Recycling mineral nutrients to farmland via compost application

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Abstract Increased cultivation of farmland has resulted in nutrient deficiency and consequently fertility degradation of soils. This research examined the application of composted wastes in terms of the feasibility and effectiveness of recycling plant essential minerals. Minerals in composts (derived from sewage sludge, livestock excrement, and municipal solid wastes, respectively) and in amended soils were observed. Ca/Mg ratios in amended soils and the effect of compost applications (mineral nutrients and heavy metals) on plant uptake were also studied. Results showed that composts, especially those made from sewage sludge and livestock excrement, were richer in mineral nutrients but also contained more heavy metals than untreated soil. The increase in some elements and plant-growth-essential Ca/Mg ratios were found in amended farmlands, implying that compost applications have made up for the nutrient deficiency and have adjusted chemical conditions of the soil. The soil contamination from heavy metals was noticeable. However, some results showed that the large existence of mineral nutrients and heavy metals in soils has caused no significant increase in the plant uptake of elements. The controlled composting process and farmland uses are believed necessary for reducing the heavy metal accumulation in agricultural plants.

Keywords Ca/Mg ratio; compost; farmland; heavy metal accumulation; mineral nutrient; transfer factor

Introduction

Mineral nutrients are essential for plant growth and human health, so the issues of nutrient deficiency and the long-term fertility degradation of cultivated lands are of great concern. On the other hand, solid wastes, mainly composed of C, H, O and N, and those abundant in inorganic nutrients, have been increasingly incinerated for landfill. All of these mineral nutrients originated from our earth, namely from farmlands. Therefore, the goal of our work is to assess the feasibility of recycling mineral nutrients to farmlands via a compost application. Finally, the heavy metal accumulation in amended soils and agricultural plants is well considered.

Methods

Site description and sampling

During a three-year period 2001–2003, a series of samplings were conducted in Yamaguchi, Nagano, and Miyazaki prefectures of Japan. In these regions, the farmland applications of composts had been carried out to different extents. Generally, composts were surface broadcast and mainly incorporated to a 15-cm depth after application. At first, five kinds of composting products [i.e. Garbage Compost (GC, derived from kitchen garbage and sawdust), Sewage Sludge Compost (SSC, from sewage sludge, 80%, and waste water sludge from food industry, 20%), Hen Excreta Compost (HEC, from hen excreta and sawdust), Swine Manure Compost (SMC, from swine manure, sawdust, tree rubbish and coffee dregs) and Cattle Excreta Compost (CEC, from cattle excreta, bark and sawdust, 1:1:1)] and three compost-amended soils (Table 1) were collected for

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Table 1 Composting-amended soils (the 1st stage of experiment)

Compost amended soil			Compost application	Plants
Garbage compost amended soil (a)	GS_a	Sandy loam	GC, 10 t/ha/yr, greenhouse, 11 yrs	White small turnip, radish
Garbage compost amended soil (b)	GS_b	Sandy loam	GC, 30 t/ha/yr, greenhouse, 11 yrs	White small turnip, radish
Garbage compost amended soil (c)	GS_c	Sandy loam	GC, 100 t/ha/yr, greenhouse, 11 yrs	White small turnip, radish
Background soil corresponding to GS	GSB	Sandy loam	Fertilizer, greenhouse, 11 yrs	White small turnip, radish
Swine manure compost-amended soil (1)	SMS-1	Andosol	SMC, 40 t/ha/yr, paddy field, 6–7 yrs	Rice
Swine manure compost-amended soil (2)	SMS-2	Andosol	SMC, 40 t/ha/yr, paddy field, 1 yr	Rice
Background soil corresponding to SMS	SMSB	Andosol	Fertilizer, upland field	Rice
Sewage sludge compost amended soil	SSS	Andosol	SSC, 60 t/ha/yr, upland field, 7–8 yrs	Pasture
Background soil corresponding to SSS	SSSB	Andosol	Nothing, upland field	–

observing the elements in composts and amended soils. Soil sampling sites were located in the four corners and central parts of selected farmlands, and only the portions in the topsoil (0 ~ 15 cm) were taken. And then, the soil-plant transfers of elements were further examined. The samples taken were seven agricultural plants (i.e. carrot, Chinese cabbage, snap pea, cucumber, rice, broccoli and cabbage) and the soils near plant roots (Table 2). "Control soil" means the farmlands where relatively lower amounts of composts were applied. Impurities (e.g. stone and glass) were removed from the soil samples. Edible parts of agricultural plants were washed and then cut into small pieces. All compost, soil and plant samples were dried for one day at 105 °C, smashed to powder, and then stored at 4 °C.

Pretreatment and chemical analysis

The contents of eleven kinds of elements including Ca, Mg, Fe, Mn, Cu, Zn, Co, Ni, Cd, Cr and Pb in composts, soils and agricultural plants were measured. The EPA standard procedure was adopted in the sample digestion (USEPA, 1996). Atomic Absorption Flame Spectrophotometer (AAS, Shimadzu AA-66GPC) and Inductively Coupled

Table 2 Farmlands where agricultural plants were collected (the 2nd stage of experiment)

Plant	Compost amended soil		Control soil	
Carrot	CEC, 20 t/ha; rice bran, 0.750 t/ha; other additives, 3.6 t/ha. Upland field	Andosol	CEC, 6 t/ha. Upland field	Andosol
Chinese cabbage	CEC, 20 t/ha; other additives, 600 kg/ha. Upland field	Andosol	CEC, 6 t/ha. Upland field	Andosol
Snap bean	SMC, 20 t/ha; Ca fertilizer, 100 kg; and other additives. Upland field	Andosol	Additives, 1.33 t/ha. Upland field	Andosol
Cucumber	CEC, 20 t/ha; additives, 6 t/ha. Greenhouse	Andosol	Additives, 3.1 t /ha. Greenhouse	Andosol
Rice	HEC, 10 t/ha. Paddy field	Gley soil	Additives. Paddy field	Gley soil
Broccoli	HEC, 10 t/ha; additives, 6 t/ha. Upland field	Gley soil	Fertilizers, ~5 t/ha. Upland field	Gley soil
Cabbage	HEC, 10 t/ha; additives, 6 t/ha. Upland field	Gley soil	Additives. Upland field	Gley soil

*Additives: general designation of various other additives in farmland applications

Plasma-Atomic Emission Spectrometry (ICP-AES, PerkinElmer Optima 3300DV) were used in the measurement.

Results and discussion

Nutrients in composts and amended soils

A variety of elements, in differing amounts, were found in various composts and amended soils.

Except for Ca, Mg and Pb, it was found that Cu, Fe, Mn, Zn, Cd, Cr, Ni and Co were more abundant in SSC and SMC than in CEC, HEC and GC. Results of Cu and Ca are shown in Figures 1 and 2, respectively. It is estimated that both calcium and magnesium are two chemical elements, commonly existing in the environment and hence abundant in GC. The same abundance of lead in GC, as in other composts, could be attributed to the geological soil condition, fertilizer and the use of lead-containing products.

Comparisons of chemical elements in composted wastes and background soils are shown in Table 3. Results indicate that SSC, HEC, and SMC are rich in Ca, Mg, Cu, Zn and Cd, whereas CEC is relatively poorer in all elements except for Ca, Zn and Cd, as is GC for the element Ca. From the viewpoint on recycling of plant essential nutrients in organic solid wastes to farmlands, the feasibility of using composted wastes, mainly SSC, HEC, SMC, as well as CEC, in soil amendment can be well substantiated. Other composts, such as GC, can be reused as "the carbon additive". Reuse of compost to enrich farmland appears to be an economic and environmentally friendly alternative to the present practice of incineration and land filling.

In many countries today, various Max Permissible (Allowable) Concentrations, or Contaminant Concentration Limits for the biosolid application to land (USEPA, 1999)

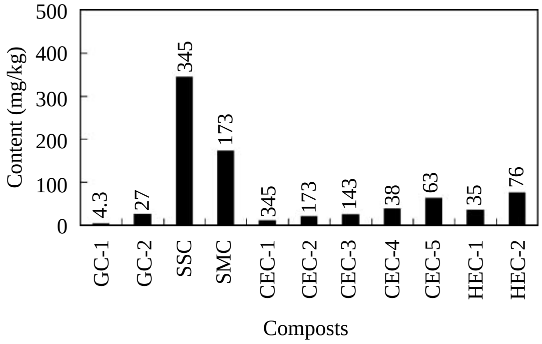

Figure 1 Cu in various composts

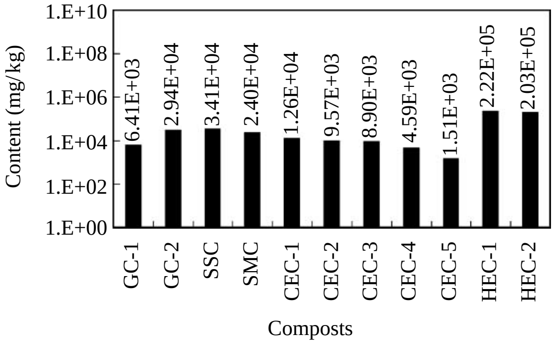

Figure 2 Ca in various composts

Table 3 Minerals in background soil and comparisons with composts

	Contents of background soil (control) mg/kg	Metal content of compost / Element content of soil (dry wt./dry wt.)				
		SSC	HEC	SMC	CEC	GC
Ca	3.13×10^3 ($109-6.33 \times 10^3$)	10.9	68.0	7.68	2.38	5.73
Mg	5.99×10^3 ($164-1.85 \times 10^4$)	1.87	1.69	2.10	0.80	0.43
Fe	4.29×10^4 ($1.93 \times 10^4-7.04 \times 10^4$)	0.50	0.03	0.14	0.07	0.17
Mn	676 ($177-1.11 \times 10^3$)	1.07	0.50	0.56	0.51	0.29
Cu	41.3 (12.8–82.5)	8.35	1.34	4.20	0.76	0.37
Zn	115 (51.5–187)	8.06	4.27	3.61	2.72	0.46
Pb	23.0 (10.6–49.3)	0.26	1.11	0.25	0.25	0.15
Cd	0.16 (0.037–0.47)	10.6	2.39	1.42	3.16	0.48
Co	13.7 (1.78–29.0)	1.36	0.02	0.08	0.04	0.09
Ni	37.8 (5.87–84.7)	3.85	0.13	0.21	0.34	0.26
Cr	41.5 (7.68–81.3)	0.01	0.21	0.00	0.36	0.39

are being applied. Here, "Ceiling Concentrations of Inorganic Pollutants in Sewage Sludge" (suggested in "EPA CFR 40 Part 503") were used for evaluating chemical elements in composts. In this regulation, elements Cd, Cu, Pb, Ni and Zn are limited to below 85, 4,300, 840, 420 and 7,500 mg/kg, respectively. Experimental results indicated that all maximum values (Cd: 1.85 mg/kg CEC-5; Cu: 345 SSC; Pb: 49.6 HEC-1; Ni: 146 SSC; Zn: 1,050 CEC-5) of composts were far below those limits. It appears conclusive, therefore, that the environmental risk of compost application with inorganic pollutants is limited or at least controllable.

Practical land applications, with different loading rates, of GC, SMC and SSC were observed here. The elements in GC-amended soils (GS) contained quite similar levels to that in the control soil (GSB) (Figure 3(a)). The elements had scarcely accumulated in amended farmlands, that is, the GC application brought about no negative effect on the soil as to the heavy metal contamination. On the contrary, that in SMC-amended (SMS) and SSC-amended soils (SSS) increased to different degrees with compost application. Figure 3(b) shows that although seven-year applications of SMC have led to copper accumulation in soils, the values were still lower than Soil Boundary Value for

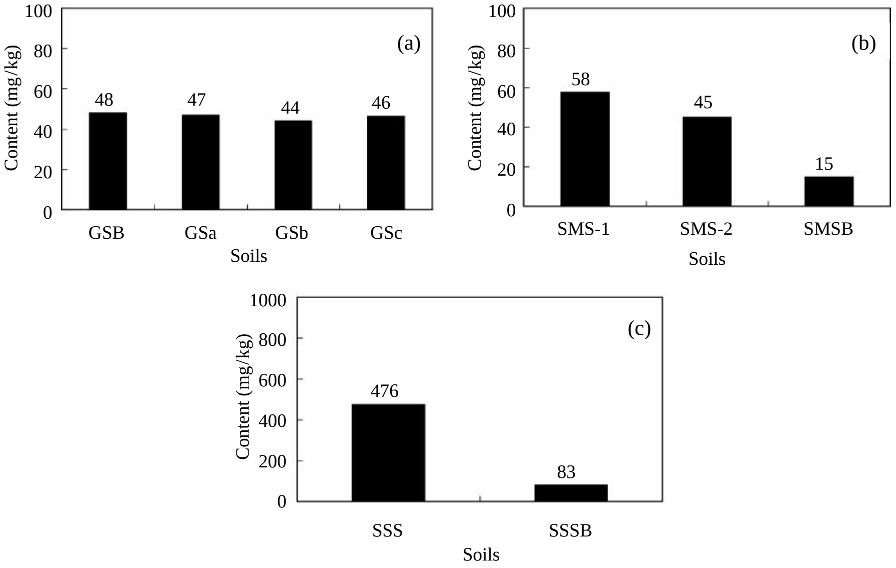

Figure 3 Cu accumulation in farmlands amended with GC (a), SMC (b) and SSC (c)

Cu, 50–140 mg/kg, recommended by the European Union (EU, 86/278/EC). Comparatively, the copper accumulation in SSC-amended farmland (476 mg/kg) was, remarkably, several times higher than the Soil Boundary Value (Figure 3(c)). Excessive compost application was considered to be one of the major causes. Another contributing factor may be that most of inorganic copper containing salts are often poorly soluble and even insoluble and therefore easily accumulate in soils. Evident accumulations of elements Mn, Zn, Cd, Ni, Co have been found in the SSC-amended farmland, while only a few appeared in SMC-amended soils. Heavy metal contamination remains a critical issue in the sewage sludge application in soil improvement. Controlled application of composted sewage sludge is essential for sustainable reuses of biosolid wastes in farmland amendment.

The optimum Ca/Mg ratio ($R_{Ca/Mg}$) in farmlands is often recommended for good crop production. Available evidence suggests that plants grow well and meet their Ca and Mg needs in soils with $R_{Ca/Mg}$ anywhere from 1:1 to 15:1 (Brady and Weil, 2001). Although the plant health and growth is not affected by soil $R_{Ca/Mg}$ in this range, $R_{Ca/Mg}$ with this range in the plant tissue may influence the mineral nutrition of grazing animals.

Results of soil samples in the three areas mentioned above (Table 1) have also demonstrated that the $R_{Ca/Mg}$ values were adequate by applying SSC, CEC and GC (Figure 4). Before composts were applied, values of $R_{Ca/Mg}$ in background soils (SSSB, SMSB and GSB) were far beyond the range from 1:1 to 15:1. In SSSB, $R_{Ca/Mg}$ went as high as 500, while those in SMSB and GSB were low, down to near 0 and 0.2, respectively. With the addition of composts, the $R_{Ca/Mg}$ gradually changed. In SSS, $R_{Ca/Mg}$ rapidly decreased down to nearly 10. Such a significant change could be attributed to both the long-term continuous application (6–7 yr) at a large loading rate of SSC (60 t/ha.yr), and considerably high contents of mineral elements in SSC. As for the application of SMC, $R_{Ca/Mg}$ was raised from 0.04 to 0.52 in the first year and then to 7.99 in the 6th to 7th year. Although the increase in $R_{Ca/Mg}$ for SMS was lower than that in SSS, due to a relatively low loading rate (40 t/ha) and fewer mineral elements in SMC, the imbalance of calcium and magnesium was largely improved. With respect to that of GC, slight but regular changes were observed: $R_{Ca/Mg}$ was gradually changed from 0.17 to 0.06

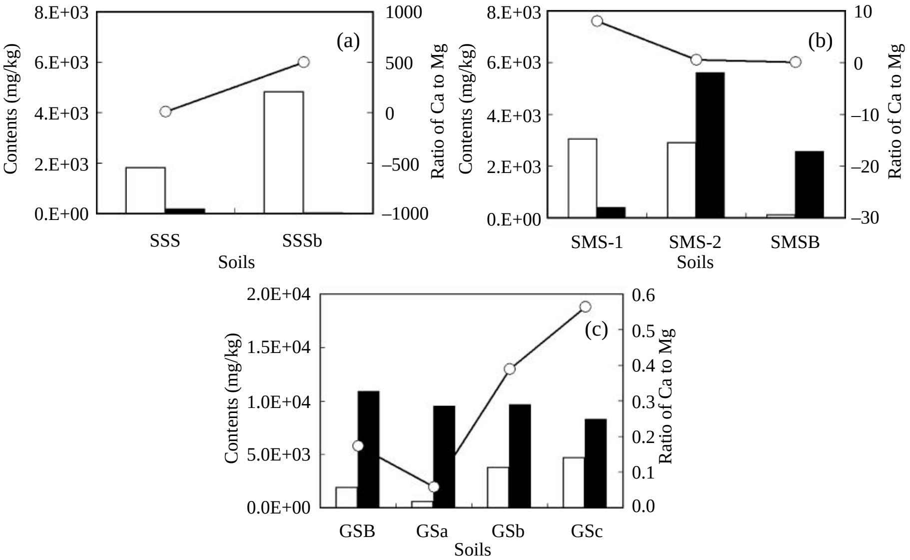

Figure 4 Contents and ratios of Ca and Mg in soils amended with SSC (a), SMC (b) and GC (c) at different degrees. □: Ca, ■: Mg, ○: Ratio of Ca to Mg

(although slightly down here), 0.39 and then 0.56, respectively. The extents of increase in $R_{Ca/Mg}$ can hardly be compared with what happened in SSS and SMS, but the improvement is still important, since the main contribution of the GC application is considered to be that of returning the chemically steady organic matters to the soil. By adjusting the ratio of calcium to magnesium (an essential plant-growth range from 1:1 to 15:1), compost applications to farmland can be very effective for soil improvement.

Plant uptake in amended soils

Minerals were even higher in organically grown potatoes and sweet corn than in conventionally grown ones (Warman and Havard, 1998). In the 2nd stage of this study, we examined seven other agricultural plants (Table 2). With a few exceptions, similar tendencies were observed. Figure 5 presents some selected results concerning carrot, Chinese cabbage, snap bean, cabbage, rice, and corresponding amended soils. It shows the comparison of metal contents before and after the compost applications, in which CEC, SMC and HEC were applied to different extents as shown in Table 2. This figure emphasizes the content changes (increase and/or decrease) of elements Ca, Mg, Fe, Mn, Cu, Zn, Co and Cr in agricultural plants and amended soils.

In carrots, the contents of minerals except Mn and Zn increased with the increase in the soils. As CEC was added, the element accumulation grew accordingly. Two exceptions showed the Mn and Zn accumulations in soils while there was a decrease in plant uptake. Such a phenomenon has also been found in the CEC application in Chinese cabbage production. Except for Mg, all elements significantly accumulated in the CEC-amended farmland soil, while there were notable decreases in Mn, Cu, Zn and Cr in the Chinese cabbage.

In the snap bean production, the SMC application caused Mn, Cu and Cr accumulations in the soil while only elemental Cu was significantly more than before. As for the HEC application in cabbage production, we found rather consistent increases in all minerals in plants and in the corresponding land amended with HEC. Previous studies show that, quite different from CEC, HEC contains plenty of water-soluble and exchangeable

	Ca	Mg	Fe	Mn	Cu	Zn	Co	Cr
SOIL								
Carrot	□	□	□	□	□	□	□	□
Chinese cabbage	□	■	□	□	□	□	□	□
Snap bean	■	■	■	□	□	■	■	□
Rice	□	□	□	■	■	□	□	■
Cabbage	□	□	□	□	□	□	□	□
PLANT								
Carrot	□	□	□	■	□	■	□	□
Chinese cabbage	□	■	□	■	■	■	□	■
Snap bean	□	□	□	□	■	□	□	□
Rice	■	□	□	■	□	□	□	□
Cabbage	□	□	□	□	□	□	□	□

Figure 5 Content changes of elements in compost-amended soils and in vegetables: □: Increase, ■: Decrease of element contents

Table 4 Transfer factors of elements in agricultural plants grown in compost-amended farmlands

Agricultural plant	**Compost**	**Elements**							
		Ca	**Mg**	**Fe**	**Mn**	**Cu**	**Zn**	**Co**	**Cr**
Carrot	CEC	0.27	0.48	6.5E-4	1.2E-2	9.2E-2	0.19	3.7E-3	4.4E-3
Chinese cabbage	CEC	4.2	1.0	2.6E-3	3.8E-2	0.16	0.42	1.7E-2	1.8E-2
Snap bean	SMC	1.31	0.90	1.3E-3	0.15	0.17	0.41	2.5E-2	4.1E-3
Cucumber	CEC	1.60	0.73	1.7E-3	4.3E-2	0.96	1.1	2.9E-2	9.7E-3
Rice	CEC, HEC	6.8E-2	0.92	9.9E-4	0.10	0.30	1.0	8.3E-3	5.9E-3
Broccoli	HEC	1.4	1.8	6.6E-3	8.4E-2	0.56	1.9	5.1E-2	1.0E-2
Cabbage	HEC	1.6	1.4	4.0E-3	3.8E-2	0.26	0.55	3.3E-2	7.4E-3

(generally named as bioavailable, and sometimes EDTA and DTPA-extractable) forms of mineral elements (Liu, 2003), easily causing simple and rapid plant uptake. However, these two forms usually are far less in CEC (1–2% of total amounts of minerals) than in HEC (high up to 10%∼20%) (Liu, 2003). Nevertheless, in another case of HEC application (rice production), the above-mentioned consistent increases didn't appear. Possibly in this case, irrigation water had reduced the influence of bioavailable minerals via efficient soil rinse. As a result, several exceptions were found for elements Ca, Mn, Cu and Cr.

Therefore, we shouldn't simply attribute the high element plant uptake to the element accumulation in soils. In practice, as reported in previous literature (Petruzzelli, 1989), the bioavailability of elements is the key factor affecting plant uptake. Further studies should focus on depressing the bioavailability of heavy metals and even the accumulation of toxic metals in edible portions of agricultural plants, effectively utilizing the plant-essential minerals. At least, the accumulation of designated components, e.g. toxic metals, in plants should be controllable.

In the studies of soil contamination and remediation involved in radioactive/toxic metals (Groudev *et al.*, 2001a,b) and of food safety (McLaughlin *et al.*, 1999), the soil-plant transfer of elements was an issue of great concern. It is often expressed by Transfer Factor (Ehlken and Kirchner, 2002; Cui *et al.*, 2004). Transfer Factor is usually regarded as a constant for one sort of plants and can be expressed as follows:

Transfer Factor = Metal content of plant tissue / Metal content of the soil where the plant grew

Here, all contents are mg/kg, based on dry weight.

Here, we estimated the Transfer Factor of minerals to agricultural plants from farmlands amended with composts in different sorts and quantities (Table 2). The dry weight basis was measured for the metal concentration in plant tissue, although the fresh weight basis is also sometimes used (Cui *et al.*, 2004). High Transfer Factors of mineral nutrients validate the compost application. Transfer of toxic elements is harmful for human health. The results (Table 4) show that:

- chinese cabbage, snap bean, cucumber, broccoli and cabbage can effectively accumulate mineral nutrients such as Ca, Mg, while all plants absorb less Fe and Mn;
- plant uptakes are low for heavy metals Cu and Zn, and especially low for Co and Cr.

Conclusions

Sewage sludge compost contains considerably more mineral nutrients and heavy metals than the composts derived from livestock excrement or from household garbage. Element contents of composts were all lower than the "Ceiling Concentrations of Inorganic Pollutants in Sewage Sludge" suggested in "EPA CFR 40 Part 503". The compost applications have brought out elemental accumulation in soil, mostly lower than the environmental criteria except for Cu, Zn and Pb. The nutrient deficiency was, to some extent, reduced. Moreover, the Ca/Mg ratios of several amended farmlands were adjusted to a range between 1:1 and 15:1, which is more suitable for promoting the healthy plant growth.

The soils with high element contents predictably generated the agricultural plants containing abundant mineral nutrients as well as heavy metals. However, there were a lot of exceptions. Some fields had a high plant uptake but low total element contents. It is probable that there was a high level available form but a low amount of elements in those fields. To some extent, the Transfer Factor was different from one element to another, i.e. generally low for heavy metals while relatively high for minerals such as Ca and Mg.

Finally, there is reason to believe that controlled farmland application of composted wastes is not only practical for soil production efficiency, but also essential for the safe and sustainable reuse of wastes. While still potentially problematic, prudent management can to some extent lessen heavy metal accumulation, and the farmland can be made more productive by the application of composted wastes.

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