Modeling Long-Term Crop Response to Fertilizer Phosphorus. I. The Model[1]

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ABSTRACT

Prediction of long-term crop response to fertilizer P should result in more efficient use of this resource. To achieve this, a simple model designed to calculate the long-term recovery of fertilizer P was developed and is presented here. In the model, both a labile and a stable P pool are distinguished. With time intervals of 1 yr, the model calculates the P transfers between the pools, the uptake of P by the crop, and the resulting pool sizes. Most input data required to operate the model can be obtained from ordinary one-season fertilizer P trials. Input data, model parameters, and initial pools can be derived from field trials, and the model can be used to calculate long-term recovery of fertilizer P. The sensitivity of the model is demonstrated by changing parameter values. The model can also be used to establish long-term fertilizer recommendations for a certain target P uptake. Required rates of fertilizer P are calculated for different soils, fertilizer types, target uptakes, and periods of time.

Additional index words: **Fertilizer recommendations, Labile phosphorus, Phosphorus uptake, Simulation model, Soil phosphorus cycle, Stable phosphorus.**

THE COMPLEXITY of P chemistry in the soil is reflected by the many forms of P that are distinguished in comprehensive models of the soil P cycle and the crop response to fertilizer application (Jones et al., 1984). Apart from P in solution, at least three pools of inorganic P are considered, labile, stable, and original soil minerals, and two pools of organic P, labile and stable. All these P pools interact directly or indirectly and affect in this way the uptake by the crop and the effectiveness of fertilizer use.

The quantitative relationships of the processes involved are poorly understood, and it is difficult to apply such comprehensive models in practical situations. For the purpose of determining the recovery of fertilizer P in the year of application and its aftereffects in the following years, a summary model will suffice. In this paper such a model is described, operating with time intervals of 1 yr.

MODEL STRUCTURE

In the model, two dynamic pools of P are distinguished, a labile and a stable pool (Fig. 1). These pools include both inorganic and organic forms of P. Crops take up P from the labile pool (LP), and the uptake per cropping period (transfer

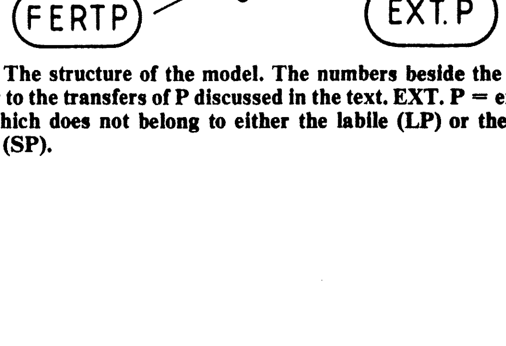

Fig. 1. The structure of the model. The numbers beside the arrows refer to the transfers of P discussed in the text. EXT. P = external P, which does not belong to either the labile (LP) or the stable pool (SP).

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1 in Fig. 1) is calculated as a fraction of the labile pool. The stable pool (SP) serves as a slow-release buffer that replenishes the labile pool (transfer 2 in Fig. 1). There is also a transfer in the opposite direction (transfer 3), from the labile to the stable pool, representing all processes rendering labile P less available.

The crop uptake of P is usually replaced in part by a net input of P (transfer 4 in Fig. 1), the result of additions by weathering of P-containing soil minerals and supply through rainfall, volcanic dust, and flood water, and losses mainly via soil erosion and leaching. Within the time scale pursued, the rate of net input can be assumed constant.

After application of fertilizer, a part of the applied P dissolves and is sorbed by soil components in the immediate surroundings of the fertilizer granules, while the remainder is converted into less soluble compounds like tri- and tetracalcium phosphate and perhaps apatite, which remain in the granule residue (Lehr et al., 1959; Henstra et al., 1981; Leenaars-Leijh, 1985). These processes take place within a few days and result in pockets with high concentrations of available P surrounding the fertilizer granules. These concentrations remain high for a long time, as shown by Van der Eijk (1985, personal communication), who found P-Olsen values of more than 100 mg kg^{-1} about 2 yr after fertilizer application. Table 1 gives the division into labile and stable P for some common P fertilizers. After fertilizer application, the resulting amount of labile P is gradually transferred to the stable pool (transfer 3 in Fig. 1), thus reducing the residual effect of applied fertilizer.

The rates of transfer between the labile and the stable pools are described in the model as fixed fractions of the pool sizes at the start of the time interval considered. The numerical values of these fractions are the reciprocals of the respective time constants of transfer. The sizes of both pools change in the course of time as a result of the transfers described above. These changes are added to the previous values of the P pools to arrive at the pool sizes at the beginning of the next year.

The stable and the labile pools, as defined in this model, are not identified with certain P components in the soil. The labile pool in the model is defined as that P stored in the soil that has an availability to crops equal to that of the labile fraction of broadcast fertilizer P. It resembles the concept of the 'a' or 'A' value from Fried and Dean (1952). However, in their concept, soil P is compared with all fertilizer P applied, and not only with the labile fraction of fertilizer P. The advantage of the present approach is that the calculated size of the labile pool is independent of the type of fertilizer. The stable pool in this model comprises that store of soil P to which the time constants of transfer apply. Thus, the sum of stable and labile P is usually less than the total amount of soil P because the soil may also contain P in minerals that weather too slowly to include them in the stable pool (see net input, discussed above).

Application method can affect first-year recovery fraction of applied fertilizer P. First year recovery of banded P is often higher than that of broadcast P (de Wit, 1953). If, however, first-year localized fertilizer P is mixed through the soil, its behavior will be similar to that of broadcast applied P. Broadcast applied P is mixed through the whole plow layer, and, therefore, its distribution resembles that of soil P, which contrasts with the distribution of localized fertilizer P.

Table 1. Indicative values of fractions of labile and stable P for some common P fertilizers.

Fertilizer type	Labile fraction	Stable fraction
Ammonium phosphates	1.0	0.0
Superphosphates	0.8	0.2
Phosphate rocks	0.1-0.2†	0.9-0.8‡

† Fractions depend mainly on hardness and solubility of the phosphate rocks.

‡ It is possible that in certain phosphate rocks a part of the P should be considered as inert, if only because the rock is not properly ground. Then the labile and stable fraction add up to less than one.

INPUT DATA

The data required to operate the model are the rate and type of fertilizer applied, the total crop uptake of P by the unfertilized crop and that by the fertilized crop during the first year after fertilizer application, the net input of P, and the time constants of transfer between the labile and the stable pools. Rate and type of fertilizer are introduced by the user. Phosphorus uptake data are derived from ordinary one-season P fertilizer trials, where crop production with and without P fertilization is established. When crop P concentration has not been determined in the trial, it may be estimated because these values are to a large extent crop specific, provided P is the limiting growth factor (Van Keulen and van Heemst, 1982). If no data from fertilizer trials are available, indicative values for the P recovery of superphosphate and the uptake fraction of labile P may be derived from Table 2. As long as P strongly limits yield, a linear relationship between rate of P application and uptake of P by the crop is found; i.e., the recovery and the uptake fractions are constant.

When other growth factors become yield limiting, which occurs especially at high P rates, the uptake fraction gradually decreases. In the discussion of the model presented in this paper, we assumed that crop yields are limited only by P supply, and, hence, the uptake fraction of the labile pool is constant. Where a sufficiently wide range of P application is used and the uptake fraction decreases at the higher P rates, uptake from the labile pool may be divided into different components to reflect more nearly actual P availability to the crop. Where the crop is unable to exploit a large labile pool as effectively as a smaller one, then adjustments in the recovery fraction with P rate may improve the predictive value of the model.

The net input is site-specific and depends on such factors as the weathering of P-containing minerals in the soil, the intensity of flooding, soil erosion, etc. While net input may be negative, it is always positive in persistent agricultural systems without P application because it compensates for P removed in crop products. Quantitative information on net input can be derived from agricultural systems where the uptake of P by crops in the absence of fertilizer application is compensated for only by the net input. In such situations, constant levels of P uptake may be observed in the long term, as illustrated in Fig. 2. The time constants of transfer between the labile and the stable pools determine the decrease in size of the labile pool after fertilizer application and, hence, the residual effect of applied fertilizer. Both time constants can only be derived from results of long-term fertilizer trials. Only a few such fertilizer trials, however, are

Table 2. Soil properties indicative for various levels of the recovery fraction of triple superphosphate P and of the uptake fraction of labile P.

Soil properties	Recovery fraction	Uptake fraction
$5 < pH < 7$ Weak P sorption Low amount of available P	0.16-0.28	0.20-0.35
$4 < pH < 7$ Weak to moderate P sorption Moderate to high amount of available P	0.08-0.16	0.10-0.20
$pH < 4$ $pH > 7$ Severe P sorption	<0.08	<0.10

available. In the second paper of this series (Janssen et al., 1987), it is shown that values of 5 and 30 yr for the time constants of transfer between the labile and the stable pools are acceptable under a rather wide range of environmental conditions.

LONG-TERM RECOVERY OF FERTILIZER PHOSPHORUS

As starting point for the calculations, a steady state situation is taken for an annually cropped soil that does not receive fertilizer P (Fig. 2a). It is a steady state, because the net input of P equals the removal by the crop.

Table 3 presents input data and shows how model parameters and initial pool sizes are derived. The calculations in Table 3 are straightforward and need little discussion. The P transfer from the stable to the labile pool (line 16) compensates for losses from the labile pool by P uptake (and removed in the crop) and the transfer of P from the labile to the stable pool (see also Fig. 2a). The pool sizes of the soil after fertilizer application (lines 18, 19) are found by adding the amount of applied P to the pool sizes of the soil before application.

Once the fraction of the labile pool taken up annually by the crop (line 13) is estimated, the uptake by the crop and, hence, the recovery of fertilizer P can be calculated for the successive years (Table 4). Because the input data were derived from a steady state situation, the pool sizes of the unfertilized soil remain constant.

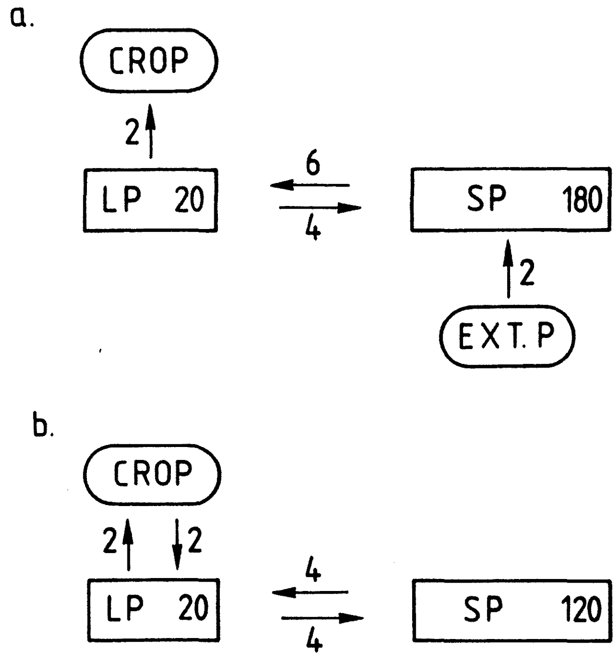

Fig. 2. Steady state situation for arable land (a) and under natural vegetation (b). The numbers beside the arrows are rates in kg P ha^{-1} yr^{-1}. EXT. P = external P, which does not belong to either the labile (LP) or the stable pool (SP).

The situation is different if the P uptake by the crop exceeds the net input, as may be the case after clearing natural vegetation. In Fig. 2b, it is assumed that under

Table 3. Input data, calculation of model parameters, and initial pool sizes for an unfertilized and a fertilized soil.

Line number	Description	Calculation†	Value‡
	Input data		
1	Type of fertilizer		Triple superphosphate
2	Rate of fertilizer P		100
3	P uptake from unfertilized soil		2
4	P uptake from fertilized soil		10
5	Net input of P		2
6	Time constant of P transfer from labile to stable pool, years		5
7	Time constant of P transfer from stable to labile pool, years		30
	Model parameters		
8	Labile fraction of fertilizer P		0.8
9	Stable fraction of fertilizer P		0.2
10	Labile P from fertilizer	2 × 8	80
11	Stable P from fertilizer	2 × 9	20
12	First year recovery	4 − 3	8
13	Uptake fraction of labile pool	12 ÷ 10	0.1
	Initial situation		
14	Size of labile pool, US§	3 ÷ 13	20
15	Transfer labile to stable, US	14 ÷ 6	4
16	Transfer stable to labile, US	3 + 15	6
17	Size of stable pool, US	7 × 16	180
18	Size of labile pool, FS	10 + 14	100
19	Size of stable pool, FS	11 + 17	200

† Numbers refer to line numbers.
‡ Sizes of pools are expressed in kg P ha^{-1}; fractions in kg P kg^{-1}; net input, transfers, changes, and P uptake and recovery in kg P ha^{-1} yr^{-1}; and time constants in years.
§ US = unfertilized soil; FS = fertilized soil.

Table 4. Calculation of P uptake by the crop, fertilizer P recovery and pool sizes during the first and the second year after a single fertilizer phosphorus application.

Line number	Description	Calculation†	Value‡
	1st year		
20	Change in labile pool, US§	−3 − 15 + 16	0
21	Final size of labile pool, US	14 + 20	20
22	Change in stable pool, US	5 + 15 − 16	0
23	Final size of stable pool, US	17 + 22	180
24	Transfer labile to stable, FS	18 ÷ 6	20
25	Transfer stable to labile, FS	19 ÷ 7	6.7
26	Change in labile pool, FS	−4 − 24 + 25	−23.3
27	Final size of labile pool, FS	18 + 26	76.7
28	Change in stable pool, FS	5 + 24 − 25	15.3
29	Final size of stable pool, FS	19 + 28	215.3
	2nd year		
30	P uptake, US	13 × 21	2
31	P uptake FS	13 × 27	7.7
32	Recovery of fertilizer P	31 − 30	5.7
33	Cumulative recovery of fertilizer P	12 + 32	13.7
34	Transfer labile to stable, US	21 ÷ 6	4
35	Transfer stable to labile, US	23 ÷ 7	6
36	Change in labile pool, US	−30 − 34 + 35	0
37	Final size of labile pool, US	21 + 36	20
38	Change in stable pool, US	5 + 34 − 35	0
39	Final size of stable pool, US	23 + 38	180
40	Transfer labile to stable, FS	27 ÷ 6	15.3
41	Transfer stable to labile, FS	29 ÷ 7	7.2
42	Change in labile pool, FS	−31 − 40 + 41	−15.8
43	Final size of labile pool, FS	27 + 42	60.9
44	Change in stable pool, FS	5 + 40 − 4	10.1
45	Final size of stable pool, FS	29 + 44	225.4

† Numbers refer to line numbers.
‡ Sizes of pools are expressed in kg P ha^{-1}; fractions in kg ha^{-1}; net input, transfers, changes, and P uptake and recovery in kg ha^{-1} yr^{-1}; and time constants in years.
§ US = unfertilized soil; FS = fertilized soil.

Table 5. Courses of P pool sizes at the beginning of the indicated years, P uptake, and recovery of fertilizer P after a single triple superphosphate application of 100 kg P ha^{-1}. Net input is 0 kg P ha^{-1} yr^{-1}.

	Unfertilized		Fertilized		P uptake		Recovery of fertilizer P	
Years	Stable	Labile	Stable	Labile	Unfertilized	Fertilized	Per year	Cumulative
	kg P ha^{-1}				kg P ha^{-1} yr^{-1}		— kg P ha^{-1} —	
1	120	20	140	100	2.0	10.0	8.0	8.0
2	120	18	155	75	1.8	7.5	5.7	13.7
3	120	17	165	57	1.7	5.7	4.0	17.7
4	119	16	171	46	1.6	4.6	3.0	20.7
5	118	15	175	38	1.5	3.8	2.3	23.0
6	117	14	176	32	1.4	3.2	1.8	254.8
7	116	14	177	28	1.4	2.8	1.4	26.2
8	115	14	177	26	1.4	2.6	1.2	27.4
9	114	13	176	24	1.3	2.4	1.1	28.5
10	113	13	175	23	1.3	2.3	1.0	29.5
11	112	13	174	22	1.3	2.2	0.9	30.4
12	111	13	172	21	1.3	2.1	0.8	31.2
13	109	13	171	21	1.3	2.1	0.8	32.0
14	108	13	169	20	1.3	2.0	0.7	32.7
15	107	13	167	20	1.2	2.0	0.7	33.4

the original vegetation, the net input is zero and all the P taken up by the vegetation is returned in full to the labile pool [theoretically, is would be more correct to allocate to the stable pool that part of the crop's P that is present in resistant organic material (ca. 15 to 20%)]. The fraction of labile P taken up by the plants and the uptake from the soil are assumed to be identical to those of the first example, implying that the size of the labile pool must also be identical (20 kg P ha^{-1}). However, the initial rates of transfer between the labile to the stable pools must be equal in this case because the net input is zero. Hence, the size of the stable pool is smaller than that in Fig. 2a (120 vs. 180 kg P ha^{-1}). During the first year after clearing, the P transfers between the pools and the uptake by the plants remain the same as under the natural vegetation.

Mineralization of organic P and its reaction with the mineral fraction may cause temporary large fluxes between pools in the field, but our best estimates from data (Janssen, et al., 1987) indicate that our assumptions are valid. Because the P in the crop is not returned to the soil, the labile pool decreases to 18 kg P ha^{-1}, resulting in an uptake of 1.8 kg P ha^{-1} in the second year. The transfer from the labile to the stable pool is one fifth of 18 kg P ha^{-1} and that from the stable to the labile pool one thirtieth of 120 kg P ha^{-1}, resulting in a net transfer from the stable to the labile pool of 0.4 kg P ha^{-1}. The decrease in the labile pool is thus 1.4 kg P ha^{-1}. The stable pool decreases in the second year by 0.4 P kg ha^{-1} to 119.6 kg P ha^{-1}. The depletion of both the labile and the stable pools continues as shown in Table 5, for 15 yr. As a consequence, the uptake by the unfertilized crop gradually decreases from 2.0 kg P ha^{-1} in the first to 1.2 kg P ha^{-1} in the fifteenth year.

Table 5 also gives the pool sizes and the recovery of fertilizer P for a soil that received a single triple superphosphate (TSP) dressing of 100 kg P ha^{-1}. Although P uptake by both the fertilized and the unfertilized crop is lower for the situation described in Table 5 than for that in Table 4, the estimated recovery of fertilizer P is the same. Thus, net input and initial pool sizes do not affect fertilizer recovery because the model is sensitive only to the difference in pool sizes of the fertilized and unfertilized soil, and this difference depends only on the rate of P application.

Model parameters that do affect the recovery of fertilizer P are the uptake fraction of the labile pool and the time constants of transfers between the pools. In Fig. 3, the cumulative recoveries of fertilizer P are

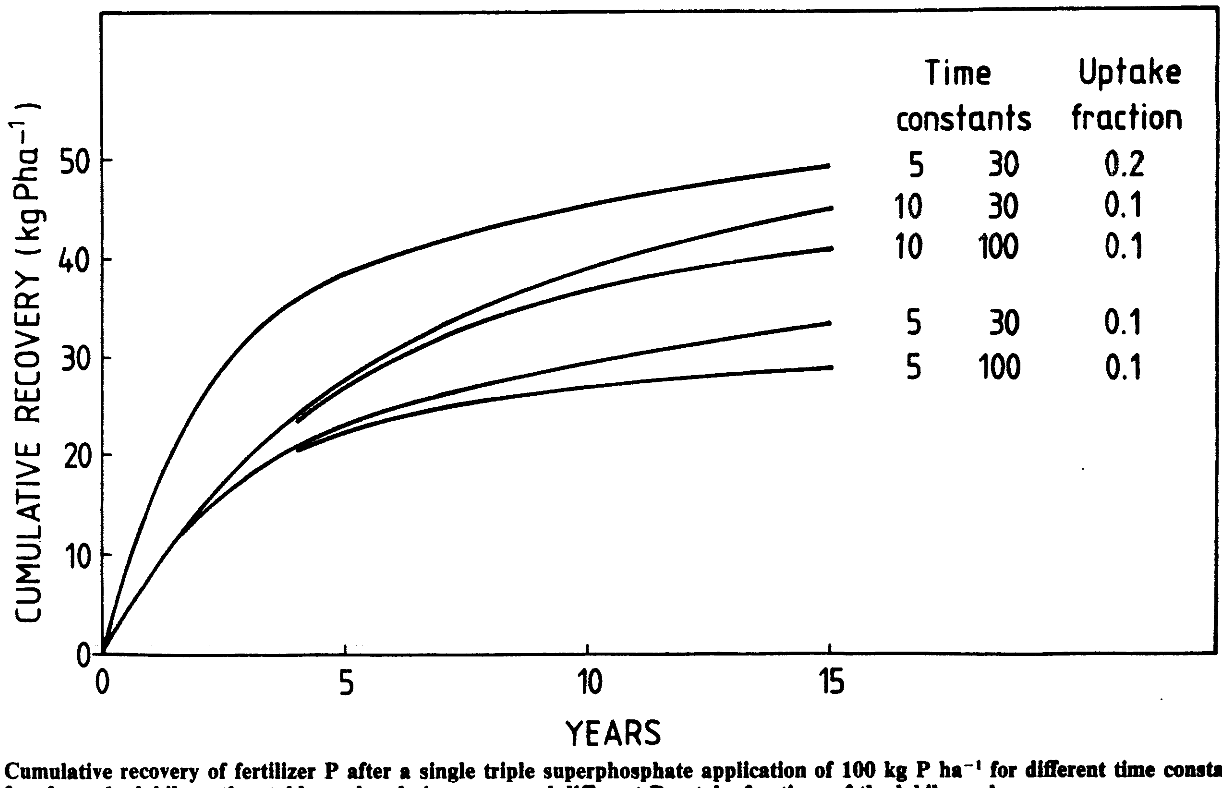

Fig. 3. Cumulative recovery of fertilizer P after a single triple superphosphate application of 100 kg P ha^{-1} for different time constants of transfers from the labile to the stable pool and vice versa, and different P uptake fractions of the labile pool.

shown for a number of different combinations of these parameters. The data of Table 5 are taken as standard (time constants equal to 5 and 30 yr and uptake fraction of 0.1). If the time constant of transfer from the labile to the stable pool is set at 10 instead of 5, which means that only 10 instead of 20% of the labile P moves annually to the stable pool, the cumulative recovery of fertilizer P increases from the second year onwards. The obvious reason is the less rapid depletion of the labile pool. The increase in cumulative recovery during the first 5 yr is 20% and during a period of 15 yr, about 30%.

Changing the time constant of transfer from the stable to the labile pool has only little effect on the cumulative recovery of fertilizer in the first 5 yr after application. Over a period of 15 yr, the cumulative recovery decreases by about 10% when the time constant increases from 30 to 100 yr; i.e., when the transfer from the stable to the labile pool decreases from about 3 to 1% per year.

The highest cumulative recovery in Fig. 3 results from changing the uptake fraction of the labile pool from 0.1 to 0.2. To keep the first year uptake of P by the unfertilized crop identical for both situations, the initial sizes of the labile and the stable pool are halved (10 and 60 kg P ha^{-1} instead of 20 and 120 kg P ha^{-1}). In the first year, the recovery of fertilizer P increases from 8.0 to 16.0 kg ha^{-1}. In comparison with the standard case, the cumulative recovery increases from 23.0 to 38.4 kg P ha^{-1} in the first 5 yr, from 29.5 to 45.3 kg P ha^{-1} in a period of 10 yr, and from 33.4 to 49.6 kg P ha^{-1} in the total period of 15 yr.

Table 6. Steady state situations for a target uptake of 20 kg P ha^{-1} yr^{-1}, for five different sets (A–E) of parameters. Time constants of transfer from the labile to the stable pool and vice versa are 5 and 30 years, respectively.

Parameter	A	B	C	D	E
Type of fertilizer	TSP†	TSP	TSP	Rock‡	TSP
	kg P ha^{-1} yr^{-1}				
P uptake, unfertilized	2	2	6	2	2
Net input of P	0	2	6	2	2
P uptake fraction of labile pool	0.1	0.1	0.1	0.1	0.2
Steady state					
	kg P ha^{-1}				
Size of labile pool	200	200	200	200	100
Size of stable pool	1320	1368	1464	1719	768
Labile to stable	40.0	40.0	40.0	40.0	20.0
Stable to labile	44.0	45.6	48.8	57.3	25.6
Net transfer stable to labile	4.0	5.6	8.8	17.3	5.6
Needed labile fertilizer P	16.0	14.4	11.2	2.7	14.4
Needed stable fertilizer P	4.0	3.6	2.8	15.3	3.6
Needed fertilizer P	20.0	18.0	14.0	18.0	18.0

† TSP = triple superphosphate. ‡ Rock = phosphate rock.

FERTILIZER RATE REQUIRED FOR A TARGET UPTAKE

The model may also be formulated in a target-oriented mode. For example, the target could be a yield that is limited either by crop characteristics, water availability, or N supply. A given target production multiplied by the P concentration will yield the target P uptake.

To illustrate the influence of some relevant factors on the required fertilizer rate, Fig. 4 and Table 6 show the results for five different cases. In all cases, the time

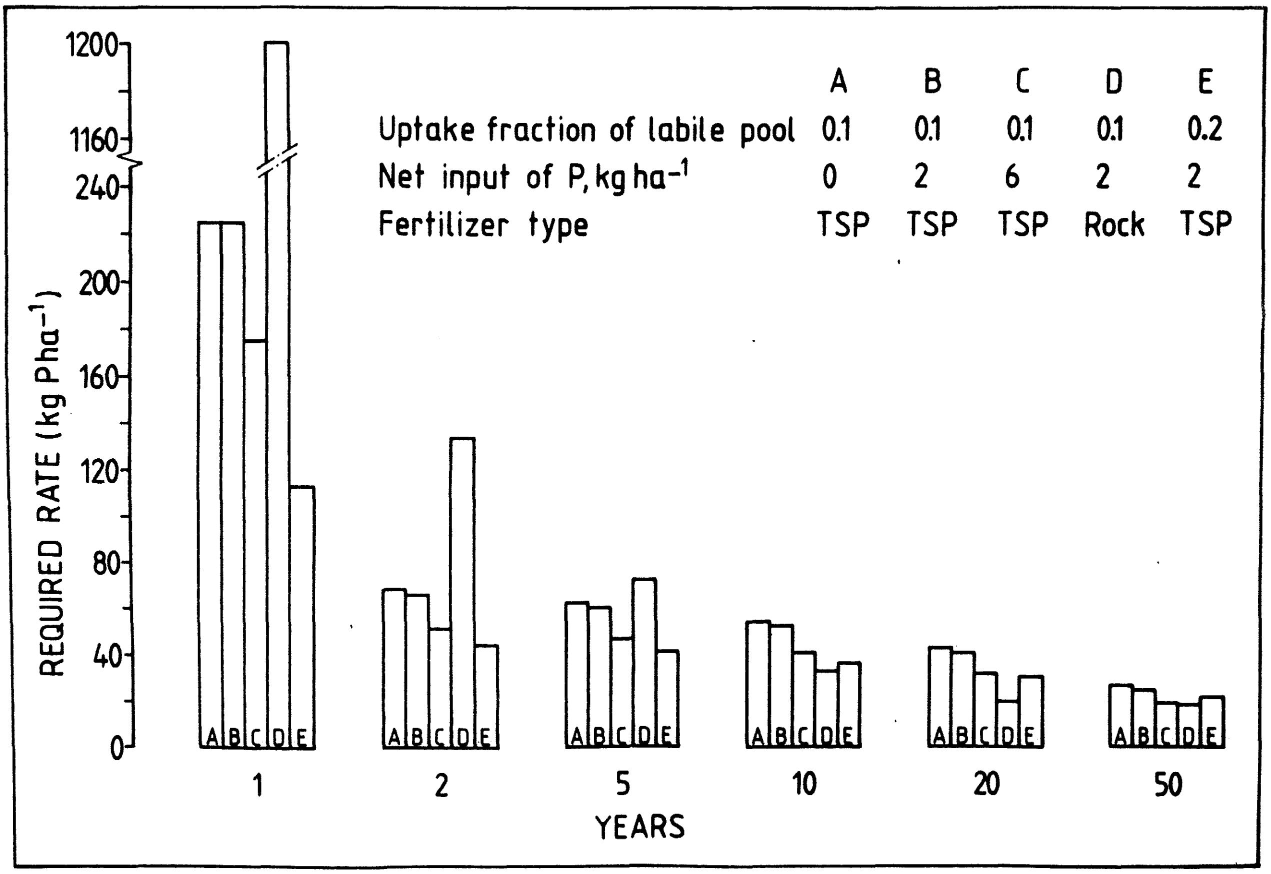

Fig. 4. Course of required fertilizer P rate for five different sets (A–E) of parameters.

constants of transfer between the labile and the stable pools are 5 and 30 yr, respectively. The target uptake is set at 20 kg P ha^{-1} yr^{-1}, which, for example, would suffice for a grain yield of maize (*Zea mays* L.) of 9000 kg ha^{-1} using a grain yield/P uptake ratio of 450. Variable factors are the uptake fraction of the labile pool, the net input, the initial uptake from unfertilized soil, and the type of fertilizer. These values are given in the top of Table 6.

The calculations are discussed for Column B, which is considered to be the standard case. The initial sizes of the labile and stable pools are 20 and 180 kg P ha^{-1}, respectively, representing the same situation as depicted in Fig. 2a. The uptake fraction of the labile pool is thus 0.1. To reach a target uptake of 20 kg P ha^{-1} yr^{-1}, the labile pool has to increase from 20 to 200 kg P ha^{-1}. The amount of fertilizer P required for this target is determined by the difference between the target and the actual size of the labile pool, divided by the fraction of labile P in fertilizer, being 0.8 for TSP (Table 1). For the first year, the required rate of P = (200 − 20)/0.8 = 225 kg P ha^{-1}. This amount of fertilizer P is distributed between the labile (180 kg P ha^{-1}) and the stable (45 kg P ha^{-1}) pools. Thus, at the start of the first year, pool sizes of the fertilized soil are 20 + 180 = 200 (labile) and 180 + 45 = 225 (stable) kg P ha^{-1}. During the first year, the labile and stable pool sizes change to 147.5 and 259.5 kg P ha^{-1}, respectively (method of calculation as in lines 26–29 in Table 4). In the second year, the required rate of fertilizer P = (200 − 147.5)/0.8 = 65.6 kg P ha^{-1}. In subsequent years, the stable pool slowly increases, resulting in a decrease in the net transfer from the labile to the stable pool and, hence, in a decrease in the required fertilizer rate. This rate is 52, 40, and 24 kg P ha^{-1} after 10, 20, and 50 years, respectively (Fig. 4, B). Finally, a steady state situation will be reached, where the sum of net input and fertilizer P equals the P removal by the crop (Table 6, Column B). In that situation there is a net transfer from the stable to the labile pool (45.6−40.0=5.6 kg P ha^{-1}), which is accounted for by the sum of net input and stable fertilizer P component applied (2.0+3.6=5.6 kg P ha^{-1}). The yearly P withdrawal by the crop (20.0 kg P ha^{-1}) from the labile pool is compensated for by the sum of net transfer from the stable to the labile pool and labile fertilizer P applied (5.6 + 14.4 kg P ha^{-1}).

Figure 4 and Table 6 also give the fertilizer requirements for some other cases. In Case A, the net input is set to zero as shown in Fig. 2b. The third case (C) has a net input of 6 kg P ha^{-1} yr^{-1}, a labile pool of 60 kg P ha^{-1}, and an initial uptake of 6 kg P ha^{-1} yr^{-1}. This is an example of a relatively rich soil that remains fertile because of a substantial yearly P input from native sources. In the first year, the required fertilizer P rates = (200 − 20)/0.8 = 225 kg P ha^{-1} for Cases A and B, and (200 − 60)/0.8 = 175 kg P ha^{-1} for Case C. The fertile soil needs less fertilizer to reach the target uptake than do the poorer soils. In the course of time, a difference in fertilizer P requirement arises between Cases A and B (Fig. 4). In the steady state situation, the difference in fertilizer P requirement is counterbalancing the difference in net input of P, the sum of both being 20 kg P ha^{-1} yr^{-1} in all three cases, A, B, and C (Table 6).

Case D is equal to Case B, except that phosphate rock instead of TSP is applied. The labile and stable fractions of P in phosphate rock are assumed to be 0.15 and 0.85, respectively. Hence, the amount of P required in the first year is (200 − 20)/0.15 = 1200 kg P ha^{-1}, a very high application rate. The required fertilizer P rates decrease to 133, 33, 19, and 18 kg P ha^{-1} in years 2, 10, 20, and 50. After about 7 yr, the fertilizer P requirement is lower for phosphate rock than for TSP. This is caused by the rapid growth of the stable pool in the case of application of phosphate rock. For the same reason, a nearly steady state is reached after 20 yr in the case of the phosphate rock, while in the case of the TSP, a steady state situation has not been reached after 50 yr. For a poor quality rock with an inert P fraction but with the same labile P fraction, 0.15, the required application rate would have been the same in the first year but higher than that in the example of Case D in the subsequent years.

The difference between Case E and the standard Case B is an increase in the uptake fraction of the labile pool (0.2 vs. 0.1). The initial uptake from unfertilized soil is again 2 kg P ha^{-1} yr^{-1} so that the initial size of the labile pool is only 10 kg P ha^{-1} for Case E. This situation could represent a light-textured soil with a low P fixation capacity. For a target uptake of 20 kg P ha^{-1} yr^{-1}, the labile pool has to be 100 kg P ha^{-1}. The amount of fertilizer P required to attain that target uptake is (100 − 10)/0.8 = 112.5 kg P ha^{-1}. The fertilizer P requirements decrease to 44, 37, 30, and 21 kg P ha^{-1} in years 2, 10, 20, and 50, respectively. These figures show that the initially required fertilizer rates become lower and a steady state will be attained earlier when the uptake fraction of the labile pool increases. The required annual fertilizer rate, however, in the steady state situation is not affected, but far less fertilizer is needed to reach that steady state.

LONG-TERM FERTILIZER RECOMMENDATIONS

The foregoing examples clearly illustrate that the fertilizer rate required to obtain a particular target uptake drastically decreases in course of time due to the residual effect of the previously applied fertilizer. However, it may be rather impractical to recommend decreasing fertilizer rates. For farmers, it is more convenient if the recommended rate is constant for a number of years. For that purpose, the target of an annual uptake of, for example, 20 kg P ha^{-1} during a period of 20 yr, must be translated into a target of a cumulative uptake of 200 kg P ha^{-1} obtained with 10 equal fertilizer applications. Figure 5 shows that the longer the period is for which the recommendation should be valid, the lower the annual application rate can be. For the example of an average uptake of 20 kg P ha^{-1} yr^{-1}, the annual rate should be 108, 82, or 65 kg P ha^{-1} if the period considered is 5, 10, or 20 yr, respectively. Figure 5 also illustrates that the required fertilizer rate increases more than proportionally if the target uptake is increased. The reason is that the contribution of the natural sources, set at 2 kg P ha^{-1} yr^{-1}, is relatively more important when the target uptake is low than when it is high. For targets of 5, 10, or 20

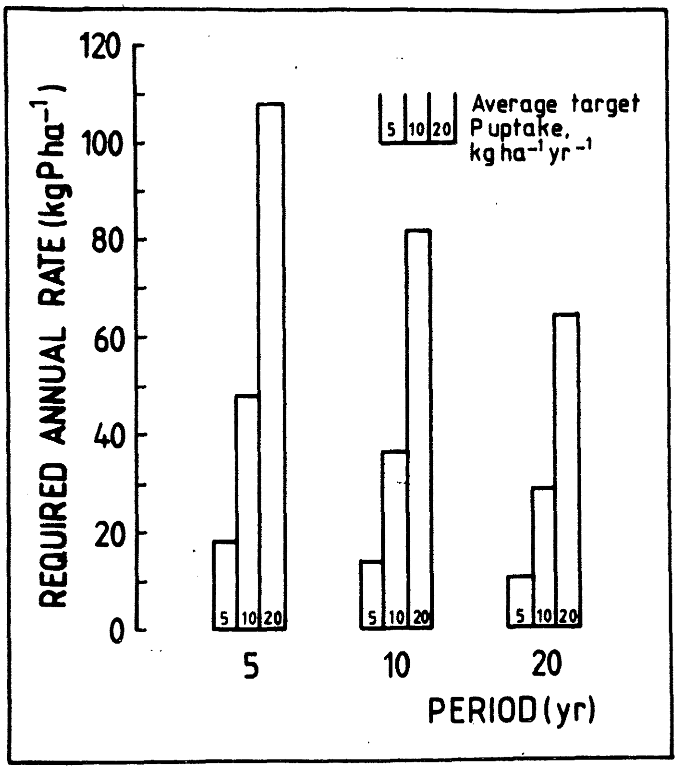

Fig. 5. Required annual P rate (triple superphosphate) for the indicated average target P uptake during a period of indicated length. Time constants for the transfers from the labile to the stable pool and vice versa are 5 and 30, respectively. Uptake fraction of the labile pool is 0.1.

kg P ha^{-1} yr^{-1}, this contribution is 40, 20, or 10%, respectively.

This approach likewise results in the target uptake of 20 kg P ha^{-1} not being achieved for the first few years and then being exceeded in the last few years. For example, target uptake is achieved by Year 4 if a 10-yr accumulation of 200 kg P ha^{-1} is desired. Uptake from the fertilized soil gradually increases as the labile pool increases as P fertilization exceeds the equilibrium rate of about 20 kg P ha^{-1} (Table 6). This implies that adjustments in fertilizer rates will be made, albeit less frequently, following this procedure. Thus, the model can be used to predict the quantity of P to be applied to reach a target after any given number of years.

CONCLUSIONS

The model presented here can easily be used for several practical purposes. Examples of two applications are: (i) calculating the residual effect of fertilizer P, and (ii) calculating the fertilizer requirement for a target P uptake and, hence, a target yield. Other uses include the calculation of long-term fertilizer recommendations to achieve a target uptake as well as the comparison of one heavy fertilizer dressing in a multiple-year crop rotation to that of several smaller annual dressings. The model distinguishes between a labile and a stable P pool and operates on a time interval of 1 yr. Time constants of transfers between these two pools can be estimated from field experiments, although the model is relatively insensitive to changes in these parameters. Recovery fractions from the labile pool are determined from field experimental data. Phosphorus in the labile pool in this analysis is considered to be equally available to plants regardless of its source. For example, based on its behavior, P from TSP is portioned 0.8 to the labile pool and is not treated differently from soil P already present in the labile pool. In addition, the recovery fraction is considered to remain constant. This assumption appears valid as long as P is the only limiting factor to plant growth.

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