Assessing the performance of phosphorus-saturated ochre as a fertilizer and its environmental acceptability

K.E. Dobbie*, K.V. Heal & K.A. Smith

Abstract. Flooding of abandoned coal mines often causes discharges of iron-rich drainage water into the environment. Treatment of these discharges results in the formation of ochre (hydrous iron oxides) for which no end-use has been identified. Ochre effectively adsorbs phosphate from solution and thus could be used for remediation of waste waters. The resulting P-enriched ochre could then potentially be recycled as a P fertilizer. Pot and field experiments were set up to assess performance and environmental acceptability of ochre in this role, using grass and barley as test crops, as well as birch and spruce tree seedlings. Soils and plant materials were analysed for total and available P, total metals and pH. Results showed that P-saturated ochre functioned as a slow-release P fertilizer, and in the short term was as effective as conventional P fertilizer in maintaining crop yields. It also raised soil pH, and did not pose any significant problem through introduction of potentially toxic trace metals into the soil.

Keywords: Ochre, phosphorus, fertilizer, iron oxides, potentially toxic elements, pot experiment

INTRODUCTION

Inputs of phosphorus (P) to rivers and lakes from point sources (e.g. sewage treatment works) and diffuse sources (e.g. runoff from agricultural land) pose an environmental problem that has received much attention in recent years (Edwards & Withers 1998). The possibility of using a waste material to remove much of this P before entry into water bodies, and then recycling the resulting P-enriched material on to land as a fertilizer, is attractive.

One such material is ochre, composed of hydrous iron oxides precipitated from acidic water discharged from flooded former coal mines. At present, ochre is stored or landfilled as no suitable end-use on a large enough scale has been identified. Previous research has shown that ochre effectively adsorbs P (in the form of inorganic phosphate) from solution (Heal et al. 2003). Hylander & Simán (2001) reported that P similarly sorbed from waste water by blast furnace slag was readily available to plants, but that further research was required to determine its usefulness as a fertilizer under field conditions. Steel slag (basic slag) without additional sorbed P has long been used as a phosphatic fertilizer (Geiseler 1996), both in agriculture (e.g. MacNaeidhe 2001) and in forestry (e.g. Jandl et al. 2003). However, even if a waste material such as slag or P-enriched ochre were a potentially useful fertilizer, it could not be applied to land if it had unacceptably high concentrations of potential contaminants such as heavy metals. Since ochre effectively removes metals from solution (Heal et al. 2003), the metal content of P-saturated ochre, and the fate of the metals after it is applied to soil, must be examined before application to agricultural land can be considered. Application to forestry land presents less of a problem (Wolstenholme et al. 1992).

To assess whether P-saturated ochre would be a useful source of P for crops without compromising soil quality, the material was compared with conventional P fertilizer in pot and field experiments using grass and barley as test crops; also year-old birch and spruce seedlings were used in a pot experiment only.

MATERIALS AND METHODS

Ochre was obtained from a drying bed at the treatment plant for mine water at Polkemmet, West Lothian, Scotland. X-ray diffraction analysis showed that the ochre was composed mainly of goethite (FeO(OH)). The ochre was air dried to form a coarse granular material (0.25–10 mm in diameter), then saturated with P by repeatedly mixing with KH₂PO₄ solution (3 g P L⁻¹) until no further P was removed from solution. The P-saturated ochre was analysed for total and extractable P, total metals and pH by the same methods as described below for soils. The neutralizing value of the air-dried ochre was determined by reacting a 0.5 g sample with 50 mL of 0.5 M HCl followed by titration with 0.5 M NaOH (Johnson 1990).
Pot experiment (July–October 2002)

Soil was collected from the Ap horizon of a P-deficient imperfectly drained Eutric Gleysol (FAO-Unesco classification) of clay loam texture from a field at Glencorse Mains Farm, Midlothian, Scotland. The soil was air-dried, sieved (4 mm) and mixed with enough sand to give a sandy loam texture. Following analysis for available P, K and Mg by the Scottish Agricultural College (SAC), fertilizer application rates of 85 kg P$_2$O$_5$ ha$^{-1}$ and 90 kg K$_2$O ha$^{-1}$ were recommended.

Each of 60, 5-L pots was filled with 4 L of the soil/sand mix. Five replicates of six P treatments were prepared for each crop (barley, grass) as follows: a control with no added P (CO), a conventional P treatment (CP) in which KH$_2$PO$_4$ was applied at the recommended rate (85 kg P$_2$O$_5$ ha$^{-1}$) and P-saturated ochre at 0.5, 1, 2 and 5 times the recommended rate as acetic acid extractable P. The quantities of P-saturated ochre required were equivalent to 20, 40, 80 and 200 ha$^{-1}$, and were designated as treatments O(0.5), O(1), O(2) and O(5), respectively. These additions of P-saturated ochre were expected to provide a wide range of available P concentrations up to a level well above that of the KH$_2$PO$_4$ fertilizer. All pots also had 0.29 g K and 0.2 g N added in the form of crystalline K$_2$SO$_4$ and NH$_4$NO$_3$, respectively. These applications were based on the volume of soil in each pot, with the conventional fertilizer materials mixed into the top 5 cm. A further 0.06 g of N as NH$_4$NO$_3$ (equivalent to 30 kg N ha$^{-1}$) was added in solution after 3 weeks.

Each pot was sown with 0.16 g of grass seed (cv. Parcour) (equivalent to 40 kg ha$^{-1}$) or 8 barley seeds (cv. Chalice) (equivalent to 200 m$^{-2}$). The pots were distributed randomly on 5 tables in an unheated greenhouse and moved around every 2 weeks. Soil water content was determined gravimetrically, and tap water added to each pot as required to maintain the soil water content at approximately 80% of field capacity.

When the barley heads had ripened (October 2002), both barley and grass were harvested by cutting at the soil surface. Barley heads were separated from the stems and threshed. All samples were dried at 60°C, weighed and milled for analysis. The mass in each pot (soil + roots) was divided in two and weiged. The soil from one part was sieved (4 mm) and frozen for later analysis. The roots were separated from the other part by washing over a series of sieves, dried at 60°C, weighed and milled.

Soil samples were analysed for total and available P and total metals. Available soil P was determined in freshly thawed soil by 2.5% acetic acid extraction (Allen et al. 1974). The remaining soil was dried at 60°C and milled prior to determination of total P concentration by Kjeldahl digestion, based on the procedure of Taylor (2000). Phosphorus concentrations in the filtered solutions (both acid digests and extracts) were determined colorimetrically (Allen et al. 1974).

Total metals (Al, As [at end only], Cd [at start only], Cr, Cu, Fe, Mn, Ni, Pb and Zn) were determined by atomic absorption spectrometry after ashing the milled soils at 430°C for 6 h followed by a HCl/HNO$_3$ digestion (Allen et al. 1974).

Fertilization with phosphorus-saturated ochre

Soil pH was determined in 1 : 2.5 fresh soil/water ratio using a pH electrode.

Vegetation samples were digested with 18 x H$_2$SO$_4$ and 30% w/v H$_2$O$_2$ in a heating block at 330°C for 6 h, and analysed for P as described above for the soils.

Grain samples were also digested in concentrated HNO$_3$ under reflux for 2 hours and analysed for Pb and Cd concentrations using atomic absorption spectrometry.

Field trial (March–August 2003)

Following the pot experiment, field trials were conducted with the same crops, and treatments were based on the results of the pot experiment. Barley was grown at Glenconcorse Mains Farm, in the same field from which soil had been collected for the pot experiment, and an acid grassland site of low P status was selected at Castlelaw Farm nearby.

At both sites, after soil sampling, four replicates of three treatments were set out in a randomized block design as follows: a control with no added P (CO), a conventional P treatment (CP) with P application rate as recommended by SAC, and an ochre treatment, O(1), which had the equivalent amount of acetic acid extractable P added in the form of P-saturated ochre as the conventional P treatment.

At the barley site, P-saturated ochre and triple super phosphate (TSP) were applied by hand at 85 kg P$_2$O$_5$ ha$^{-1}$ to each of the relevant 3 m x 2 m plots. The seedbed was then cultivated to a depth of 15 cm using a rotary tined implement. Barley seeds (cv. Golden Promise) were sown at a rate of 200 kg ha$^{-1}$, the plots rolled, 60 kg N ha$^{-1}$ as NH$_4$NO$_3$ and 60 kg K$_2$O ha$^{-1}$ were applied throughout, and a further 60 kg N ha$^{-1}$ was applied 3 weeks later.

The grass plots (1 m x 1 m) were on an existing sward that had been grazed the previous summer by sheep and cattle. Phosphorus-saturated ochre and TSP (at 30 kg P$_2$O$_5$ ha$^{-1}$) along with N as NH$_4$NO$_3$ (62 kg N ha$^{-1}$) were applied by hand to each of the appropriate experimental plots. The plots were covered by cages to prevent grazing.

At the end of the trials in August, 5 soil cores were taken from the top 15 cm (barley) and 7.5 cm (grass) of each plot using a 2.5 cm diameter ‘c’ auger and bulked to give one soil sample per plot. Available P and soil pH were determined immediately on a portion of the fresh soil, the remainder being dried and milled for determination of total P and metals. All the analytical techniques used were as described above for the pot experiment.

Grass samples were collected by harvesting a 25 cm x 25 cm area by hand within each plot in March before treatments were applied, and again in June and August. After each sampling, the whole plot area was cut and the excess grass discarded. Barley was harvested by hand in a 50 cm x 50 cm area within each plot in August. Barley heads were separated from the stems, dried, then threshed to obtain the seed. All vegetation samples were dried and weighed, and total P and metals determined as described above for the pot experiment.

Tree seedling pot experiment (April–November 2003)

Fifteen, 1-year-old birch (Betula pendula) and spruce (Picea sitchensis) seedlings were sorted by height and every third
tree chosen to give 5 replicates of each of three treatments as follows: a control with no added P (CO), a conventional P treatment (CP) and an ochre treatment, O(1). To 3-L pots filled with peat, P was applied at a rate of 60 kg P ha\(^{-1}\), either as P-saturated ochre or \(\text{KH}_2\text{PO}_4\) plus N as \(\text{NH}_4\text{NO}_3\), equivalent to 200 kg N ha\(^{-1}\) and K as KCl, equivalent to 130 kg K ha\(^{-1}\). The pots were arranged randomly outdoors in the University of Edinburgh garden and watered as required throughout the growing season.

Tree height and stem diameter were measured at the start and end of the experiment (April and November 2003) and the tree volume calculated.

Statistical analysis
All data were analysed with Minitab v.13 using ANOVA followed by Tukey tests. Significance levels throughout are for \(P < 0.05\), unless otherwise stated.

RESULTS

Soil P concentrations
In the pot experiments with barley and grass, total soil P concentration increased as expected with increasing amounts of added P-saturated ochre (Figure 1). For both crops, the soil from treatment O(5), to which the most P-saturated ochre had been added, contained significantly more total P than the other treatments, while the soil from treatment O(0.5), to which the least amount of P-saturated ochre had been added, was not significantly different from the control. Similarly, in the field experiment (results not shown), the soil from treatment O(1) with P-saturated ochre applied contained significantly more total P than either the conventional P treatment (CP) or the control (CO). However, only about 4% of the measured total P in the ochre was immediately plant-available (Table 1). Figure 2 shows that the amount of plant-available P in the soil at the start and end of the pot experiment increased with increasing ochre concentration. Soil in the O(5) treatment contained significantly more available P than the other treatments. The CP treatment was not significantly different from O(1), the equivalent ochre treatment, at the start of the experiment. However, at the end, the O(1) treatment contained significantly more available P than the CP treatment for the barley soil, but not for the grass soil. The same results (not shown) were found at the end of the field trial: for barley, significantly more plant-available P was measured in soils from the O(1) plots compared with the CP plots, but this was not the case in the grass plots.

GLM analysis showed that the plant-available P concentration was significantly lower at the end of the pot experiment than at the start in both the grass and barley soils \((P < 0.01)\). However, there was a significant interaction between treatment and time \((P < 0.01)\). In both soils the concentration of available P decreased in all treatments during the experiment, but the decrease was less pronounced in the ochre treatments than in the CP treatment.

Soil pH
Soil pH increased with increasing ochre content in both the pot and field experiments, but there was no difference in pH between the CO and the CP treated soils. In the pot experiment, the pH of the O(5) treatment \((6.8 \pm 0.1)\) was significantly higher than the other treatments. The pH of the O(1) soil \((6.0 \pm 0.2)\) was significantly higher than that of the CP treatment \((5.5 \pm 0.1)\). In the field experiment, the pHs of the O(1) plots were also higher than in the CP plots; but this was only significant in the barley soil \((CP 5.5 \pm 0.2, O(1) 5.9 \pm 0.1 and not in the grass soil (CP 5.5 \pm 0.1, O(1) 5.6 \pm 0.1)).

Soil metal concentrations
Metal concentrations measured in the P-saturated ochre are shown in Table 1. Total soil metal concentrations measured at the end of the barley pot experiment are shown in Figure 3 (grass results are similar). There were generally no significant differences between treatments in soil concentrations of Al, Cr, Ni and Zn in either the barley or the grass pot experiment. Cu and Pb concentrations were low in all soils; the soils with ochre added were not significantly

![Figure 1](image1.png)  
**Figure 1.** Total soil P concentration (± s.e.) in grass and barley soils at the start of the pot experiment. CO = unfertilized control; CP = conventional fertilizer; O(0.5)--O(5) = ochre at 0.5--5 times available P in CP treatment. Bars with the same letter are not significantly different.
different from each other but contained more Cu and Pb than the unfertilized control. Soil Fe concentration increased with ochre content, as expected, with the O(5) treatment containing significantly more Fe than the other treatments in both barley and grass soils. Similarly, soil Mn concentration increased with increasing ochre content, especially in the barley soil where the O(5) treatment contained significantly more Mn than the other treatments (Figure 3).

There were no significant differences in metal concentrations among any of the treatments at the end of the field trials (results not shown).

An attempt was made to determine the Cd concentrations of the soil digests at the start of the pot experiment, but concentrations were below the limits of detection. The same was true for digests of the ochre. Soil As concentrations were determined in the O(5) and CO treatments at the end of the pot experiment. Concentrations were very low (<2 mg As kg\(^{-1}\) dry soil) and there was no significant difference between the two treatments. The concentration of As in P-saturated ochre itself is very low (0.10 mg kg\(^{-1}\) dry weight), so ochre additions should not significantly increase soil As content. Thus, no further analysis of soil Cd and As concentrations was carried out.

**Vegetation analysis**

There were no significant differences between treatments in total biomass of either grass or barley in the pot experiment. Barley grain mass was not significantly different between treatments (Figure 4). However, for both grass and barley, there was an increasing trend in stem mass and a decreasing trend in root mass as the ochre content of the soil increased (illustrated in Figure 4 for barley only). In the field trials, plots to which ochre had been added yielded more barley grain and grass dry matter than the conventionally fertilized plots; however, these were not significant differences (barley grain yield: O(1) = 5.42 ± 0.78; CP = 4.84 ± 0.20; CO = 4.51 ± 0.42 t ha\(^{-1}\); dry grass yield in June: O(1) = 4.9 ± 2.2; CP = 4.6 ± 1.4; CO = 4.8 ± 0.6 t ha\(^{-1}\)).

In general, the concentrations of P in both barley and grass in the pot experiment increased with increasing ochre application rate to the soil (data shown in Table 2 for barley only). No significant difference in the amount of P was found in the plants grown in the O(1) and CP treatments. In the field trial, there was significantly more P in the barley stems grown in the O(1) plots. In contrast, there was no difference between treatments in the amount of P in the grass (results not shown).

No significant differences were found in the Pb and Cd contents of the barley grain between plants grown in the O(1) and CP treatments of the field experiment (results not shown).

In the tree seedling experiment, the volume of the seedlings fertilized with ochre treatment O(1) and with conventional fertilizer (CP) was significantly greater than that of the controls (CO) (Figure 5).

**DISCUSSION**

**Soil P concentration**

The results from both the pot and field experiments showed that adding P-saturated ochre to soil increased both plant-available and total P concentrations in the soil. Available P decreased in all soils during the experiments, but the change was greater in the conventional P (CP) treatment than in the ochre treatments (Figure 2).

In the pot experiment, the P uptake by plants in the P-saturated ochre treatments and in the control substantially exceeded the depletion of available P in the soils (Table 2, Figure 6). The P uptake by grass in the CP treatment at the end of the pot experiment was slightly greater than the depletion of plant-available P in the soil, and also greater than the amount of conventional P added (70 mg). In contrast, barley from the CP treatment contained less P.
than the depletion of plant-available P in the soil, suggesting that net fixation of P by soil minerals had occurred during this experiment.

The difference between the plant P uptake and the depletion of available P in the P-saturated ochre-treated soils during the experiment is attributed to the gradual conversion of initially unavailable P in the ochre (and in the soil minerals) into plant-available forms. Possible mechanisms include the action of organic acids from root exudates, which can dissolve unavailable soil Ca, Fe and Al phosphates (Dakora & Phillips 2002) and increase the concentration of P in soil solution (Hinsinger 2001). Helal & Sauerbeck (1984) studied the influence of plant roots on P metabolism in soils and showed that there was considerable mobilization of P from less available fractions occurring in the root zone. Such an effect could be expected to operate
It is important when assessing the potential supply of P to take into account not only the amount that is immediately available to plants, but also the amount that can be released by desorption from solid surfaces during the growing season. Frossard et al. (2000) suggested that there is a continuum of mobility between the P found in soil solution and the P sorbed on to the solid phase, and that it is arbitrary to distinguish between available and unavailable fractions.

In this context, the P-saturated ochre appears to act as an effective slow-release fertilizer, and the greater amounts of available P left in the ochre-treated soils at the end of the experiments indicates an advantage for future crops, reducing the need for further applications of P fertilizer. For example, on the basis of these results, an addition of 40 t ha⁻¹ of P-saturated ochre would supply enough P for at least a second year’s cropping (Figure 2). Furthermore, the insolubility of P bound to ochre in water means that P loss as surface runoff is less likely than when conventional water-soluble P fertilizer is used. The modest liming effect of ochre (neutralizing value equivalent to 8% CaO, Table 1) would also be agronomically beneficial, 40 t ha⁻¹ of ochre being equivalent to 3.2 t ha⁻¹ of CaO. Loss of plant-available P in soils occurs by phosphate fixation, which is stronger in acid mineral soils. Such losses can be reduced by increasing the pH to between 6 and 7 (Mengel 1997). Increasing the soil pH would also inhibit the release of several potentially toxic metals from soil minerals.

**Plant responses**

No differences in barley grain yield between the ochre treatments were found in the pot experiment, despite the initial variation in available P concentration in the soil (Figures 2 & 4). The relationship between crop yield and available soil P concentration followed a classical asymptotic response curve (Higgs et al. 2000; Figure 7), with a critical soil P content above which increasing soil P did not significantly increase yield. Crop yields from the ochre treatments were greater than those from the CP and CO treatments, but not always significantly so. Yields from the O(0.5) treatment were greater than those from the CP treatment which initially contained twice as much available P, reinforcing the idea that in the soils treated with P-saturated ochre, P was gradually released from the ochre-bound form(s), providing plant-available P throughout the growing season.

Results from the field trials showed that crop yields were greater from the O(1) plots than from the CP plots, although not significantly so. Similarly, in the tree seedling experiment, seedlings grown in the O(1) treatment were larger than those grown in the CP treatment, but again not significantly so. Thus, using P-saturated ochre as a substitute for conventional fertilizer had no adverse effect on crop yield; rather, there was a tendency for greater yield from using P-saturated ochre.

A direct relationship was seen between the crop yield and the concentration of P in both the barley grain and the grass above-ground dry matter in the pot experiment: the greater the yield, the higher the P concentration in the plant material. Above-ground biomass from soils treated with P-saturated ochre had a higher P concentration than that from either the CP or CO treatments, again suggesting the continuing availability of P due to the gradual release of P bound to ochre.

**Potentially toxic elements**

One concern about applying ochre to soils would be the possible accumulation of potentially toxic elements (PTEs) such as Zn, Cu, Pb, and their uptake by plants. In this context, the most relevant soil quality guidelines for application of ochre to soil are those relating to the application of sewage sludge to agricultural land (MAFF 1998), which provide a series of soil PTE concentrations that indicate the need for action or further investigation (Table 3).
The results from the pot experiment show that there were no significant differences between the treatments for the Cr, Ni and Zn soil concentrations for either barley or grass soils at the end of the experiment. After treatment with P-saturated ochre, the average soil Cr, Ni and Zn concentrations were 163 ± 33, 94 ± 19 and 40 ± 9 mg kg\(^{-1}\) dry weight, respectively. For Cr and Zn the concentrations were well below the guidelines of 400 and 200 mg kg\(^{-1}\) dry weight, respectively. In contrast, the soil Ni concentration was much higher than the guideline values of 60 or 75 mg kg\(^{-1}\) dry weight (depending on soil pH). However, the Ni concentration of the ochre-treated soils was not significantly different from the unfertilized control, so the soil had not been contaminated because of the addition of ochre. At the end of the field trials, there were no significant differences between treatments in either the barley or grassland soils. Soil from ochre-treated barley plots had Cr, Ni and Zn concentrations of 147 ± 22, 65 ± 11 and 80 ± 21 mg kg\(^{-1}\) dry weight, respectively. Again, Cr and Zn were within guideline values, while Ni concentrations were around the guideline value, although again this was not significantly different from the control soil. The soil from the pot experiment had been taken from the barley field, so this observation reinforced the conclusion that the Ni had been present in the soil prior to the establishment of the experiment.

Soil Cu and Pb concentrations in all treatments were <20 and <45 mg kg\(^{-1}\) dry weight, respectively, in both the pot and field experiments, which were well below the guideline values of 100 and 300 mg kg\(^{-1}\) dry weight,
respectively. Soil As concentrations were measured in the O(5) and CO soils at the end of the pot experiment and found to be < 2 mg kg\(^{-1}\) dry weight, considerably below the guideline value of 50 mg kg\(^{-1}\) dry weight. Soil Cd concentrations were below the limit of detection. Thus, the addition of P-saturated ochre did not affect soil As and Cd concentrations.

Regarding plant uptake, the relevant maximum levels of Pb and Cd permissible in foodstuffs are set by the European Commission (Commission Regulation (EC) No. 466/2001). The values measured for barley seeds from ochre amended soil in the field experiment were 0.087 ± 0.142 mg Pb kg\(^{-1}\) wet weight and 0.005 ± 0.011 mg Cd kg\(^{-1}\) wet weight (adjusted to a grain moisture content of 15%), which are below the regulation values of 0.2 mg kg\(^{-1}\) wet weight set for both metals, and not significantly different from the Pb and Cd contents of grain from the conventionally fertilized soils. Thus the addition of P-saturated ochre to soil did not adversely affect the concentration of Pb or Cd in the grain.

With the exception of Ni, an annual application of 40 t ha\(^{-1}\) of P-saturated ochre would result in metal applications that are within the limits allowed for sewage sludge. For example, the maximum permissible average application rates of Zn, Cu and Pb over 10 years are 15, 7.5 and 15 kg ha\(^{-1}\) yr\(^{-1}\), respectively (MAFF 1998); an application of 40 t ha\(^{-1}\) of P-saturated ochre would result in additions of 4.0, 0.6 and 0.3 kg ha\(^{-1}\) yr\(^{-1}\), respectively. Furthermore, since P-saturated ochre acts as a slow-release P fertilizer, annual application would not be necessary in normal agricultural practice to maintain soil P concentrations, thus further reducing the average rate of metal additions and keeping them all within acceptable limits, including Ni.

No maximum application rate is given for Fe in the UK regulations (MAFF 1998). Although the amount of Fe added to the soil seems large (10.9 t Fe in 40 t ochre), this is only equivalent to raising the Fe concentration from 2.4 to 2.6% and 3.1 to 3.4%, still well within the range for soils in this region (Paterson et al. 2003).

The use of sewage sludge in forestry does not significantly affect the human food chain and trees are less susceptible to metal toxicity than agricultural crops (Wolstenholme et al. 1992). However, Wolstenholme et al. (1992) recommend that metal additions and subsequent soil concentrations should not exceed the levels prescribed in the Sludge (Use in Agriculture) Regulations (SI 1989), as updated in Table 3.

### CONCLUSIONS

Applying P-saturated ochre as a fertilizer increases the P status of soils and has a useful liming effect. Ochre P is less water-soluble than conventional P fertilizer, thus reducing the potential for diffuse pollution from agricultural land. The ochre from Polkemmet caused no metal contamination, but other sources would need to be monitored to ensure that they did not contain undesirable concentrations of metals.

The slow release of P from P-saturated ochre means that less frequent applications would be required than when using conventional P fertilizer. All crops studied here grew as well when fertilized with P-saturated ochre as with conventional P fertilizer.

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### REFERENCES


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Table 3. Maximum permissible concentrations of potentially toxic elements (PTEs) in soil after application of sewage sludge to agricultural land (MAFF 1998).

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<th>PTE</th>
<th>Max. permissible concentration (mg kg(^{-1}) dry wt)</th>
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