessarily provide a good measure of the availability of P to crops during the growing season. For example, soil structure, soil moisture content, the spatial distribution, density and activity of roots, the presence of vesicular-arbuscular (VA) mycorrhiza, and the spatial distribution and solubility of several co-existing calcium phosphates can play a role too (Lindsay, 1979; Harmsen, 1984).

Lentil DM yield at Breda did not increase much between flowering and harvest (Table 3), whereas at the wetter sites DM yields increased significantly. Averaged over all sites (excluding Breda, 1985/86), yields at harvest tended to be about 15% higher than at flowering. The lower yield at harvest at Breda may point at translocation of assimilates from the above-ground plant parts to the roots in late spring when moisture stress is increasing, and possibly to the loss of some above-ground DM.

P uptake was lower at harvest than at flowering (Table 3). Averaged over all sites (excluding Breda, 1985/86) about 7% less P was taken up at harvest than at flowering. The lower P uptake at harvest was largely caused by lower P contents in the crop This may suggest translocation of P within the plant, from the above-ground parts to the roots during moisture stress in late spring, or loss of leaves caused by ageing.

In the early vegetative stage of crop development, lentil responded significantly to directly applied P, and much less so to residual P (Table 4). This was to be expected. In the early vegetative stage, the crop's root system is not yet fully developed, whereas the directly applied P is mixed with the seed, i.e., located in the immediate vicinity of the developing root system. Also, early in the season the directly applied P is still present in a relatively soluble form. At harvest, the differences in response to directly applied and residual P had largely disappeared. This suggests that when the root system develops and the crop explores a larger soil volume, the native soil P (P_s) and the residual P (P_r) become relatively more important than the directly applied fertilizer P (P_f).

If the observation that lentil used directly applied and residual P about equally efficient (Table 4 and Figure 4) were confirmed by future research, this would imply that lentil is relatively efficient in using residual P and relatively insensitive to a decrease in solubility of applied fertilizer P with time. In other words, if indeed lentil uses directly applied P and residual P from fertilizer with equal efficiency, there would be little point in applying P to the lentil crop in a wheat-lentil rotation.

Conclusions

The response of rainfed wheat and lentil to fertilizer P in a Mediterranean environment can be described by a modified Mitscherlich equation that accounts for the effect of available moisture on potential yield and for the effect of soil moisture on the availability of P in soil. At the same level of soil P, yields of wheat and lentil increase with increasing rainfall if P is limiting yield. Lentil seems to be efficient in using residual P, in particular under favourable rainfall conditions (300–400 mm year^{-1}). If the observation that lentil uses directly applied and residual P about equally efficiently were confirmed by future research, this would further add to the tentative conclusion that in a wheat-lentil rotation P fertilizer can be applied to the wheat crop only, without reducing lentil yields. This would reduce the cost of lentil production.

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