# 4

Using treated municipal wastewater effluents and sludge on agricultural land provides an

production of crops. Sewage sludge and wastewater effluents can provide essential plant nutri-ents

the physical condition of the soil and render it a more favorable environment to manage the nutrients and water. However, unlike manufactured fertilizers, whose nutrient pro-perties can be formulated to

applying treated sludges and effluents at agronomic rates to satisfy the requirement for one nutrient may cause the levels of other nutrients to be excessive or remain deficient.

nickel, and zinc) could be phytotoxic if added to the soil in excess of critical levels. Trace elements and trace organics in sludge are of concern if they are taken up by crops in amounts harmful to consumers

in the environment are also of concern. If the constituents from sludge and effluent application are not immobilized in the surface soil, they may escape the root zone and leach to ground water. This chapter

ground water resources, and includes a brief discussion of landscape-level perspectives.

## SLUDGE AS A SOURCE OF PLANT NUTRIENTS

nitrogen and phosphorus are the most abundant major plant nutrients in sludge (Metcalf and Eddy,

fertilizer.

## Nitrogen

Typically, treated sludges include about 1 to 6 percent nitrogen on a dry weight basis (Metcalf and Eddy, 1991; Dean and Smith, 1973). By contrast, nitrogen in commercial fertilizers range from 11 to 82 percent (Lorenz and Maynard, 1988). The nitrogen in treated sludge occurs in both organic and plant-available inorganic forms. The relative proportions of each depend upon the way sludges are processed. In anaerobically digested liquid sludges, microbial oxidation of the organic materials is incomplete, and the nitrogen occurs in both soluble ammoniacal and insoluble organic forms, primarily, in microbial cells (Broadbent, 1973). In aerobically digested sludges, microbial oxidation is greater and there is less residual organic nitrogen than in anaerobically digested sludges. Ammoniacal nitrogen is about 10 percent of the total nitrogen in aerobically digested sludge and about 30 percent of the total nitrogen in anaerobically digested sludge (Linden et al., 1983). In aerobically digested sludge, the ammoniacal nitrogen is further oxidized to nitrate, of which part is lost to wastewater when sludge is dewatered. Likewise, when anaerobically digested sludges are dewatered, part of the am-moniacal nitrogen is lost with the water.

Where sludges are used as a source of nitrogen, the nitrogen application rates should not exceed the agronomic rate (a rate equivalent to the amount of fertilizer nitrogen applied to the soil for the crop grown). As with any fertilizer, nitrogen that leaches beyond the root zone could contaminate ground water. To determine the quantity of sludge needed for the crop's nitrogen requirement, it is important to know the relative proportions of inorganic and organic nitrogen. The inorganic forms of nitrogen (nitrate and ammonium) are immediately available to the crop. Organic forms of nitrogen are not available to the crop and must first be mineralized by microorganisms to inorganic forms. The rate of mineralization depends on a number of factors including sludge type, carbon-to-nitrogen ratio of the soil and/or sludge, climate, soil type, and water content. The rate of mineralization of sludge-borne organic nitrogen in soil ranges from a high of essentially 100 percent per year to a low of a few percent during the initial year of application (Parker and Sommers, 1983). Nitrogen not mineralized during the initial cropping year is mineralized in subsequent years, but usually at a diminishing rate. In general, mineralization rates of organic nitrogen in composted and dry sludges are less than those of liquid sludges and dewatered sludge cake.

A theoretical example is presented in Table 4.1 of a 5-year change in available nitrogen from applying a sludge containing 2 percent organic and 1 percent inorganic nitrogen. In the example, the organic nitrogen mineralization rate is 40 percent the first year, and this rate is reduced by 50 percent each succeeding year (the computation assumes that the only removal of nitrogen from the system is through plant uptake). In this example, the amount of plant-available nitrogen from 5 annual applications of 1 ton of sludge increases from 18 kg/ton to 22 kg/ton, and the amount of sludge required to supply 180 kg available nitrogen per ha decreases from 10 tons to 8.2 tons from year 1 to year 5. The example shows the importance of min-eralization of organic nitrogen in succeeding years following the application. If organic nitrogen mineralization is not properly accounted for, overfertilization may occur that will subsequently lead to nitrogen leaching.

TABLE 4.1 Effect of Organic Nitrogen Mineralization on Plant-available Nitrogen (N) from Sludge Applications.[a]

| | Available inorganic | Available organic | Total available N | Sludge required[b] |
|---|---|---|---|---|

| Year | N (kg/ton) | N(kg/ton) | (kg/ton) | (tons) |
|---|---|---|---|---|
| 1st | 10 | 8.0 | 18.0 | 10.0 |
| 2nd | 10 | 10.4 | 20.4 | 8.8 |
| 3rd | 10 | 11.4 | 21.4 | 8.4 |
| 4th | 10 | 11.8 | 21.8 | 8.3 |
| 5th | 10 | 12.0 | 22.0 | 8.2 |

[a]The analysis assumes that sludge contains 1.0 percent inorganic and 2.0 percent organic nitrogen. Mineralization rate is 40 percent the first year, reduced by one-half in each succeeding year (40, 20, 10, 5).

[b]Amount of sludge required to supply 180 kg available nitrogen per hectare.

### Phosphorus

Commercial fertilizers typically contain between 8 and 24 percent phosphorus (Lorenz and Maynard, 1988). By contrast, sludges typically contain between 0.8 and 6.1 percent phosphorus (Metcalf and Eddy, 1991; Dean and Smith, 1973). Like nitrogen, the phosphorus in sludges is present in inorganic and organic forms. The proportions of each vary and depend on the source of municipal wastewater and on sludge treatment. Unlike nitrogen, inorganic forms of phosphorus are quite insoluble and phosphorus tends to concentrate in the organic and inorganic solid phases. Almost without exception, the amount of phosphorus applied is more than sufficient to supply the needs of the crop where sludges are applied as a source of nitrogen. For example, a sludge containing 1.5 percent phosphorus, applied at a rate of 10 metric tons per ha, would supply 150 kilograms of phosphorus per ha. At this application rate, available phos-phorus may be excessive in many areas, particularly where animal manure is plentiful and where phosphorus is well-above levels needed for maximum crop yields. These high levels could significantly increase the risk of surface water contamination. Based on long-term evaluations of treated sludge use over periods ranging from 9 to 23 years, the Water Environment Research Foundation (1993) has recommended soil phosphorus levels be monitored where sludge applications are used continuously over time, and that sludge application rates may need to be determined by crop phosphorus levels rather than the nitrogen needs of the crop.

### Other Essential Plant Nutrients

In addition to nitrogen and phosphorus, treated sludges contain all other nutrients es-sential for the growth of crops, including calcium, iron, magnesium, manganese, potassium, sodium, and zinc (Linden et al., 1983). Where treated sludges are applied according to agronomic rates for nitrogen, many of these essential nutrients, with the possible exception of potassium, are usually present in amounts adequate to meet the needs of the crop (Chaney, 1990).

## TREATED MUNICIPAL WASTEWATER AS A SOURCE OF PLANT NUTRIENTS AND IRRIGATION WATER

## Plant Nutrients

Although treated municipal wastewaters are usually applied as a source of irrigation water for crops, they are also a source of plant nutrients, especially nitrogen. The concentration of nutrients in wastewaters depends upon the water supply, the quality of the wastewater, and the type and degree of wastewater treatment. Usually, each stage in the treatment process reduces the concentration of both nitrogen and phosphorus. Typically, conventionally treated municipal wastewaters contain from 10 to 40 mg of nitrogen per liter and from a few to 30 mg of phosphorus per liter (Asano et al. 1985). In the arid southwestern United States, the quantity of irrigation water required to meet the needs of most crops is the equivalent of about 1 meter depth per ha per crop season. This quantity of treated wastewater, containing typical con-centrations of nitrogen and phosphorus of 20 and 10 mg/liter respectively, would add 200 kg nitrogen and 100 kg phosphorus per ha. These application rates will meet or, in some cases, exceed the nitrogen and phosphorus fertilizer needs of many crops over the growing season. Further, plants require varying amounts of nutrients and water at different stages in the growth cycle, and the timing of irrigation may not correspond to when plant nutrients are needed. Wastewater applications at times when the plant needs are low can potentially lead to leaching of nitrate-nitrogen and possible contamination of ground water.

When plant nutrient needs are not in phase with irrigation needs, the presence of nutrients in irrigation water may interfere with its use. For example, ill-timed and over-fertilization with nitrogen can cause excessive growth, reduce crop yield, and encourage weed growth (Asano and Pettygrove, 1987; Bouwer and Idelovitch, 1987). Yield and crop quality have been harmed by excess nitrogen in many crops, including tomatoes, potatoes, citrus, and grapes (Bouwer and Idelovitch, 1987). To minimize the undesirable effects of excess nutrients, their levels in reclaimed water should be kept within stipulated guidelines, crops should be selected to match nutrient levels, ground water quality should be monitored, and excess water should be diverted elsewhere (Bouwer and Idelovitch, 1987). In the Water Conserv II wastewater reclamation project in Orlando, Florida, excess water not used by citrus growers is diverted into rapid in-filtration basins for disposal (Jackson and Cross, 1993). Because the underlying aquifer is a drinking water source, it is closely monitored as part of the Conserv II project.

## Irrigation Water Quality Concerns

The feasibility of using treated municipal wastewater as a source of irrigation water depends upon its quality. This in turn depends upon the quality of the municipal water supply, the nature of the constituents added during water use, and the kind and degree of wastewater treatment. Wastewater constituents that can degrade water quality for irrigation include salts, nutrients and trace contaminants. Quality criteria for salinity, permeability, specific ion toxicity, and miscellaneous elements are presented in Table 4.2. The effects of reclaimed water on soil
chemical properties, including the accumulation of trace contaminants are discussed in a succeed-

TABLE 4.2 Irrigation Water Quality Criteria

| Diagnostic Measurement | Degree of restriction on use[a] |
|---|---|
| | Slight to |

| Parameter restricting use | (units) | None | Moderate | Severe |
|---|---|---|---|---|
| Salinity | EC (dS/m)[b] | 0.7 | 0.7-3.0 | >3.0 |
| | TDS (mg/1)[c] | | 450-2000 | >2000 |
| Permeability/ infiltration | SAR $(mmole/l)^{1/2}$[d] and EC (dS/m) | | | |
| | EC @ SAR 0-6 | >1.2 | 1.2-0.3 | <0.3 |
| | EC @ SAR 12-20 | >2.9 | 2.9-1.3 | <1.3 |
| | EC @ SAR 20-40 | >5.0 | 5.0-2.9 | <2.9 |
| pH | | <8.5 | >8.5 | |
| Phytoxicity (mostly tree crops ornamentals) | | | | |
| With surface irrigation | | | | |
| Sodium | SAR $(mmole/l)^{1/2}$ | <3 | 3.9 | >9 |
| Chloride | (mg/l) | <140 | 140-350 | >350 |
| Boron | (mg/l) | <0.7 | 0.7-3.0 | >3.0 |
| With sprinkler irrigation | | | | |
| Sodium | (mg/l) | <70 | >70 | |
| Chloride | (mg/l) | <100 | >100 | |
| Boron | (mg/l) | <0.7 | 0.7-3.0 | >3.0 |
| With overhead sprinkling only | | | | |
| Bicarbonate | (mg/l) | <90 | 90-500 | >500 |
| Residual chlorine | (mg/l) | <1 | 1.0-5.0 | >5 |
| Crop quality/ground water protection | | | | |
| Nitrogen (total N) | mg/l | <5 | 5-30 | >30 |

[a] Restriction on use but does not indicate that water is unsuitable for use, that there may be a limitation such as crop species or soil type and special management practices may be necessary for full productive capacity.

[b] Electrical conductivity

[c] Total dissolved solids

[d] Sodium Adsorption Ratio

SOURCE: Adapted and condensed from Westcot and Ayers, 1985.

ing section of the chapter.

## EFFECTS OF SLUDGE AND WASTEWATER ON SOIL PHYSICAL PROPERTIES

### Organic Matter

Soil organic matter enhances the structural properties of a soil by binding together soil particles into aggregates or lumps and creating large (non-capillary) pores through which air and water move.

As land is cropped, soil organic matter is gradually lost, leading to a deterioration of its physical properties. Soils under continuous cultivation are very deficient in organic matter because the rate at which organic matter returns from crop residues is lower than the rate of organic matter decomposition in soils. Where organic matter is lacking, the less stable soil aggregates easily fall apart in the presence of rain or percolating water; in spite of cultivation, the larger soil pores are lost, soil air decreases, water movement is restricted, the soil becomes more closely packed, and the bulk density increases.

### Water Retention Properties

Generally, the application of sludge increases the capacity of the soil to retain water. The organic carbon content of sludge may affect water retention either through the direct effect of sludge organic particles themselves or through its indirect effect on other physical properties (such as bulk density, porosity, and pore size distribution). Several researchers have reported an increase in the water retention capacity of soils at field capacity[1] and at the wilting point[1] following sludge application (Chang et al., 1983; Metzger and Yaron, 1987).

### Structure and Aggregation

Sludge, like other organic materials, is less dense than the mineral fraction of soil and can improve the structure of soil by reducing bulk density and promoting soil aggregation. However, Chang et al. (1983) cautions that far greater quantities of sludge than normally needed to supply nutrients for crop growth are required to induce significant changes in soil physical properties. Low annual application rates (22.5 and 45 metric tons per ha) of municipal sludge compost improved agronomic performance, but higher amounts (80 metric tons per ha) were required to significantly change soil physical properties (Chang et al., 1983). Nevertheless, even at lower annual rates of sludge application (27 metric tons per ha) the bulk density of soils of various textural classes, including fine-textured soils, are reduced (Hall and Coker, 1983; also see Metzger and Yaron, 1987). As with manures and composts, the organic matter in sludge can increase soil porosity because of improved soil aggregation (Guidi et al., 1983; Pagliai et al., 1981).

The addition of sludge increases the number and size of water-stable aggregates. In-creases in aggregate formation, by approximately one-third, were observed by Epstein (1975). This has been substantiated in field experiments on various soil types, in various climates, and with various sludges and composts. Aggregate formation is the result of both chemical and mi-crobial agents.

Aggregate stabilization must occur along with aggregate formation if a permanent in-crease in soil aggregation is to occur. In a comparative study of four organic materials added to soil at 25 metric tons per ha, aggregate stability was increased by 24 percent with sludge, 22 percent with manure, 40 percent with alfalfa, and 59 percent with straw (Martens and Franken-berger, 1992). Anaerobically digested sludges provided the best stabilizing effect compared to other sludge treatment processes (Pagliai et al., 1981).

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[1]Field capacity is approximately equal to the amount of water that is held at -0.33 bar; the wilting point is when plants begin to show moisture stress, defined as -15 bars.

### Water Transmission Properties

Organic matter in sludge and wastewater can impede infiltration and aeration by temp-orarily plugging the soil surface. However, the net effect of organic matter on soil aggregation, as explained above, is improved soil structure, which enhances water transmission, water infiltration and, in some instances, reduces the soil's susceptibility to erosion.

Under certain conditions, the levels of sodium, calcium, and magnesium in treated eff- luents can adversely affect soil structure and worsen the soil's infiltration, friability, and tillage characteristics. Sodium, when present in high concentrations relative to calcium and magne-sium, can cause dispersion of soil aggregates leading to reduced infiltration and permeability. The degree to which the various concentrations of sodium may affect soil structure is related not only to concentrations of calcium and magnesium but also to the salinity of the effluent. Techniques used to predict the effects of sodium on infiltration and permeability of water are based on the Sodium Adsorption Ratio (SAR), a ratio of the concentration in water of sodium to the square root of the sum of the concentrations of calcium plus magnesium (all concentrations are expressed in millimoles per liter). Waters with high SAR but low salinity disperse the soil, making it less friable, harder to work and less permeable to water. For example (as was shown in Table 4.2), water with a SAR of 12, a total dissolved solids (TDS) level of about 1200 (at an Electrical Conductivity [EC] of about 1.9 deciSiemens per meter [dS/m]) causes no permeability or infiltration problems, while water with a SAR of 3 and a TDS of about 200 (at an EC of about 0.3 dS/m) causes severe permeability problems. The salinity of soil water also affects the growth of crops through its effect on water availability (Bouwer and Idelovitch, 1987). Plants vary in their tolerance of soil salinity (Maas, 1990).

## EFFECTS OF SLUDGE AND WASTEWATER ON SOIL CHEMICAL PROPERTIES

Biologically stabilized sewage sludge contains an average of approximately 50 percent organic matter on a dry weight basis. Following addition to soil, the sludge undergoes de-composition to carbon dioxide, water, low molecular weight soluble organic acids, residual organic matter and inorganic constituents. Although most of the organic fraction of the sludge is converted to carbon dioxide and water, some becomes part of the stable soil humus layer (Boyd et al., 1980; Hernandez et al., 1990) and serves to increase the soil's net negative charge and its cation exchange capacity (CEC) (National Research Council, 1977; Thompson et al., 1989). CEC is a measure of the capacity of the soil to retain cations. A high CEC is desirable because it lessens or prevents essential nutrient loss by leaching (Broadbent, 1973; National Research Council, 1977). Collectively, constituents released from sludge following decomposition and present in wastewater may be put into four groupings: 1) the more soluble cations, anions and molecules, 2) trace elements which form sparingly soluble reaction products, 3) potentially harmful inorganic chemicals, and 4) potentially harmful organics.

### Soluble Cations, Anions, and Molecules

The soluble cations, anions, and molecules found in effluents and sludge, and which are of concern in agricultural operations, generally include potassium, sodium, calcium, magnesium, chloride, sulfate, nitrate, bicarbonate, selenate, and boron (as boric acid and borate) in lesser concentrations. All of the above are absorbed by plants and those which are essential contribute to the nutrient-supplying power of effluents and sludges. They enter into ion exchange equilibria and those of lesser affinity are leached away by drainage water. Because boric acid is usually uncharged and is weakly adsorbed, it normally is leached to levels safe for most crops where water is applied in excess of evapotranspiration (Keren and Bingham, 1985). Above concen-trations of about 0.7 mg/liter in irrigation waters, boron may be toxic to sensitive plants (Maas, 1990). Consequently, precautions must be taken to insure that the boron concentrations in the soil solutions of sludge-amended soils and soils irrigated with municipal wastewater do not exceed this critical level for sensitive crops. Tolerant crops (e.g. cotton) normally withstand irrigation waters containing boron concentrations as high as 10 mg/liter without damage (Maas, 1990).

As with normal irrigation practices, salts in reclaimed wastewater need to be managed to preserve the productivity of the soil. Typical concentrations of salts in treated effluents are within accepted criteria for irrigation water quality (see Table 2.1); however, their concentration can vary widely. Unless salts are removed from the root zone by plants or leaching, they accumulate and eventually reach a level that will prevent the growth of all but the most tolerant plants. Even under the most ideal conditions, plants remove less than 10 percent of the salts applied through irrigation water (Oster and Rhodes, 1985). Therefore, to sustain growth, salts must be leached from the root zone. In temperate and humid regions where irrigation is practiced only during dry periods, precipitation is usually sufficient to leach salts to an acceptable level. However, in semiarid and arid regions, continued irrigation in the absence of leaching will lead to an accumulation of salts in the soil profile to levels that will inhibit the growth of crops. This problem is usually circumvented by adding more water than is used by the crop. The quantity of water in excess of crop requirements is referred to as the leaching requirement. Methods used to manage irrigation waters of varying quality to avoid the ac-cumulation of salinity problems are outlined by Kruse et al. (1990).

## Trace Elements

Following organic matter decomposition, trace elements from wastewater and sludge are released and form sparingly soluble reaction products. These trace elements include arsenic, cadmium, copper, cobalt, nickel, lead, selenite-selenium, molybdate-molybdenum, and others. Because of their sparingly soluble nature and their limited uptake by plants, they tend to accumulate in the surface soil and become part of the soil matrix (McGrath et al., 1994). With repeated applications of wastewater, and particularly sludges, these elements could accumulate to levels toxic to plants (Chang et al., 1992) and soil organisms (McGrath et al., 1994). They could also accumulate in crops where they could, in turn, build up to potentially harmful levels in humans, domestic animals, and wildlife that consume the crops (Logan and Chaney, 1983). EPA developed soil concentration limits considered safe for agricultural crops in its Part 503 Sludge Rule (EPA, 1993a) and these limits are presented in Chapter 7.

In general, crops grown on acid soils accumulate higher concentrations of most trace elements in their tissues and are more susceptible to phytotoxicity than are crops grown on neutral or calcareous soils. Because repeated sewage sludge applications lead to accumulations of trace elements in soil, concern has been expressed over possible adverse effects associated with the use of sludge on soils that are acid or that may become acid (McBride, 1995). In an attempt to address this concern, Ryan and Chaney (1994) compared the pH distribution of soils used by EPA in the development of the Part 503 Sludge Rule with pH values of all U.S. soils (as compiled by Holmgren et al. 1993). From this comparison it was evident that acid soils were well represented in EPA's analysis. An additional safeguard arises from a set of con-servative assumptions used in EPA's risk assessment. In setting the standards for trace elements, EPA assumed a cumulative application limit of 1000 metric tons of dry sludge per ha. Because sludge application rates used in most of the available research studies were lower than this, EPA used a linear regression technique to extrapolate crop uptake to the limit of 1,000 metric tons. Chaney and Ryan (1992) showed that crop uptake usually reaches a plateau with increasing sludge application and that the actual crop uptake of trace elements should be far lower than predicted by the linear regression values used by EPA. Finally, in normal agri-cultural practice, crops grown in extremely acid soils with excess zinc, copper, and nickel would show visual phytotoxicity symptoms. In practice, when these symptoms are observed, the soil is limed to correct the problem. In fact, problems associated with soil acidity are normally corrected through routine management operations because, almost without exception, acid soils are limed prior to cropping. This neutralizes acidity to avoid phytotoxicity from naturally occurring aluminum present in the soil (Pearson and Adams, 1967). Therefore, as long as agricultural use of treated sludges and wastewater is in keeping with existing regulations and sound agronomic practices, the possibility that trace elements applied from this practice would adversely affect the yield or wholesomeness of crops is remote.

Concerns have been expressed about what may happen once a site has reached its cumulative limit for metals and sludge application stops (McBride, 1995). The chemical properties of the soil will likely change over time. The availability of certain trace elements may increase and potentially cause phytotoxicity problems and/or cause greater bioaccumulation of trace elements in crops. While there is little published information on this long-term prob-lem, the city of Chicago has accumulated soils and crop data on both reclaimed strip-mined fields and natural soils following termination of sludge applications. Table 4.3 shows an ex-ample of some data collected on organic carbon, zinc, cadmium, and copper from seven fields that had received an average of 226 tons per acre of sludge from 1972 through 1984, where monitoring had continued to the present. Additional research is needed in this area, but these preliminary results indicate that trace elements are not necessarily more available for periods of up to 10 years following cessation of sludge applications.

TABLE 4.3 Organic Carbon and Availability of Zinc, Cadmium, and Copper After Cessation of Long-Term Sludge Application

| Year | Organic Carbon % | Zinc | | Cadmium | | Copper | |
|---|---|---|---|---|---|---|---|
| | | soil[a] | corn[b] | soil | corn | soil | corn |
| 1984 | 4.4 | 747 | 26.0 | 56.5 | 0.27 | 295 | 2.05 |
| 1985 | 4.4 | 668 | 33.0 | 58.3 | 0.26 | 321 | 0.95 |
| 1986 | 4.8 | 655 | 26.8 | 49.8 | 0.07 | 261 | 1.29 |
| 1987 | 4.2 | 701 | 25.5 | 53.5 | 0.20 | 295 | 2.59 |
| 1988 | 4.0 | 614 | 35.5 | 45.9 | 0.07 | 240 | 1.62 |
| 1989 | 3.9 | 689 | 33.5 | 45.5 | 0.38 | 255 | 2.57 |
| 1990 | 4.3 | 586 | 33.5 | 46.2 | 0.11 | 232 | 1.94 |
| 1991 | 4.1 | 584 | 33.0 | 45.8 | 0.05 | 242 | 1.62 |
| 1992 | 4.1 | 676 | 33.0 | 52.1 | 0.17 | 289 | 0.97 |
| 1993 | 3.9 | 635 | 20.0 | 49.6 | 0.11 | 275 | 2.00 |

[a]Zinc, cadmium, and copper soil measurements are 0.1 M HCl extractable concentrations in mg $kg^{-1}$ for the top six inches of soil as measured annually on samples from each field.
[b]Corn grain concentrations in mg $kg^{-1}$

Note: Farm fields received an average of 226 tons/acre of sludge from the Metropolitan Water Reclamation District of Greater Chicago from 1972 through 1984. None of the fields have received sludge since 1984. The cumulative loading rate for Zn, Cd and Cu was 1,532, 827 and 127 kg $ha^{-1}$ (1,367, 738, and 113 lb/acre), respectively.

SOURCE: Granato, 1995.

## Accumulation of Potentially Harmful Inorganic Chemicals in Soils and Crops

Treated municipal wastewaters rarely contain harmful trace elements at concentrations in excess of criteria established for irrigation water (as was shown earlier in Table 2.1). There-fore, where industrial pretreatment programs are effectively enforced, it would seem reasonable to permit treated municipal wastewaters that meet irrigation water quality criteria to be used for crop irrigation. Assuming this to be the case, municipal wastewater applied at the limits pre-scribed for irrigation water at the rate of 1.5 m/ha (per growing season) should add relatively minor amounts of trace elements.

The concentrations of trace elements in sewage sludges vary, depending on the con-tributions from industries and households to the common sewer system and the effectiveness of industrial pretreatment programs (see Chapter 3). Ranges of trace elements based on the EPA 1990 National Sewage Survey (NSSS) are presented in Table 4.4 from Kuchenrither and Carr (1991). Using these data for a typical sludge applied at 10 metric tons per ha, one can compute annual soil loading of trace elements. Data presented in Table 4.5 show annual loading of trace elements with compositions at the 50th, 95th, and 98th percentiles compared to typical soil concentration and the EPA cumulative loading limits from the Part 503 Sludge Rule. Although applications of sludges with compositions at the 95th and 98th percentile add substantially to the

TABLE 4.4 Summary of Results for Regulated Inorganic Pollutants From the EPA 1990 Na-tional Sewage Sludge Survey

| Pollutant | Number of Times Detected[a] | Mean (mg/kg) | Minimum (mg/kg) | Maximum (mg/kg) |
|---|---|---|---|---|
| Arsenic | 194 | 12.4 | 0.3 | 316 |
| Cadmium | 194 | 65.5 | 0.7 | 8,220 |
| Chromium | 231 | 258 | 2.0 | 3,750 |
| Copper | 239 | 665 | 6.8 | 3,120 |
| Lead | 213 | 195 | 9.4 | 1,670 |
| Mercury | 184 | 4.1 | 0.2 | 47.0 |
| Molybdenum | 148 | 13.1 | 2.0 | 67.9 |
| Nickel | 201 | 77.0 | 2.0 | 976 |
| Selenium | 163 | 6.2 | 0.5 | 70.0 |
| Zinc | 239 | 1,693 | 37.8 | 68,000 |

[a]The values represent the number of times the chemical was detected in samples taken from 209 wastewater treatment plants. Plants were randomly selected from all regions of the U.S. The total number of samples is 239 because of multiple samples taken at some plants.

SOURCE: Adapted from Kuchenrither and Carr, 1991.

background concentrations in soils, additions are well within U.S. EPA limits. In the most limiting cases of copper, lead, and zinc, a sludge with an element concentration equal to the 95th percentile could be applied annually at 10 metric tons per ha for a period of about 75 years be-fore regulatory limits would be reached.

Actual experience at numerous sewage sludge land application sites has indicated that uptake of metals by plants has been minimal. Bray et al. (1985) analyzed three years of silage crop on land amended each year by municipal sludge at moderate to high rates (15-90 metric tons per ha). The silage contained elevated though not excessive levels of cadmium and zinc, but elevated levels were not observed for the other 12 elements tested, including arsenic, chrom-ium, lead, mercury, and selenium.

In developing the Part 503 Sludge Regulations, EPA conducted an extensive review of trace element uptake by crops in relation to amounts added in the form of sewage sludge (EPA, 1993a; 1993b). Table 4.6 lists uptake slopes for different food crops and shows that crops differ substantially in their tendency to bioconcentrate sludge-borne trace elements added to soils. An uptake slope is calculated as the concentration of a chemical in plant tissues (in mg/kg) divided by the amount of chemical added to the soil (in kg/ha). Based upon the geometric mean of uptake slope values, the elements arsenic (As), copper (Cu), lead (Pb), mercury (Hg), and nickel (Ni) consistently show the lowest uptake values across all food groups. The elements cadmium (Cd), selenium (Se), and zinc (Zn) have the highest uptake values in the majority of the food

TABLE 4.5 Annual Loading of Trace Elements for Sludges With Compositions Equal to the 50th, 95th and 98th Percentile From the National Sewage Sludge Survey When Applied at a Rate of 10 m tons/ha Compared to Typical Soil Concentrations and the EPA Loading Limits. All Values are in kg/ha.

| Element | Annual Loading at Percentile Compositions | | | Typical Concentration in Soil | EPA Cumulative Loading Limit |
|---|---|---|---|---|---|
| | 50th | 95th | 98th | | |
| Arsenic | 0.10 | 0.40 | 0.54 | 12.0 | 41 |
| Cadmium | 0.07 | 0.15 | 0.58 | 0.15 | 39 |
| Chromium | 1.2 | 5.0 | 10.0 | 200.0 | 3,000 |
| Copper | 7.4 | 21.0 | 35.0 | 40.0 | 1,500 |
| Lead | 1.4 | 4.0 | 8.0 | 30.0 | 300 |
| Mercury | 0.05 | 0.19 | 0.38 | 0.06 | 17 |
| Nickel | 0.04 | 2.0 | 2.9 | 80.0 | 420 |
| Selenium | 0.05 | 0.19 | 0.27 | 0.4 | 100 |
| Zinc | 12.0 | 35.0 | 60.0 | 100.0 | 2,800 |

groups, although the uptake slopes are reasonably low in most cases. Molybdenum (Mo) is unique in that its uptake slope is very high for leguminous vegetables. The elements copper, molybdenum, and zinc are essential for the growth of plants, so these data indicate that sludge could correct deficiencies of these elements. The element cadmium, if present in the human diet in sufficient quantities over extended periods of time (decades), is a chronic toxin (Kostial, 1986); molybdenum and selenium are toxic to wildlife and domestic animals if consumed above critical levels (Mills and Davis, 1986; Levander, 1986). The public health concerns about exposure to trace elements through the consumption of crops grown on sludge-amended soils are discussed in Chapter 6.

### Accumulations of Potentially Harmful Organics in Soils and Crops

Organic chemicals, when added to the soil may volatilize, decompose, or be adsorbed. Consequently, only those that are nonvolatile and are relatively resistant to decomposition will accumulate in soils. Most organic compounds found in treated municipal wastewater occur at concentrations of less than 10 mg/liter, and accumulation in soil from this source is usually so small that it is below the limits detectible by conventional analytical methods (O'Connor et al.,

1991, Webber et al., 1994). Based upon the 99th percentile concentration from the NSSS, EPA computed annual loading for 12 reasonably persistent organic chemicals. Available evidence indicates that most trace organics are either not taken up or are taken up in very low amounts by crops (O'Connor et al., 1991, EPA, 1993b). A discussion of possible implications and health consequences of toxic organic compounds in sludges is presented in Chapter 6.

## EFFECTS OF SLUDGE ON SOIL MICROORGANISMS

Soil microorganisms include bacteria, actinomycetes, fungi and algae. They are impor-tant in the decomposition of organic matter and in the cycling of plant nutrients such as nitrogen, phosphorus, and sulfur. Metal accumulations in soils associated with the long-term applications of sewage sludge have been shown to affect microbial activity and biomass, biological nitrogen fixation, and vesicular-arbuscular mycorrhizae (Giller et al., 1989; McGrath et al., 1988; McGrath et al., 1994; Smith, 1991). Vesicular-arbuscular mycorrihizae refers to the symbiotic association between plants and certain fungi, in which the fungi obtain carbohydrates and the plants obtain nutrients such as phosphorus and zinc for growth.

### Microbial Biomass and Activity

The application of sewage sludge will temporally increase microbial populations due to the addition of an exogenous food supply. Depending upon the carbon to nitrogen (C/N) ratio of the added material, the demands of the increased microbial population for nitrogen could reduce the plant-available nitrogen to levels that are deficient for crop growth (Alexander, 1977). This process, referred to as immobilization, occurs when the C/N ratio in the sludge-soil mixture is about 20 or more and microbes convert inorganic nitrogen to organic nitrogen—a form unavailable to crops (Alexander, 1977). However, immobilization of nitrogen is usually tempor-ary. As decomposition proceeds, carbon is volatilized to carbon dioxide, and as the C/N ratio becomes less than about 20, mineralization of the organic nitrogen exceeds immobilization, and excess inorganic nitrogen becomes available to plants.

The accumulation of metals following long-term applications of sewage sludge has been observed to reduce levels of microbial biomass (Brookes et al., 1986b). In a long-term field ex-periment that compared sludge-amended soils to manure-amended soils, McGrath et al. (1994) reported microbial biomass levels in the high-metal sludge-treated soils to be approximately half those of the manure-treated soils. Similar observations were made by Boyle and Paul (1989) who also reported increased levels of nitrogen in soil biomass following eight years of sludge application. A one time high-rate sludge application has also been reported to decrease soil bio-mass (Stark and Lee, 1988).

### Biological Nitrogen Fixation

The accumulation of metals in soils following long-term applications of sewage sludge has been reported to adversely affect the symbiotic relationship between certain strains of rhizobia (McGrath et al., 1994; Giller et al., 1989). McGrath et al. (1988) observed lesser concentrations of nitrogen and decreased yields of white clover in a soil that had received sludge applications over a period of 20 years. Clover root nodules in the treated group were smaller and ineffective in nitrogen fixation. Clover rhizobia isolated from high metal-contaminated soil were ineffective in nitrogen fixation (Giller et al., 1989). Nitrogen fixation was restored by inoculation of the soil with large numbers of effective rhizobium of the same strain (greater than 10,000 cells per gram of soil) followed by incubation in a moist condition for two months (McGrath et al., 1994). The authors concluded that clover rhizobia were unable to survive in the free-living state outside the protected root nodule in metal-contaminated soils.

The inhibition of rhizobium bacteria following sludge applications is inconclusive, and other studies have shown little or no effect of sludge on nitrogen fixation. Heckman et al. (1987), for example, examined the effects of sludge-amended soil on the symbiotic fixation of nitrogen by soybean. They found no effect of sludge metals on nitrogen fixation at one site but observed a decrease in the amounts of nitrogen fixed where high metal sludges were applied at another site. Kinkle et al. (1987) studied soybean rhizobia in soils that had received sludge 11 years earlier. They observed no long-term detrimental effect of sludge applications on soil rhizobial numbers and no shift in serogroup distribution. Similarly, Angle and Chaney (1989) observed no effect of sludge applications on rhizobia. More recently Ibekwe et al. (1995) reported reduced nodulation and ineffective symbiosis for alfalfa, white clover, and red clover grown in sludge-amended soils (pH equal to or less than 5.2). However, the investigators observed no effect on plant growth, nodulation, and nitrogen fixation when these legumes were grown in sludge-amended soils maintained at pH 6.0 and greater.

Long term applications of sewage sludge resulting in metal accumulations in surface soils have been shown to reduce nitrogen fixation by free-living heterotrophic bacteria (Brookes et al, 1986a; Lorenz et al., 1992; Martensson and Witter, 1990). In an experiment where sludge-treated soils were compared to manure-treated soils, nitrogen-fixing activity by diazotrophs in the sludge-treated soil was decreased to 2 percent of that of the manure-treated soil. Lorenz et al. (1992) also observed reduced nitrogen fixation in plots treated with sludge compared to plots treated with farmyard manure. Nitrogen fixation by cyanobacteria (blue-green algae) has also been reported to be reduced in soils having a history of repeated sludge applications as compared to soils with a long history of farmyard manure applications (Brookes et al., 1986a).

Symbiotic functions between plants and soil microbes are negatively impacted only if the soil microbes affect uptake of nutrients by the associated plants. Studies on vesicular-arbuscular mycorrhizas (VAM)-plant associations in sludge-treated soils are confounded by the rather large amounts of phosphorus added with sludge and the effect of soil pH on VAM, both of which in addition to the effect of metals, could inhibit infection. Available information suggests that sludge applications to soil act to delay rather than suppress mycorrhizal infection (Koomen et al., 1990).

A tractor spreading sewage sludge on a stubble field before the growing season (photo courtesy of Robert Bastian, U.S. Environmental Protection Agency).

## EFFECTS ON GROUND WATER

Because municipal wastewater contains only traces of pesticides (O'Connor et al., 1991; Kuchenrither and Carr, 1991), land application of treated wastewater effluents and sludge presents a much smaller hazard of pesticides than does the usual, direct application of pesticides to crops for the control of pests.

Nitrate pollution of ground water is often reported as an effect of excessive application of conventional fertilizers to crops (Hallberg and Keeney, 1993). As described earlier in this chapter, nitrate pollution of groundwater from application of wastewater effluent and sludge can be controlled by the same nutrient management techniques used in traditional agriculture.

The potential for ground water contamination by microorganisms, trace elements and toxic organic compounds from wastewater and sludge is evaluated below. (Chapters 5 and 6 discuss other public health effects of these contaminants.)

### Pathogenic Microorganisms

There are three kinds of microorganisms in sewage which are of concern for their effects on human health: bacteria, viruses, and parasites. All have been found in treated secondary effluent and sludges. Wastewater irrigation can potentially transport bacteria and viruses to ground water under certain conditions, as described below. In contrast, because bacteria and viruses in sludge are strongly sorbed to sludge solids, they are not usually desorbed in the soil, and are not likely to be transported to ground water. Helminth cysts and worm eggs are reported to be too large to be transported to ground water (Gerba, 1983).

Viruses are a special concern in wastewater irrigation because virus particles are small, may percolate through soil, and may persist for months in the soil environment (Gerba, 1983). Using traditional methods of virus sampling and assay of water from soil lysimeters at sites irrigated with undisinfected secondary wastewater effluent, Moore et al. (1981), have found coliphage virus particles at a depth of 1.37 meters. Using more sensitive detection methods, several ground water samples were taken 27.5 meters below wastewater soil application sites and were found to be positive for animal viruses. In the same study, the test soil site receiving disinfected wastewater had only one sample which was positive for viruses, significantly less than soils irrigated with undisinfected wastewater effluent (Goyal et al., 1984).

Disinfection appears to be advisable in preventing ground water contamination by viruses from irrigation with treated municipal wastewater. In the context of food crop production, EPA guidelines recommend a minimum of secondary treatment plus disinfection (EPA, 1992). Current state regulations for reclaimed water use on crops vary depending on water quality and process requirements, site restrictions, monitoring, and crop type allowed. Of the 18 states that regulate irrigation of food crops with reclaimed water, only 3 (Arkansas, Nevada, and Michigan) do not have requirements for disinfection or criteria for microbiological water quality; however other restrictions or ground water monitoring may apply (see discussion of state regulations in Chapter 7).

In a summary of virus removal from treated wastewaters, Asano (1992) has estimated that undisinfected effluent has approximately 90 percent of viruses removed (1 log removal) from sewage as a result of primary and secondary wastewater treatment processes. Effluent disinfection accounts for an additional 2 to 5 logs removal, that is, a total of 99.9 to 99.999 percent virus removal. When combined with natural soil sorption processes, virus removal from disinfected effluent applied to soils for the purpose of groundwater recharge has been estimated to be 12.6 to 17 logs of reduction. Using a risk assessment approach, Asano et al. (1992) developed an exposure scenario that uses the nearest well to a ground water recharge site containing 50 percent reclaimed wastewater that has percolated through three meters of soil for six months. The most exposed individual is assumed to consume two liters per day of this wellwater, equivalent to 1 liter per day of reclaimed wastewater. The authors have estimated that the lifetime risk of an individual contracting a single infection from poliovirus or echovirus from drinking ground water recharged with disinfected (tertiary treated) wastewater effluent was very low, in the range of $10^{-6}$ to $10^{-9}$. While not the subject of this report, the use of treated municipal wastewater as a source for ground water recharge has been evaluated by the National Research Council (1994). Its report concludes that where treated municipal wastewater is used to recharge ground water that is a potable water supply, uncertainties remain concerning the transport and fate of viruses in ground water.

Bacteria that are used as indicators of wastewater contamination (fecal coliform and fecal streptococci) have been found in soil water at a depth of 1.37 meters below fields irrigated with treated but undisinfected wastewater effluent. Bacterial counts in lysimeter water ranged from 2 to 370 viable cells per 100 milliliters water for fecal coliform bacteria and from approximately 1 to 77 fecal streptococcus bacteria per 100 milliliters of water (Moore et al., 1981).

In summary, application of treated wastewater effluents to soils may pose some risk of ground water contamination by viruses and bacteria, but that risk is minimized to extremely low levels by disinfection of reclaimed wastewater and by slow infiltration rates (Asano et al., 1992; Gerba, 1983).

## Heavy Metals

Through cation exchange, chemical exchange, chemical sorption, precipitation, and complexation reactions, metallic ions are readily removed from wastewater and are concentrated in sludges. Soil particles act to further sequester most heavy metals, and this preference of metals for particulates has been observed often in agricultural soils. (Chang and Page, 1983; Pettygrove and Asano, 1985; Gallier et al., 1993). Therefore heavy metal cations would not be expected to leach out of the unsaturated soil zone into ground water. In fact, of the toxic heavy metals regulated under the Part 503 Sludge Rule, (EPA, 1993b), a scientific peer review panel suggested that the risk of ground water contamination be used only to determine the heavy metal standard for hexavalent chromium (Chaney and Ryan, 1992). Hexavalent chromium is an unstable and rare form of chromium, and is rapidly reduced in most environmental conditions to its trivalent form, which is quite immobile in soils and not expected to leach to ground water.

Heavy metals from sludges may remain in soils for years after application. However, when sludges are applied to soils at rates controlled by agronomic nutrient uptake rates, transport of heavy metals from sludges to ground water is unlikely unless the sludges have unusually high levels of metal ions (Logan and Chaney, 1983).

## Toxic Organic Compounds

PCBs and detergents are the only classes of synthetic organic compounds that occur in municipal wastewater sludges and effluents in concentrations higher than those in conventional agricultural irrigation water or soil additives (O'Connor et al., 1991; Brunner et al., 1988; Giger et al., 1987; Furr et al., 1976). In municipal treatment plants, both PCBs and detergents are concentrated into the sludge fraction.

PCBs have been found in sludges from municipal wastewater treatment plants, especially those receiving industrial waste discharges or urban storm drainage. Furr et al. (1976) reported concentrations of PCBs from single sample analyses of sludges from major cities to be in the range of less than 0.01 mg/kg dry weight for San Francisco, California to 23.1 mg/kg for Schenectady, New York. An average PCB concentration in sludges from the 15 cities in this survey was 4.8 mg/kg dry weight, with PCBs detected in 87 percent of the samples. More recently, the NSSS reported that PCB concentration in sludges averaged 3.2 mg/kg dry weight, and PCBs were detected in approximately 10 percent of the samples from about 200 treatment plants (Kuchenrither and Carr, 1991).

PCBs have a strong affinity for particulate material and, under certain circumstances, can be volatilized. They are not very soluble, and it is unlikely that PCB compounds would be transported to ground water from the unsaturated soil zone. Gan and Berthouex (1994) have studied sludge application sites from the Madison (Wisconsin) Metropolitan Sewerage District from 1985 to 1990. They report that there were no measurable PCBs in runoff water from these sites. From their study, it seems that while PCBs may persist in the soil itself and may be taken up by plants, they are not a significant risk for ground water contamination.

Testing for 330 toxic organic compounds in the NSSS found infrequent occurrence in the 209 POTWs sampled. However, one organic compound, bis(2-ethylhexyl) phthalate, was detected in 90 percent of the samples with an average concentration of 108 mg/kg dry weight (Kuchenrither and Carr, 1991). Bis(2-ethylhexyl) phthalate is thought to sorb very strongly to soil, and therefore would not be expected to leach into ground water. Also, the compound is relatively biodegradable with an estimated half-life in soil ranging from 5 to 23 days (Howard et al., 1991). Phthalates are commonly used as plasticizers, such as in polyvinylchloride, and over one million metric tons of phthalates are produced annually worldwide. Because phthalates are so ubiquitous in the environment, laboratory-derived phthalates are reportedly a frequent source of errors in sample analyses (Schwarzenbach et al., 1992).

Detergent compounds, including surfactants like linear alkylbenzene sulfonates and nonylphenol ethoxylates and binders like nitriloacetate, have been found in sludges in relatively high concentrations, in the range of 0.5 to 4 g/kg dry weight (Brunner et al., 1988; Giger et al., 1987). However, in field and laboratory tests, it has been observed that detergents are rapidly removed from the soil-root zone by biodegradation, and are not transported out of the unsatur-ated soil zone by leaching (Holt et al., 1989).

In summary, a few toxic organic compounds and detergents have been found in sludges; however, because they are either biodegradable in soils or sorb strongly to soil particles, these compounds are not a risk for ground water contamination. Overcash (1983) has stated that leaching of toxic organic constituents to ground water will not occur when application rates for either treated wastewater effluent or sludge to agricultural soils are controlled by crop water and nutrient demands. However, it is cautioned that soils should be allowed to drain after each application and that the ground water table should be more than 0.3 to 1 meter (about 1 to 3 feet) from the soil surface.

## LANDSCAPE-LEVEL CONSIDERATIONS

The foregoing discussion is mainly focused on the application of municipal or wastewater sludge on single fields or farms. However, the solution to both pollution problems and the sustainability of agriculture depends on conducting investigations at broader scales, such as communities and watersheds. For example, the impact of agricultural nonpoint pollution on streams and water supplies depends upon the combined effects of all farm practices within a watershed rather than the application of sludge to one field for one year (for example, see Barrett et al., 1990; Barrett and Bohlen, 1991). Indeed, Barrett (1992) noted that a new field of study—agrolandscape ecology—must evolve if society is to develop and manage agriculture in a sustainable and cost-effective manner for future generations. As alternative agricultural (National Research Council, 1989) gains acceptance, the role of sludge at these levels of in-tegration should be evaluated.

## SUMMARY

Municipal sewage sludge can be used as a source or supplemental source of nitrogen and phosphorous in the production of crops. Sludge also contains all other essential plant nutrients and, when used as an nitrogen source at agronomic rates, will usually satisfy crop requirements for all essential nutrients, except possibly potassium. The salts, nitrogen, trace elements and trace organics in sludge and wastewater effluents need to be managed properly to avoid damage to the soil, crop, consumer of the crop, and ground water. If the constituents from sludge and wastewater applications are not removed in the harvested crop, volatilized, or degraded, they may escape the root zone and leach to ground water. The accumulation of metals in sludge-amended soils may inhibit the activity of certain strains of clover rhizobia and cyanobacteria, and cause reductions in microbial biomass. This may be of concern to the sustainability of cer-tain native legume species, but should not impact commercial food crop production.

As with the addition to soils of other organic materials, such as hay and animal manures, the addition of organic matter accompanying successive sludge additions improves the physical properties of soils. This, in turn, exerts a positive influence on water penetration, porosity, bulk density, strength, and aggregate stability.

Concentrations of potentially harmful trace elements in sludges are, almost without exception, greater than their concentrations in typical soil. Consequently, sludge applications usually increase the concentrations of trace elements in soils. Because most trace elements are immobile, the added sludge-borne trace elements tend to concentrate in the surface to the depth of incorporation. Where sludge has been applied to soil according to existing guidelines and regulations, there have been no reports of phytotoxicity or accumulation of harmful levels in consumers attributed to the trace elements. Also, as long as agricultural use of treated sludge follows current regulations, no adverse effects on acid soils or potentially acid soils, are anticipated.

A few toxic organic compounds and detergents have been found in sludges; they are either not absorbed or are absorbed by crops through the root systems in such small amounts that they do not present a threat to consumers. Some trace organics may be absorbed by the aerial part of the plant through volatilization of the compounds from the soil surface. However, this pathway does not seem important, particularly where sludges are incorporated into the soil. Because the concentrations of toxic organic compounds in sludge are low and they are either biodegradable in soils or strongly sorb to soil particles, they do not represent a risk to ground water contamination. At application rates of either sludge or treated municipal wastewater to agricultural soils that are controlled by water or nutrient demand by crops, the leaching of organic wastewater constituents to ground water will not occur if soils are allowed to drain after application and the ground water is more than 0.3 to 1 meter from the surface.

Where treated municipal wastewaters are used to irrigate crops, users must take into account nutrients (nitrogen and phosphorous) accompanying the water and adjust fertilizer practices accordingly. Under certain soil-plant systems, it is recommended that soil phosphorus levels be monitored so that the accumulation of soil phosphorus does not exceed crop requirements (usually about 150 kg/ha). As long as treated municipal wastewaters meet irrigation water quality criteria and state regulations governing disease-causing organisms in the water, they should be considered safe for agricultural use.

Treated municipal wastewater effluents and sludge resemble normal irrigation water and manures. Although they may contain some exotic compounds and fertilizer elements in different proportions than an ideal fertilizer, they present no significant hazards to agricultural soils, crops, or the environment if they are applied in quantities commensurate with crop needs.

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TABLE 4.6  Uptake Slopes of Trace Elements in Various Food Groups in Relation to Quantity Applied in the Form of Sludge [mg/kg of trace elements in plant tissue] [kg/ha of trace elements applied]$^{-1}$

| | Potatoes | | Leafy vegetables | | Legumes | | Root vegetables | | Garden fruit | | Grain/Cereal | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Element | Mean | | Mean | Max | | Max | Mean | | Mean | Max | | Max |
| As | | 0.006 | 0.018 | | 0.001 | 0.002 | | 0.014 | 0.001 | | 0.002 | 0.013 |
| | 0.004 | 0.038 | | 7.06 | 0.002 | | 0.032 | 0.594 | | 0.636 | 0.031 | |
| Cu | 0.003 | | 0.014 | 0.200 | | 0.339 | 0.003 | | 0.014 | 0.068 | | 0.080 |
| Pb | | 0.001 | 0.003 | | 0.001 | 0.006 | | 0.009 | 0.001 | | 0.001 | 0.004 |
| | 0.001 | 0.005 | | 0.046 | 0.001 | | 0.007 | 0.043 | | 0.043 | 0.043 | |
| Mo | 0.011 | | - | - | | 4.21 | 0.012 | | - | - | | 1.48 |
| Ni | | 0.024 | 0.016 | | 0.031 | 0.502 | | 0.067 | 0.003 | | 0.033 | 0.055 |
| | 0.021 | 0.048 | | 0.038 | 0.012 | | 0.011 | 0.048 | | 0.039 | 0.003 | |
| Zn | 0.012 | | 0.125 | 2.24 | | 0.055 | 0.022 | | 0.022 | 0.197 | | 0.86 |

Uptake values are concentrations of trace elements in plant tissue in mg/kg.
1
2

sent either 0.001 or less than 0.001.