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ORIGINAL PAPER

Concentration and vertical distribution of total soil phosphorus in relation to time of abandonment of arable fields

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Abstract Abandonment of agricultural soils is a common practice in Western Europe to increase the area of nature and to counteract agricultural overproduction. However, it has been suggested that abrupt changes in management of land, such as abandonment of heavily fertilized agricultural fields, could trigger leaching of phosphorus into deeper soil layers and groundwater. In a previous study we observed that total phosphorus (P) in the upper 10 cm of ex-arable soils in the Netherlands was negatively related to the time of abandonment. In a subsequent study in the region reported here, we measured total P concentrations at different soil depths in four ex-agricultural fields that differed in time since abandonment to examine if the decrease in total P with increasing time of abandonment could be due to leaching of P into deeper soil layers. At each site total P concentration decreased with increasing depth, and for each soil profile depth, total P also decreased with increasing years since abandonment. We calculated, based on estimated P fertilizer gifts over the last decades and the regression coefficient of the relation between total P in a core of 95 cm and time of abandonment, the amount of net total P that should have accumulated in the oldest ex-arable field to reach the P level of the most recently abandoned field. The continuation of accumulation of P for a longer period of time in recently abandoned fields appeared to be the most reasonable explanation for the decrease of P with years of abandonment. Therefore, abandonment of agricultural land does not seem to trigger a 'chemical time bomb' to explode as no large amounts of P seem to leach into deeper soil layers.

Keywords Phosphorus · Land abandonment · Leaching · Vertical distribution · Accumulation of P · Soil restoration

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Introduction

In a previous study we observed that total phosphorus (P) concentrations in the top 10 cm of ex-arable sandy soils in the Netherlands was inversely related to time since abandonment from agriculture. Fields that had been abandoned for 34 years had lower total P in the topsoil than fields that were recently abandoned (Van der Wal et al. 2006). There are a number of possible explanations for the inverse relationship between period of abandonment and total P in the topsoil, i.e., (1) larger cumulative P enrichment of the topsoil, via inorganic fertilizer and manure, of fields that have been abandoned only recently, (2) variations between sites in initial P content, (3) uptake of P from the topsoil by the above-ground plant biomass after abandonment, and (4) leaching of P from the topsoil to the subsoil.

Phosphorus is an essential nutrient for plant growth and most arable sandy soils cannot supply sufficient amounts of this element to the crops. Therefore, application of P-fertilizers is needed to overcome this deficiency. From the early 20th century relatively cheap P fertilizers became available and the amounts of P in animal manure increased rapidly during the second half of the 20th century. The use of huge amounts of both these inorganic and organic fertilizers has led to P enrichment of the topsoil of agricultural land in the Netherlands and elsewhere in Europe. The enrichment greatly depended on the intensity of farming, with largest accumulations in areas with intensive animal production on sandy soil in the central, eastern and southern half of the Netherlands (Breeuwsma et al. 1990; Reijerink and Breeuwsma 1992). Phosphorus enrichment was most severe in the period 1950 and 1985. From 1985, P fertilization decreased following the implementation of a series of governmental policies and measures restricting the application of animal manure (RIVM 2002). However, the sorption capacity of sandy soils for P is in general limited and P enrichment in the past may have increased the risk for P leaching into deeper soil layers or even into the groundwater, especially in flat areas with high groundwater levels (Sims et al. 1998; Schoumans and Groenendijk 2000). This phenomenon is speculated to be triggered by abrupt changes in management of the land, such as abandonment of heavily fertilized agricultural land, and has been referred to as the signal for a 'chemical time bomb' to explode (Van Latesteijn 1998).

Soil P can exist in inorganic and organic forms. Phosphate is the main inorganic form of P that is available to plants and can be divided into two forms: labile and occluded P (Bardgett 2005). The amount of labile P is very low relative to the total P pool and can rapidly be fixed in occluded forms unavailable to plants: Al- and Fe-phosphates in acid soils and Ca-phosphates in alkaline soils. A large proportion, 29–65%, of total soil P is present in organic form (Harrison 1987). Organic P compounds range from readily available plant residues and microbes within the soil to stable compounds that have become part of the soil organic matter. Biological processes in the soil control the mineralization and immobilization of organic P.

The mobility of soil P depends on the chemical form and nature of the element, the chemical and mineralogical nature of the soil and the physical and biological environment of the soil, e.g. absorption by plant roots or leaching by drainage (Stewart and Tiessen 1987; McBride 1994). Mycorrhizal fungi play an important role in the uptake and transport of soil P to the host plants. They can access and enhance the availability of soil P that is beyond the reach of roots, thereby increasing the upwards transport of P (Bardgett 2005). The actual downward movement of P in the soil can be described by the "tipping bucket" model (McBride 1994). In this model, the soil profile is visualized as a stack of empty "buckets," each bucket symbolizing the sorption capacity of one soil horizon. As phosphate is added to the surface layer, the top bucket must be completely filled before any phosphate can flow into the bucket below.

In this study, we address the question whether or not the decrease in total P in the root zone with increasing time of abandonment of former arable land is due to leaching of P into deeper soil horizons. To study this, we measured the total concentration of phosphorus at different depths in soils of four ex-agricultural fields that differed in time since abandonment. Calculations, using data on past fertilization regimes, were made to interpret the results. The data were compared with that of a heathland soil that had not been fertilized as agricultural fields are abandoned to hopefully eventually return to heathland. Heathlands are highly valued because of their historical cultural associations and their important role in preservation of flora and fauna (Aerts and Heil 1993). Hence, the restoration of heathlands is receiving much attention, especially in countries with very intensive farming systems, which fragment the landscape.

Material and methods

Soils and sampling

For this study, 5 sites in the central part of the Netherlands were selected from the chronosequence study that has been described previously (Van der Wal et al. 2006). The sites consisted of 4 abandoned arable fields, which differed in the time since abandonment and 1 reference heathland, which is the restoration target of the ex-arable fields. All soils were well drained with groundwater levels below (>2 m) the sampling depth (Gehrels et al. 1994). A summary of the soil characteristics of these sites is given in Table 1. In November 2004, five soil cores (3.5 cm diameter) were collected in a 25 × 25 m plot in each of the selected sites. Soil was sampled from 0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–70 cm and 70–95 cm deep and each layer was collected. Samples were air-dried and ground before analysis.

Chemical analyses

Total P was determined colorimetrically after digestion of samples with a mixture of H_2SO_4-Se, H_2O_2 and salicyclic acid (Novozamsky et al. 1984). Although this wet oxidation of soil organic matter is probably not complete (Novozamsky et al. 1995), P contents of the obtained extracts correlate well with P obtained after applying a dry ashing technique and is suggested as a useful method for analyzing total P (Akinremi et al. 2003).

Statistical analyses

All data were analyzed in SPSS for Windows (Release 11.5.0; standard version). Differences between the distribution and the absolute amount of total P in different soil layers (depths) within fields were calculated by a one-way ANOVA with soil depth as factor at $p < 0.05$. Differences between total P in a core of 95 cm and fields were also tested with one-way ANOVA. The assumption for normality was tested with Shapiro-Wilk statistics and homogeneity of variances with Levene's test. Differences between groups were tested by Tukey's honestly significant difference test or, when variances were unequal, by Tamhane's T2 test at $p < 0.05$. When only one replicate was available (which was sometimes the case with the deepest layer because of the hardness of the soil), one-Sample t test was performed in order to compare means of different depths. The relation between total P in the deepest horizon and time since abandonment was calculated by the coefficient of the linear equation at $p = 0.05$.

Estimation of P accumulation and uptake of P by plants

The following parameters and assumptions were used to estimate the amount of net total P that should have accumulated in the oldest ex-arable field to reach the P level of the most recently abandoned field: (1) the regression coefficient of the relation between total P in a core of 95 cm and time of abandonment, (2) the bulk density of sands and sandy loams is on average 1.43 g/cm^3 (Hartge 1978), (3) the amount of kg soil in a soil core of 95 cm is 1.3 kg, (4) the uptake and removal of P via harvest of crops remains the same every year.

To estimate the possibility that P is taken up from the top soil via the plant biomass after abandonment we assumed that (1) the content of P in plant dry weight is about 0.2%

Table 1 Soil characteristics (0–10 cm) of the fields under study (Van der Wal et al. 2006)

Field name	Years since abandonment	Former crop or vegetation at sampling	% Loam (2–50 μm)	pH	C (g/kg)	P total (mg/kg)
Assel	2	Maize	1.29	5.6	25.6	918
Kartellenberg	9	Wheat	9.84	5.5	19.0	723
Dennenkamp	22	Rye, potatoes, asparagus	5.88	5.7	34.3	432
Boerschbos	35	Wheat	1.66	3.9	48.5	251
Mossel	Reference	Heathland	3.09	4.0	64.0	156

(Schachtman et al. 1998), (2) the above and belowground biomass in 10 year old ex-arable land is around 9780 kg/ha (Bezemer et al. 2006) and (3) no P is removed from the system via plant biomass since the ex-arable field was not mown.

Results and discussion

The amount of total phosphorus in a core of 95 cm decreased with time since abandonment (Fig. 1). In addition, the portion of total P per layer compared to the total amount of P present in 95 cm generally decreased with depth (Fig. 2). P content of the deeper soil horizons was always lower than the P content of the upper 30 cm (Fig. 3). The P levels measured in soil got closer to the levels measured in heathland reference soil as the years since abandonment form agriculture increased (Fig. 3). Differences in phosphorus content in the upper layer (0–30 cm) and the lowest layer (70–95 cm) were decreasing with time since abandonment ($p < 0.01$). There was no significant change in P with time of abandonment in the lowest depth layer ($p > 0.17$). These results indicate that the previous observed decrease of total P in the upper soil (10 cm) with years of abandonment is probably not due to leaching of large amounts of P in the top soil to lower layers of the soil. It may be that part of the P decrease in the top layer is apparent and due to limitations of the wet oxidation to release all P from soil organic matter. On the other hand, fertilization histories of the fields may have been different. Soils that were longer in production have received fertilization for a longer period than the oldest abandoned fields. In this way, P could accumulate in the youngest ex-arable soils. We can estimate the amount of net P that has to accumulate per year to remain at a constant level of total P. The regression coefficient of the relation between total P in a core of 95 cm and time of abandonment was 14.8 mg P/kg soil/year ($p < 0.10$). This number times the amount of kg soil in a soil core

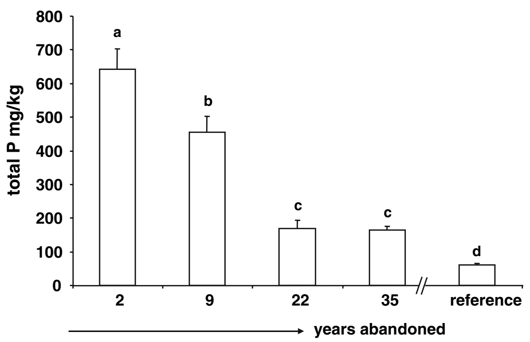

Fig. 1 Total phosphorus in the 0–95 cm soil layer of 4 ex-arable fields and a heathland

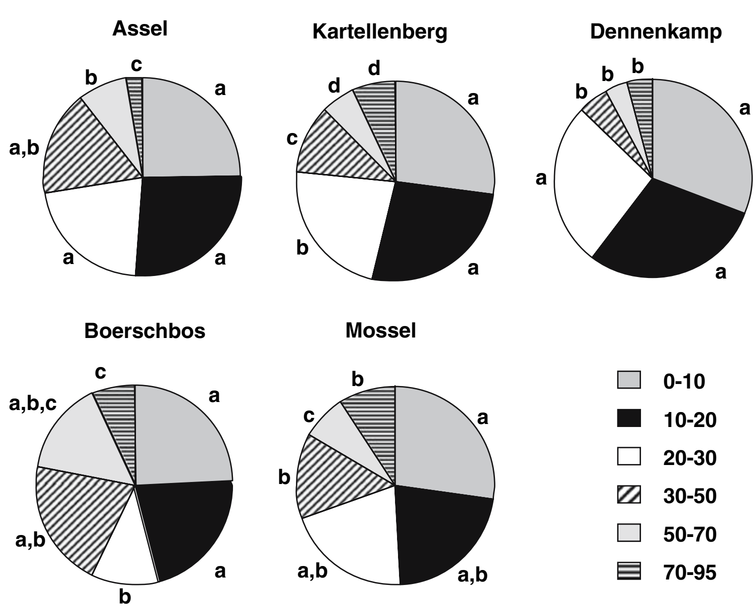

Fig. 2 Vertical distribution of total phosphorus in the 0–95 cm layer of 4 ex-arable fields (Assel abandoned since 2 years, Kartellenberg since 9 years, Dennenkamp since 22 years and Boerschbos since 35 years) and a heathland. Given are the percentages of total P, on basis of dry weight soil, per depth

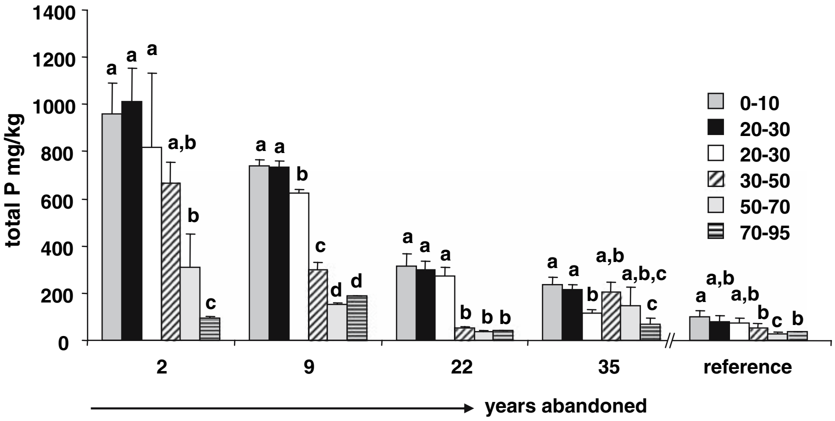

Fig. 3 Vertical distribution of total phosphorus in the 0–95 cm layer of 4 ex-arable fields. Given are the total amounts of phosphorus, on basis of dry weight soil, per depth

(1.3 kg) results in the amount of net P that has to accumulate per year (19.3 mg). The area of the soil core was 9.621 cm^2, so 19.3/9.621 = 2.00 mg/cm^2 = 200 kg/ha/year should had been applied to the oldest abandoned field to reach the level of total P that was found in the most recent abandoned field. In 33 years, 33 * 200 = 6600 kg P/ha must have accumulated in the soil during the total period of abandonment. Based on the assumptions given in the Material & methods section, the estimated amount of P fixed in plant biomass (9780 kg/ha in 10 years) after abandonment, 0.2% * 9780 = 196 kg P/ha, is negligible compared to 6600 kg P/ha. Thus, 200 kg P/ha is the estimated amount that must have accumulated annually in order to keep the P level equal over a period of 33 years. However, it should be kept in mind that this amount can be higher or lower due to variation between (e.g. historical differences) and within (e.g. heterogeneity of soil) locations. The amount of 200 kg added P/ha/year is more than twice as high as the average net surplus (added fertilizer minus output via harvest) of 84 kg P/ha/year on agricultural maize fields in the Netherlands in the period 1986–2000 (Schoumans et al. 2004). The difference could be due to the removal of P in plant biomass by herbivores. The largest maximum uptake of P under optimal conditions via plant biomass is calculated as 50 kg P/ha/year (Sival and Chardon 2004). This is a strong overestimation for the fields in this study, since the systems are more or less closed and the conditions are likely not optimal for plant growth, but even under optimal growth and removal of plant biomass this number can not compensate for the difference between 200 and 84 kg p/ha/year. The estimated surplus of P as mentioned by Schoumans et al. (2004) is, however, an average of arable sandy fields in the Netherlands and can be an underestimation of the P that has actually been applied in the past. Farmers were only restricted in the gift of P via animal manure and the introduction of artificial fertilizer was unlimited (RIVM 2002). It is likely that in the past the gift of P was much higher than officially documented. Therefore, accumulation of P for longer periods of time in recently abandoned fields is the most reasonable explanation for the inverse relation between P and years of abandonment, although some uncertainty remains as the initial conditions and former management of the soil could be different between locations.

The fields showed differences in soil profile development; the ex-arable sites showed some features of podzols (Assel, Boersbosch) and arenosols (Kartellenberg, Dennenkamp). However, all soils of the ex-arable fields were homogenous in the upper 30 cm and had disturbed profiles due to tilling in the past. The reference heathland had an undeveloped podzol profile as it lacked an E horizon (AE/Bs/C), possibly due to sod-cutting in the past. Some depth layers contained different soil horizons (Table 2). The upper 30 cm contained the highest amount of phosphorus in every field, although the percentage of total P in the upper 30 cm in the podzols (Assel, Boerschbos and the heathland) was lower (57.2–72.3%) than in the arenosols (Kartellenberg,

Table 2 Soil horizons present in each depth layer per field

Depth	Assel Horizon	Kartellenberg Horizon	Dennenkamp Horizon	Boerschbos Horizon	Mossel Horizon
0–10	A/AE	A/AE	A/AE	A/AE	A/AE
10–20	A/AE	A/AE	A/AE	A/AE	A/AE
20–30	A/AE	A/AE	A/AE	A/AE	A/AE
30–50	E/Bs	C	C	A/AE/E	Bs
50–70	Bs	C	C	Bs	C
70–95	C	C	C	C	C

A and AE stands for humic and transitional horizon; E stands for eluviation horizon; Bs stands for illuviation horizon and C stands for parent material. The suffix 's' stands for accumulation of sesquioxides (Fe, Al) in the B-horizon (Bs) (FAO 1990)

Dennenkamp) (76.6% and 87.2%, respectively). In addition, the distribution of total P in the different depth layers differed between the fields, especially Boerschbos showed higher amounts of total P in the 50–70 cm depth layer, which was identified as a Bs horizon (Table 2). Phosphate sorption in different soil horizons is especially likely to depend on the degree of eluvation and illuviation of Al and Fe oxides from one layer into another. The possibility of a storage layer of phosphate may be applicable for soils, which contain a Bs soil horizon that is characterized by the illuvial accumulation of aluminum and iron, since inorganic P can react with these irons to form solid compounds (Barrow 1983; Van der Zee et al. 1987). Therefore, the Bs layer in this podzol may become a storage layer in future when possibly more phosphate leaches out of the surface layers.

Conclusions

The previous observed inverse relation between total P in the upper soil (10 cm) and years of abandonment can not be explained by leaching of large amounts of P to lower layers of the soil since total phosphorus values were decreasing with soil depth in every field. We estimated that 200 kg P/ha/year must have been applied to the abandoned fields to keep the level of total P of that of the most recent abandoned field. This amount may be reasonable considering the high amounts of P application in the past century and therefore, accumulation of P for longer periods of time is the most likely explanation for the lower amount of P in longer abandoned fields. Based on these results, abandonment of agricultural land does not seem to trigger a 'chemical time bomb' to explode and no large amounts of P appear to leach into deeper soil layers. However, increasing amounts of total P in the Bs horizon may indicate that in future, when more P leaches out of the upper layers, this horizon is likely to become a storage layer for P.

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