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Soil phosphorus and relationship to phosphorus balance under long-term fertilization

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ABSTRACT

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Temporal changes in the concentrations of plant-available phosphorus (P) in soil (Olsen-P), total soil-P and P activation coefficient (the ratio of Olsen-P to residual-P (i.e. an approximation to total-P)) were measured in plots that received consistent inorganic nitrogen, phosphorus and potassium plus organic fertilizers annually. Maize and winter wheat crops were grown in rotation for 24 years. Olsen-P and P activation coefficient declined significantly in the earlier years (< 12 years) for treatments that did not include any P fertilizer, and increased over the same period for the P-fertilized treatments. The rates of change in the Olsen-P and P activation coefficient values were positively related to P balance. In the later years, the Olsen-P and P activation coefficient plateau values were positively related to the P balance.

Keywords: loess soil; phosphorus activation coefficient; wheat-maize rotation

For optimal crop yield, sufficient available phosphorus (P) is required and P use efficiency is improved by matching crop demand with supply. P accumulation in soils typically occurs when P fertilizer is added, whilst P depletion can occur under intensive cropping unless there is an external supply (Benbi and Biswas 1999, Yang et al. 2009). In contrast to most nitrogen (N) fertilizers, fertilizer P use efficiency is generally low in the year of fertilizer application, but the fertilizer P continues to provide available P for several years. This is because P is relatively immobile in soil and much of the residual fertilizer P from one application can remain available to subsequent crops (Dobermann et al. 1996). This highlights the importance of soil P testing prior to making decisions on fertilizer use (McLaughlin et al. 2011, Mühlbachová et al. 2017). Maximizing fertilizer P use efficiency in the year of application is, therefore, less important than predicting the amount of fertilizer necessary to achieve both optimum yield and maintain available soil P in subsequent years.

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Olsen-P is typically increased by between 2 and 6 mg P/kg soil by a fertilizer application of 100 kg P/ha (Aulakh et al. 2007) but as the risk of losses of P soil to water increases with excess P fertilizer application (Heckrath et al. 1995, Hesketh and Brookes 2000) it is important not to over-fertilize (Sharpley and Rekolainen 1997). Therefore, it is necessary to balance the need to maintain soil P and yet reduce the risk of P transfer to water. In China, only 15–20% of the fertilizer P applied was taken up by plants in the growing season of application. The potential P accumulation in soil as a result of fertilizer applications to arable land in China between 1980 and 2007 was more than 240 kg P/ha as determined from the balance of P inputs and outputs (Zhang et al. 2008).

In this paper, the results of a long-term (24 years) wheat-maize rotation cropping experiment on a calcareous loamy Eum-Orthic Anthrosol (Loess soil) are presented showing the changes in the concentrations of plant-available P in soil (Olsen-P), residual soil-P and the P activation coefficient with continuous fertilization, the relationship between P harvested in the crops and the P balance, and the relationships between residual soil-P and Olsen-P concentrations and P balance.

MATERIAL AND METHODS

A long-term, small plot experiment was established in October 1990 at the Chinese National Soil Fertility and Fertilizer Efficiency Monitoring Base for Loess Soil (34°17'51''N, 108°00'48''E). This site is at the altitude of 525 m a.s.l. located in Yangling, Shaanxi province, China. The soil is a Lou soil (Eum-Orthic Anthrosol) derived from loess with silt clay loam texture. The soil contains 7.44 g organic C/kg, 0.93 g total N/kg, 9.57 mg Olsen P/kg and 191 mg exchangeable K/kg, with the pH value of 8.6. The site has a mean annual temperature of 13°C and mean annual precipitation of 550 mm most of which falls from June to September. The fields were conventionally tilled with a mouldboard plough.

The cropping regime was a winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) rotation; the wheat was sown in October and harvested in the following June, and the maize was sown in June and was harvested at the end of September or early October. The plots were 14 m × 14 m and unreplicated, and each received the same fertilizer treatment since 1990. There were nine fertilizer treatments (summarized in Table 1). The control received no added fertilizers and five treatments (N, NK, NP, PK and NPK) received N, P and K as urea, triple superphosphate and potassium sulphate, respectively. Three treatments received inorganic NP and K plus organic fertilizers as straw (SNPK) or a low (M1NPK) or a high (M2NPK) application of cow manure. The SNPK treatment received 4.5 t (air-dried) wheat straw/ha annually from 1990 to 1998 and all the above-ground maize stalks from the plot after 1999. The added straw and stalks were chopped into ca 3 cm pieces and incorporated into the soil in autumn before sowing the wheat. Dairy cow manure was added once a year before wheat sowing. The plots were irrigated with ground water from a well using a sprinkler irrigation system. Irrigation was performed annually, 1 to 2 times during the winter wheat season and 2 to 4 times during the summer maize, depending on rainfall, with approximately 90 mm of water on each occasion.

Soil samples (0–20 cm depth) were collected annually after the maize harvest from multiple sites within each plot and bulked to give one composite sample per treatment, which was then sub-divided into pseudo-replicates. Plant-available P (Olsen-P) was extracted by 0.5 mol/L $NaHCO_3$ (pH 8.5). An approximation of the total soil-P was obtained by extraction with HNO_3-HF-$HClO_4$/NaOH using the method of Emteryd (1989). This is not a complete P extraction and is referred to as 'residual P'. The concentrations of P in the extracts were determined by the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962).

Table 1. Nutrient addition rates from inorganic fertilizers and organic amendments

Treatment	N	P	K
	(kg/ha/year)		
Control	0	0	0
N	353	0	0
NK	353	0	147
PK	0	83	147
NP	353	83	0
NPK	353	83	147
SNPK	375	88	156
M1NPK	252	88	156
M2NPK	278	118	192

P activation coefficient was the amount of available P (Olsen-P) calculated as a proportion of residual-P and is expressed as a unit-less ratio. The P uptake in the crop ([grain yield × P concentration of grain] + [straw yield × P concentration of straw]) for each crop was expressed in kg P/ha/year. The P balance was calculated as the difference between the fertilizers P addition and residual soil-P uptake in the crop.

Because the plots were unreplicated, a detailed hypothesis testing using the analysis of variance was not possible. Instead, the data were analysed primarily by regression analysis. Segmented linear regression (broken stick) or linear regression were used to summarize the data. For yields, P uptake and residual soil P, simple linear regression provided satisfactory regression and in many cases superior regressions compared to segmented regressions. For the Olsen-P and the P activation coefficient data, the segmented linear regression with a slope (positive or negative depending on the P fertilizer treatment) between 0 years and a breakpoint, followed by a plateau from the breakpoint to 24 years was used. Regression analyses were conducted using the SegReg routines (www.waterlog.info/segreg.htm, accessed 10 August 2016).

RESULTS

All elements of the harvested biomass and P uptake (for grain and straw for both crops) accumulated linearly with time and although there was some year-by-year variation in yields, linear regression provided good summaries of the data (Table 2). The lowest yielding treatments were

Table 2. Harvest and phosphorus (P) uptake rates for wheat and maize over 24 years under different fertilizer treatments

Treatment	Wheat grain	R^2	Wheat straw	R^2	Total wheat	R^2	Maize grain	R^2	Maize straw	R^2	Total maize harvest	R^2	Total wheat plus maize	R^2
	(t/ha/year)													
Control	0.9	0.996	1.8	0.989	2.7	0.994	2.3	0.997	1.8	0.992	4.1	0.998	6.8	0.997
N	0.9	0.992	1.7	0.985	2.6	0.989	2.8	0.997	1.8	0.988	4.6	0.995	7.2	0.995
NK	1.2	0.996	2.0	0.999	3.2	0.999	3.3	0.999	2.0	0.998	5.4	1.000	8.6	1.000
PK	1.3	0.994	2.1	0.993	3.4	0.995	2.8	0.991	2.2	0.993	5.0	0.996	8.4	0.997
NP	5.6	0.999	7.1	0.998	12.7	0.999	6.5	0.999	7.0	0.999	13.5	0.999	26.2	0.999
NPK	5.8	0.998	7.9	0.998	13.7	0.998	6.3	0.999	7.9	0.998	14.2	0.999	27.9	0.998
SNPK	5.9	0.997	8.4	0.998	14.4	0.997	6.6	0.999	8.4	0.998	15.1	0.999	29.4	0.998
M1NPK	6.1	0.996	9.2	0.997	15.3	0.997	6.9	0.999	9.1	0.997	16.0	0.998	31.3	0.998
M2NPK	6.3	0.997	10.0	0.999	16.3	0.998	7.1	0.998	9.9	0.999	17.0	0.999	33.3	0.999
Treatment	**Wheat grain P**	**R^2**	**Wheat straw P**	**R^2**	**Total wheat P**	**R^2**	**Maize grain P**	**R^2**	**Maize straw P**	**R^2**	**Total maize P**	**R^2**	**Total wheat plus maize P**	**R^2**
	(kg P/ha/year)													
Control	2.8	0.988	0.9	0.982	3.6	0.987	4.5	0.994	1.3	0.973	5.8	0.992	9.4	0.990
N	2.3	0.968	0.9	0.976	2.3	0.968	4.8	0.988	1.5	0.994	4.8	0.988	7.0	0.984
NK	3.5	0.991	1.0	0.991	3.5	0.991	5.0	0.994	1.7	0.994	5.0	0.994	8.5	0.998
PK	5.1	0.987	1.9	0.996	7.0	0.991	7.4	0.997	2.8	0.987	10.3	0.997	17.2	0.996
NP	18.7	0.998	4.2	0.986	22.9	0.998	16.4	0.990	7.9	0.989	24.3	0.998	47.2	0.999
NPK	18.2	0.996	4.7	0.995	22.9	0.997	16.4	0.994	7.7	0.997	24.0	0.998	46.9	0.999
SNPK	19.9	0.997	4.9	0.992	24.8	0.997	17.9	0.992	8.4	0.989	26.3	0.998	51.1	0.998
M1NPK	21.8	0.994	6.7	0.987	28.5	0.994	19.4	0.999	9.7	0.995	29.1	0.999	57.6	0.998
M2NPK	23.8	0.996	8.8	0.996	32.6	0.997	20.1	0.999	11.0	0.995	31.1	0.999	63.6	0.998
n	24		24		24		24		24		24		24	

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Table 3. Annual phosphorus (P) input, P uptake and P balance

Treatment	P input	P uptake	P balance
	(kg P/ha/year)		
Control	0	9.4	–9.4
N	0	7.0	–7.0
NK	0	8.5	–8.5
PK	82	17.2	64.8
NP	82	47.2	34.8
NPK	82	46.9	35.1
SNPK	88	51.1	36.9
M1NPK	185	57.6	127.4
M2NPK	278	63.6	214.4

the control, the N only or the NK treatments, depending on which parameter is considered, but all were very similar. The next highest yields were PK, NP and NPK in an increasing order, thus all N, P and K had positive effects on yield when used in combination. The highest yielding treatments were SNPK, M1NPK and M2NPK in an increasing order. The differences in yield did not follow exactly the amounts of particular nutrients for NPK, SNPK, M1NPK and M2NPK. For example, SNPK had the largest N addition (Table 1), but not the largest yield. This was because of the effect of the different nutrient combinations and, in the case of the SNPK, M1NPK and M2NPK treatments, other effects on the fertility associated with the organic matter additions.

Despite the P depletion in the control, N and NK treatments, the yields were maintained over the 24-year period, albeit at low vales. In the control, N and NK treatments, the P uptake obviously exceeded P additions leading to negative P balance, whereas for all the other treatments the P balance was positive (Table 3).

The trends in Olsen-P with time were all satisfactorily described by segmented regression (slope then plateau) models (Table 4). The Olsen-P values followed one of two trends depending on the treatment. In the treatments that did not include P (control, N and NK), Olsen-P concentrations declined with time initially followed by plateaux. For the P-containing

Table 4. Summary of regression analyses for different soil phosphorus (P) parameters

		Treatment								
		control	N	NK	PK	NP	NPK	SNPK	M1NPK	M2NPK
Olsen-P; segmented linear regression with time	slope 1 (mg P/kg soil/year)	–0.46	–0.73	–0.53	3.33	1.68	2.24	3.14	12.54	17.48
	Y-intercept P (mg P/kg soil)	7.81	9.88	8.11	11.39	10.21	9.38	10.01	27.24	49.20
	breakpoint on time axis (years)	11.56	9.82	9.60	9.41	11.23	8.17	7.95	8.66	8.51
	plateau P (mg P/kg)	2.46	2.72	3.05	42.77	29.02	27.69	34.97	135.80	198.18
	R^2	0.667	0.617	0.589	0.684	0.616	0.527	0.526	0.821	0.722
	n	23	22	24	24	24	24	24	24	24
Residual-P; linear regression with time	slope (g P/kg soil/year)	0.0020	0.0028	–0.0001	0.0237	0.0159	0.0133	0.0203	0.0380	0.0544
	Y-intercept P (g P/kg soil)	0.557	0.556	0.604	0.574	0.587	0.611	0.588	0.629	0.667
	R^2	0.071	0.103	0.000	0.759	0.508	0.534	0.744	0.725	0.759
	n	23	22	24	24	24	24	24	24	24
Phosphorus activation coefficient; segmented linear regression with time	slope 1 (/year)	–0.00074	–0.00132	–0.00086	0.00248	0.00245	0.00196	0.0023	0.0108	0.0137
	Y-intercept P	0.142	0.183	0.143	0.194	0.141	0.172	0.194	0.414	0.433
	breakpoint on time axis (years)	13.42	10.72	11.22	9.15	6.91	8.53	7.99	5.87	5.79
	plateau P	0.00366	0.00414	0.00465	0.0420	0.0311	0.0339	0.0378	0.105	0.123
	R^2	0.744	0.717	0.775	0.646	0.397	0.414	0.599	0.661	0.514
	n	19	19	18	18	19	18	18	18	16

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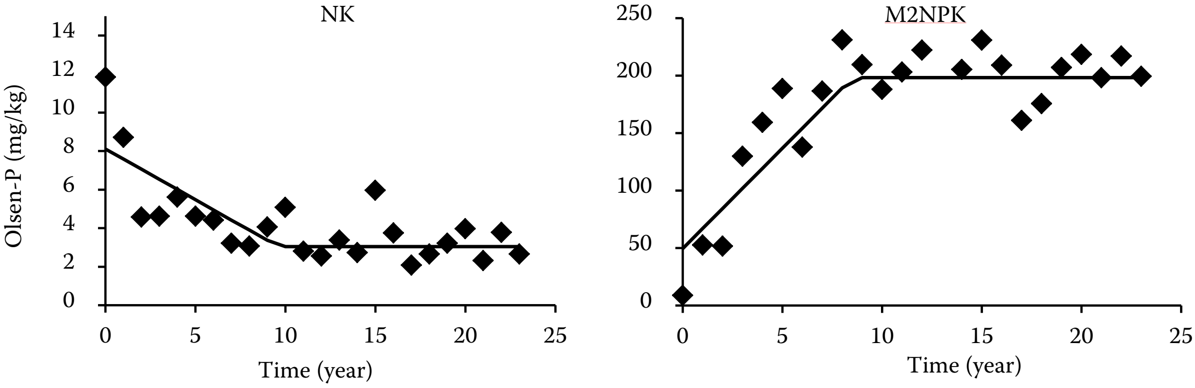

Figure 1. Olsen-P values with time for the NK and the M2NPK treatments. For regression parameters see Table 4

treatments, there were initial increases in Olsen-P followed by plateaux. Examples of the two patterns are shown for the two extreme treatments (NK and M2NPK) in Figure 1. The breakpoints in the regressions for Olsen-P occurred between 7.95 and 11.6 years, but there was no relationship between the timing of the breakpoint and the P balance. There were, however, significant positive linear relationships between P balance and both the slopes and the plateau values in the segmented, as would be anticipated. For the control, N and NK treatments, the Olsen-P concentrations declined by between 0.46 and 0.73 mg P/kg soil/year, whereas for the P-containing treatments the rates of increase ranged from 1.68 to 17.5 mg P/kg soil/year, depending on the P balance (Table 4). For the control, N and NK treatments, the plateau values were in the range 2.46 to 3.05 mg P/kg soil, whereas for the P-containing treatments the plateau values ranged from 27.7 to 198 mg P/kg soil (Table 4).

There were no significant relationships between residual soil P and time for the control, N and NK treatments (Table 4) because the P uptake in these low yielding treatments was not large enough to be detected in the soil-P analysis. The trends in residual soil-P for the P-containing treatments were all satisfactorily described by linear regression with R^2 values ranging from 0.574 to 0.667 ($P < 0.05$; Table 4). Examples of the relationships are shown for the two extreme treatments in Figure 2. For all treatments, including those that did not include P addition, there was a significant relationship between the P balance and the rate of change in residual soil P, and the relationship was improved slightly by the removal of the control, N and NK treatments ($R^2 = 0.979$). Assuming a bulk density of 1.2 g/cm^3 for the soil, the P balance can be converted to the same units as the residual soil-P (g/kg soil) and then used to estimate that the effect of the net P addition in fertilizer and manures on the residual soil-P. This indicated that there was an increase of 0.57 g residual soil-P per g of net P input for the 0–20 cm depth of soil. This relationship is influenced by the large excesses of P (large

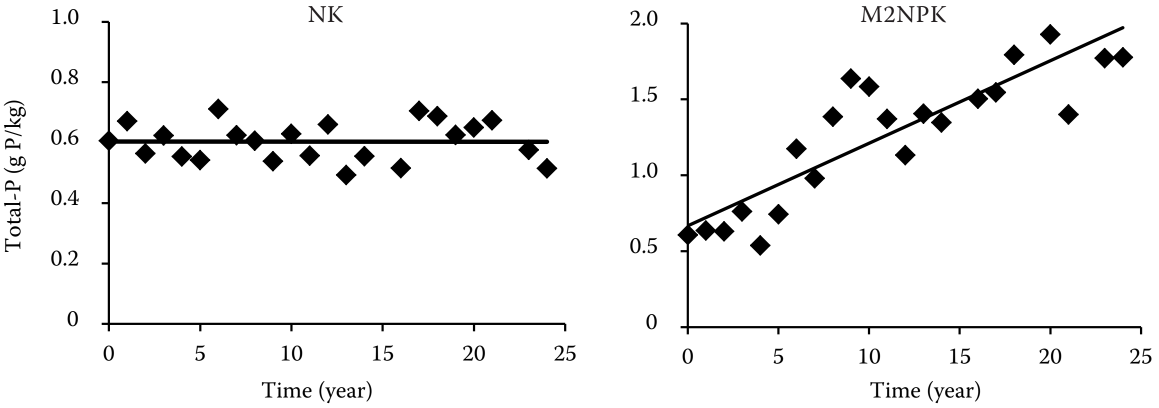

Figure 2. Residual soil-P values with time for the NK and the M2NPK treatments. For regression parameters see Table 4

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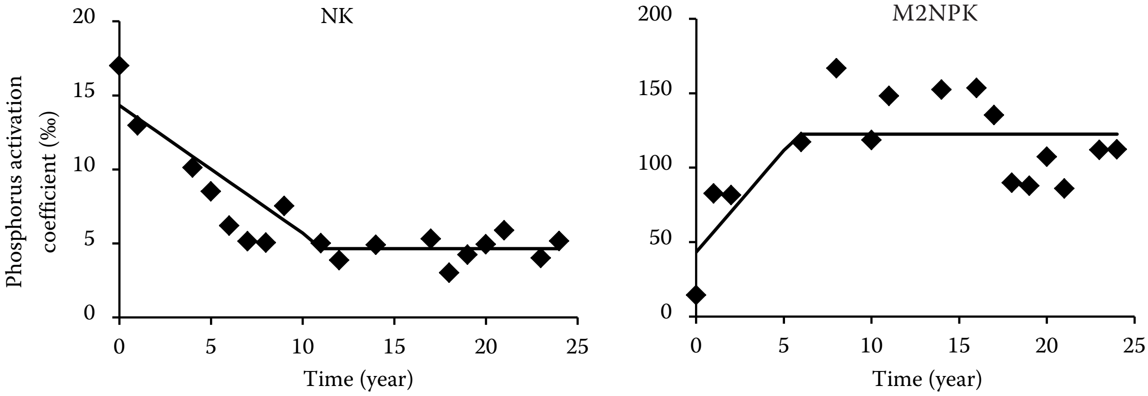

Figure 3. Phosphorus activation coefficients with time for the NK and the M2NPK treatments. For regression parameters see Table 4

positive P balances for some of the treatments. In particular, it is influenced by the PK treatment which had a moderate P input (82 kg P/ha/year) in the context of this experiment, but a low P uptake (17.2 kg P/ha/year; Table 2) because the yield was constrained by N limitation (PK yield = 8.4 kg/ha/year, compared to NPK yield = 27.9 kg/ha/year; Table 3). Second, it is influenced by the M1NPK and the M2NPK treatments in which the P additions far exceeded the P requirements of the crops (Table 2).

The trends in P activation coefficient followed similar patterns to the Olsen-P, with the control, N and NK treatments fitting segmented regressions with declining values over time between zero years and the breakpoint followed by plateaux, and the P-containing treatments having increasing values between zero years and the breakpoints followed by plateaux (Table 4). Examples of the relationships are shown for the two extreme treatments (NK and M2NPK) in Figure 3. There were significantly positive relationships between the P balance and both the slopes and the plateaux. Unlike the Olsen-P values, there was also a significant relationship between the breakpoint and the P balance, with the breakpoint occurring earlier with increasing P balance.

DISCUSSION

With cropping, available P concentration in the top soil usually decreases unless P fertilizer is added, and can increase if excess P fertilizer is applied. Most previous studies either have compared the differences between initial and final available P concentrations or used linear models to describe the changes in plant-available P over time (Colomb et al. 2007) and may have not considered a long enough run of data for the details of P dynamics to be fully characterized (Yang et al. 2009). When considered over an extended period (e.g. > 20 years), as it was done in this study, the trend in both Olsen-P fitted and P activation coefficient conformed to a linear slope-plateau model. The fact that no significant decline in residual soil-P was detected in treatments without P fertilizer applications is consistent with Yang et al. (2009).

Our data show that Olsen-P concentrations and P activation coefficient can be predicted from the P balance. Even with consistently negative P balances, both parameters stabilized between 2.46 and 3.05 mg P/kg and between 0.037 and 0.047, for the Olsen-P and the P activation coefficient, respectively. Similarly, where P balances were positive these parameters also reached plateaux, indicating that excess P was held elsewhere (i.e. a different fraction) in the residual soil P pool or was lost. Not all of the excess P could have been lost, however, because the residual-P concentrations continued to increase after the Olsen-P concentrations had reached plateaux. Furthermore, the relationship between P balance and Olsen-P would suggest that an Olsen-P concentration of about 4.0 mg P/kg soil would correspond to a zero P balance. If the P balance is approximately 35 kg P/ha/year, as occurred in the NP, NPK and SNPK treatments, the Olsen-P would be stable at about 36 mg P/kg soil, which is slightly higher than that of NP (29 mg P/kg soil) and NPK (28 mg P/kg soil) as simulated from the change over time. The Olsen-P predicted from the P balance values differed from those estimated from the change in

Olsen-P in treatments with relatively low P balance; probably because some minor P inputs were omitted, such as P in seeds, irrigation water and atmospheric deposition, and the potential greater allocation of P to roots which were not harvested and which could have carried P into the subsoil beneath the sampling depth distribution.

Tang et al. (2009) previously showed that the critical values of Olsen-P were 16 and 17 mg P/kg soil for summer maize and winter wheat, respectively, for a comparable anthropogenic loess soil. According to our results, the P harvested in crops was about 47 kg P/ha/year on average for the treatments that most closely matched typical farming practice in the region (i.e. NP or NPK fertilizers). If topsoil Olsen-P needs to be maintained between 16 and 17 mg P/kg soil, the relationship between Olsen-P and P balance needs to be about 13 kg P/ha/year, and the amount of P fertilizer needs to be 59 kg P/ha/year (or 135 kg P_2O_5/ha/year). This is less than the current typical application rates of approximately 82 kg P/ha/year when NP or NPK inorganic fertilizers are used in this region.

Our results show that Olsen-P and P activation coefficient declined significantly in the first 12 years for treatments without any P fertilizer, and initially increased for the P-fertilized treatments. The changes in Olsen-P and P activation coefficient values were positively related to P balance. In the later years, the Olsen-P and P activation coefficient plateau values were positively related to the P balance. Whilst Olsen-P is commonly used and an accepted method for assessing plant available P, by combining it with estimates of P activation index and residual-P, a more comprehensive understanding of soil P and the dynamics of P which could influence agronomic practice is possible. A key issue is that soils that have been fertilized with P often contain significant reserves of P that could be released for plant uptake or may contribute to pollution, so it may be important to make multi-pool assessments of P in soil.

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