TRACE ELEMENTS IN MUNICIPAL SOLID WASTE COMPOSTS: A REVIEW OF POTENTIAL DETRIMENTAL EFFECTS ON PLANTS, SOIL BIOTA, AND WATER QUALITY

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Abstract—Composts produced from municipal solid waste (MSW) contain trace amounts of metals and metalloids. Existing data from field experiments with MSW compost suggest that plant uptake of copper, nickel, arsenic, and lead will be slight, but boron may occasionally cause phytotoxicity. Most plant species take up little cadmium, but uptake of cadmium from MSW compost-amended soils by species that most readily accumulate cadmium has not been examined under field conditions. Some mushroom species can accumulate cadmium and mercury from MSW compost. The average values of lead, copper, and zinc in MSW composts may exceed limits recommended to protect invertebrates in soils, but these limits may be conservative. There is some evidence that metals in MSW composts can harm some soil microbiota, but such effects have not always been found. Metal concentrations in MSW compost leachates can exceed U.S.A. and E.E.C. drinking water standards, but under field conditions subsoil will presumably serve as a sink for metals, at least for many decades.

Keywords—Waste, compost, metal, metalloid, uptake, quality, plant.

1. INTRODUCTION

In this review, the term "MSW compost" is used to refer to compost produced from municipal waste after some degree of separation has been performed to remove inorganic (non-compostable) materials. Municipal solid waste (MSW) is a heterogeneous mixture of materials, some of which contain trace metals and metalloids. Composts made from the organic material in solid waste will inevitably contain these elements, albeit at low concentrations after most inorganic materials have been removed. This review will focus primarily on how these elements are taken up by plants growing in soil to which MSW composts have been added. A brief discussion of the effects of these elements on soil biota and water quality is also included.

While considerable attention has been paid to the issue of land application of sewage sludges and composted sewage sludges in the U.S.A. during the last twenty years, land application of MSW composts has received comparatively little attention. However, there has been a recent resurgence of interest in this topic as other options for solid waste disposal such as landfilling and incineration become less publicly acceptable and increasingly costly. Since relatively little research has been done on the U.S.A. on MSW composting, much of the material reviewed herein is from European sources. The composts used in many older studies were produced using much simpler technology than that available today. Some of these composts contained higher levels of trace metals than those produced today, but the data from these studies are still valuable for assessing metal uptake by plants.

Since MSW composts are similar to sewage sludge in some respects, much of what has been learned about sewage sludge may also apply to MSW composts. Numerous reviews of the effects of adding sewage sludge and composted sewage sludge to land have been written. For example, Chaney1,2 discusses a recent risk assessment approach used by the U.S.A. Environmental Protection Agency (E.P.A.) as a basis for regulating trace metals and other contaminants in sewage sludge for land application. He suggests that most aspects of this assessment can be used directly to evaluate the risks of trace metals in MSW composts.3 A discussion of many aspects of land application of sewage sludge to cropland, particularly oriented toward the northeastern United States, can be found in a bulletin of the Pennsylvania State University.4
In discussing trace metals and metalloids it is important to recognize that many elements are naturally present in trace amounts in the soil and water as a result of the weathering of rocks. Elements that are present in soils can be leached into surface water or groundwater, be taken up by plants, volatilized, or may be complexed with soil components such as clay and organic matter. Many trace elements are recognized as essential for plant growth; of these, this review will focus on boron (B), zinc (Zn), copper (Cu), and nickel (Ni). While these elements are required by plants in small amounts, higher amounts are phytotoxic (deleterious to plants). For agricultural crops, deficiency can occur even when these elements are present in the soil, since at high pH or in the presence of large amounts of organic matter these elements may not be available for plant uptake. Other elements of concern primarily due to their toxicity to animals and humans that consume contaminated plants include: arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg). While this review will focus on the potential for toxicity, there are also potential beneficial effects of trace metals in MSW composts for agriculture and horticulture. Soils that have been cropped for many years may be deficient in nutrients such as Zn and Cu, and MSW compost could mitigate such deficiencies. MSW compost may also limit phytotoxicity by tying up trace pollutants and phytotoxic organic compounds. These and other benefits of MSW composts for plant growth and soil stabilization are beyond the scope of this review, but are reviewed in part by Shiraliipour et al.

Toxicity to plants, animals, and humans due to these elements occurs only rarely with certain unusual soil types such as those derived from serpentine rocks, which naturally contain high concentrations of heavy metals, or in areas where these metals are mined, or when soils become acidic. Occasionally, industrial processes and the application of a few highly contaminated sewage sludges to cropland have produced toxicity problems for plants and animals.

The purpose of this review is to summarize what is known about the effects of trace elements in MSW composts on plants and the environment, and also to identify gaps in our current knowledge. This review is based primarily on experimental studies in which plants were grown in soil to which MSW composts were added. Priority is given to field experiments which were carried out for more than one growing season with high doses of MSW composts, i.e. realistic “worst case” situations. While many studies of metal uptake by plants have been conducted in greenhouses, the results may not be applicable to field situations, since metal uptake can be much higher in greenhouse studies. For example, uptake of Cd by lettuce grown in sewage sludge and soil was 6 times greater when grown in the greenhouse than when grown in the field. In that same study, the difference for onions was even greater, and 25 times more Cd was taken up in the greenhouse study. The results for several other metals were similar. The reasons for such increased metal uptake in greenhouse studies are not fully understood, but may include altered water regimes and restricted root growth. Field studies extending for several years are crucial, since long-term real-world effects should be used as a basis for establishing regulations.

Before proceeding, some terms should be defined. Trace element is used here simply to mean any element that is present in trace amounts. This term encompasses metals such as iron (Fe), chromium (Cr), Cu, Ni, Zn, Cd, Pb, and Hg and also metalloids such as As and B. Heavy metals are metals with a density greater than 5.0, including all of the above-mentioned metals. The term “heavy metals” is often used specifically for certain metals such as Hg and Pb that can be toxic to animals at low concentrations under unfavorable conditions, but also includes metals such as Fe that are required in plant and animal nutrition. Micronutrients are essential for plant growth, but are needed in only very small amounts, less than 50 μg g⁻¹ in the plant tissue. Examples are chlorine (Cl), manganese (Mn), B, Cu, Fe, Zn, and Ni. The critical toxic foliar concentration is the foliar concentration associated with a 10% decrease in the growth of a plant species.

2. FACTORS CONTROLLING TRACE ELEMENT AVAILABILITY IN SOILS

The availability to plants of heavy metal cations including Cd, Pb, Ni and Cu in soils decreases strongly as pH increases from 4 to 6. Similarly, the availability of these cations decreases with increasing cation exchange capacity of soils. Organic matter in soil can
decrease the plant-availability of these cations. Since mature composts consist primarily of organic matter, the application of composts to cropland can actually decrease the uptake of these metals by plants even though the concentration in the soil may be increased. Organic matter does not react with all metal cations equally, but instead generally forms complexes decreasing in strength in the following order: Cu > Pb > Zn > Cd. Interactions between soil organic matter and metals are complex, and additions of organic matter can increase metal availability or leaching. A thorough discussion of current theories explaining the interactions of organic matter and metals is beyond the scope of this paper, but this topic was recently reviewed by Livens.

Naturally, plant species differ in their ability to take up various trace metals. For example, when exposed to 10 µg g⁻¹ Cd (note—all concentrations are on a dry mass basis unless otherwise specified) in soil to which Cd-enriched sewage sludge had been added, the concentration of Cd in spinach was 160 µg g⁻¹, while that in field bean was less than 15 µg g⁻¹. Even varieties within a species can differ considerably in their ability to take up metals; the concentration of Cd in lettuce cultivars ranged from 0.5 to 8.7 µg g⁻¹ when grown in solution culture with 0.1 µg g⁻¹ Cd. Fungi can also take up trace metals, particularly Hg and Cd. Since soils vary greatly in their effect on the availability of trace metals to plants, and since plants also vary in their ability to take up these metals, extrapolations beyond the available data must be made with caution.

3. ELEMENTS PRIMARILY OF CONCERN FOR PLANT HEALTH

3.1. Boron

Like other essential trace elements, B is more likely to be deficient in soils than to cause toxicity. Hence B in MSW composts may be beneficial as a fertilizer, but a thorough discussion of such benefits is beyond the scope of this review. Boron toxicity can occur in semi-arid and arid regions due to excess B in irrigation water. The concentration of B that cause phytotoxicity in these situations may not cause phytotoxicity in soils high in organic matter, such as soils with significant additions of compost. This is because B can bind to organic matter, and this binding is only partially reversible. Plants differ greatly in their sensitivity to B; for example the critical foliar concentration of B for maize is 100 µg g⁻¹, while that of squash is 1000 µg g⁻¹. The application of MSW composts can cause phytotoxicity due to excess B. In container grown arborvitae and forsythia, growth was decreased and foliar tip necrosis was produced due to B toxicity. In that study, compost containing 225 µg g⁻¹ B was added to sand in a 1:1 ratio, the resulting mixture had a neutral pH. The foliar content of B in arborvitae was 146 µg g⁻¹ and in forsythia was 773 µg g⁻¹ when toxicity was observed. If water-soluble B is greater than 3 µg g⁻¹, phytotoxicity can occur in a number of vegetable crops, with beans being particularly sensitive. Purves and McKenzie found that the mean water soluble B content of soils after a 100 Mg ha⁻¹ application of MSW compost was 3.92 µg g⁻¹. Leaching of the compost prior to application eliminated the problem of B phytotoxicity. In greenhouse experiments, the addition of mineral fertilizers has been found to decrease the availability of B in MSW composts. Hence leaching or fertilization may be important management tools to prevent phytotoxicity caused by high-boron MSW composts.

3.2. Copper

For the majority of crop plant species, Cu causes toxicity when the foliar Cu content is 20–30 µg g⁻¹. When the foliar Cu content is in this range, the root content will be much higher, and thus root growth is usually inhibited before shoot growth.

When MSW compost containing 400 µg g⁻¹ Cu was applied at a rate of 30 Mg ha⁻¹ for four years, the concentration of Cu in maize grain increased to 4.2 µg g⁻¹, nearly double that of the control (soil) treatment (see Table 1). This concentration was still much too low to cause phytotoxicity. In a study by Andersson, MSW compost was applied for 5 years at up to 20 Mg ha⁻¹. The Cu content of the compost was 505 µg g⁻¹, and crop species including winter wheat and fodder rape grown with MSW compost did not accumulate significantly more Cu than crops grown without compost. When MSW compost containing 618 µg g⁻¹ Cu was applied at rates up to 40 Mg ha⁻¹ for 13 years, there was only a moderate increase in the Cu content of potatoes. Specifically, for a sandy soil, the Cu content of potatoes was 4.4 µg g⁻¹ without compost, and 5.3 µg g⁻¹ with compost. On a clay soil, the Cu content of potatoes was
Table 1. The effect of municipal solid waste (MSW) compost application in multi-year field experiments on the copper content of crops

<table>
<thead>
<tr>
<th>Compost application rate (Mg ha(^{-1}))</th>
<th>Number of applications</th>
<th>Cu in compost</th>
<th>Cu in compost-amended soil*</th>
<th>Cu in treated crop*</th>
<th>Cu in control crop*</th>
<th>Soil pH</th>
<th>Crop species</th>
<th>Comments</th>
<th>Reference</th>
</tr>
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<td>40</td>
<td>1:22</td>
<td>76</td>
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<td>4.4</td>
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<td>sandy soil</td>
<td>37</td>
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<td>---</td>
<td>40</td>
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<td>106</td>
<td>5.0</td>
<td>4.0</td>
<td>---</td>
<td>potato</td>
<td>clay soil</td>
<td>37</td>
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<td>30</td>
<td>4:42</td>
<td>---</td>
<td>4.2</td>
<td>2.4</td>
<td>7.6--8.0</td>
<td>maize (grain)</td>
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<tr>
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<td>327</td>
<td>2:56</td>
<td>---</td>
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<td>4.0</td>
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<td>sorghum</td>
<td></td>
<td>87</td>
</tr>
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<td>548</td>
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<td>1:74</td>
<td>71</td>
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<td>13.7</td>
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<td></td>
<td>88</td>
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<td>83</td>
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<td>0.4</td>
<td>5.5--7.1</td>
<td>grape juice</td>
<td>on an acid soil</td>
<td>24</td>
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<tr>
<td>---</td>
<td>150</td>
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<td>83</td>
<td>0.08</td>
<td>0.11</td>
<td>5.5--7.1</td>
<td>grape juice</td>
<td>new wine</td>
<td>24</td>
</tr>
<tr>
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<td>75</td>
<td>6:63</td>
<td>19</td>
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<td>7.4</td>
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<td>pH not changed on</td>
<td>24</td>
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<td>19</td>
<td>0.3</td>
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<td>an alkaline soil</td>
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<tr>
<td>(150 m(^3) ha(^{-1}))</td>
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<td>89, 90</td>
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<td>230</td>
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<td>carrot root</td>
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</tr>
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<td>7</td>
<td>137</td>
<td>230</td>
<td>26.00</td>
<td>26.00</td>
<td>7.2</td>
<td>carrot shoot</td>
<td></td>
<td>89, 90</td>
</tr>
</tbody>
</table>

20--30 (Foliar toxicity threshold)

349 (Average for centrally-sorted MSW compost in North America)

1200 (Proposed United States of America Environmental Protection Agency Alternative Pollutant (APL) limit for sewage sludge)

*All values are µg g\(^{-1}\) on a dry mass basis unless otherwise noted.
Trace elements in MSW composts

4.0 μg g⁻¹ without compost and increased to just 5.0 μg g⁻¹ with compost application.

When large quantities of MSW compost were added to two vineyard soils over a 10-year period, no increase in the content of Cu was found in the wine produced or in the grape leaves, even though the Cu content of the first soil increased from 18 to 145 μg g⁻¹ when 1500 Mg ha⁻¹ of MSW compost was added, and the Cu content of the second soil increased from 16 to 55 μg g⁻¹ when 750 Mg ha⁻¹ of MSW was added.23 Similar results were found in another experiment using grapevines24 (Table 1).

In an experiment with carrots, beets, turnips, peas, and beans, 40 Mg ha⁻¹ of MSW compost with an average of 630 μg g⁻¹ Cu was applied 14 times from 1948 to 1975. The Cu content of the soil increased nearly 350%, but the Cu content of the crops did not increase significantly.25 These long-term field studies suggest that very little increase in the Cu content of crops will occur even with substantial additions of MSW composts. The organic content of the composts forms complexes with the Cu and reduces its availability to plants. Thus Cu toxicity is unlikely to occur due to the application of MSW composts. Copper is also a plant micronutrient, thus in regions where Cu is deficient, Cu in MSW composts may serve as a valuable fertilizer.

3.3. Nickel

While Ni is an essential element, at least for legumes, it causes phytotoxicity in many crop species when the foliar concentration reaches a critical value of 10-50 μg g⁻¹.26,27 Nickel causes damage by replacing other elements in metalloproteins. The few field studies that have examined plant uptake of Ni from MSW composts are summarized in Table 2. These studies do not suggest that Ni is likely to cause phytotoxicity due to application of MSW composts, since the tissue concentrations observed were lower than those reported to cause phytotoxicity.

The concentrations are generally low in MSW composts. The average value for mixed MSW composts in North America is 31 μg g⁻¹,28 while soils average 22 μg g⁻¹ worldwide.29 Thus Ni is not likely to cause phytotoxicity due to applications of MSW composts.

3.4. Zinc

Zinc is an essential element for plants and the foliar concentration ranges from 1.2 to 73 μg g⁻¹ in various crop species.29 Phytotoxicity to
crops can occur when tissue concentrations are 200–500 µg g⁻¹.²⁸ In soils, the Zn concentration commonly ranges from 17 to 125 µg g⁻¹.²⁹

When MSW compost containing 814 µg g⁻¹ Zn was applied at a rate of 30 Mg ha⁻¹ for 4 years, the concentration of Zn in maize grain was 35.8 µg g⁻¹, considerably higher than that of the control treatment²¹ (see Table 3). In other studies, similar increases were observed, but phytotoxicity was not reported (Table 3). Although Zn toxicity has been observed in a variety of plant species grown under greenhouse conditions, phytotoxicity is rare under field conditions. The available data suggest that applications of MSW composts may greatly increase the Zn content of soil with only slight to moderate increases in the Zn content in foliage. Only under unusual conditions with sensitive species and at low soil pH, could Zn from MSW composts potentially injure crops. Applications of sewage sludge containing very high levels of Zn have caused phytotoxicity. For example, lettuce and beets were damaged when 112 Mg ha⁻¹ of sewage sludge containing 17,000 µg g⁻¹ Zn was applied.³¹ However, MSW composts contain much less Zn than this; the average for the U.S. is 771 µg g⁻¹.²⁸ Thus Zn in MSW composts has a low potential to cause phytotoxicity, and may be beneficial in regions deficient in Zn.

4. ELEMENTS PRIMARILY OF CONCERN FOR ANIMAL AND HUMAN HEALTH

4.1. Arsenic

Arsenic can occur in different chemical forms that have very different environmental effects, but a discussion of As speciation and biotransformation is beyond the scope of this review. Arsenic species are rarely measured in agricultural experiments, and models of chemical speciation based on fundamental chemical properties of soils may not adequately predict the uptake of metals and metalloids by plants.³² Arsenic is not readily taken up by plants and so should not be of great concern in relation to the application of MSW composts to cropland. For example, as the concentration of As in soils increased from less than 30 to approximately 330 µg g⁻¹, the concentration of As in barley grain increased from less than 0.1 to just 0.3 µg g⁻¹ (Thoresby and Thornton as cited by Davies³³). While the As concentration in the grain did increase with increased As in the soil, the total As uptake by most species is apparently low under field conditions (ibid.).

Phytotoxicity due to As can occur when the foliar concentration is as little as 1 µg g⁻¹ for sensitive species, but tolerant crop species are not affected until foliar concentrations are 100 µg g⁻¹ or greater.³³,³⁴ Arsenic has caused phytotoxicity in agricultural situations, but primarily due to foliar applications of pesticides containing arsenate, not uptake from the soil. There are few data on the concentration of As in MSW composts. However, even after more than 30 years of application of MSW compost in the Netherlands, the As concentration in the soil increased less than 100%, while that in crops decreased slightly.²⁵ Hence, substantial plant uptake of As due to application of MSW composts to agricultural land seems unlikely.

4.2. Cadmium

Cadmium is taken up readily by many plant species under favorable conditions and can be toxic to plants, but is primarily of concern due to its toxicity to animals and humans. Cadmium is much less toxic when consumed in food, since its bio-availability is restricted in this route. However, the primary exposure route for humans in uncontaminated regions is food. Thus Cd should receive close scrutiny in relation to the application of MSW composts to agricultural soils.

The Cd content of surface soils varies considerably depending on the parent material, but an average value for topsoil worldwide is 0.53 µg g⁻¹.²⁹ Cadmium is also a contaminant in many sources of phosphate fertilizers, which can contain between 9 and 13Oµg g⁻¹.³⁰ If the ratio of Cd to Zn is kept below 0.01, it has been suggested that crops will be damaged by Zn phytotoxicity before the Cd content of the crop is excessive.³⁶ Based on this approach, MSW composts should be evaluated not only for total Cd content, but also for the ratio of Cd to Zn. Calculated from the data presented by Richard and Woodbury,²⁸ the Cd:Zn ratio is <0.01 for all but a few MSW composts for which metal content data are available.

With an increasing dose of MSW compost, the Cd content of numerous crops including barley, oats, wheat, fodder rape, and red clover was observed to decrease in comparison to those treated with commercial fertilizers.³² A commercial fertilizer with a low concentration of Cd was chosen for the experiment. The compost doses
Table 3. The effect of municipal solid waste (MSW) compost application in multi-year field experiments on the zinc content of crops

<table>
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<tr>
<th>Zn in compost* (Mg ha⁻¹)</th>
<th>Compost application rate (Mg ha⁻¹)</th>
<th>Number of compost applications</th>
<th>Zn in compost-amended soil* (mg kg⁻¹)</th>
<th>Zn in treated crop* (mg kg⁻¹)</th>
<th>Zn in control crop* (mg kg⁻¹)</th>
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<td>7.2</td>
<td>29</td>
<td>carrot root</td>
<td></td>
<td>89, 90</td>
</tr>
</tbody>
</table>

50–500 (Foliar toxicity threshold)
64 (Average for soils worldwide)
771 (Average for centrally-sorted MSW compost in North America)
2700 (Proposed United States of America Environmental Protection Agency Alternative Pollutant (APL) limit for sewage sludge)

*All values are µg g⁻¹ on a dry mass basis unless otherwise noted.
were 2.5, 5, 10, and 20 Mg ha\(^{-1}\) year\(^{-1}\), and were applied for 5 years, with different species grown in different years. The average concentration of Cd in the compost was not particularly high (5.2 \(\mu g\) g\(^{-1}\)), but resulted in a doubling of the Cd content of the soil after 5 years.

In another long-term field experiment, MSW compost with an average of 8 \(\mu g\) g\(^{-1}\) of Cd was found either to decrease the uptake of Cd by a crop or to cause no change in the uptake, depending on the soil type\(^3\) (see Table 4). By the end of the experiment, the concentration of Cd had increased 270% in a sandy soil and 170% in a clay soil. Potatoes grown in the sandy soil had a concentration of 0.12 \(\mu g\) g\(^{-1}\) Cd without MSW compost application and 0.07 with MSW applied at 40 Mg ha\(^{-1}\) for 13 years. Potatoes grown in the clay soil had a concentration of 0.06 \(\mu g\) g\(^{-1}\) Cd both with and without MSW compost.

When very high amounts of MSW composts were added to two vineyard soils over a 10-year period, no increase in the content of Cd was found in the wine produced or in the grape leaves, even though the Cd content of the first soil increased from less than 0.1 to 1.6 \(\mu g\) g\(^{-1}\) when 1500 Mg ha\(^{-1}\) of MSW compost was added, while the Cd content of the second soil was less than 0.1 \(\mu g\) g\(^{-1}\) both with and without the addition of 750 Mg ha\(^{-1}\) of MSW compost.\(^2\) Similar results were observed in another investigation of Cd uptake by grapevines\(^2\) (see Table 4).

In an experiment with carrots, beets, turnips, peas, and beans, 40 Mg ha\(^{-1}\) of MSW compost with an average of 6 \(\mu g\) g\(^{-1}\) Cd was applied 14 times from 1948 to 1975. The Cd content of the soil increased nearly 350%, but there was no increase in the Cd concentration in the crops.\(^2\) Conversely, in a four-year experiment with corn, the addition of 30 Mg ha\(^{-1}\) caused the concentration of Cd in the grain to increase from 0.02 (without MSW compost) to 0.10 (with MSW compost).\(^2\) In this instance the average concentration of Cd in the MSW compost was slightly higher, 8 \(\mu g\) g\(^{-1}\). The value of such long-term experiments is demonstrated in that no increase in the Cd content of the grain was found in the first two years of the study, but in the third and fourth years a significant increase was observed. In the roots, the concentration of Cd was considerably higher than in the grain: in the untreated soil, corn roots contained 0.22 \(\mu g\) g\(^{-1}\), and with MSW compost application the roots contained 1.31 \(\mu g\) g\(^{-1}\).

This pattern of lower Cd concentration in the grain than in the roots of many crops has been observed frequently and can be viewed as providing an extra margin of safety to avoid accumulation of Cd and other metals in grains. However, as discussed previously, other crops such as spinach might accumulate considerably more Cd in the edible portion of the crop than does maize under these conditions.

A conservative approach to allowing unrestricted use of MSW composts would require that even crops that accumulate Cd could be grown safely. Field experiments evaluating the uptake of Cd by spinach and other known Cd accumulators from MSW compost applications are lacking. However, information is available on Cd uptake by leafy crops from field experiments with sewage sludge and from gardens with elevated Cd levels due to a nearby Zn smelter. These data suggest that Cd uptake by leafy vegetables such as lettuce does not increase linearly with increasing dose in the soil. Instead, additional increments of Cd eventually result in little Cd increase in the plant, particularly at moderate pH (greater than 6.5).\(^3\) If the availability of Cd in MSW composts is similar to these other materials, increases in the Cd content of agricultural soils will not result in proportional increases in the Cd content of most crops, even in plant species that readily take up Cd.

Tobacco accumulates Cd more readily than many other crops and is commonly grown on low pH soils to control soil-borne diseases. Tobacco grown on soils amended with sewage sludges can accumulate as much as 44 \(\mu g\) g\(^{-1}\) when the soil contains 1 \(\mu g\) Cd g\(^{-1}\).\(^3\) This is especially important because when tobacco is burned and inhaled, much more of the Cd is taken up by the human body than is taken up with ingestion. For this reason, MSW composts containing Cd above the background levels present in soil should probably not be applied to land on which tobacco is grown.

Some species of fungi can accumulate Cd even in pristine areas. One species, *Agaricus silvicola*, was found to accumulate 53–130 \(\mu g\) g\(^{-1}\) when the soil Cd content was 0.2–1.1 \(\mu g\) g\(^{-1}\).\(^9\) In Slovenia, the average Cd content of 27 species of edible fungi was found to be 5 \(\mu g\) g\(^{-1}\), but seven species contained more than 10 \(\mu g\) g\(^{-1}\).\(^1\) There are few data on the metal content of commercial mushroom species produced using MSW composts. In one study with commercial button mushrooms (*Agaricus bisporus*)
Table 4. The effect of municipal solid waste (MSW) compost application in multi-year field experiments on the cadmium content of crops

<table>
<thead>
<tr>
<th>Cd in compost* (Mg ha(^{-1}))</th>
<th>Number of applications</th>
<th>Cd in compost-amended soil*</th>
<th>Cd in treated crop*</th>
<th>Cd in control crop*</th>
<th>Soil pH</th>
<th>Crop species</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>13</td>
<td>0.3</td>
<td>0.8</td>
<td>0.07</td>
<td>0.12</td>
<td>potato</td>
<td>sandy soil</td>
<td>37</td>
</tr>
<tr>
<td>40</td>
<td>13</td>
<td>0.9</td>
<td>1.5</td>
<td>0.06</td>
<td>0.06</td>
<td>potato</td>
<td>clay soil</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>1.0</td>
<td>0.2</td>
<td>0.10</td>
<td>0.02</td>
<td>maize (grain)</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>15</td>
<td>224</td>
<td>2.0</td>
<td>2.6</td>
<td>5.7</td>
<td>1.1</td>
<td>maize shoots</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>224</td>
<td>0.4</td>
<td>2.6</td>
<td>0.8</td>
<td>0.5</td>
<td>maize grain</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>224</td>
<td>0.4</td>
<td>2.6</td>
<td>0.4</td>
<td>0.3</td>
<td>bean vines</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>224</td>
<td>0.4</td>
<td>2.6</td>
<td>0.1</td>
<td>0.1</td>
<td>bean pods</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>3.3</td>
<td>50</td>
<td>1.0</td>
<td>0.26</td>
<td>0.27</td>
<td>0.53</td>
<td>rye grass</td>
<td></td>
<td>88</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
<td>1.1</td>
<td>1.0</td>
<td>94</td>
<td>95</td>
<td>grape leaves</td>
<td>compost increased pH</td>
<td>24</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
<td>0.1</td>
<td>1.0</td>
<td>1.6</td>
<td>1.7</td>
<td>grape juice</td>
<td>on an acid soil</td>
<td>24</td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>0.1</td>
<td>0.3</td>
<td>61</td>
<td>61</td>
<td>grape leaves</td>
<td>pH not changed on</td>
<td>24</td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>0.1</td>
<td>0.3</td>
<td>0.6</td>
<td>0.8</td>
<td>grape juice</td>
<td>an alkaline soil</td>
<td>24</td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>new wine</td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>

3.80 (Foliar toxicity threshold)
0.53 (Average for soils worldwide)
3.7 (Average for centrally-sorted MSW compost in North America)
25 (Proposed United States of America Environmental Protection Agency Alternative Pollutant (APL) limit for sewage sludge)
0.5 (Recommended maximum for forage crops)

*All values are μg g\(^{-1}\) on a dry mass basis unless otherwise noted.
the Cd content of the mushrooms was 0.2–1.1 μg g⁻¹ when grown on pure horse-manure compost and increased to between 0.4 and 2.0 with a 1:1 mixture of horse-manure compost and MSW–sewage sludge compost (Fleckenstein and Grabbe, 1981 as cited by Fleckenstein and Grabbe\(^9\)). In another study, the Cd concentration in this species increased from 0.13 to 0.42 μg g⁻¹ on a fresh weight basis (all other data are on a dry weight basis) when 75% MSW–sewage sludge compost containing 11.1 μg Cd g⁻¹ dry weight was added to horse-manure compost.\(^5\) The horse-manure compost alone contained 1.6 μg Cd g⁻¹ and the mixture containing 75% MSW–sewage sludge compost contained 9.6 μg Cd g⁻¹. Since mushrooms can contain high levels of Cd, it has been recommended that individuals should limit their consumption of them (Lorenz et al., 1978 as cited by Marschner\(^4\)). In France, it has been reported that in 1984, 37% of the MSW composts produced were used for mushroom production\(^4\). Based on the limited data available, MSW composts containing Cd above the background level found in soils may not be suitable for mushroom cultivation.

There appears to be only a minor potential for phytotoxicity due to Cd in MSW composts. As shown in Table 4, in only a few experiments did the concentration of Cd in plant tissues exceed that reported to cause phytotoxicity in sensitive species.

The National Research Council of the United States\(^2\) has recommended that the Cd content of forage crops be 0.5 μg g⁻¹ or less in order to limit the concentration of Cd in the liver and kidney of animals feeding on these crops in order to protect humans who may consume these organs. As shown in Table 4, applications of MSW composts containing low levels of Cd can result in crop tissue concentrations that exceeded this value. Even some of the plants grown without compost applications contained Cd in excess of this recommended value. However, evidence from research with sewage sludges indicates that plant uptake from sludge with low Cd content is less than that from sludges with higher Cd content, even if the same total amount of Cd is applied.\(^7\) This is one of the arguments supporting the establishment of a "clean sludge" standard, referred to by EPA as an Alternative Pollutant Limit (APL). Based on the available data (Table 4), MSW composts are well below the alternative pollutant limit of 25 μg g⁻¹ proposed for sewage sludge. This recommended APL is based on data from a number of field studies of the uptake of Cd from sewage sludges. This value may need to be lower for MSW composts, since they contain lower concentrations of Fe, which can serve to adsorb Cd and other metals and decrease their bio-availability.\(^3\)

### 4.3. Chromium

Chromium in its reduced (trivalent) form is a nutritional requirement for animals, and has a rather low toxicity to plants, animals, and humans. The chromate anion (hexavalent form) has a greater potential to cause toxicity to plants, animals and microorganisms. The uptake of Cr by plants growing in soils treated with MSW composts is low, since it is usually present in the reduced state, which is not particularly mobile in soils. When MSW–sewage sludge compost containing 500 μg g⁻¹ Cr was added to soil in a greenhouse experiment, the concentration of Cr in corn did not increase.\(^4\) In this same study, additions of sewage sludge containing 1.36% Cr did not increase the foliar concentration of Cr. The few data available from field studies indicate that the application of MSW composts will not cause a large increase in the foliar Cr content (Table 5), and thus Cr is unlikely to cause toxicity to plants.

### 4.4. Lead

Although plants take up only a small proportion of the Pb from most soils, this metal should receive close attention due to its lack of benefit to almost all species and toxicity to animals and humans at low concentrations. Relatively high concentrations of Pb have been found in vegetation near roads, but this is primarily due to the deposition of Pb aerosols on plants rather than uptake from the soil. The decrease in the use of leaded gasoline in the U.S.A. during the last 10 years should substantially reduce this problem in the U.S.A., although it will persist in some other countries.

In the study by Andersson\(^2\) previously discussed, MSW compost was applied for 5 years at up to 20 Mg ha⁻¹. The average Pb content of the compost was 482 μg g⁻¹, and the Pb content of crops grown with MSW compost increased to only 104% of that of crops grown without compost in soil with a Pb concentration of 22 μg g⁻¹. In the study by Petruzelli and others\(^2\), MSW compost containing an average 605 μg g⁻¹ was applied at a rate of 30 Mg ha⁻¹ for 4 years (Table 6). The Pb content of corn grain
Trace elements in MSW composts

increased from 0.12 to 0.17 µg g⁻¹, although this difference was not found to be statistically significant. Conversely, in another study the Pb content of corn grain was lower with MSW compost application than without⁴⁵ (Table 6). However, in this second study, Pb in the corn foliage increased from 7.7 to 17.5 µg g⁻¹ when MSW compost was applied. Very slight increases in Pb content due to MSW compost application was observed for beans in this study. One difficulty with studies of Pb is that Pb-bearing dusts may enter stomata, thus concentrations in foliage and grain may reflect uptake from the atmosphere as well as the soil.

When MSW compost containing a high average concentration of Pb, 1280 µg g⁻¹, was applied at rates up to 40 Mg ha⁻¹ for 13 years, there was a slight increase in the Pb content of potatoes⁴⁵ (Table 6). When very high quantities of MSW compost were added to two vineyard soils over a 10-year period, no increase in the content of Pb was found in the wine produced or in the grape leaves, even though the Pb content of the first soil increased from 26 to 367 µg g⁻¹ when 1500 Mg ha⁻¹ of MSW compost was added, and the Pb content of the second soil increased from 13 to 113 µg g⁻¹ when 750 Mg ha⁻¹ of MSW was added.²³ Similar results were reported from another study of Pb uptake by grapevines²⁴ (Table 6).

In an experiment with carrots, beets, turnips, peas, and beans, 40 Mg ha⁻¹ of MSW compost with an average of 900 µg g⁻¹ Pb was applied 14 times from 1948 to 1975. The Pb content of the soil increased just over 400%, but Pb content of the crops did not increase significantly.* These long-term field studies suggest that very little increase in the Pb content of crops will occur even with substantial additions of MSW composts. In fact, there is some evidence that MSW composts can actually decrease the uptake of Pb by crops. In a greenhouse study, MSW compost containing 26 µg g⁻¹ Pb was mixed with sandy soil containing 6 µg g⁻¹ Pb in ratios up to 100 g compost for each 1 kg of soil. The Pb content in the leaves of Chinese cabbage and radish decreased from 1.3 µg g⁻¹ with soil alone to 0.5 µg g⁻¹ at the highest dose of MSW compost.⁶ Presumably, the decrease in Pb uptake by plants was due to the organic matter in the MSW compost binding the Pb and decreasing its availability to plants.

In summary, while the application of MSW composts will increase the Pb content of soils, there is very little uptake of Pb by plants, even
Table 6. The effect of municipal solid waste (MSW) compost application in multi-year field experiments on the lead content of crops

<table>
<thead>
<tr>
<th>Pb in compost*</th>
<th>Compost application rate (Mg ha(^{-1}))</th>
<th>Number of applications</th>
<th>Pb in compost-amended soil*</th>
<th>Pb in treated crop*</th>
<th>Pb in control crop*</th>
<th>Soil pH</th>
<th>Crop species</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>13</td>
<td>27</td>
<td>144</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
<td>potato</td>
<td>sandy soil</td>
<td>37</td>
</tr>
<tr>
<td>25.4</td>
<td>13</td>
<td>57</td>
<td>180</td>
<td>1.1</td>
<td>0.9</td>
<td></td>
<td>potato</td>
<td>clay soil</td>
<td>37</td>
</tr>
<tr>
<td>605</td>
<td>30</td>
<td>4</td>
<td>25.4</td>
<td>1.7</td>
<td>1.2</td>
<td>7.6-8.0</td>
<td>maize (grain)</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>450</td>
<td>224</td>
<td>2</td>
<td>8</td>
<td>17.5</td>
<td>7.7</td>
<td>5.4-6.3</td>
<td>maize shoots</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>430</td>
<td>224</td>
<td>2</td>
<td>8</td>
<td>76</td>
<td>1.0</td>
<td>2.0</td>
<td>maize grain</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>430</td>
<td>224</td>
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<td>8</td>
<td>76</td>
<td>8.3</td>
<td>6.7</td>
<td>bean vines</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>430</td>
<td>224</td>
<td>2</td>
<td>8</td>
<td>76</td>
<td>14.3</td>
<td>12.9</td>
<td>bean pods</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>216</td>
<td>50</td>
<td>1</td>
<td>13</td>
<td>176</td>
<td>6.8</td>
<td>5.7</td>
<td>rye grass</td>
<td></td>
<td>88</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
<td>19</td>
<td>176</td>
<td>3.4</td>
<td>3.1</td>
<td>5.5-7.1</td>
<td>grape leaves</td>
<td>compost increased pH</td>
<td>24</td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>14</td>
<td>42</td>
<td>2.7</td>
<td>2.5</td>
<td>7.4</td>
<td>grape leaves, pH not changed on an alkaline soil</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>14</td>
<td>42</td>
<td>0.02</td>
<td>0.02</td>
<td>7.4</td>
<td>grape juice, new wine</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>88</td>
<td>7</td>
<td>137</td>
<td>230</td>
<td>&lt;6.25</td>
<td>13.00</td>
<td>7.2</td>
<td>lettuce</td>
<td></td>
<td>89, 90</td>
</tr>
<tr>
<td>89, 90</td>
<td>(150 m(^{3}) ha(^{-1}))</td>
<td>7</td>
<td>137</td>
<td>230</td>
<td>5.75</td>
<td>6.50</td>
<td>carrot root</td>
<td></td>
<td>89, 90</td>
</tr>
<tr>
<td>89, 90</td>
<td>(150 m(^{3}) ha(^{-1}))</td>
<td>7</td>
<td>137</td>
<td>230</td>
<td>32.00</td>
<td>48.00</td>
<td>carrot shoot</td>
<td></td>
<td>89, 90</td>
</tr>
</tbody>
</table>

35->50 (Foliar toxicity threshold)
324 (Average for centrally-sorted MSW compost in North America)
300 (Proposed United States of America Environmental Protection Agency Alternative Pollutant (APL) limit for sewage sludge)

*All values are µg g\(^{-1}\) on a dry mass basis unless otherwise noted.
when the soil Pb content is increased several hundred percent. Indeed, for contaminated soils, particularly those low in organic matter or pH, the addition of MSW composts may even decrease the availability of Pb to plant roots. Thus, plant uptake of Pb from MSW composts is unlikely to be a serious problem. However, Pb in MSW composts may pose a risk due to dust inhalation and consumption by animals and children with pica (habitual consumption of non-food materials).3*47 For this reason, Pb is likely to be the metal requiring the closest regulatory attention for land application of MSW composts.

4.5. Mercury

Mercury is not particularly toxic to plants but is toxic to animals and humans at very low concentrations. While its concentration in MSW composts is usually very low, it can be taken up by plants, particularly when volatilized, and thus is of concern. Little research has been done on the Hg content in MSW composts and how Hg may be taken up by plants. When a yard waste compost was applied to a vegetable garden, Hg was found to accumulate in vegetables, although the level in the plant tissues was quite low; 0.14 μg g⁻¹.48 Methyl mercury is one of the most toxic forms of Hg to animals and humans, and in this same study it was found to be taken up by plants four times more readily than inorganic Hg. The author suggests that the high organic matter content of the compost may actually enhance the formation of methyl mercury from the inorganic state. When sewage sludge was added until the concentration of Hg in the soil reached 15 μg g⁻¹ Hg, tomatoes grown in this amended soil contained 12.2 μg g⁻¹ Hg compared to just 0.24 when no sludge was added.49 Other crops took up very little Hg. This very high apparent uptake of Hg by tomatoes may indicate that surface contamination rather than uptake was measured.

Some species of fungi readily accumulate Hg. One species, *Agaricus silvicola*, was found to accumulate 1.5–20 μg g⁻¹ when the soil Hg content was 0.05–0.7 μg g⁻¹.79 The average found in 27 species in Slovenia was 2.3 μg g⁻¹ on uncontaminated sites, but values as high as 35 μg g⁻¹ were found when soil values were elevated to 1.5 μg g⁻¹.12 In artificial composts with Hg added as Hg(NO₃)₂·H₂O, a linear increase was observed in the Hg content of oyster mushrooms.50 The highest level of Hg found in mushrooms was 23.3 μg g⁻¹, with 0.2 μg g⁻¹ in the substrate. In MSW composts, uptake could well be lower if the Hg is less readily available. In a study with commercial button mushrooms the Hg content was 0.2–1.1 μg g⁻¹ when grown on pure horse-manure compost, and increased from 2.7 to 3.7 μg g⁻¹ with a 1:1 mixture of horse-manure compost and MSW–sewage sludge compost (Fleckenstein and Grabbe, 1981, as cited by Fleckenstein and Grabbe). In a similar study, the concentration of Hg increased from 0.13 to 0.53 μg g⁻¹ fresh weight when 75% MSW–sewage sludge compost containing 2.4 μg Hg g⁻¹ dry weight was added to horse-manure compost.11 As discussed above in relation to Cd, it has been recommended that individuals should limit their consumption of mushrooms to avoid possible heavy metal toxicity (Lorenz et al., 1978 as cited by Marschner). However, much of the concern about toxicity of Hg is due to methyl mercury, which accounts for less than 10% of the Hg in *Agaricus bisporus* and other species.51 Recommendations about limiting consumption of mushrooms due to Hg should take into account the relatively low proportion of Hg that is present as methyl mercury. Still, MSW composts containing levels of Hg much higher than the background levels in soils may not be suitable for mushroom production.

5. EFFECT OF TRACE ELEMENTS IN MSW COMPOSTS ON WATER QUALITY

In addition to affecting plant and animal health, trace elements contained in MSW composts may be leached from the soil and enter either groundwater or surface water. The factors that control the availability of trace elements to plants also affect their availability for leaching. Thus, at low pH, many trace elements will be free in the soil solution rather than complexed within the soil matrix, hence greater leaching is possible.

Based on a mass balance scenario including application of MSW compost meeting strict metal standards (1 μg Cd g⁻¹), at rates of 1–6 Mg ha⁻¹ year⁻¹, Cd inputs were found to exceed outputs.52 In a model of Cd behavior in a sandy soil at pH 5.0 (without compost addition), little Cd was leached into groundwater for many decades, but eventually as adsorption sites were saturated the loss of Cd in leachate closely approached the Cd input to the soil.53 This model does not account for changes
such as increased organic matter and cation exchange capacity that would occur with compost additions. Likewise, changes in pH, metal speciation, volatilization, erosion and other processes that might alter metal concentrations or bio-availability are not addressed. Hence this model is not directly applicable to examining the effect of MSW compost addition to soil.

In a study of 50 day old MSW-sludge compost, more than half of the Cd, Cr, and Zn were leached after 32 weeks in a lysimeter 1.5 m in height. This was an artificial situation, and was anaerobic, and may not be relevant to field conditions. While soil characteristics can strongly influence the movement of heavy metals through soils, the organic carbon concentration of leachates has recently been shown to be more useful for predicting the potential mobility of some metals.

At neutral and alkaline pH, most trace elements of concern will be in relatively insoluble forms, thus little leaching will occur. If leaching does occur, the subsoil can become enriched in trace elements, and several investigations of the effect of MSW composts on the trace element content of subsoils have been carried out. For example, when 14 Mg ha⁻¹ of MSW compost was added to soil, the Cu and Zn content of the topsoil increased significantly over two cropping cycles, but that of the subsoil did not, suggesting that little leaching occurred.

In a greenhouse study, leaching tests were conducted with mixtures of MSW compost and a sandy subsoil (C horizon of a Typic Udipsamment) in PVC tubes 10 cm in diameter and 30 cm in length with and without bean plants. The equivalent of 152 cm of water was applied over a 60-day period. Higher amounts of metals were leached from the treatment containing 100% compost than from those with mixtures of compost and soil. No differences were found in the leachate of pots with and without bean plants. The compost contained the following concentrations of metals prior to leaching: 506 μg Cu g⁻¹, 1420 μg Zn g⁻¹, 4.3 μg Cd g⁻¹, 35.8 μg Ni g⁻¹, and 597 μg Pb g⁻¹. The following average concentrations of metals were found in the leachate from the 100% compost treatment: 840 μg Cu l⁻¹, 1090 μg Zn l⁻¹, 60 μg Ni l⁻¹, and 290 μg Pb l⁻¹. The Cd concentration was below the detection limit. The concentration of Pb in the leachate was much higher than the U.S. drinking water action level of 15 μg l⁻¹. This action level means that if this level is reached at the customer’s water tap, remedial action must be taken. The concentration of all metals in leachate was apparently decreasing during the study. Thus, the averages presented above are presumably higher than would be found under most field conditions, at least after the first few months. Additionally, under field conditions the subsoil would act as a sink for metals, further decreasing the amounts reaching groundwater.

A controlled field study was conducted using soil lysimeters containing the layers of MSW compost (with 5% sewage sludge) 15–50 cm deep. No crops were grown in the lysimeters, and they were shielded from rainfall. The lysimeters were irrigated weekly with deionized water for a total application of 680 mm H₂O each year. Composts collected from different facilities and at different times of the year were tested. These composts contained 200–830 μg Cu g⁻¹, 1050–8350 μg Zn g⁻¹, 5.3–9.7 μg Cd g⁻¹, 50–100 μg Ni g⁻¹, 500–1010 μg Pb g⁻¹, and 65–455 μg Cr g⁻¹. The pH of the composts ranged from 6.9 to 7.7. The following results were reported as averages of all the experiments. For Cu, initial concentrations were 1000–3000 μg l⁻¹, decreasing to 300 μg l⁻¹ after 1 year. For Zn, initial concentrations were 2000–5000 μg l⁻¹, decreasing to 1000 μg l⁻¹ after 2.5 years. For Cd, initial concentrations in the leachate were 10–25 μg l⁻¹, rapidly decreasing to less than 5 μg l⁻¹. For Ni, initial concentrations were 500–5000 μg l⁻¹, decreasing to 100–1000 within 6 months. For Pb, initial concentrations were 200–700 μg l⁻¹, decreasing to 50 μg l⁻¹ after 2.5 years. For Cr, initial concentrations were 50–300 μg l⁻¹, decreasing to 50 μg l⁻¹ after 6 months. The following percentages of the original metal contents of the compost were leached within the first year: 0.21% of the Cd, 0.07% of the Pb, 0.4% of the Zn, 0.7% of the Cu, and 1.9% of the Ni.

There were few differences noted in the leaching characteristics of composts of different origins and ages in this study, except that leaching of Zn was less in the compost from Flensburg, Germany than that from Frederikssund, Denmark. Initially, the leachate concentrations of all the metals studied exceeded the E.E.C. drinking water standard, but after 1.5 years of leaching, only Ni still exceeded the E.E.C. limit (Table 7 shows U.S. and E.E.C. drinking water standards). Lead still exceeded the U.S. drinking water action level of 15 μg l⁻¹ after 2.5 years. It should be noted that...
Table 7. Drinking water standards for selected metals in the U.S.A. and the E.E.C.

<table>
<thead>
<tr>
<th>Metal</th>
<th>U.S.A. (MCL*)</th>
<th>E.E.C.†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Nickel</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Zinc</td>
<td>1300</td>
<td>5</td>
</tr>
<tr>
<td>Copper</td>
<td>100-3000‡</td>
<td>50</td>
</tr>
<tr>
<td>Lead</td>
<td>0-15§</td>
<td>50</td>
</tr>
<tr>
<td>Chromium</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

*Maximum contaminant levels (primary standards) in current or anticipated Federal regulations as of January 1992, as summarized by Pontius.58
†Drinking water standards for the European Economic Community as of 1980 as summarized by Christensen and Tiell, 1984.
‡The limit at the water works is 100 µg l⁻¹, the limit at the tap is 3000 µg l⁻¹.
§The maximum contaminant level goal is 0 µg l⁻¹, the action level is 15 µg l⁻¹, meaning that at this level at the customer’s tap, remedial action must be taken.

The amount of compost applied in these experiments was much greater than would be used in normal agricultural practice.

Christensen and Tjell61 reviewed other data on the concentration of metals in leachates from MSW composts and report that, while high concentrations were sometimes observed, these may not be realistic due to either the immaturity of the composts or the leaching protocol. As mentioned above, under most circumstances in agriculture and horticulture, subsoil would attenuate the concentration of trace elements reaching groundwater, at least for many years, so the data reported above represent a worst-case scenario. It should also be noted that not all of the trace metals in leachates are in a free ionic form. For example, in leachates from MSW composts, 7–25% of the Cd was found to be in stable complexes associated with organic matter.62 Trace elements in such complexes may differ from free ionic forms in mobility and bio-availability, and this should be taken into account in evaluating the toxicity of such leachates. While other data on leaching from MSW composts are scarce, there are some data from long-term applications of sewage sludges that may be useful. A review of the downward movement of sludge-borne metals after land application concluded that there was little evidence of such movement.63 Yet more recent evidence suggests that substantial movement of sludge-borne metals may occur. In one experiment, 25 years after the last sludge application, a sandy loam soil contained 71–96% of the original content of Cd, Zn, Cu, Ni, and Pb, suggesting that substantial quantities of some metals were removed.64 In another experiment, after 14 years of annual sludge application to a silt loam soil (pH in upper 0.2 m = 5.5–6.5, total sludge application 765 Mg ha⁻¹ dry weight basis) 4.1% of the Cd and 4.8% of the Zn applied were found to have moved below the zone of incorporation.65 However, only 47% of the Cd was 48% of the Zn applied were recovered, making it difficult to assess the total amount of metals that leached downward. Leaching of metals from sludge is most likely to occur with heavy repeated applications of sludge over many years in regions with acidic sandy soils low in organic matter that receive high rainfall or irrigation,64 and similar conditions would apply to leaching from MSW compost. Groundwater is most likely to be affected if it is close to the surface, or if karst formations or other conditions limit the opportunity for adsorption and complexation of metals by soil components.

One limitation of the leaching studies cited herein is that no assessment of the importance of different pathways such as channeling and macropore flow in total solute movement. Without such information, it is difficult to predict long-term leaching rates. As discussed above, mass balance and other modelling approaches suggest that the rate of leaching into groundwater may increase over many decades, hence the possibility that leaching of metals could decrease water quality cannot be ruled out.

6. EFFECT OF TRACE ELEMENTS IN MSW COMPOSTS ON SOIL BIOTA

6.1. Soil invertebrates

There are few data on the effect of trace elements in MSW composts on soil invertebrates. This topic deserves investigation since soil invertebrates are important for many soil processes, and serve as a food source for other organisms. When sewage sludges are applied to land, the concentration of some trace metals in earthworms is increased. For example, in a sludge-amended soil with a Cd content of 2 µg g⁻¹, the Cd content of earthworms was found to be 101 µg g⁻¹. In the control plot, soil Cd was 0.14 µg g⁻¹ and the Cd content of earthworms was 8.6 µg g⁻¹.66 The Cu, Zn, and Pb contents of earthworms were also significantly greater on sludge-amended plots than on control plots, though they accumulated to a lesser extent. No investigation of the effects of these metals on earthworms was made in this study, but the
authors suggest that this Cd content could be deleterious to wildlife that consumes worms. However, the EPA pathway analysis approach for sewage sludge did not conclude that soil invertebrates were exposed to undue risk from application of sewage sludge.

A recent review of the literature on the critical metal concentrations for forest soil invertebrates suggests the following allowable metal concentrations in soil to prevent adverse effects: $100-200 \mu g \, g^{-1}$ Pb, $100 \mu g \, g^{-1}$ Cu, $500 \mu g \, g^{-1}$ Zn, and $10-50 \mu g \, g^{-1}$ Cd. The authors consider these suggested values to be tentative and conservative since few adequately designed dose-response experiments have been conducted to investigate this issue. Naturally, factors such as soil pH, cation exchange capacity, and organic matter content that alter the availability of trace elements to plants will also affect their availability to soil invertebrates. Additionally, invertebrate fauna in forest soils might differ from those in agricultural soils. The average values of Pb, Cu, and Zn in MSW composts produced from centrally-separated waste in North America exceed the recommended limits suggested above and therefore may have the potential to harm soil invertebrates. However, these suggested limits do not consider that the bioavailability of metals may well be lower in MSW composts than in soils, and thus they may overestimate the potential for toxicity to soil invertebrates.

6.2. Soil microbiota

Soil microbes are important since they alter the chemical form of important plant nutrients and are a crucial link in the biogeochemistry of many elements. Some microorganisms are quite sensitive to trace metals. Thus, it is important to determine how trace metals in MSW composts affect them. To evaluate toxicity, effects on the biomass of taxonomic groups or total microbial biomass can be measured, although accurate measurements of biomass are difficult to obtain. In addition to biomass, metabolic parameters such as respiration can be measured. One important group, nitrogen-fixing bacteria, have been examined as discussed below.

In general, the ranking of toxicity of trace metals to soil microbiota of forest soils is as follows: Cd > Cu > Zn > Pb. While higher organic matter was found to be associated with decreased toxicity, the relative ranking of metals did not change. In one of the few long-term studies on the effects of trace metals in MSW composts on soil microbiota, 25 Mg ha$^{-1}$ of compost was applied yearly for 24 years, resulting in the following content of metals in the soil: 1.2 $\mu g \, g^{-1}$ Cd, 43 $\mu g \, g^{-1}$ Cr, 59.7 $\mu g \, g^{-1}$ Cu, 255.2 $\mu g \, g^{-1}$ Ni, 174 $\mu g \, g^{-1}$ Pb, and 296 $\mu g \, g^{-1}$ Zn. The addition of MSW compost increased the biomass of soil microbiota, the soil respiration, and the dehydrogenase activity of the soil as compared to that of soil treated with mineral fertilizers. Trace elements in sewage sludge composts have been shown to decrease soil microbial biomass as compared with a farmyard manure treatment even 20 years after the last application. The available (EDTA extractable) Cu content of the sludge compost treated soil ranged from 40 to 890 $\mu g \, g^{-1}$, while that of the manure treated soils ranged from 10 to 45 $\mu g \, g^{-1}$. For Ni, these values were 5–10 $\mu g \, g^{-1}$ for the sludge compost treated soils and 1–5 $\mu g \, g^{-1}$ for the manure treated soils. The concentration of other metals in the soils was not reported. Similar results were found 4 years after the last of 12 applications of sewage sludge, but the metal concentrations in the soils were not reported. In a three year study, mixed MSW and sewage sludge composts increased the activity and numbers of selected microbial inhabitants of the maize rhizosphere, as compared to a manure treatment. Again, the metal content of the soils was not reported. Four MSW composts in Spain were found to lack nitrifiers even though the pH and ammonium concentrations were adequate for them. The authors attributed this lack to heavy metals in the compost, but did not report the metal concentrations.

Some plant species, notably legumes, are able to fix nitrogen by producing specialized root nodules that contain N-fixing bacteria in the genus *Rhizobium*. In a pot experiment, white clover was grown in soil that had received either farmyard manure or sewage sludge, with the final application more than 20 years prior to the experiment. Different doses of trace metals in the soils were produced by mixing the sludge-amended and manure-amended soils in different proportions. The N-fixation decreased with increased doses of the sludge-amended soil, presumably due to its trace metal content. The following concentrations of metals in the soil were associated with a 50% reduction in N-fixation: 334 $\mu g \, g^{-1}$ Zn, 99 $\mu g \, g^{-1}$ Cu, 27 $\mu g \, g^{-1}$ Ni, and 10 $\mu g \, g^{-1}$ Cd. The content of these metals in the foliage was below that shown previously to cause phytotoxicity in this species.
(400 μg g⁻¹ Zn and 10 μg g⁻¹ Cd). Clover growth was also decreased by the sludge-amended soil treatment, but this effect was completely reversed with the addition of nitrogen fertilizer, lending added credence to the claim that the trace metals affected the N-fixing bacteria rather than affecting the plant directly. More recently, the decreased nitrogen fixation in this experiment was shown to be due to ineffective rhizobia in the sludge-amended soil. Thus the metal contamination may have resulted in selection for strains of rhizobia that cannot fix nitrogen. Similarly, nitrogen fixation by white clover was found to be decreased when plants were grown in soils contaminated with heavy metals.

Conversely, no such effect was found on another species of rhizobium inhabiting soils contaminated for many years with Zn and Cd from a smelter, nor were nodulation and nitrogenase activity of roots of alfalfa significantly affected. An earlier field experiment demonstrated that less N was fixed and that fewer nodules were present on soybeans grown in plots where high metal sludges had been applied, but not where lower metal sludges had been applied. A greenhouse experiment using these same soils demonstrated that soybean nodulation increased linearly with increased applications of sludge, particularly in a high pH treatment (7.0), but also in a lower pH treatment (6.2). An investigation of the effect of sludge applied 11 years previously (up to 112 Mg ha⁻¹) found no differences in the distribution of metal-resistant strains of Bradyrhizobium japonicum nor a decrease in rhizobial numbers. In summary, decreases in activity and numbers of rhizobia have been reported in some cases, but not in others. This discrepancy may be due to differences in metal sensitivity among species or strains of rhizobia, since Rhizobium leguminosarum bv trifolii was found to be adversely affected by metals while Rhizobium meliloti and Bradyrhizobium japonicum were not, except in one case when high metal sludges were applied.

As is clear from these examples, relatively little research has been conducted on this topic, and reported results are not consistent. At present, no firm conclusions about the effects of MSW composts on soil biota can be drawn, except that applications of moderate quantities of compost containing low concentrations of metals are unlikely to have deleterious effects while applications of large quantities of compost containing high concentrations of metals may have deleterious effects.

7. EFFECT OF ORGANIC MATTER DECOMPOSITION ON METAL CONCENTRATION

As organic matter decomposes and is lost as carbon dioxide, the concentration of metals in composts on a mass basis will increase. Similarly, if large quantities of MSW compost are added to soils for many years, the concentration of metals in the soil may increase as the organic matter decomposes. Thus, it is important to determine the rate at which MSW composts will decompose when added to soil. While there is virtually no information on the decomposition rate of MSW composts, data on other types of compost are available from long-term experiments at the Rothamstead and Woburn experiment stations in Great Britain. At Woburn, composts containing different combinations of crop residues, manure, and sewage sludge were applied to cropland at either 34 or 67 Mg ha⁻¹ each year for 10 years. Nine years after the last addition, 63% of the organic matter from the application of 34 Mg ha⁻¹ of sludge remained, but only 55% remained from the 67 Mg ha⁻¹ sludge treatment. When a compost produced from crop residues and sewage sludge was used, 74% of the organic matter remained 9 years after the last addition in the 34 Mg ha⁻¹ treatment and 60% remained from the 67 Mg ha⁻¹ treatment. In an experiment at Rothamstead, a grassland was plowed and kept fallow for 30 years. During this time, the organic carbon in the soil decreased from nearly 80 Mg ha⁻¹ to just over 40 Mg ha⁻¹. These data were corrected for changes in the bulk density of the soil. Interestingly, only slight decreases in organic carbon were seen over 30 years at two sites that had been cropped for many years. At these sites, organic carbon was 30–40 Mg ha⁻¹.

These examples point out that the rate of decomposition of organic matter is dependent on the amount present. Hence the addition of large quantities of MSW composts may result in much more rapid decomposition of the organic matter than is seen in most cultivated soils. Since the decomposition rate can be approximately described as exponential decay, the concept of half-life may be useful for characterizing decomposition rates. Johnston et al. found that the rate of decomposition of manure and sewage sludge could be adequately described as
exponential decay. At Woburn, during 40 years of cropping, these authors found the carbon half-life to be 20.1 years. At Rothamstead, under fallow, the carbon half-life was 10.1 years. Naturally, such rates and half-lives will be strongly dependent on edaphic and climatic conditions, as well as tillage practices. Clay content, soil pH, temperature, and moisture may all strongly affect the rate of decomposition of MSW composts applied to soil. The few available data suggest that, if large amounts of MSW composts are applied to agricultural soils, half of the organic matter may decompose within one or two decades. If compost becomes a significant portion of the soil present, the metal concentration could increase in the soil over time after compost application ceases. However, metals will be removed from the soil due to such processes as leaching and plant uptake. The concentration of metals in the soil at any time will be the sum of these processes.

8. SUMMARY AND CONCLUSIONS

Several of the trace elements in MSW composts have the potential to cause toxicity to plants, soil biota, or animals that feed on contaminated crops. The uptake of these elements by plants is affected strongly by soil type and soil pH and varies substantially for different crops. While relatively few data are available from field research with MSW composts, some tentative conclusions can be drawn from these data and also from data on the application of sewage sludge to cropland.

Boron can be toxic to some crops when the water-extractable concentration in the soil is 3 μg g⁻¹. Such concentrations are sometimes found in MSW composts, but will rarely occur if MSW compost is applied to soil due to dilution. Leaching of the compost prior to application can eliminate this problem.

Long-term field studies with MSW composts suggest that Cu, Ni, Zn, As, and Pb will rarely pose a problem due to plant uptake from MSW composts applied to cropland. While the soil content of these metals will increase with MSW application, contents in foliage apparently do not reach phytotoxic levels.

Most long-term studies of application of MSW composts to cropland have shown a decrease or little change in the Cd content of crops. But these experiments have not included species that accumulate Cd most readily, such as spinach and tobacco. Mushrooms can accumulate Cd readily, thus MSW composts with elevated Cd levels may not be suitable for mushroom production. While the Hg content of MSW composts is usually low, it can be bio-accumulated. Mercury can be taken up by mushrooms. MSW composts with elevated Hg may not be suitable for mushroom production.

When high doses of MSW composts are applied, the concentrations of many metals in leachate have been shown to exceed drinking water standards within the first year under extreme experimental conditions. Under field conditions subsoil will presumably serve as a sink for metals, at least for many decades. Leaching of metals into groundwater is only likely to occur with heavy repeated applications of MSW composts over many years in regions with sandy soils, shallow groundwater, karst formations or other conditions that limit the opportunity for adsorption of metals by soils.

The average values of Pb, Cu, and Zn in MSW composts in North America exceed limits suggested to protect invertebrates in forest soils. However, these suggested limits do not consider that the bio-availability of metals may well be lower in MSW composts than in soils, and thus they may overestimate the potential for toxicity to soil invertebrates.

At present, there is contradictory evidence as to whether metals in MSW composts cause deleterious effects to populations of soil micro-biota, including those responsible for fixing atmospheric nitrogen. Such effects may not be widespread, and are unlikely to significantly decrease crop yields, since composts also often have beneficial effects on soil microbiota.

The available data suggest that, if large amounts of MSW composts are applied to agricultural soils, half of the organic matter may decompose within one or two decades. If compost becomes a significant proportion of the soil present, the metal concentration could increase in the soil over time after compost application ceases. However, metals will be removed from the soil due to such processes as leaching and plant uptake. The concentration of metals in the soil at any time will be the sum of these processes.

Based on studies of plant uptake under field conditions, only a small percentage of the metals in compost-amended soil are in chemical forms that are bio-available to plants and other organisms. Compost application may even decrease metal availability on highly contaminated sites.
The most challenging task is to determine the long-term effects of the application of MSW composts to cropland, since such studies are difficult and time-consuming to conduct. However, field experiments with MSW composts have rarely found evidence of deleterious effects to plants or other organisms.

While this review is restricted to examining potential detrimental effects of MSW composts, readers should also bear in mind the many beneficial effects of MSW compost. These benefits include: fertilization by trace elements such as Zn and B, improved soil physical characteristics such as increased water holding capacity, improved chemical characteristics such as nutrient retention capacity, and stimulation of microbial activity. These benefits can improve plant growth, and decrease the leaching of pollutants such as nitrates into water supplies. Any assessment of land application of MSW compost should include these potential beneficial effects, as well as the potential detrimental effects discussed herein.

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REFERENCES

25. S. de Haan, Results of municipal waste compost research over more than fifty years at the Institute for Soil Fertility at Haren/Groningen, the Netherlands. Neth. J. Agric. Sci. 29, 49–61 (1981).
54. W. Werner, Effect of long-term application of sewage sludge and garbage compost on chemical...


