Dynamics of plant-available phosphorus for 11 years in a French loamy soil amended with biological sewage sludge amended or not with lime

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Abstract

The fate of phosphorus (P) derived either from mineral fertilizer (TSP) or two urban sewage sludge, one biological (SS1) and one biological and limed (SS2), in relation with the cumulative P budget (P applied minus P removed in crops harvests) has been studied in a field experiment for 11 years. In average 38.3, 53.9 and 38.4 kg P ha^{-1} yr^{-1} were applied as SS1, SS2 and TSP, respectively. Plant-available soil P has been assessed by (i) a process-based approach that consisted to measure in soil suspensions both P ions in solution and associated time-dependent diffusive Pi at the solid-to-solution interface; and (ii) by the standard Olsen method (chemical extraction with 0.5 M sodium bicarbonate). There were strong linear relationships between cumulative P budgets and changes in the stocks of the plant-available soil P within the plough layer. Phosphorus from TSP and SS1 and SS2 fell on the same regression lines, suggesting that SS1 and SS2 would be equally effective as TSP. For this soil, the variation in the Olsen P method only account for 8.8% of the P budget whereas the process-based assessment of plant-available soil P accounted for the totality of the P budget.

Introduction

Domestic wastewater treatment has been improved to reduce water pollution. As a result, the quantity of wastewater residues, i.e. sewage sludge, has increased worldwide. In France in 2001, the collective system for waste and storm water collection covered 328 700 km and carried 5.6 billion m^3 of effluents to 16 100 public treatment plants which produced 963 700 tons of dried sludge of which 56 per cent was used in agriculture, either spread on the land or used for compost [1]. Urban sewage sludge represents a source of plant nutrients, but their availability can vary considerably [2]. Their P fertilizer value is significant, but varies considerably depending on origin and processing prior to application. Monitoring soil phosphorus changes under continuous cropping receiving urban sewage sludge over decades is an important agronomic and environmental issue. A field experiment was carried out, in which five spreading of one biological (SS1) and one biological and limed (SS2) sewage sludge were applied every 2 years. A triple superphosphate (TSP, $Ca(H_2PO_4)_2$, 45% P_2O_5) treatment was also applied. The aim was to determine soil P dynamics in the plough layer for the three treatments as a function of cumulative P budgets (Bcum) across eleven years of cropping. We present here: (1) the effects of SS1, SS2 and TSP on the plant-available soil P determined either by a process-based approach or by the Olsen chemical extraction; (2) the P fertilizer value of SS1 and SS2, i.e. the plant-availability of P in SS1 and SS2 related to the plant-availability of P-TSP.

Material and Methods

Field experiment

The field experiment comprised 4 replicates and 3 treatments, SS1, SS2 and TSP. In average 38.3, 53.9 and 38.4 kg P ha^{-1} yr^{-1} were applied in the SS1, SS2 and TSP treatments, respectively. In the SS1 and SS2 treatments, P-TSP was sometimes applied to complete the P supply by sewage sludge: 132 and 21 kg P-TSP ha^{-1} was applied over the eleven years of experimentation for the SS1 and SS2 treatments, respectively. It represented 46% of the P applied as SS1 and 4% of the P applied as SS2. Trace-elements (Cd, Cr, Cu, Hg, Ni, Pb, Zn) contents and the cumulative trace-elements inputs of SS1 and SS2 spreading are lower to the limits of French legislation [3]. The experimental site was located at Ensisheim (Haut Rhin department (68), France) on a sandy (31%) clay (23%) loam (46%) soil (néoluvisol fersiallitique according to the "référentiel pédologique" [4]). The C content was 1.0%, pH was 6.0 and the CEC was 128 meq. kg^{-1}. The soil apparent density during the field experiment was 1.6 kg m^3 making 3200 t soil ha^{-1}.

Table 1. Average (and standard deviation) for the five spreading (1995, 1998, 2001, 2003 and 2004) of the main agronomic characteristics of sewage sludge.

Sewage sludge	Dry matter	P	N	K	pH	Ca
	%	kg t DM^{-1}	kg t DM^{-1}	kg t DM^{-1}		kg t DM^{-1}
SS1	15.6 (0.6)	21.7 (3.1)	66.9 (4.2)	7.4 (0.9)	7 (0.7)	31 (9)
SS2	32.5 (8.2)	21.4 (5.3)	36.4 (8.0)	2.4 (1.0)	10 (1.8)	168 (34)

The crop rotation was a monoculture of irrigated-maize (except wheat in 2005). Grain yields and their P contents were determined every year for all plots. The annual P budget was calculated as the added P to soil minus the P removed in grain yields. Other fluxes that can play a role in P cycling such as atmospheric deposit, leaching, preferential, subsurface and surface flows were neglected. The cumulated P budgets (Bcum) are the sum of annual P budgets with periods of cultivation and fertilization. The 20 cm depth layer of soils was sampled every year from 1995 (before any P application) to 2006 (the end of the field experiment) except in 2005.

Plant-available soil P

We analyzed soil samples for plant-available soil P by two experimental methods:

- A process-based assessment that considers both the amount of phosphate ions (Pi) in solution (Q_w) and the time-dependent Pi amount (P_r) bound to the soil solid phase that equilibrates Pi in solution under the effect of a gradient of concentration. Soil analyses were performed in soil suspensions having a volume-to-mass ratio of 10 using a ^{32}Pi-dilution method at steady-state. Details about this procedure are presented in [5, 6]. A data set of P_r values is obtained for a range of soil solution Pi concentration and time which is used to parameterize a mathematical equation which accurately fitted the P_r values. This equation is then used to calculate by extrapolation the P_r values after much longer periods, up to one year. For this study, we extrapolate the P_r values after one year ($P_{r(1yr)}$) of equilibration. The plant-available soil P was therefore assessed by the sum of P ions in solution plus diffusive Pi at the solid-to-solution interface for one year ($Q_w + P_{r(1yr)}$).
- Plant-available soil P was also estimated by the common world-wide chemical extraction with sodium bicarbonate 0.5 M at pH=8.5for 30 minutes in 20:1 volume-to mass ratio (P_{Olsen}).

The plant-available soil P contents (mg kg^{-1}) of the analyzed soil depth were converted to stocks (kg P ha^{-1}) considering 3200 t soil ha^{-1}. All soil samples were analyzed for ($Q_w + P_r$) and P_{Olsen} (except in 1997 and 2004 for P_{Olsen}).

Statistical analysis

The change in the stock of plant-available soil P with Bcum was determined for each individual plot. A linear regression was used to determine the initial stock of plant available soil P, i.e. the y-intercept of the linear regression, and then to calculate the variation between the stock of plant available soil P after a given period of experimentation and the initial stock.

Results and discussion

The average of the main agronomic characteristics of the two urban sewage sludge, one biological sewage sludge (SS1) and one biological and limed sewage sludge (SS2), are in Table 1. Both have a similar P content although SS2 was diluted by adding lime. A total of 13.3 t and 27.3 t DM ha^{-1} were applied over the 11 years for SS1 and SS2, respectively. In agreement with the sludge composition (Table 1), the amounts of major nutrient elements provided by the five spreading were 882 kg N ha^{-1}, 289 kg P ha^{-1}, 99 kg K ha^{-1}, and 416 kg Ca ha^{-1} for SS1, and 960 kg N ha^{-1}, 572 kg P ha^{-1}, 62 kg K ha^{-1}, and 4738 kg Ca ha^{-1} for SS2.

A total amount of 421, 593 and 422 kg P ha^{-1} (in average, 38.3, 53.9 and 38.4 kg P ha^{-1} yr^{-1}) were applied in the SS1, SS2 and TSP treatments, respectively. The amount of P annually exported in grains (in average 25.0 kg P ha^{-1} yr^{-1}) did not vary significantly between treatments. As a consequence, the annual P budget of P applied minus P removed by crop harvests varied significantly between P treatments: +13.3 and +13.7 kg P ha^{-1} yr^{-1} for the SS1 and TSP treatments, respectively, and +28.5 kg P ha^{-1} yr^{-1} for the SS2 treatment. The sum of annual P budgets, i.e. the cumulative P budgets (Bcum), were +147, +313 and +150 kg P ha^{-1} for the SS1, SS2 and TSP treatments, respectively, at the end of the experiment in 2006 (Figure 1). This range is similar and representative to those reported in many publications [4, 6]. The Bcum values and the change in the stocks of (Q_w+P_r) and P_{Olsen} were significantly influenced by cropping periods and applied P.
The central objective of this study was to ascertain whether the soil test P change with P budgets was invariant or not following different forms of P application either as mineral fertilizer, TSP, or urban sewage sludge, SS1and SS2. For each soil P test, all means fell on the same regression line for all periods of cropping and fertilization periods indicating that the P transformation rates were similar for all treatments and only depended on applied P.

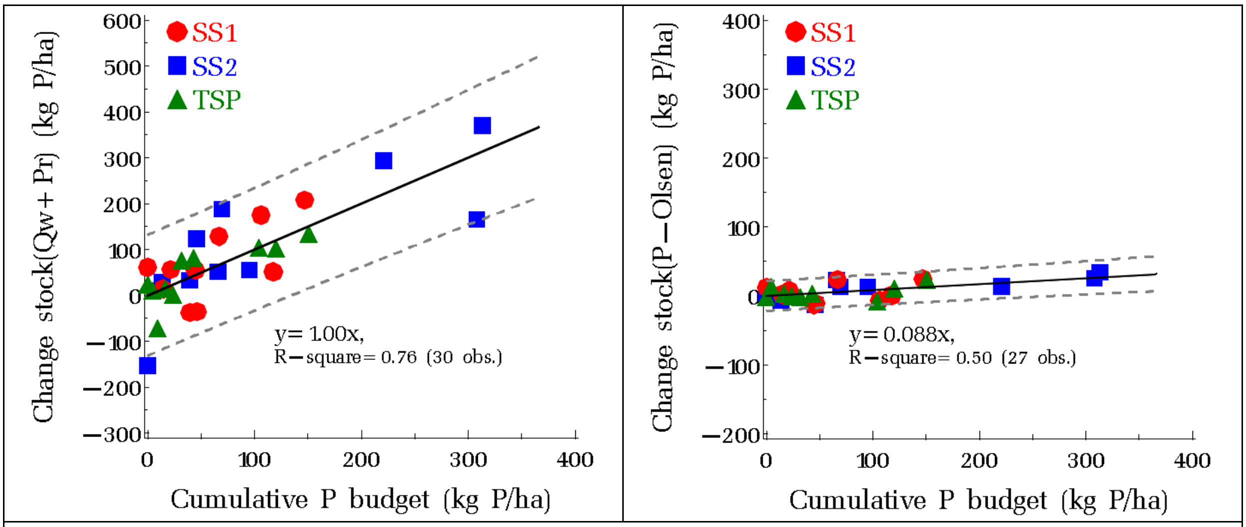

Figure 1. Changes in the stocks of Pi in solution plus diffusive Pi for 1 year (Q_w+$P_{r(1yr)}$) (left) and changes in the stock of P_{Olsen} (right) within the 0-20 cm soil layer in relation with the cumulative P budgets (P applied minus P offtake) for the different P treatments from 1995 to 2006. Each symbol is the mean of the four blocks. Full lines are linear regressions. Dotted lines are confidence interval at 95%.

Plant-available soil P appreciated by Olsen' chemical extraction

The changes in stocks of P_{Olsen} as a function of Bcum values were described the following linear regression (Figure 1 right):

$y=0.088_{(\pm 0.017)}x$, $r^2=0.50$ for 27 obs.

As reported in many non-carbonaceous soils, P_{Olsen} stocks often changes in direct proportion to the positive and negative P budget but only accounted for a low percentage. For this specific soil, a surplus of +100 kg P ha^{-1} would change P_{Olsen} stocks by 8.8 kg P ha^{-1}. This value is consistent with many published values [3, 6]. The influence of soil properties, such as sorption-desorption of P ions at the solid-to-solution interface partly explains the range of variation encountered in long-term field experiments [6]. This might suggest that P available for plant uptake is being replenished by P from other soil sources not measured by Olsen's method. Olsen's extraction, but also more generally chemical extractions, fails to predict P availability as these methods do not provide reliable quantitative information on the P replenishing ability of soils. It raises the fundamental question of the relevance of chemical extractions to correctly assess plant-available soil P. It is well known that chemical extractions have scientific limitations because they are operationally defined; they extract unidentified P forms of soils. In addition, redistribution of P occurs between liquid and solid phases of soils during the period of extraction, obscuring results. This redistribution depends on soils, their P status and extraction time. Finally, kinetics of reactions are not accounted for since the common chemical extractions only last for few minutes.

Plant-available soil P assessed by Pi in solution plus diffusive Pi at the solid-to-solution interface
One original and important result is obtained using the process-based approach to assess plant-available soil P. We determine both Pi in solution (Q_w) and associated time-dependent diffusive Pi at the solid-to-solution interface (P_r) in soil suspensions for short periods. The data set obtained allowed us to parameterize a mathematical function [4, 5] and then to calculate by extrapolation the amount of Pi in solution plus diffusive Pi at the solid-to-solution interface for one year. This scientific assessment focus not only on well-identified P forms, i.e. phosphate ions (Pi), which are the P forms that are absorbed by growing roots but also on the Pi replenishing ability of soils. It is a dynamic process mainly influenced by the rate of depletion of Pi in the soil solution at the root surface and the gradient of Pi concentration between liquid and solid phases of soils which controlled the diffusion of Pi towards roots.. The changes in the stocks of (Q_w+$P_{r(1yr)}$) stocks as a function of Bcum were significantly described by the following linear regression (Figure 1 left):

$y=1.00_{(\pm 0.11)}x$, $r^2=0.76$ for 30 obs.

For this soil, the changes of (Q_w+$P_{r(1yr)}$) stocks fully explained the cumulative P budgets. This 1:1 correspondence suggests that P available for plant uptake is the sum of Pi in solution plus diffusive Pi at the solid-to-solution interface for one year.

Conclusion and perspectives
Monitoring soil phosphorus (P) changes under continuous cropping over decades is an important agronomic and environmental issue. Our results suggest that the cultivation periods and P fertilizer rates affect soil P status proportionally to the cumulative P budget for all treatments. As a consequence, the P budget approach at field scale can be considered a useful and accurate driving variable to monitor changes in soil P status over time and for contrasting P application rates.
The P fertilizer value of SS1 and SS2 corresponded to that of P-TSP. Using a mechanistic assessment of plant-available soil P by (Q_w+$P_{r(1yr)}$), we recovered the totality of the cumulative P budget whereas P_{Olsen} only extract 8.8%. The next step in the generalization of our results would be to test the ability of the (Q_w+$P_{r(1yr)}$) stocks to recover the totality of the P budget in other field conditions.

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