Journal of Zhejiang University SCIENCE B
ISSN 1673-1581 (Print); ISSN 1862-1783 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Prediction of the P-leaching potential of arable soils in areas with high livestock densities*

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Received May 17, 2006; revision accepted May 29, 2006

Abstract: Due to long-term positive P-balances many surface soils in areas with high livestock density in Germany are over-supplied with available P, creating a potential for vertical P losses by leaching. In extensive studies to characterize the endangering of ground water to P pollution by chemical soil parameters it is shown that the available P content and the P concentration of the soil solution in the deeper soil layers, as indicators of the P-leaching potential, cannot be satisfactorily predicted from the available P content of the topsoils. The P equilibrium concentration in the soil solution directly above ground water table or the pipe drainage system highly depends on the relative saturation of the P-sorption capacity in this layer. A saturation index of <20% normally corresponds with P equilibrium concentrations of <0.2 mg P/L. Phytoremediation may reduce the P leaching potential of P-enriched soils only over a very long period.

Key words: P-balance, P-accumulation, P-saturation index, Subsoil, P equilibrium concentration, Phytoremediation
doi:10.1631/jzus.2006.B0515 **Document code:** A **CLC number:** S15

INTRODUCTION

Phosphorus losses from cultivated soils should be avoided or at least minimized from both ecological and economical aspects. These losses contribute to eutrophication of surface waters, river systems, estuaries and sea coasts at river mouths and are equivalent to a waste of rock phosphate as a highly limited natural resource as well.

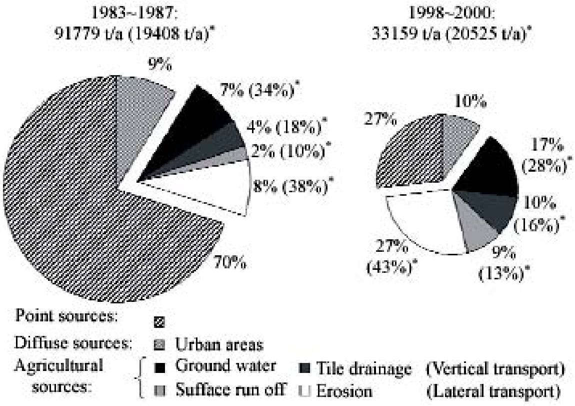

Fig.1 P-input into the river systems of Germany and its pathways

* Numbers in brackets show the amounts of the agricultural P-input only and the percentages of the four different agricultural sources on total agricultural P-input (Behrendt *et al.*(2003), modified)

In Germany the P-inputs into rivers by point sources from municipal sewage treatment plants and industrial discharges as well could be drastically reduced within the last 15 years, whereas the input via diffuse pathways from agriculture could not be decreased significantly (Behrendt *et al.*, 2003) (Fig.1). P losses from the soil are caused by lateral transports (surface run-off, erosion) and vertical leakage of percolating water through the soil matrix (and/or short-time preferential flow via macro pores) into the ground water and/or the pipe drainage system. The shares of the different pathways of the total P-losses from a special site are controlled by its textural, topographical and hydrological characteristics. As far

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* A Keynote Lecture of the "1st International Symposium on Phytoremediation and Ecosystem Health" Held at Hangzhou, China

as the mean values for Germany are concerned erosion is still the most important pathway.

The diffuse P-losses by surface run-off and erosion can meanwhile be satisfactorily calculated from precipitation and specific run-off data in combination with specific topsoil data or the P-supply status (Behrendt *et al.*, 2005), whereby the erosion is estimated with the revised universal soil loss equation (RUSLE) of Wischmeier and Smith (1978) after having updated the factors for German conditions with thousands of new measurements. The prediction of the potential for vertical P-losses via displacement of soil solution into drainage water and ground water, however, needs additional knowledge on the P-household, in particular the P-sorption characteristics of the subsoil layers.

From the aspect of water protection newly formed ground water or drainage water should not exceed a threshold value of 0.20 mg P/L (Hamm, 1991). The aim in the Netherlands is a limit concentration of 0.10 mg ortho-P/L (Breeuwsma and Schoumans, 1987; van der Zee *et al.*, 1987). Within a soil profile, therefore, the equilibrium P concentration of the soil solution directly above the ground water table or of the pipe drainage water is decisive for the prediction of the endangering of ground water and surface water by diffuse P-inputs.

We have carried out those investigations in a region of the Federal State of Northrhine-Westphalia in Germany, which is particularly characterized by farms with high intensity of animal production.

P-SUPPLY STATUS IN THE INVESTIGATION AREA

Farms with high livestock density in Germany are generally characterized by high imports of P via commercial feedstuffs resulting in positive P-balances when comparing the P removal from soils with crops and the P-input with manure. This situation exists in the survey area with its accumulation of intensive livestock farms (Werner and Brenk, 1997) (Fig.2).

In the Federal State Northrhine-Westphalia about 90% of all dry-stock farms and 50% of the dairy farms have positive net P-balances (Fig.3).

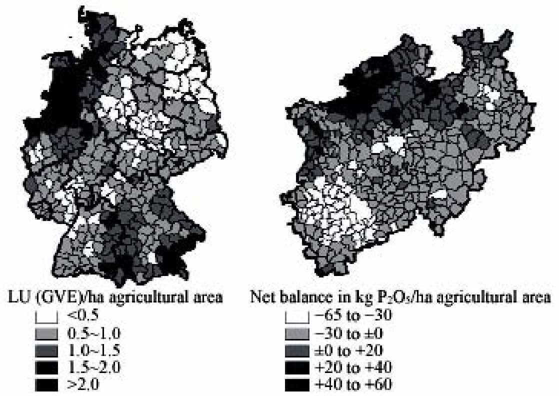

Fig.2 Density of livestock units in Germany (Kreins *et al.*, 2003) and net balances of phosphorus (P-removal minus P in farm manures) in the communities of Northrhine-Westphalia (Werner and Brenk, 1997)

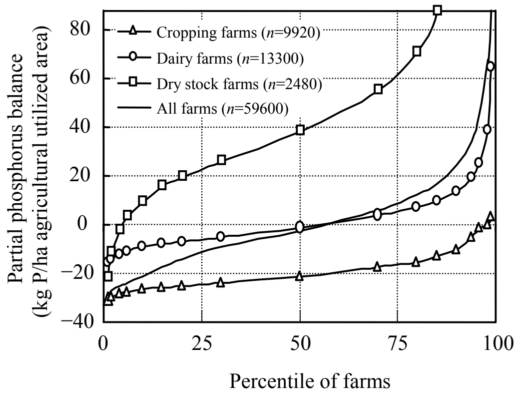

Fig.3 Cumulated frequency of the partial phosphorus balance of the farms of Northrhine-Westphalia

In consequence, the P-supply status of many arable soils meanwhile has reached excessive values (Fig.4) and potential for unwanted P-losses not only into surface waters via surface run-off and soil erosion, but also into ground water and drainage water via vertical leaching.

For better characterization of this leaching potential we have characterized a great number of soil profiles (0~60 or 0~90 cm) from this area by the following chemical parameters (Pihl, 2000; Werner, 1999):

1. “Available” P: Extractable with Calciumacetatelactate (CAL) solution (Schüller, 1969);

2. P_W: Water-soluble P (1:2);

3. P_{SSE}: P-concentration of the soil solution (saturated soil extract, SSE) or calculated by correlation from P_w (r^2=0.99);

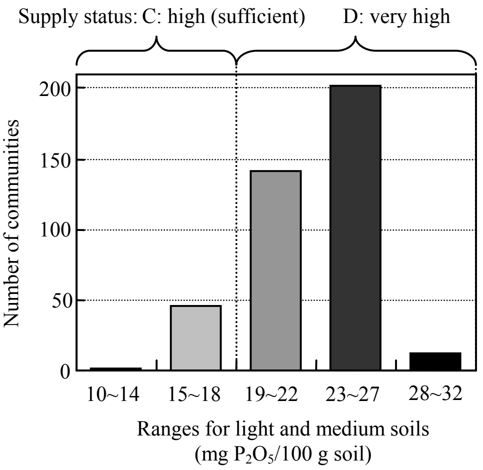

Fig.4 Phosphorus supply status of the arable soils in Northrhine-Westphalia. Community-related average values of the official soil survey 1991 to 1994 (n= 229.000)

4. P-fractionation (Kurmies, 1972);

5. P_{ox}: Ammoniumoxalate-soluble P (Schwertmann, 1964; modified by Houba *et al.*, 1988);

6. Fe_{ox} and Al_{ox}: Active iron-/aluminium -oxides (Schwertmann, 1964; 1973);

7. P_{max}: Maximum P-sorption capacity by Langmuir isotherms (batch experiments) or calculated by multiple regression from Fe_{ox} and Al_{ox} (r^2=0.80);

8. P-saturation index: P_{ox} in percentage of P_{max}.

RESULTS

In this paper only a few exemplary data of our extensive studies can be presented.

The assumption that the endangering of ground water via P-pollution by vertical P-movement in the soil could be assessed solely from the P-supply status of the topsoil has to be rejected by two primary results:

1. There was only weak correlation between the CAL-P-contents in topsoil and subsoil (Fig.5).

2. The P-concentration of the soil solution in deeper soil layers does not correlate with the P-status of the topsoil (Table 1).

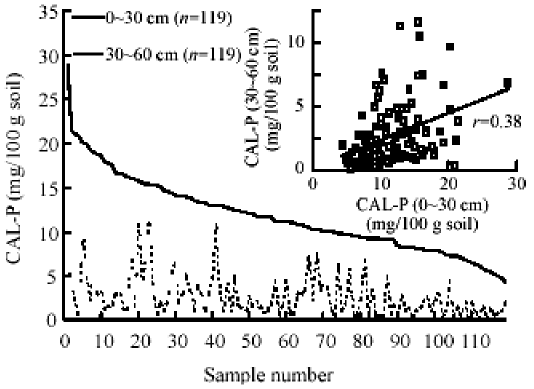

Fig.5 Available P-status (CAL-P) in different depth of gley-podsolic soils in Münsterland area

Table 1 Correlation (r^*) between CAL-P contents and P-concentrations in soil solutions at saturation (P_{SSE}) of different soil layers: gley-podsolic soils of Münsterland area (n=50)

CAL-P	P-concentration (P_{SSE})		
	0~30 cm	30~60 cm	60~90 cm
0~30 cm	0.56^{**}	0.08	0.08
30~60 cm	–	0.57^{**}	0.49^{**}
60~90 cm	–	–	0.66^{**}

* Coefficient of correlation between CAL-P (mg/100 g soil) and log P_{SSE} (mg/L); ** Level of significance: α=0.1%

To solve that prognostic problem, we must know more about the P-household of the deeper soil layers, like CAL-P, sorbed P by iron and aluminium oxides (P_{ox}), P-sorption capacity (P_{max}) and the already realized saturation percentage of that capacity. Our investigations on the correlation between the P-saturation index and the P-equilibrium concentration at water saturation resulted in coefficients of determination (r^2) between 0.73 and 0.80, dependent on the pH range of the sandy gley-podsolic soils (Table 2).

Table 2 Coefficient of determination (r^2) of the correlation* between P-saturation index of the soil and P-concentration in soil solution at water saturation (P_{SSE}) (sandy gley-podsolic soils)

pH-range	n	r^2
<7.6	123	0.73
<7.0	117	0.75
<6.5	110	0.77
<6.0	90	0.80

* Correlation between P_{ox}/P_{max} and log P_{SSE} (mg/L)

The results of our first survey of P-characteristics of typical fields from intensive husbandry farms are summarized in Table 3. It is concluded that on average the topsoils are oversupplied with P. The mean P-saturation index is about 30% even in the 60~90 cm layer. The P-concentration of the zone's soil solution exceeds already by 26% that of the fields' limiting value of 0.20 mg P/L.

Table 3 Survey on P-characteristics of typical fields from husbandry farms in the Münsterland area (gley-podsolic soils; average values at *n*=58)

Parameter	Soil layer		
	0~30 cm	30~60 cm	60~90 cm
CAL-P (mg/100 g soil)	10.7	3.0	1.5
P_{max} (mg/kg)	555	451	469
P_{ox} (mg/kg)	411	158	136
P-saturation index (%)	74	35	29
P_{SSE} (mg/L)	1.19 (0.66)*	0.40 (0.22)*	0.20 (0.08)*
Samples (%) (>0.20 mg P/L)	86	54	26

* 50% (median) in brackets

There are two proposals from the Netherlands for assessing the potential endangering of ground and drainage water to vertical P inputs, both based on a limit concentration of only 0.10 mg ortho-P/L in the outflowing soil solution which should not be exceeded from limnological reasons (eutrophication). To keep this limit concentration:

1. The average P-saturation index of the soil profile above the highest ground water level should not exceed 70% (Breeuwsma and Schoumans, 1987);
2. The saturation index of the soil layer right near the ground water table should not exceed 25% (van der Zee *et al*., 1987).

In our studies average P-saturation of 54% was found in the 0~90 cm soil profiles where 12% average P-saturations was more than 70%. According to Breeuwsma and Schoumans (1987), it should be expected from this result that only in about 12% of the profiles the limit concentration of 0.10 mg P/L in the deepest soil layer should be exceeded. In reality, however, there were 36% profiles with higher P-concentrations in the 60~90 cm layer in the soil solution.

A second survey was focused on 240 farm fields with high livestock densities in an area where high ground water levels (<1 m) are very frequent. A shown in Table 4 the average P-saturation in the 30~60 cm subsoil layer was already 39%, with the consequence that the P-concentration of the soil solution in that layer exceeded 0.10 mg P/L in 74% and 0.20 mg P/L in 39% of the fields. For this area, therefore, the potential endangering of ground water to vertical P-input, should not be underestimated.

Table 4 P-saturation index and P-concentration of soil solution (P_{SSE}) in topsoil and subsoil samples of gley-podsolic soils of Münsterland area (*n*=240)

		Soil layer	
		0~30 cm	30~60 cm
P-saturation index	Mean	84%	39%
P_{SSE} (mg/L)	Mean	0.78	0.23
	Median	0.58	0.12
Samples with P-concentration	≥0.20 mg/L	80%	39%
	≥0.15 mg/L	89%	62%
	≥0.10 mg/L	94%	74%

As demonstrated by Werner (2000) we can conclude that in the area of high livestock density in Northwest-Germany there is a coincidence of some factors promoting vertical P-losses from soil to ground water: Highly positive farm P-balances, high to very high P-supply status of the soils, increased P-saturation index even in deeper soil layers, high ground water level and fairly high precipitation and seepage loss.

CAN PHYTOREMEDIATION HELP TO DECREASE THE P-INPUT TO GROUND WATER BY PERCOLATION WATER?

There are numerous results from long-term field experiments on the influence of the P-uptake of crops on the P-content of the soil. At excessive high levels of available P, which is the reality in many husbandry farms, and due to the P-buffer capacity of the soil it needs many years without any further P-supply (>10 a) to decrease the P-content to an extent, that would significantly reduce the P-concentration of the soil solution in the soil layers relevant for direct P-discharge into ground water. With normal P-withdrawal rates of 20~30 kg/ha a year by agricultural crops, yearly decreases of available P (CAL-soluble) between 0.15 and 0.50 mg P/(100 g soil) were measured (Albert and Suntheim, 2004; Hege and Offenberger, 1996; Werner, 1995). This is in agreement with necessary application rates of 60 to 120 kg P/ha to increase the CAL-P for 1 mg/(100 g soil) (Kerschberger and Richter, 1978; Jungk *et al*., 1993; Kerschberger and Schröter, 1996).

Model experiments of Koopmans *et al.*(2004) showed that the risk of P-leaching from P-enriched soils could be efficiently decreased by mining soil P via long-term exhaustive cropping with grass (*lolium perenne*). In these experiments 65% of the enriched P_{ox} could be removed, whereby the P-concentration in $CaCl_2$-extract was 71% lower than the initial concentration. However the threshold P-content for good nutrient value for grass can already be reached when only 15% of the initial P_{ox} is removed.

What makes phytoremediation still more difficult is the fact that this measure have to include also the subsoil. But P-uptake from the subsoil is comparatively low when the topsoil is still well supplied with P (Kuhlmann and Baumgärtel, 1991).

CONCLUDING REMARKS

The endangering of ground water and drainage water, both important sources for surface waters, to vertical P-losses from soils oversupplied with P cannot be satisfactorily predicted by only considering the P-supply status of the topsoil. It is also important to know the chemical characteristics responsible for the P-sorption capacity in the deeper soil layers. The P-concentration of the soil solution in all soil layers is highly determined by the relative saturation of the P-sorption capacity. P-saturation indices in the soil layer directly above the ground water table or the pipe drainage system of <~20% may secure to some extent that P-equilibrium concentrations of newly formed ground water or drainage water stay below the threshold value for water protection of 0.20 mg/L which also is equivalent to a still "tolerable" leaching loss of 0.5 kg P/ha with 250 mm percolation water into ground water.

Phytoremediation of soils with unnecessarily high P-accumulation is very time consuming, especially when the subsoils have also already increased available P-contents. But nevertheless it is the only available measure for a long-term improvement of the situation. The best way, however, to avoid ground water pollution with too high P-concentrations is to avoid in the fertilization management unnecessary P-accumulation of the topsoils due to long-term surpluses of the P-balance.

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