Selected requirements on a sustainable nutrient management

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Abstract Nutrients are a limited resource and call for management. A sustainable nutrient management strategy reintegrates nutrients in the environment without accumulating harmful substances above an acceptable level. In this study a methodology to assess the environmental compatibility was developed. For this assessment both the (i) enrichment of pollutants in the soils and (ii) the area specific nutrient demand of the crops were taken into account. The method considers, that products applied on soils also contain stable substances, and as a consequence the accumulation of pollutants diminishes. Additionally, it is considered, that increasing substance concentrations in the soil will lead to an increase of substance flows out of the soil by percolation, plant-removal (and erosion). In practice long term management strategies are restricted by the time span considered, the accepted accumulation of substances, the plants real needs and legal constraints. The rating of various goods can be made with the ratio of the added nutrients, considering the pollution criteria, the legal constraints and the plants real needs.

Keywords Accumulation; dilution; nutrient management; pollution; soil

Introduction
Nutrients are a limited resource and need to be managed properly. The phosphate-reserves will last according to different estimations between 88 (Global 2000, 1976) and 500 years (Finck, 1992), and those having low cadmium concentrations are even more limited (Semi Island Kola: 1 mg Cd/kg DM, Taiba/Senegal: 68–111 mg Cd/kg DM) (Sauerbeck and Rietz, 1980). Additionally, the production of mineral N- and P-fertilizers demands (fossil) energy input.

Sewage sludge contains considerable amounts of nutrients that can be reintegrated into the nutrient cycle. Together with the nutrients sewage sludges contain potentially hazardous substances having different origins. The heavy metal contents of sewage sludge can be highly influenced by diffuse sources (corrosion of roofings, etc.) (Zessner and Lampert, 2002). These substances might be accumulated in the long run in the environment if their quantity is not properly considered.

Therefore the challenge of a sustainable nutrient management strategy is to reintegrate nutrients in the environment without accumulating harmful substances above an acceptable level. In order to optimize the nutrient management the plants real needs have to be considered.

This paper is focused on heavy metals and their accumulation in agricultural soils.

Substance concentrations of goods (nutrient concentrations, concentrations of potential hazardous substances) are not sufficient to derive nutrient management concepts. The combination of nutrients and heavy metals such as the ratio of Cd and P which is often used to characterize sewage sludges enables us to assess comparable goods (e.g. various sludges). However, this ratio is not an effective tool to compare different goods like compost, sludges and manure. In Table 1, where all goods depicted represent a Cd : P ratio of 100 mg Cd/kg P, this can be seen clearly:

It is obvious that the good “soil” has the lowest potential to accumulate Cd in soil
without increasing the P-content. On the other hand mineral P-fertilizers are to be preferred to achieve a high fertilizing effect.

In the following section aspects of a sustainable nutrient management are presented, which are not restricted to sewage sludge only.

Method

The methods used are based on the methodology of materials accounting (Baccini and Brunner, 1991). To calculate the accumulation of pollutants in soils, the additional inputs and the counteracting outputs have to be considered. Inputs can be the application of manure, of mineral fertilizer, of compost, of sewage sludge, pesticides and deposition. The output-flows from the soil are plant-removal, percolation to the underground/groundwater and erosion. If the total input of a substance exceeds the total output, a stock is formed, increasing the substance concentration in the soil.

To estimate substance accumulation in the soils, often linear models have been used until now (e.g. Chawla et al., 1976; von Steiger and Baccini, 1990; Wintzer et al., 1996). These models do not consider the “diluting effect” of the stable matrix applied on the soil and the increasing outflows of substances due to their increased concentration in the soils. In the following, the outline of a dynamic model is shown.

Diluting effect

The goods applied on agricultural soils consist of organic and inorganic matter. The content of organic matter in these goods differ in a broad range: mineral fertilizer 0%, compost 30%, sewage sludge 50%, manure 90%. Depending on the type of organic matter (easily degradable –stable) the organic matter will be mineralised partly or completely within a certain time span. The solubility of the inorganic components varies (slightly soluble –

Table 1  Identical Cd:P ratios of different goods

<table>
<thead>
<tr>
<th></th>
<th>100 mg Cd/kg P</th>
<th>mg Cd/kg DM</th>
<th>mg P/kg DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>0.1</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Compost</td>
<td>0.6</td>
<td>6,000</td>
<td></td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>1.5</td>
<td>15,000</td>
<td></td>
</tr>
<tr>
<td>Mineral P-fertilizer</td>
<td>12.6</td>
<td>126,000</td>
<td></td>
</tr>
</tbody>
</table>

DM = dry matter

Figure 1  System agricultural soil

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non-soluble) too. In the long run, most of the organic matter will be decomposed and the inorganic matter will be partly dissolved. The remaining part (“stable matrix”) has a “diluting effect” on the heavy metal load of the goods applied on the soils. Therefore, it is not the total heavy metal load applied which causes accumulation.

Depending on the good a different amount of “stable matrix” is applied. Assuming that the substance concentration within the “stable matrix” (final concentration) was similar to a “geogenic” (or background) substance concentration no accumulation would take place due to the application of this good. The net accumulation is only due to the difference between the concentration in the stable matrix (final concentration) and the geogenic concentration (background concentration), i.e. the resulting substance load (= anthropogenic additional load (Lampert and Brunner, 1999)).

The anthropogenic additional load can also be related to one nutrient unit to give the specific anthropogenic additional load; e.g. mg Zn/1kg P) (Lampert, 2001). The accumulation-effective pollutant load can be calculated using this unit if the amount of nutrients applied on the soil is known.

In Table 2, Zn- and P-concentrations and the anthropogenic loadings of the goods “mineral P-fertilizer”, “pig manure”, “sewage sludge” and “compost” are compared. As can be seen, the impact of the “diluting effect” for compost is the highest. In the example chosen, mineral fertilizer has the lowest risk of Zn-accumulation.

Output flows depending on the stock

All output-flows are related to the substance concentration in the soil. The relation, especially for the plant removal depends on the substance considered, the soil conditions, the type of crops, etc. In general, an increase in the substance concentration of the soil causes a concomitant increase in that of the output flows.

In order to calculate the resulting substance concentration in the soil, the “layer model” was developed. The “diluting” effect of the stable matrix can be considered if the reference layer of the soil is kept at a constant thickness (e.g. 30 cm plough layer). This is required if the concentration of the substances e.g. within the plough layer is of interest. In fact the “layer model” has some similarities with the “Dynamic Soil Composition Balance” developed by (Moolenaar et al., 1997).

The layer model includes:

- if a “stable matrix”-layer is applied to the “top” of the soil, the soil-compartment is “growing” in height. To keep the compartment constant at 30 cm, a layer of an equal dimension has to be reduced from the “bottom” of the reference layer.
- If erosion takes place, again the reference layer has to be kept constant. Therefore a layer equal to the thickness of the eroded soil layer is to be added at the bottom of the reference layer. Two cases can be distinguished: the thickness of the soil layer eroded is higher than the application of “stable matrix” and vice versa.

<table>
<thead>
<tr>
<th>Goods</th>
<th>Zn-conc. in OM</th>
<th>OM in %</th>
<th>Anth. add. load</th>
<th>P-conc. in OM</th>
<th>mgZn/kg P</th>
<th>spec. anth. add. load mgZn/kgP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. P-fertilizer</td>
<td>220</td>
<td>0</td>
<td>193</td>
<td>32,700</td>
<td>6,628</td>
<td>5,900</td>
</tr>
<tr>
<td>Pig manure</td>
<td>1,300</td>
<td>90</td>
<td>1,294</td>
<td>26,500</td>
<td>50,189</td>
<td>48,850</td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>800</td>
<td>50</td>
<td>772</td>
<td>20,000</td>
<td>40,000</td>
<td>38,575</td>
</tr>
<tr>
<td>Compost</td>
<td>200</td>
<td>30</td>
<td>160</td>
<td>4,000</td>
<td>50,000</td>
<td>40,025</td>
</tr>
</tbody>
</table>

Assumptions: background Zn-concentration in the soil: 60 mgZn/kgDM; Decomposition of the organic matter (OM): all 100%; easily soluble inorganic matter : mineral fertilizer 55%, all others 5%
A general formula for the calculations used:

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mx_n = mx_{n-1} + \frac{h - aB}{h} + mx_a - E - P + mx_{n-1} \times \frac{eB}{h}
\]

**Results and discussions**

Figure 2 underlines the importance of the diluting effect through the example of compost application. The diluting effect for sewage sludge would be lower as the non degradable substance is less and the substance concentration is higher. In each case 4 kg Zn/ha.y (1 ha = 0.01 km²) are applied on the soil. In Figure 2 neither additional input flows, nor the output flows of zinc from the soil are considered.

Although the same annual zinc load of 4 kg Zn/ha is applied, the accumulation differs up to 30% after a time span of 300 years. Keeping the Zn-load constant (at 4 kg/ha.y), a reduction in the amount of compost by 50% (from 13.33 Mg DM/ha.y to 6.67 Mg DM/ha.y) yields a difference in the accumulation of 19%. A further reduction from 6.67 Mg DM/ha.y to 3.33 Mg DM/ha.y changes the increase of the Zinc-stock by only 9%. The calculated accumulations have significantly different gradients and change of the gradient of the stock-increase.

The final concentration (gradient = 0) in this example applying the compost with 300 mg Zn/kg DM would be 430 mg Zn/kg soil, applying the compost with 1,200 mg Zn/kg DM it would be 1,725 mg Zn/kg soil.

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**Figure 2** Change of the Zinc-stock in the soil due to the application of compost containing 4 kg Zn/ha.y (different substance concentration and related amount of dry matter (DM))

Further assumptions: 30% organic matter, out of this 10% non degradable; 5% of the inorganic matter is slightly soluble; background concentration in the soil: 70 mg Zn/kg DM (equal to a Zn stock in the soil of 315 kg Zn/ha.y, at a plough layer of 30 cm and a soil density of 1.5 kg/dm³) (t = Mg)
The following conclusion can be drawn: the “diluting effect” is the higher the (i) more the portion on “stable matrix” is and the (ii) more similar the natural background concentration and the “final” substance concentration (substance concentration of the stable matrix) in the good applied is.

In the following example a “pure” Zinc load of 4 kg Zn/ha.a was applied and the output-flows percolation, plant removal and erosion have been considered.

According to the a conventional linear model, the annual increase of the Zinc-stock in the soil is constantly 0.46 kg Zn/ha (Figure 3). Using the layer model, the output flows increase from originally 0.35 kg Zn/ha (less than in the linear model, as the net-flow due to erosion is negligible) to 1.35 kg Zn/ha after 300 years (about 4 times higher as in the first year respectively about 3 times higher as in the conventional calculation). The Zinc-stock amounts to about 1,400 kg Zn/ha.30 cm after 300 years using the linear model, but 1,200 kg using the layer model (therefore more than 15% less even if the output by erosion is not corrected in the conventional calculation).

As shown in Figure 3 the substance output due to erosion only amounts to the difference of the substance concentration on the top and on the bottom of the reference layer. This means, in many cases the output–load due to erosion with respect to the substance concentration in the reference layer is only of slight importance. Erosion would be of greater concern in other environmental compartments such as receiving waters.

In the example given, the increasing substance outputs diminish the difference between the total input and the total output from initially 3.65 kg Zn/ha.y to 2.6 kg Zn/ha.y, amounting to about 30%. In the conventional calculation, the annual change of stock remains constant with 3.54 kg Zn/ha.y (including the output by erosion) (see Figure 4).

Implementation

Time horizon. In order to implement this model into agricultural practice (e.g. to calculate the “acceptable” amounts applied) a time horizon has to be included. Usually soil standards do not include a time horizon, this means that various constraints like laws, ordinances,
guidelines, etc. do not differentiate if the standard will be reached/exceeded in a few, in some or in many generations. For a sustainable soil protection strategy, there is a need to supplement the various constraints by a time horizon – a time span has to be incorporated in all possible strategies. Depending on the time span selected and the acceptable accumulation defined, the annual application rates of goods can be calculated (e.g. in Mg DM/ha.y).

Acceptable accumulation. Substance balances of soils show that for some substances (e.g. Cd, Pb), accumulation in soils takes place even without any agricultural activities. The atmospheric deposition rate exceeds the substance outflows from the soil through plant removal, percolation, and erosion. To postulate “Input flows into the soils have to be equal to the Output flows” is to neglect the actual case in many regions.

Therefore, to enable (traditional) feed and food production, an additional accumulation of potential hazardous substances has to be taken into account. Obviously, discussion on the extent of this accumulation is crucial. We still lack clear evidence on the acceptable levels of substances in the soil. The standards, in terms of maximum concentrations allowed in soil, differ from country to country in a wide range. It seems that these standards are influenced more by the national geological situation than by potential hazards for the biosphere. Therefore, the question on acceptable accumulation is not answered yet.

At least three strategies can be identified for soil protection concerning the accumulation of pollutants which are adapted to the (regional) soil characteristics:

(i) to define a maximum allowable substance concentration in the soil (e.g. 300 mg Zn/kg DM), (ii) to define a maximum allowable change of the various stocks of substances in the soil (e.g. maximum increase of the Cd-stock by 10% in), and (iii) to define an acceptable absolute change of substances in the soil (e.g. maximum increase by 300 kg Zn/ha).

As mentioned above, deposition itself can lead to an accumulation of hazardous substances. To enable agricultural practice for single goods applied and for all goods applied, the acceptable accumulation has to be defined. This acceptable accumulation has to be defined restrictive to be on the “safe side” of soil protection, to remain a buffer space for pollutant accumulation due to unavoidable (?) substance input by deposition.

The time horizon chosen and the definition of the acceptable accumulation characterize
the “pollution criteria” and serve as a starting point for the calculations. E.g.: “A 10% increase of the Zinc-concentration within 250 years in the plough layer, through sewage sludge is accepted.”

**Legal constraints can restrict application rates.** In practice, various laws, ordinances and guidelines limit the amounts of goods that can be applied on soils. Regulations on the application of sewage sludge and compost can limit the maximum concentrations, the amount applied on the soils or the accepted pollutant load, like 2.5 Mg DM sewage sludge/year, 8 Mg DM compost/year; 5 g Cd/ha.y. The water act (BGBl. 1990/252) limits the amount of Nitrogen applied on arable land by 175 kg N/ha.y. Therefore, also the legal constraints influence the regional nutrient management.

**Orientation of amounts toward the plant’s real needs.** In addition to the accumulation of pollutants in the soils (pollution criteria) and the legal constraints the amounts of sewage sludge applied should correspond to the plants real needs. This means to consider the nutrient content in the soils, the kind of crops, the yields aimed at, etc. Only this orientation ensures that the limited resource nutrients are not disposed of but used in adequate amounts. As a consequence there will be no general advice on the amounts of goods applied like 2.5 Mg DM/ha.y.

To consider the plant’s real needs will lead to the following situation: if the “pollution criteria” of substances in the soils is defined strict (small accumulation, long accumulation period) possibly the “pollution criteria” will be the limiting one. If it is defined permissible (short time period, high accumulation) the crop’s real needs will limit the amounts applied.

To rank various competing goods the following procedure can be applied: In the first step for each good the most restrictive constraint is identified (i.e. legal constraints, pollution criteria) and the related nutrient amount is calculated. In the next step the ratio between the calculated nutrient amount and the plants real needs is determined. This ratio can be used as ranking criteria. The ratio varies between 0 and 1. A ratio of 1 would indicate, that the plants real needs can be satisfied completely without an unacceptable pollutant accumulation and considering legal constraints.

**Conclusions**

To calculate the amount of goods (sewage sludge, compost, manure, etc.) that can be applied annually, (i) an acceptable concentration in the soil and (ii) a time horizon has to

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**Figure 5** Calculation of applicable amounts

![Diagram showing the calculation of applicable amounts]
be defined. In addition, the calculations have to consider (iii) the diluting effect of the “stable matrix” applied as well as (iv) that the output-flows will increase if the substance concentration in the soil increases. As a consequence identical loads of pollutants applied may cause different accumulation in the soil and a “steady state” of the pollutant concentration in the soils will be achieved in the long run. (v) Legal restrictions can limit the application of goods. (vi) The amounts applied should be oriented towards the crop’s real needs. The amounts of dry matter applied can be restricted by the “pollution criteria”, by the plant’s real needs or by legal constraints.

The ratio between the nutrient amount applied (considering the pollution criteria and the legal constraints) and the plants real needs allows the ranking of various goods.

References