

Land Application of Biosolids:

A Review of Research Concerning Benefits, Environmental Impacts, and Regulations of Applying Treated Sewage Sludge



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Oklahoma Agricultural Experiment Station and
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Cover photos:

Cattle graze on the improved pasture of Mr. Grant Silvadon near Mounds, Oklahoma. Pasture grass quality and yield has been improved through sewage sludge injection from the City of Tulsa land application program. The land application vehicle (bottom right) is used for injecting sewage sludge into pasture land. Photos by Sue Talley, Soil Scientist, City of Tulsa.

Nicholas T. Basta, Editor
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EXECUTIVE SUMMARY

The Water Quality Act of 1972 that mandated development of technologies to treat, dispose, and recycle nutrients in wastewaters and sludges dramatically increased land application of sewage sludge by municipalities across the nation. Since then, extensive research has documented benefits and environmental impacts associated with land application of sewage sludge. Regulations have been promulgated at the federal and state levels that maximize utilization of benefits and minimize/eliminate risks. However, scientific information and regulations are highly technical and are not easily accessible to the public. Public perception that reflects reality is formed from accurate, credible information. The purpose of this document is to present a comprehensive review of benefits and environmental impacts documented by research studies and to describe current regulations governing land application of sewage sludge.

Sewage sludge is produced from wastewater treatment plants operated by municipalities. Sewage sludge solids consist mainly of partially decomposed organic matter and significant amounts of plant nutrients including nitrogen, phosphorus, sulfur, calcium, magnesium, and micronutrients (iron, copper, manganese, zinc, nickel, boron, cobalt, and molybdenum). Undesirable constituents that may be present in trace amounts in sewage sludge are heavy metals, organic chemicals, and pathogens. Sewage sludge composition depends on both wastewater input and treatment processes. Land-applicable sewage sludge is *not* toxic waste.

Land-applied sewage sludge undergoes chemical and biological transformations that affect plant nutrient availability and determine the environmental fate of its constituents. Sludge decomposition releases nitrogen, phosphorus, sulfur, and other plant nutrients. Soil chemical processes limit heavy metal and micronutrient solubility and bioavailability. After land application, sewage sludge-borne metals enter soil chemical pathways common to indigenous natural-occurring heavy metals. Many studies show heavy metals are not leached and pose no threat to water quality. Numerous studies have shown that mobility and plant uptake of several heavy metals are increased in acid soils. Long-term studies suggest that soil chemical processes decrease heavy metal availability with time. Research results do not support the “time bomb” theory where heavy metal availability increases with time.

After land application, most organics are rapidly adsorbed, volatilized, or decomposed and present little risk to the food chain. The sewage sludge treatment process significantly reduces human and animal pathogens but does not eliminate them. Pathogen survival is prolonged in low temperature, wet soils but most pathogens die rapidly in hot, dry soils. Research findings indicate that combined soil adsorption and climatic conditions virtually eliminate risk from sludge-borne pathogens. The HIV virus that results in AIDS has never been found in treated sewage sludge. At present, there appear to be no public health hazards due to HIV transmission from land application of sewage sludge.

Land application of sewage sludge benefits crop production by supplying a wide range of plant nutrients. Extensive research has documented the fertilizer benefits of sewage sludge. Research has shown that land-applied sewage sludge produces high crop yields and high quality crops similar to commercial fertilizer. Agronomic rates of sewage sludge do not significantly increase crop heavy metal content or impair crop quality. Significant heavy metal crop uptake can occur from land application of excessive amounts of sewage sludge or application of sewage sludge to strongly acidic soils. Regulated management practices are designed to prevent these conditions.

Forages grown on sludge-fertilized lands have been utilized by grazing ruminants, principally beef cattle, while grain crops from these sites have been used by both monogastrics and ruminants. Research trials and long-term experience with land application of sludge to forage and crop lands show that natural soil-plant-animal barriers act to minimize risks from toxic trace elements, organic compounds, and pathogenic organisms. Livestock that graze forages or use feed grains grown on sludge-amended soils are healthy and safe for human consumption.

Sludge utilization projects on forestland for reforestation, biomass production, and fertilization have been established in 23 states. Sewage sludge application increases growth of trees and other forest vegetation. The growth response is highly variable and is greatest in stands of young trees on infertile soils. Sludge application benefits forest soils by increasing nutrient availability, organic matter content, and water holding capacity. Sludge application increases growth and quality of plants used by wildlife. Significant increases in plant nitrogen, crude protein, and phosphorous content have resulted from sludge application. Deer and elk preferentially browse plants in sludge-treated areas because of the increased plant protein content. Increases in small mammal populations have also been found. Impacts of sludge application to forest soils include accumulation of heavy metals in the organic horizons of forest soils. However, research studies show no significant movement of heavy metals. Increases of cadmium in organs of mice and voles and in earthworms taken from sludge-treated sites have been found. However, these animals did not show any toxic effects. No increases in cadmium concentrations in deer were observed. Little information is available on accumulation of metals to higher animals in the food chain. Excessive sludge applications can increase nitrate leaching but limited application rates reduce impacts on water quality. Approximately 1.9 million acres of forestland in eastern Oklahoma has the best potential for achieving the benefits of sludge utilization. Research performed in other forested regions in the United States provides good background for sludge utilization, but differences in soils, vegetation, and climate of Oklahoma raise some concerns that should be addressed.

Several research studies have examined the effect of land application of sewage sludge because of the concern that it could contaminate surface or ground waters. Two comprehensive, long-term studies of sludge application and several shorter experiments, reviewed here, indicate that heavy metals, synthetic organic compounds, and microorganisms are not likely to reach ground water in a well-managed land application site. These same studies show that nitrate contamination of ground water and surface water is possible if application rates exceed crop nitrogen needs.

Use of sewage sludge as a source of plant nutrients and as a soil amendment on native ecosystems such as forest and grassland has been studied. Sludge application to degraded rangeland increased production of blue grama (*Bouteloua gracilis*), a highly desirable forage species; and broom snakeweed (*Gutierrezia sarothrae*), an undesirable invading shrub, had a complete die-off. Nutrient additions can have negative impacts on native grasslands. Increases in broad-leaved plants or annual grasses that are considered to be weeds may have to be controlled in some cases.

Because native ecosystems are sensitive to mechanical disturbances and may show long-term effects of such treatments, sewage sludge should be surface-applied. Wildlife benefits from increased quantity and quality of vegetation in native ecosystems after sludge application. In general, studies have found increases in metal levels in wildlife animals. However, metal increases were small and limited to specific organs such as liver, kidneys, or bone. These increases have not affected the overall health and vigor of the monitored wildlife populations.

There has not been an outbreak of human disease attributed to land application of sewage sludge *within* practices mandated by U.S. EPA regulations. A comprehensive sewage sludge land application project was conducted in Ohio to clearly define health risks to local residents and their livestock. In this study, human health effects on 47 farms that land-applied sewage sludge were compared with 46 control farms that did not land-apply any sewage sludge for a five-year period. Results clearly showed no negative human health effects or adverse effects on livestock associated with land application of sewage sludge.

Land application of sewage sludge has been used to reclaim coal strip-mine spoils, gravel spoils, coal refuse, clay strip-mine spoils, iron ore tailings, abandoned pyrite mine spoils, and sites devastated by toxic fumes. A review of available literature indicates stabilized municipal sludge revegetates disturbed lands with no significant adverse effects on vegetation, soil, groundwater quality, or animal or human health. Sewage sludge improves properties, nutrient content, and microbial life of reclaimed soils. Because revegetation reduces surface runoff and soil erosion, surface water quality is often improved. Municipal sludge can accelerate reestablishment of a normal functioning soil ecosystem and accelerate land reclamation by years and in some cases decades.

All aspects of sewage sludge disposal are regulated by the U.S. EPA. Recently, new regulations (Part 503) were promulgated governing land application of sewage sludge. To qualify for land application, sewage sludge must (1) contain less heavy metal than the pollutant Ceiling Concentrations, (2) meet Class B pathogen reduction requirements, and (3) meet vector attraction reduction requirements. Sewage sludges that do not meet these requirements *cannot* be land-applied and they must be incinerated or landfilled. Land application of "Exceptional Quality" (EQ) sludge has fewer restrictions than lower quality land-applicable sewage sludge. Part 503 is a risk-based regulation designed to protect the public health and the environment from reasonable worst-case scenarios. Part 503 was developed by pollutant identification, determination of pollutant exposure pathways, risk determination, and derivation of pollutant concentration limits. Sewage sludge is applied at agronomic rates that satisfy crop nitrogen require-

ments and minimize nitrate movement to ground water. Crop nitrogen requirements and other information needed to determine the agronomic application rate can be obtained from County Extension Service agents, State Extension soil fertility specialists, and Soil Conservation Service agents. The sewage sludge application rate may be limited by the amount of heavy metals in the sewage sludge. Land-applicable sludge that contains pollutants above EQ Pollutant Concentration Limits are subject to cumulative loading limits and finite site lifetimes. Exceptional Quality sewage sludges are not subject to site lifetimes—they can be land-applied indefinitely. Many states, including Oklahoma, have passed regulations that are more stringent than federal regulations. Recently, new regulations have been drafted in response to U.S. EPA Part 503 promulgated regulations. Notable differences between federal and the more restrictive state of Oklahoma regulations include limits on heavy metal contents of sewage sludge, pH limits, and restrictions on phosphorus loading. State of Oklahoma regulations simultaneously advocate beneficial use of sewage sludge through land application and promote production of “cleaner sludges” with reduced heavy metal contents.

Many of the trends associated with land application of sewage sludge established during the last 25 years are likely to continue. Land application will increase, and incineration, landfilling, and other alternative sludge disposal methods will decrease. The next 25 years will bring an increase in beneficial land application of new waste materials including municipal solid waste and possibly “designer sludges.” Knowledge gained from sewage sludge research and methods used to regulate land application will be essential for beneficial land application of new materials.

INTRODUCTION

by Nicholas T. Basta

Extensive research on land application of sewage sludge has been conducted during the last 25 years. Results from this research have been used to design and regulate beneficial land application of sewage sludge in an environmentally safe manner.

However, public perception of sewage sludge has changed slowly during the last two decades. Many times the public does not understand the wastewater treatment process, the composition of sewage sludge, or the land application process. Public perception is often misled by information on earlier (early 1970s) reports that showed some sewage sludge contained high levels of heavy metals. Today's sewage sludge does not contain high levels of heavy metals. Pretreatment processes and regulations have led to production of "clean" sludges that have low heavy metal contents. However, "sewage sludge" is often associated with "heavy metals" by the public. Sometimes, scientific information does not directly influence public perception. As with other solid waste issues, (1) perception equals reality (perceived risks are real even if scientific information finds no risk), and (2) in decision-making, perception *outweighs* reality.

Such was the case in late 1991 when MERCO, Inc. proposed a project involving application of New York City sewage sludge to land in Thomas, Oklahoma. In this project, sewage sludge shipments from New York would be applied to farmland in the vicinity of Thomas, Oklahoma. All operations would have been subject to state and federal regulations. Although there was extensive scientific information available documenting the safety of this project, the public reaction was outrage. Scientific information was too technical and was not readily available to the public. Public perception was formed from claims made by several opposition groups. The public was misinformed that land application of New York sludge would: contaminate their aquifer with heavy metals and spread AIDS and "killer TB" throughout their communities. Being unfamiliar with sludge spreading, some of the public exaggerated dangers out of all proportion. Decisions were made against this land application project based on public perception. Land application operations in Colorado and Texas are currently receiving sewage sludge from New York City. These land owners (from neighboring states) have a completely different perception of land application of sewage sludge, and some claim it is equivalent to "organic" farming. Land owners from New Mexico may start importing sewage sludge soon.

Public perception is properly formed by providing accurate, credible information. The purpose of this document is to present information from research studies and describe current regulations governing land application of sewage sludge in an unbiased manner. This document was produced in conjunction with the Center for Agriculture and the Environment (CAGEN), which is part of the Division of Agricultural Sciences and Natural Resources at Oklahoma State University. The mission of CAGEN includes "serving as an information clearinghouse to various public and user groups."

HISTORICAL PERSPECTIVE

by *Nicholas T. Basta*

Human waste from small communities has been land-applied for centuries. Unfortunately, some human waste carrying a spectrum of pathogenic organisms would contaminate waterways and drinking water. In many cities before the nineteenth century, polluted water was a prime cause of human disease (Coker, 1983; Diamant, 1980). Drinking water was often contaminated and cholera, typhoid fever, and other enteric diseases were common. Systematic collection, treatment, and disposal of wastewater became a widespread practice in the last century. Municipal wastewater treatment systems were designed to remove pathogens from wastewater before release into streams. Wastewater treatment has broken the human-to-human disease cycle and has greatly reduced transmission and incidence of human diseases (Gerba, 1983).

Interest in land application of wastewater spurred research in the 1960s. Concurrently, wastewater treatment systems were designed to remove nutrients, contaminants, and pathogens prior to discharge into streams, lakes, and other waterways. These systems produce a solid by-product, sewage sludge, that contains plant nutrients and trace amounts of contaminants. Interest in utilization of sludge-derived plant nutrients led to land application of sewage sludge by municipalities and associated research in the late 1960s.

The late 1960s and early 1970s also brought nationwide concern regarding environmental degradation. Rachel Carson's book *Silent Spring* raised public concern over eutrophication of lakes from nitrate and phosphorus pollution of rivers and other waterways. New diseases from heavy metal poisoning were reported. Minamata (mercury poisoning) and Itai-itai (cadmium) diseases in Japan sharply focused attention on pollution of the environment by heavy metals (Davies, 1992). Trace element pollution was linked to degradation of the environment and human health. Public concerns were legislated by the Water Quality Act (WQA) of 1972, which mandated development of technologies to treat, dispose, and recycle nutrients in wastewaters and sludges in an environmentally sound manner. The 1972 WQA dramatically increased land application of sewage sludge by municipalities across the nation. However, technical data needed to assess pollution potential or impact of land application of sludge on the environment was lacking. In 1973, a joint conference sponsored by a subcommittee of the U.S. Environmental Protection Agency, U.S. Department of Agriculture, and the National Association of Land Grant Colleges to set a research agenda on recycling municipal sewage sludge and effluents on land was held (U.S. EPA, 1973). Priority research needs identified included (1) development of management systems for nutrient recycling, (2) environmental fate of heavy metals and other sludge-borne pollutants, and (3) fate and control of pathogenic organisms (Page, 1983). Many research projects were initiated in the 1970s, and a large body of technical information was generated. This information was used in development of federal regulations governing land application of sewage sludge in 1979 (U.S. EPA, 1979). The 1980s showed continued increases in research activity, amounts of land-applied sewage sludge, and regulation promulgation governing land

application by state and federal agencies. In 1987, Congress amended Section 405 of the Clean Water Act (CWA) and set forth a comprehensive program for maximizing the beneficial use of sludge while reducing the potential environmental risks. A comprehensive rule was proposed in 1989 by the U.S. EPA (U.S. EPA, 1989a) that would be “adequate to protect human health and the environment from any reasonably anticipated adverse effect of each pollutant,” according to Section 405 (d)(2)(D) of the 1987 CWA. In part, proposed regulations were developed from findings from research conducted by members of several technical committees. Members of Cooperative State Research Service (CSRS) Regional Research Technical Committee W-170 (preceded by CSRS NC-118 and W-124 committees) have contributed a great deal of technical information concerning land application of sewage sludge. Public comments from W-170 members and others (U.S. EPA, 1993b) led to the U.S. EPA’s final rule on February 28, 1993 (U.S. EPA, 1993a).

Dramatic changes in land application of sewage sludge have taken place during the last two decades. Land application of sewage sludge has increased from 20% (0.6 million dry tons) to 33% (1.8 million dry tons) of the total sludge produced in the United States from 1972 to 1989 (U.S. EPA, 1993b). Oklahoma is well above the national average with more than 60% of its sewage sludge currently being land-applied. During the last two decades, more than 2200 technical papers have been published regarding sewage sludge. Research findings from these studies have provided the technical basis to plan and design beneficial sewage sludge land application systems. Long-term research studies (lasting 20 years or longer) and thousands of municipal operations across the world have shown that benefits may be realized from land application of sewage sludge without hazard (Page et al., 1993). Future research and regulatory activities will likely address “new contaminants,” new sewage sludge-derived products, beneficial sludge management for new agronomic cropping systems, and benefits and risks associated with “new” agroecosystem pathways and components.

SEWAGE SLUDGE COMPOSITION AND TRANSFORMATIONS

by *Nicholas T. Basta*

Sewage Sludge Generation and Composition

Sewage sludge is produced from wastewater treatment plants operated by municipalities. Wastewaters may contain domestic wastes (soaps, human excrement, food, detergents, household hazardous waste), pretreated industrial wastes, and/or stormwater runoff. Sludge is defined as a material that contains more than 0.5% solids by weight. Unprocessed sewage sludge is generally 93 to 99.5% water and contains substances that were present in the wastewater or that were added or produced by the wastewater treatment process. *Untreated* sewage sludge contains organic solids, nutrients (e.g., nitrogen, phosphorus, and micronutrients), pathogens (e.g., bacteria, viruses, protozoa, and eggs of parasitic worms), and trace amounts of organic chemicals and inorganic chemicals (e.g., heavy metals). The chemical and biological constituents of untreated sludge depend upon the composition of the wastewater entering the treatment facility and the subsequent treatment process. Municipal wastewater treatment works may use one or more levels of treatment (primary, secondary, or tertiary). Each level of treatment generates both greater wastewater cleanup and greater amounts of sewage sludge.

Primary treatment processes remove the solids that settle out of the wastewater by gravity. Secondary treatment produces a sludge generated by biological treatment processes. Biological treatment processes (e.g., activated sludge systems, trickling filters, and other attached growth systems) use microbes to break down and convert organic substances to microbial residue. Tertiary treatment processes include chemical precipitation. Chemical precipitation uses chemical flocculants to remove organics and nutrients and to separate the solids from the wastewater.

Prior to disposal, treatment works generally thicken, stabilize, and de-water sewage sludge. Sludge thickening is the removal of water from sludge to achieve a volume reduction. The reduction in sludge volume decreases the capital and operating costs of subsequent sludge processing and disposal operations. Treatment works digest or compost their sewage sludge to reduce the level of pathogens and odors. Digestion processes significantly reduce pathogen numbers and virtually eliminate risks of pathogenic diseases.

The composition of treated sewage sludge depends on the combination of the treatment process used. Sewage sludge ranges from mostly liquid to greater than 90% dry matter. Sewage sludge solids consist mainly of partially decomposed organic matter (30-60%) (U.S. EPA, 1983) mixed with soil and other chemicals added during the treatment process (e.g., alum, lime). Sewage sludge contains significant amounts of plant nutrients that include nitrogen (0.5-10%), phosphorus (1-6%), sulfur (0.5-1.5%), calcium (1-20%), and magnesium (0.3-2%); and micronutrients such as iron (0.1-5.0%), copper, manganese, and zinc (< 0.2%), nickel, boron, cobalt, and molybdenum (<0.05%) (Furr et al., 1976; Sommers, 1977). Three types of undesirable constituents may be present in trace

amounts in sewage sludge: (1) heavy metal and inorganic pollutants, (2) toxic organic chemicals, and (3) pathogens.

In order to characterize the quality of final process sewage sludge and to produce national estimates of concentrations of pollutants in municipal sewage sludge, the U.S. EPA conducted the National Sewage Sludge Survey (NSSS) (U.S. EPA, 1988). In the NSSS, sewage sludge from 208 treatment plants were analyzed for 412 chemical constituents, including many organic chemicals (pesticide, dibenzofuran, dioxin, and PCB for which the EPA had gas chromatography and mass spectrometry standards), heavy metals, and many other inorganic pollutants (U.S. EPA, 1993b). Most pollutants were not found in these sewage sludges. Few organic pollutants were found in measurable amounts in any of the sludges analyzed. Statistics from some of the NSSS data of inorganic contaminants in sewage sludge are shown below (Table 1).

Several significant discoveries made by NSSS are worth noting. In the 1980s, the EPA implemented programs that required pretreatment of industrial wastewater before discharge to the municipal plant. NSSS data shows a dramatic reduction in the amount of pollutants in sewage sludge was achieved (as much as tenfold). Therefore, earlier sewage sludge composition data overestimates current sewage sludge pollutant contents. Today's sludge is much "cleaner" due to "front of the pipe" pretreatment programs.

Sewage sludge composition depends on both wastewater input and treatment processes. Metropolitan areas have many different municipal plants with varying degrees of industrial input and pretreatment. For example, New York City has 14 public-owned treatment works with a wide range of industrial inputs and pretreatment. This results in a wide range of chemical and biological contents. It is an oversimplification and inaccurate to assume that (1) all New York City sludge is similar, and (2) that based on population, all New York City sludge should contain more contaminants than sewage sludge generated in Oklahoma (NYCDEP, 1991). A comprehensive study conducted in Iowa showed there is not a direct relationship between pollutant content and size of city (Tabatabai and Frankenberger, 1979). Several towns with less than 2000 people had

Table 1. Statistical summary of select inorganic contaminants found in sewage sludges of the national sewage sludge survey. (All values are mg of contaminant per kg of dry sludge.)

Metal (mg/kg Dry Wt)	Mean 50th Percentile	67th Percentile	98th Percentile
Arsenic	10	29	48
Beryllium	0.3	1	1
Cadmium	7	19	31
Chromium	119	458	797
Copper	741	1,703	2,665
Lead	134	332	530
Mercury	5	21	37
Molybdenum	9	26	43
Nickel	43	137	231
Selenium	5	12	19
Zinc	1,202	2,756	4,310

similar chemical composition compared to cities with populations exceeding 0.6 million people and a significant industrial base.

The EPA Office of Solid Waste (OSW) uses the Toxicity Characteristic Leaching Procedure (TCLP) to determine whether solid wastes, including sewage sludges, are hazardous. Results from a 1985-86 OSW study (U.S. EPA, 1993c) showed pollutants in sewage sludge were far below TCLP levels considered hazardous and that tested sewage sludges were not toxic nor hazardous waste. Federal and state regulations require extensive analysis of treated sewage sludge before transport from treatment works for disposal (U.S. EPA, 1993a; ODEQ, 1994). The same regulations prohibit land application of sewage sludges that are considered toxic or hazardous. Sewage sludges that exceed "ceiling limits" (much lower pollutant concentrations than mandated by toxic levels measured by TCLP) cannot be land-applied and must be incinerated or landfilled.

Transformations of Land-Applied Sewage Sludge

Shortly after land application, sewage sludge undergoes dramatic chemical and biological transformations. These transformations affect plant nutrient availability and determine the environmental fate of sewage sludge constituents.

Mainly because sewage sludge is predominantly organic matter, the primary transformation observed first is decomposition. In general, sludge decomposition decreases with time after application and is essentially complete (>90%) within the first two years. Decomposition rates depend on the sewage sludge treatment process and the soil conditions (U.S. EPA, 1993b). A substantial portion is decomposed by several sewage sludge treatment processes. Decomposition rates of land-applied sludges reflect the extent of prior decomposition at the treatment works and follow the trend primary > secondary, aerobic > secondary, anaerobic > secondary, composted. Soil properties that influence decomposition rate include temperature, water content, soil pH, and carbon-nitrogen ratio. Optimum decomposition conditions are soil water content of approximately 50% of the soil water holding capacity, soil pH levels between 5 and 8, and carbon-nitrogen ratio values less than 10. Sludge decomposition rate increases with temperature, providing other soil conditions are adequate. Decomposition of sludge also releases plant nutrients including nitrogen, phosphorus, and sulfur.

Nitrogen Transformations

Sewage sludge contains both organic and inorganic forms of nitrogen. Most of the nitrogen in sewage sludge is in organic forms (>1%), with smaller amounts (< 0.5%) present as ammonium, and only trace amounts present as nitrate. After land application, these sludge-derived sources enter the soil nitrogen cycle (Figure 1). Transformation of organic nitrogen to plant-available ammonium is governed by factors affecting sludge decomposition previously discussed. Incubation studies have shown the amount of organic nitrogen mineralized in the first year after application parallels organic matter decomposition. Amounts of nitrogen mineralized depend heavily on the sewage sludge treatment process and range from 10 to 40% (U.S. EPA, 1983). However, nitrogen mineralization rates under field conditions are more variable and range from 7 to 55% of the organic nitrogen mineralized (Fox and Axley, 1985). Nitrogen provides the larg-

Nitrogen Cycle

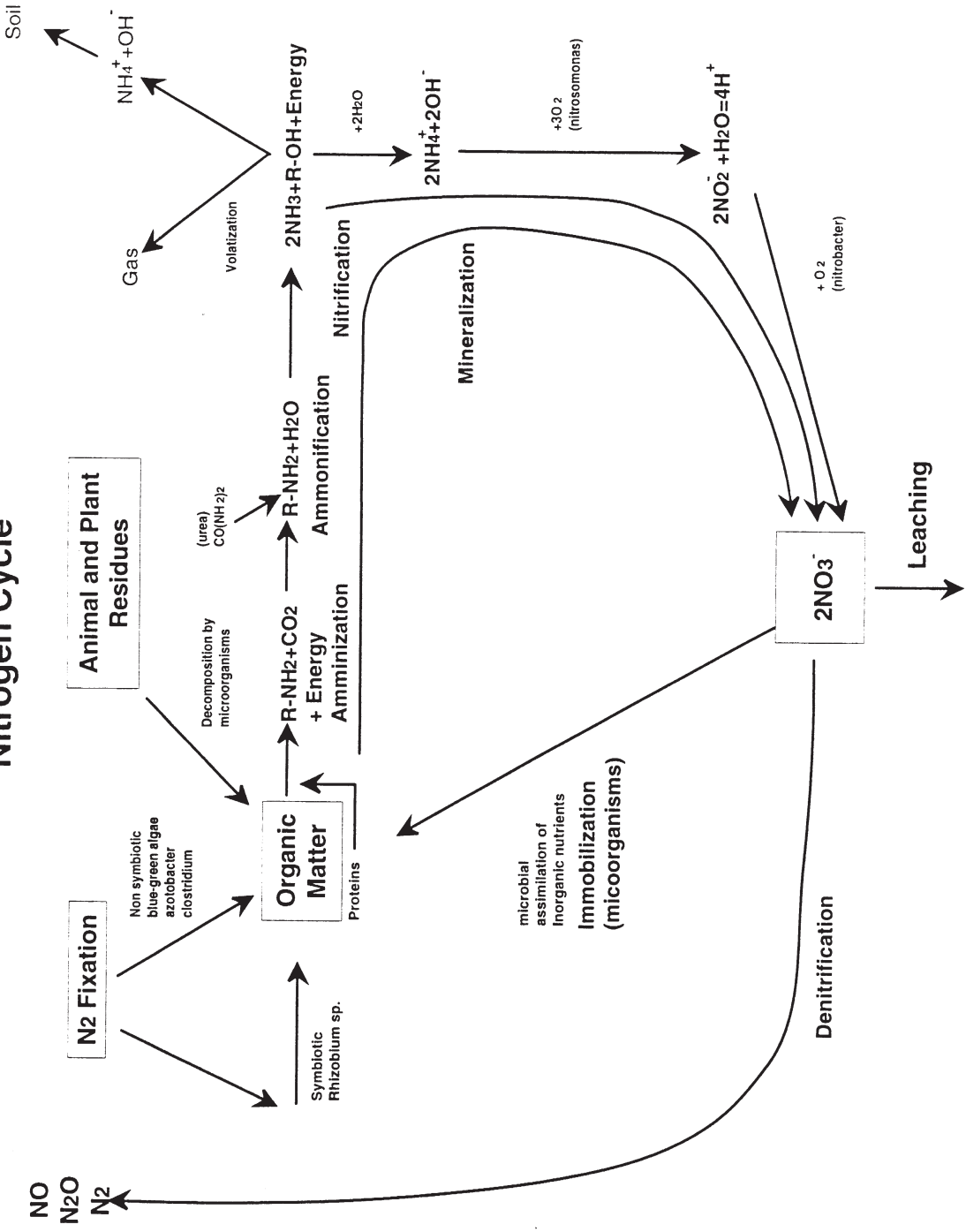


Figure 1. The plant-soil nitrogen cycle (Raun et al., 1993).

est amount of sludge-borne nutrients. Therefore, both federal and state regulations base land application rates on the “agronomic rate,” which is defined as the amount of sludge that will meet the crop nitrogen requirement (U.S. EPA, 1993a,b; ODEQ, 1994). Although general guidelines are used to calculate nitrogen mineralized (U.S. EPA, 1983), field studies that measure nitrogen mineralized under specific soil-climate conditions should provide a more accurate estimate of nitrogen mineralization.

Both inorganic ammonium and nitrate are plant-available forms of nitrogen. Positively charged ammonium is retained by the soil cation exchange capacity, but negatively charged nitrate is not. Excessive sludge applications that result in large amounts of soil nitrate may result in nitrate leaching and potential ground water contamination. Application at agronomic rates minimizes contamination risk (U.S. EPA, 1993b).

Phosphorus Transformations

Similar to nitrogen, sewage sludge-borne phosphorus occurs in both organic and inorganic forms. However, unlike nitrogen, the majority of sludge phosphorus is inorganic (70 to 90%) (Wolf and Baker, 1985). After land application, sewage sludge phosphorus enters the soil phosphorus cycle (Figure 2). Mineralization of organic phosphorus is governed by processes that affect sludge decomposition, and some organic phosphorus is converted to plant-available dissolved phosphate. However, shortly after release, soil chemical adsorption and precipitation processes decrease dissolved phosphorus to a low concentration in soil solution. These processes impact the environmental fate of sludge-borne phosphorus. Mobility and leaching of phosphorus to ground water is insignificant (Knuteson et al., 1988). Surface applications of sewage sludge may lead to surface enrichment with phosphorus. Excessive phosphorus fertilizer and animal manures may lead to eutrophication of surrounding streams and lakes (Verduin, 1967). However, sewage sludge is usually incorporated into soil by injection or disking operations thereby minimizing transport of sludge-derived phosphorus to surface waters. It is recommended that soil phosphorus levels be monitored to prevent buildup of excessive amounts of soil phosphorus that may lead to surface water contamination (ODEQ, 1994; Pierzynski, 1993).

Trace Element Transformations: Micronutrients and Heavy Metals

Trace elements can be defined as “elements that occur in natural and perturbed systems in small amounts and that, when present in excessive amounts, are toxic to living organisms” (Adriano, 1986). All trace elements have a natural abundance in soils (Alloway, 1992; Bowen, 1979; Adriano, 1986). Two subgroups of trace elements are heavy metals and micronutrients. Heavy metals are defined as metals having densities greater than 6.0 g/cm³. Micronutrients are nutrients that are required in small amounts for plant growth. Several heavy metals are also plant micronutrients including copper, zinc, iron, manganese, and molybdenum.

Content of several trace elements is larger in sewage sludge than in their natural abundance in soil. These include cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), mercury (Hg), molybdenum (Mo), lead (Pb), and zinc (Zn). Potential contamination of soil and productive land from heavy metals in sewage sludge was a serious concern

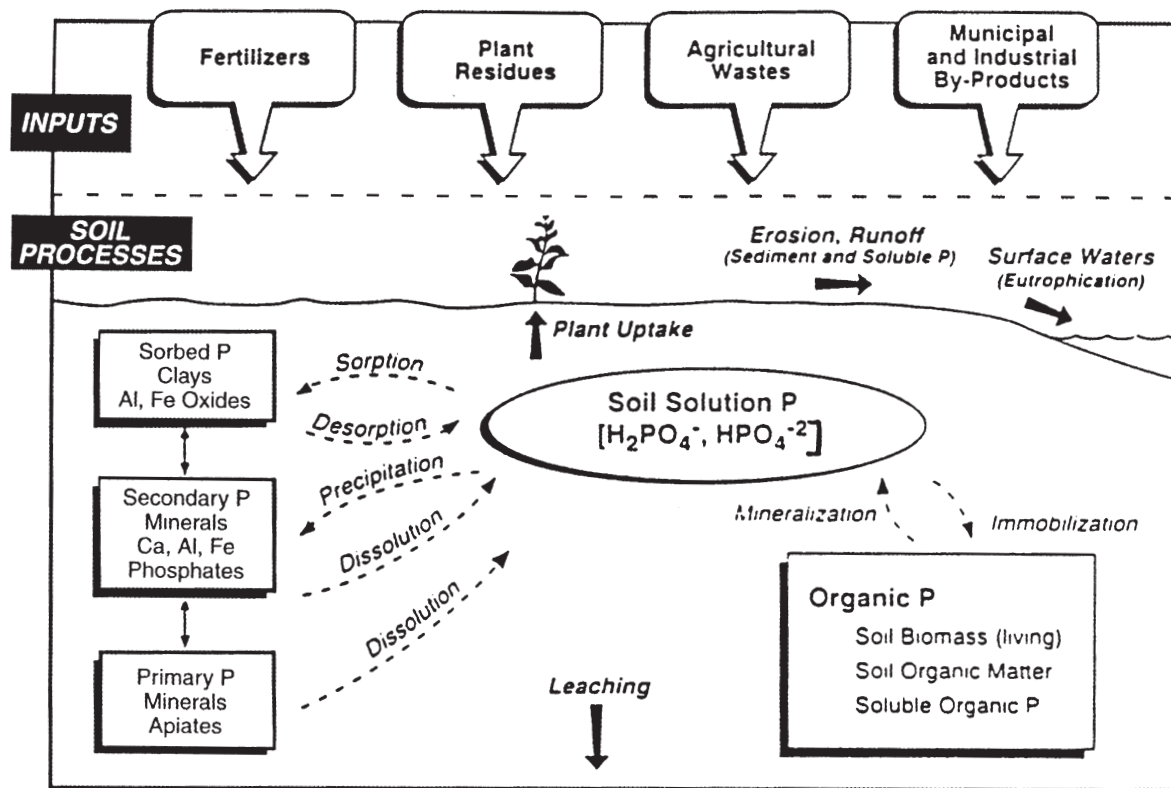


Figure 2. The soil phosphorus cycle (Pierzynski et al., 1993)

shortly after the CWA was passed in 1972 (CAST, 1976; Chaney, 1973). Concerns about environmental fate included toxicity to crops (phytotoxicity), plant uptake and movement of metals through the food chain, and leaching of metals and ground water contamination. Since then, hundreds of studies have investigated transformations and the environmental fate of sludge-borne heavy metals.

Heavy metals occur in sewage sludge as insoluble precipitates (carbonates, phosphates, sulfides), surface-adsorbed mineral complexes, and insoluble organic matter chelates (Corey et al., 1987). After land application, sewage sludge-borne metals enter soil chemical pathways common to indigenous natural-occurring heavy metals. Metals are strongly adsorbed by soil minerals and soil organic matter. Other chemical reactions (precipitation, complexation) further limit their solubility (McLean and Bledsoe, 1992). Because of their limited solubility, heavy metals are not easily leached or moved through the soil by water and pose a low risk to water quality (Dowdy and Volk, 1983; Logan and Chaney, 1983). Conversely, heavy metals accumulate in soil with residence times of several hundreds to thousands of years (Alloway, 1992; Bowen, 1979). Therefore, research has focused on transformations (both short- and long-term) that would increase heavy metal mobility and toxicity in sewage sludge-amended soils. Chemical extraction methods are commonly used to “speciate” different forms of metals in soils and predict their plant availability and leaching potential (Shuman, 1991). Chemical speciation methods have also been useful in studying the effect of chemical transformations on potential heavy metal mobility and movement through the food chain. Numerous studies have shown that soil pH has dramatic effects on heavy metal mobility and plant uptake

(Logan and Chaney, 1983; Sommers et al., 1987; Dowdy and Volk, 1983). With the exception of molybdenum, decreases in soil pH increase heavy metal availability, especially at soil pH levels below 4.5. However, soil pH is usually not strongly acidic ($\text{pH} < 4.5$), and sewage sludge is not usually applied to strongly acidic soil. Under these circumstances, results from long-term experiments (lasting longer than 10 years) show heavy metal mobility is greatest in the first year and decreases with time (Chang et al., 1987). Results from long-term studies suggest soil chemical processes decrease heavy metal availability with time. This is in direct contradiction to the “time bomb” effect suggested by Beckett and Davis (1979). They believed that sewage sludge decomposition would release heavy metals that would eventually result in heavy metal toxicity in soil. Research results do not support the time bomb theory. Conversely, research results support the “heavy metal reversion” concepts postulated by Chaney (1973, 1983), where soil chemical processes reduce heavy metal availability in sludge-amended soils with time.

Organic Chemical Transformations

Sewage sludges can theoretically contain thousands of man-made organic chemicals. However, most sewage sludges (Jacobs et al., 1987; U.S. EPA 1993b) contain considerably fewer organic chemicals, and their content is low ($< 0.001\%$). The most common organic compounds detected in Chicago sewage sludge were toluene, trans-1,2-dichloroethane, chlorobenzene, and lindane (Lue-Hing et al., 1986). Most organic compounds are strongly adsorbed to organic matter in sewage sludge. After land application, most organics are rapidly volatilized, decomposed, or cometabolized with sewage sludge organic matter (Jacobs et al., 1987; Lue-Hing et al., 1986; O'Connor, 1993). Significant amounts of sludge-borne organics are not absorbed by plants and have little potential for risk to the food chain (Page et al., 1987; O'Connor et al., 1990). Most research has focused on persistent organic compounds such as PCBs. PCBs are persistent in soils and have demonstrated both acute and chronic toxicity (Babish, 1985). However, studies have shown that low concentrations of PCB in sewage sludge are not harmful to man or the food chain (Lue-Hing et al., 1986; O'Connor et al., 1990). Federal regulations ban land application of sewage sludge that contains more than 50 ppm PCB (U.S. EPA, 1993a).

There has been limited research on transformations of organics in sludge-amended soils because (1) after land application of sewage sludge, concentrations of organics in soil or soil leachates are well below the detection limits of most analytical equipment (below $\mu\text{g}/\text{kg}$) levels, and (2) sludges cannot be fortified with organics because the sludge matrix absorbs the added organic tightly and prevents analytical measurement of organic chemicals. Most of our understanding of transformations of these chemicals are based on mathematical models and information derived from extensive research on organic pesticides. Although this approach is valid, research studies with sewage sludge containing measurable amounts of toxic organics is desirable.

Pathogen Transformations

Sewage sludge treatment significantly reduces human and animal pathogens but does not eliminate them (Gerba, 1983). Sewage sludge may contain pathogenic bacteria (e.g., Salmonella and Shigella), viruses (e.g., Enterovirus and Poliovirus) and parasites

(e.g., *Ascaris ova* and *Entamoeba histolytica*). Survival and transformation of pathogens land-applied with sewage sludge depends on soil and climatic conditions. Survival is prolonged in low temperature wet soils but most pathogens die rapidly in hot, dry soils (Angle, 1993). For example, poliovirus was recovered at 0.01% of the original concentration 100 days after a winter sludge application seeded with this virus; after a summer application, the same decline in viability only required 7-10 days of exposure on soil (Tierney et al., 1977). Bacterial pathogens perish within a few weeks, but viruses and certain parasites may survive for months or years (Gerba, 1983; Angle, 1993; Hunt, 1985). Bacteria, protozoa, and other parasites exhibit little movement in soils (Coker, 1983; Gerba, 1983). Viruses are strongly absorbed to soil clay but, because of their small size, can move through soil. Research findings indicate that combined soil adsorption and climatic conditions virtually eliminate risk from sludge-borne pathogens (Zenz et al., 1976; Liu, 1982; Gerba, 1983; Coker 1983). In addition, regulations that minimize risk by sludge-borne pathogens are in place (U.S. EPA, 1993a).

Recently, public concern has been raised over transmission of the human immunodeficiency virus (HIV) that causes AIDS in the environment. In 1988, the first investigations of environmental transmission of HIV were sparked by public concern when traces of HIV were found on used syringes in urban litter. At a recent symposium at Johns Hopkins School of Public Health, participants concluded "there appear to be no public health hazards due to HIV transmission in the outside environment since the virus is extremely sensitive to temperature, synthetic and biological chemicals and occurs in concentrations too low for transmission" (Johns Hopkins, 1991). Also, there are "no known cases of HIV transmission through an air-borne route or an outdoor environment" (including sewage) (Johns Hopkins, 1991). However, because AIDS and HIV will likely increase in the future, they also recommended that sewage sludge be monitored for HIV in the future.

CROP PRODUCTION AND PLANT-SOIL RELATIONSHIPS

by *W.R. Raun and G.V. Johnson*

Land application of sewage sludge benefits crop production by supplying plant nutrients. Sewage sludge contains a wide range of plant nutrients, including fairly large amounts of plant macronutrients. Less, but significant, amounts of secondary and plant micronutrients include calcium, magnesium, sulfur, iron, copper, zinc, and molybdenum. Extensive research has documented the fertilizer benefits of sewage sludge. Because crops require substantial amounts of nitrogen, sewage sludge application rates are based on the "agronomic rate." The agronomic rate is the amount of sewage sludge required to satisfy the crop nitrogen requirement. Research results have shown that sewage sludge benefits are similar to commercial fertilizers. Both commercial fertilizer and sewage sludge produce high crop yields and high quality crops (Coker, 1983; Ippolito et al., 1992; Knuteson et al., 1988). In addition to nutrients contained in commercial fertilizer, sewage sludge contains micronutrients. Deficiencies of iron in sorghum have been corrected by land application of sewage sludge (McCaslin et al., 1987).

Work by Peterson et al. (1991) suggests that sludge applied at a rate of 6.6 MT/ha supplied corn with approximately 200 kg N/ha per year. Ippolito et al. (1992) indicates that less than 6.72 MT/ha of dry sludge should be applied in order to avoid overapplication of nitrogen in a continuous winter wheat production system. Applied sludge in winter wheat increased protein, straw nitrogen, grain zinc, copper, and nickel when compared to conventional fertilizers (Ippolito et al., 1992). Sludge applications at extremely high rates ranging from 56 to 448 MT/ha increased concentrations of zinc, cadmium, manganese, and nickel in wheat grain (Kirleis et al., 1984). This study further found that sludge applications decreased the baking quality of flour by increasing protein content. Zwarich and Mills (1979) found a sixfold increase in the cadmium content of wheat kernels and similar increases in the forage, while no increases were found in the straw. Considerable increases in the zinc content of all crops was noted, but levels were not excessive. The increased cadmium levels were undesirable; however, Zwarich and Mills (1979) indicate that cadmium levels can be controlled by restricting the sludge application rate. Similar work by MacLean et al. (1987) note that the uptake of heavy metals by grass and legume plants was variable in plots having received 44.9 kg/ha domestic sewage sludge. Heavy metal contents were all within the levels normally found in grass and legume plants, with copper being the only metal which was significantly higher. Hinesly et al. (1979) note that within 3 to 4 years after sludge application grain tissue from control and treated plots could not be distinguished by differences in zinc and cadmium concentrations.

Studies conducted by Day et al. (1988) found that heavy metal concentrations in wheat hay after continuous application of sewage sludge at recommended plant-available nitrogen rates were similar to the heavy metal concentrations in wheat hay fertilizers with inorganic nitrogen. Sewage sludge rates used in their work resulted in plant growth yield and quality of wheat hay, grain, and straw that were similar to that fertil-

ized with commercial nitrogen fertilizers. Utschig et al. (1986) note that sewage sludge served as a good source of nitrogen without increasing significant concentrations of trace metals in plants. Menelik et al. (1991) found that fall-applied sewage sludge was just as effective as spring-applied inorganic nitrogen. Sewage sludge applied at a rate of 80 kg N/ha increased nitrogen, phosphorus, zinc, and copper concentrations in wheat grain. Concentrations of manganese, zinc, and copper were lower in the wheat grain when comparing lime-stabilized sewage sludge to polymer-conditioned forms (Menelik et al., 1991). Work by Sims (1990) found that applications of composted sewage sludge at the recommended agronomic rates produced satisfactory wheat plant growth and increases in soil, and that plant concentrations of nonessential heavy metals should not be a limiting factor in compost use.

Sewage sludge contains various amounts of heavy metals. One of the greatest concerns when applying sewage sludge to cropland is plant uptake and soil accumulation of trace elements (Utschig et al., 1986). Kirleis et al. (1984) stress that one of the major considerations in applying municipal sewage sludges on agricultural land is the potential for increased concentrations of heavy metals in the human diet.

Land application of sewage sludge may lead to accumulation of the soil's heavy metal content (Adriano, 1986). However, these heavy metals are present primarily in chemical forms that plants can not absorb (Corey et al., 1987; Logan and Chaney, 1983). The amount available for crop uptake depends on properties of both sewage sludge and soil. Heavy metal availability varies between different soil types and soil conditions. Extensive research has shown that soil pH controls metal availability to plants grown in sludge-amended soils. The solubility of these heavy metals (excluding Mo and Se) is inversely related to pH due to the formation of hydroxides, carbonates, and phosphates and complexation and chelation with other anions (Logan and Chaney, 1983). Solubility of solid phase minerals including metal carbonates, phosphates, and sulfides is enhanced at low soil pH (Lindsay, 1979). Soil adsorption is also decreased at low soil pH (Basta and Tabatabai, 1992a,b,c). Metal availability is increased in acid soils. Results show that when soil pH is greater than 5, heavy metal uptake is minimal (Lue-Hing, 1986; Chaney 1993; Chang et al., 1987).

Corey et al. (1987) conclude the following: 1) if the equilibrium trace element soil solution concentration (and buffer power) supported by the sludge is less than the amount which will result in excessive concentrations in plant tissue or damage to the plant, there is no need to limit application rates of that sludge on the basis of metal content; and 2) if the equilibrium metal concentration (and buffer power) supported by the sludge at a specified pH is high enough to cause excessive concentrations in plant tissue or plant damage, determining maximum loading rates based on both soil and sludge characteristics will be required.

The amount of heavy metal adsorbed by the crop will depend on crop species, crop cultivar, and growth conditions (Logan and Chaney, 1983). In general, leafy green vegetables (e.g., lettuce) accumulate more metal than other crops. Many studies have found that, generally, less than 1% of the heavy metal added to soil by sewage sludges is taken up by crops. Also, the amount adsorbed by crops grown on soil treated with sludge is similar to the heavy metal content of crops grown on normal, untreated soils (Page et

al., 1987). In addition to the reduced plant availability in soil, heavy metals that are adsorbed may not be in the edible portion of the crop or animal (Logan and Chaney, 1983).

Movement of heavy metals through the food chain is affected by the “soil-plant barrier” as described by Chaney and Giordano (1977). The “barrier” protects the food chain by:

1. soil chemical processes that prevent crop uptake,
2. crops that do not translocate metals into their edible portions, and
3. crops that are killed by metals at levels that are not injurious to animals or man.

The actual amount of protection provided by the soil-plant barrier depends on metal, soil, and cropping conditions. Most heavy metals do not breach the soil-plant barrier and will not threaten the food chain (Logan and Chaney, 1983; Chaney et al., 1987). Under certain conditions, cadmium can pass through the soil-plant barrier and enter the food chain. These conditions include (1) low soil pH (acid soils) and (2) high cadmium/zinc soil content ratios. Management practices are specifically designed to avoid these circumstances. Cadmium occurs under natural conditions, and some cadmium is present in all foodstuffs. Although it is impossible to eliminate cadmium from our diet, crop production practices should strive to minimize cadmium content of crop commodities. Regulated crop production management practices governing land application of sewage sludge minimizes cadmium enrichment.

LAND APPLICATION OF SEWAGE SLUDGE: USE OF FORAGES AND CROPS BY LIVESTOCK

by *Keith S. Lusby*

Background

The content of organic matter, nitrogen, phosphorus, and trace elements makes municipal sludge attractive as a fertilizer and soil conditioner. Forages grown on sludge-fertilized lands can and have been well utilized by grazing ruminants, principally beef cattle, while grain crops from these sites have been used by both monogastrics and ruminants. Concerns about the use of sludge have centered on three areas: heavy metals such as cadmium and lead, toxic organic compounds like PCBs, and pathogenic organisms such as bacteria and viruses. A great body of research and experience on sludge use for production of livestock feeds has been accumulated over the past 25 years. This research and experience has generally shown that the potential problems with sludge can be predicted and managed and that application to pasture and crop lands is a viable use for sludge.

Soil-Crop-Animal Pathway

A number of metals in sludge can be toxic to animals. However, research has shown that conclusions about the toxicity of these elements in sludge cannot be made by feeding the individual elements in inorganic form directly to animals. The reasons are numerous, but a few principle points help explain why. First, metals in sludge do not exist as metal salts that are highly available to animals, but rather are found in complex mixtures that act to reduce mineral availability to plants and animals by complexing, chelation, precipitation, and other mechanisms. The reduced availability is observed even when sludge is consumed directly by animals (Cottenie et al., 1984). Second is the concept of the "soil-plant barrier" (Logan and Chaney, 1983). Soil chemistry is complex, but many of the potentially toxic metals are rendered unavailable to plants by the soil. For example, the presence of adequate concentrations of zinc reduces the potential absorption of cadmium by plants. Sludge analysis provides adequate information to prevent adverse effects of sludge trace elements on the feed and food chain. Soil pH is important, but enough is known to predict potential problems. Another protective mechanism is known as "phytotoxicity," which in simple terms means that some metals such as copper and zinc will kill the plant before the plant will accumulate enough of the element to be toxic to animals.

Plant-Animal Pathway

The same complex mixtures of elements in sludge that reduce bioavailability to plants also act to reduce bioavailability to animals. Body retention of cadmium from ingestion of sewage sludge itself has been reported at less than 1% compared to up to 9% when cadmium salts were fed. Most of the absorbed cadmium appears to stay in the kidney and liver and not in the muscle tissues (Bray et al., 1985; Dowdy et al., 1983; Komsta-Szumaska, 1986).

Toxic Organic Compounds and Pathogens

Sludges can contain numerous man-made organic chemicals, a legitimate concern when applying sludges to soils to produce feed for livestock. However, detailed risk assessment by the EPA has concluded that bioavailability of toxic organic compounds to plants and animals is low, especially at the rates at which sludge is applied to land (U.S. EPA, 1993b). Direct consumption of sewage-treated soil is probably a greater concern than consumption of forages/feeds grown on such soils. There appears to be no significant effect on man or animals from PCBs at the levels found in most sludge (Baxter et al., n.d.). The greatest risks for PCBs occur when sludges are sprayed directly on crops and ingested by livestock. Monitoring levels of organic compounds at the sources of the sludge will be important.

A variety of pathogenic organisms including Hepatitis A virus, *E. coli*, and *Salmonella* bacteria can be found in wastewater entering a sewage treatment plant. Most pathogenic bacteria are killed during treatment, although some viruses survive treatment. Parasites are especially resistant to treatment (Gerba, 1983).

Long-term Experience With Grazing of Sludge-Fertilized Lands

Three sites with about 20 years each of history of sludge application are available for study. These include the former Lowry Bombing Range, operated by the City of Denver (Baxter et al., n.d.), a site in Fulton County, Illinois, operated by the City of Chicago (Lue-Hing et al., 1986), and the Rosemont Watershed study, owned by the University of Minnesota, using sludge from local towns (Knuteson et al., 1983).

At the Fulton County site, cattle were allowed to graze for up to 8 years on pastures on which anaerobically digested sludge was applied. Cows on both control and test herds calved normally without complications. Zinc, copper, and cadmium increased in the livers of cows in test herds but remained below tolerable levels for food products. Further studies at the Fulton County site showed that metal accumulations were not a problem in fish from water receiving runoff from sludge-applied fields. Other studies at the site showed that feed grains from sludge-fertilized fields could be used for poultry. Long-term results from the Rosemont and Denver sites have been similar. It was shown that negligible amounts of trace elements are removed by crops grown on sludge-amended soils. No health problems could be foreseen.

Summary

Knowledge about the origin and treatment of sludges applied to soils for forage or crop production will remain important. Numerous research trials and long-term experience with soil application of sludge to forage and crop lands have shown that natural soil-plant-animal barriers act to minimize risks from toxic trace elements, organic compounds, and pathogenic organisms in sludge. Stringent analysis and control of these potentially toxic factors in sludge at the treatment sites make most problems manageable. Sludge can be a valuable source of nutrients and organic matter for soils. Livestock that graze forages or use feed grains grown on sludge-amended soils are healthy and safe for human consumption.

POTENTIALS AND PROBLEMS OF MUNICIPAL SLUDGE UTILIZATION ON OKLAHOMA FORESTLANDS

by *Donald J. Turton*

Municipal sludge has been used on forest and rehabilitated mine lands since the late 1970s. Sludge utilization projects on forestland for rehabilitation and reforestation, biomass production, and fertilization have been established in 23 states (Bastian, 1986), and the benefits and environmental effects of sludge utilization on forestlands have been extensively researched (Bastian, 1986).

Potentials

The large forestland area in the United States represents a vast resource where sludge can be used. There are about 662 million acres of forestland in the United States; 43% is owned by the federal government and 57% is in private ownership (Bastian, 1986). Forestlands have several characteristics that give them a high potential as sludge utilization sites. Many forestlands are located on sites having low nutrient content and productivity. Sludge utilization can boost the productivity of soils by increasing available nutrients (Burd, 1986). In fact, the greatest increases in forest productivity as a result of sludge utilization have occurred on sites that were originally low in productivity (Bastian, 1986). Forest-wood products are not in the human food chain. As a result, public health concerns about contaminants in sludge are lower than those of agricultural crops. The vegetation on forestland tends to be more tolerant of contaminants found in municipal sludges than agricultural crops (Cole et al., 1983). Municipal sludges are high in nitrogen. Nitrate leaching to ground water is a major concern of sludge application (Bastian, 1986). The upper soil horizons of forest soils tend to be higher in organic matter (Pritchett and Fisher, 1987). As a result, the carbon-nitrogen ratio of forest soils is high (140 to 32) compared to agricultural soils (Berry, 1986; Pritchett and Fisher, 1987). Nitrogen is immobilized in soils having high carbon-nitrogen ratios. Unlike most agricultural crops, forest vegetation maintains active root systems year round. Active year-round uptake of nutrients from forest root systems may allow for the application of sludge to forestlands during periods of the year when agricultural crops are dormant (Bastian, 1986).

Potential Problems

Despite the fact that about 40% of the land area of the continental United States is forested, much of the area may be unsuitable or unavailable for sludge application. Land steeper than 30 to 20% is considered to be unsuitable for sludge applications (Zasoski and Edmonds, 1986). A large portion of forestland is located in mountainous regions that have slopes greater than 30%. Accessibility in steep and remote mountainous regions may also limit the forestland base to which sludge may be applied.

Many forest soils are more acidic than agricultural soils. The pH of most forest soils is below 5.5 (Pritchett and Fisher, 1987). Low soil pH increases the mobility of some heavy metals. As a result, extremely acid soils may be unsuitable for sludge application. On the other hand, sludge application tends to raise the pH of soil, so the high mobility of metals due to acid soils may be reduced by the sludge application itself (Zasoski and Edmonds, 1986). Although forest wood products are not in the human food chain, trees, shrubs and grasses are in the food chains of wildlife. Potential adverse affects to wildlife and uptake of heavy metals by edible mushrooms and berries must be addressed (Bastian, 1986).

Unlike agricultural applications, sludge applied to forestland is not tilled into the soil. Sludge is applied to the land surface where it remains until it decomposes. As a result, there is a potential for sludge to be washed into water courses by surface flow if it is applied too heavily or on steep slopes (Bastian, 1986). Due to surface application, sludge may be applied to forest soils at less frequent intervals than to agricultural soils, thereby limiting the land area on which sludge can be applied. Application intervals of once every 4 years have been recommended for forest soils in the Pacific Northwest (Zasoski and Edmonds, 1986). Forest soils tend to be highly permeable and structured (Pritchett and Fisher, 1987). Old root channels and stable soil cracks form preferential flow paths (Luxmoore, 1991) through which sludge contaminants may travel rapidly into ground or subsurface water. Forest land use conflicts may also restrict the land area on which sludge may be applied. Sludge application is not compatible with wilderness or recreational uses. These uses are occupying more and more of the federally-owned forestland base.

Environmental Effects

In general, the environmental effects of sludge application on forestland are determined by sludge chemical characteristics, application rate, soil characteristics (such as cation exchange capacity, organic matter content, texture, and permeability), land slope, proximity to streams or water tables, climate, and vegetation type.

Tree Growth

For a sludge utilization project to be successful, nutrients in the sludge must be used by vegetation. Increases in the growth of trees and other forest vegetation have occurred following sludge application. The growth response is highly variable, depending on the sludge application rate, climate, and vegetation type and age. In general, the greatest growth responses have occurred in stands of young trees on otherwise infertile soils (Bastian, 1986). Sludge was applied at two rates (400 and 800 kg N/ha) to loblolly pine plantations on a sandy soil in South Carolina (McKee et al., 1986). The growth of 8- and 28-year-old trees was increased following application at 400 kg N/ha. The growth response at the high application rate, 800 kg N/ha, was no greater than at the low application rate, 400 kg N/ha. The largest growth response occurred in the 8-year-old stands. No increase in growth was observed after sludge was applied to 3-year-old stands due to increased competition from weeds (McKee et al., 1986). Nguyen et al. (1986) reports a 63% increase in 3-year diameter growth for mixed hardwoods in northern Michigan following the application of 400 kg N/ha (8 MT dry solids/ha) of liquid

sludge. The growth response differed between tree species. Red maple exhibited no significant increase in diameter growth during the three-year period. Red and white oak diameter growths were 39 and 61% greater, respectively, on the sludge-treated areas than in an untreated control.

Soils

Increased tree growth following sludge application is in part due to improvements in forest soil physical and chemical characteristics. Positive aspects of sludge application to forest soils include increased nutrient availability, organic matter, and water holding capacity. These positive changes are especially significant for severely disturbed soils such as mine spoils (Berry, 1986). Nguyen et al. (1986) reported 48, 6, 54, 29, and 23% increases in available nitrogen, phosphorous, potassium, magnesium and calcium, respectively, in the forest floor (O1 and O2 horizons) following sludge application to a hardwood forest in northern Michigan. Small but not statistically significant increases in nutrient content in the mineral soil below were also observed (Nguyen et al., 1986). One negative aspect of sludge application to forest soils is heavy metal accumulation. Numerous studies have shown that heavy metals accumulate in the organic horizons following sludge application. However, the same studies show no significant accumulations in mineral horizons below or in soil solution collected from the mineral horizons (Berry, 1986; Harris and Urie, 1986; Nguyen et al., 1986).

Water Quality

The leaching of plant nutrients to ground water and subsequently to streams may occur following sludge application. Increases in nitrate leaching in soil solutions below sludge-treated sites have been reported. The concentration of nitrate in soil solution is a function of the sludge application rate, vegetation, growth, climate, and soil characteristics (Zasoski and Edmonds, 1986). Wells et al. (1986) found that nitrate-nitrogen concentrations at the 1 m depth in a sandy soil exceeded 60 ppm four months after sludge application of 800 kg N/ha to a 28-year-old loblolly pine stand, but only 20 ppm below 3- and 9-year-old stands. The younger stands were faster-growing and used nutrients from the sludge more efficiently. Nitrate-nitrogen levels declined to 10 ppm 18 months after treatment and returned to pre-treatment levels 3 years after application. Increases in potassium, calcium, and magnesium concentrations were also observed at the 1 m depth. About 22% and 8% of the applied nitrogen was leached past the 1 m depth on sites treated with 800 and 400 kg/ha nitrogen sludges, respectively. Therefore, reducing the application rate of sludge can reduce water quality problems. Nguyen et al. (1986) reported peak nitrate-nitrogen levels never exceeded 10 ppm 1.2 m deep in a sandy outwash soil treated with 400 kg N/ha in northern Michigan. For the Pacific northwest, sludge application rates of 20 dry tons per acre on slopes less than 30% have been found to not significantly reduce water quality (Zasoski and Edmonds, 1986).

Wildlife

Direct effects on wildlife of sludge application by spraying, truck traffic, or spreading have been found to be insignificant (Haufler and West, 1986). Sludge improves wildlife habitat by changing vegetative composition and structure and increasing pro-

ductivity. Sludge application increases the growth of plants used by wildlife. Increased growth of grasses, sedges, aspen, red oak, and red and sugar maple have been measured on sludge-treated forests in northern Michigan (Haufler and West, 1986). Common understory plants of Douglas-fir forests showed increased growth after sludge application to forestlands in Washington. Plant nutrient quality also increases following sludge application. Significant increases in nitrogen, crude protein, and phosphorous content result following sludge application (Campa et al., 1986). Deer and elk preferentially browse plants in sludge-treated areas because of the increased protein content (Haufler and West, 1986). Increases in small mammal populations also result from sludge application. Populations of mice, chipmunks, and voles increased following sludge application in Michigan (Haufler and West, 1986).

Sludge contains heavy metals and trace organic that may become bioavailable to wildlife. Cadmium is the metal of greatest concern, although other metals such as zinc, lead, copper, and mercury are also of concern. Increases of cadmium in the organs of mice and voles and in earthworms taken from sludge-treated sites have been found. However, the animals did not show any toxic effects (Haufler and West, 1986). No increases in cadmium concentrations in deer were observed in studies in Washington and Michigan (Campa et al., 1986). Accumulation of metals to higher animals in the food chain are of concern, but little information is currently available. The chemical composition of sludge varies greatly, depending on the source and method of treatment. Potential toxicological effects to wildlife, therefore, depend on a sludge's characteristics. Sludge from treatment facilities that contain no industrial effluents will most likely have the least toxic effects on wildlife (Haufler and West, 1986).

Sludge Utilization Potential and Problems on Oklahoma Forestlands

Sludge application on Oklahoma forestlands has the same potential benefits as have been realized in other regions in the United States. Problems associated with sludge application encountered in other regions in the United States also potentially hold true for Oklahoma. To date, no research data on the benefits or environmental effects of municipal sludge application on Oklahoma forestlands is available. However, potential benefits and problems can be discussed by studying the available forestland base and comparing differences in vegetative, soil, and climatic characteristics in Oklahoma with those in regions where research data is available.

Potential Forestland Base

About 17%, or 7.5 million acres, of the land area of the state of Oklahoma is classified as forestland (Lewis and Goodier, 1990). Of the 7.5 million acres of forestland in Oklahoma, 5.4 million acres are classified as timberland, defined as land capable of producing 20 cubic feet per acre per year of industrial wood. Oklahoma's forests are classified into four major species associations (Figure 3): Pine-Hardwoods (1.7 million acres), Oak-Hickory (2.8 million acres), Post-Blackjack Oaks, sometimes called the Cross-Timbers (2.1 million acres), and Bottomland Forests (0.9 million acres) (OSDA Forestry Services, 1992).

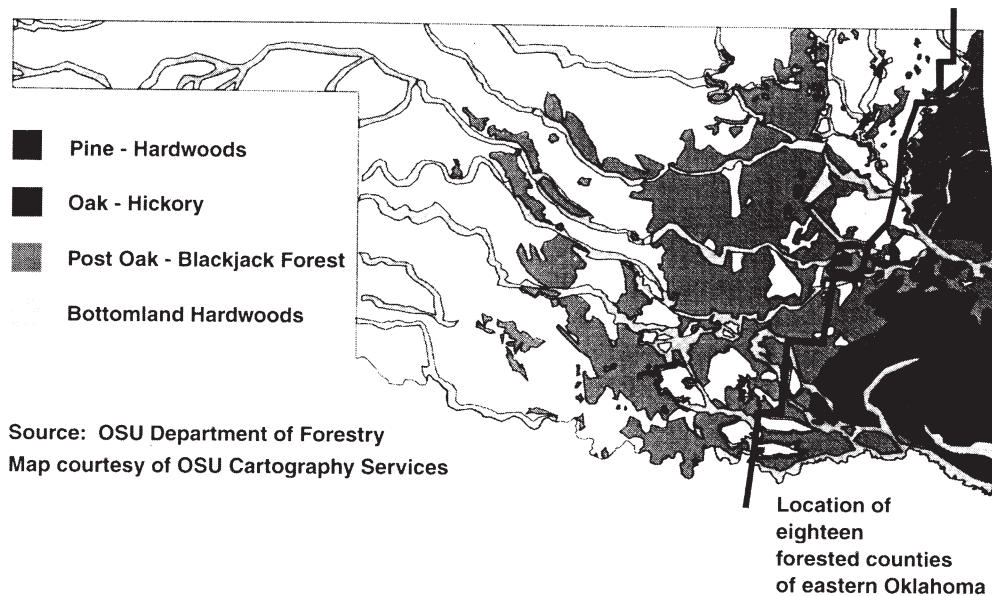


Figure 3. The composition of Oklahoma's forests (Oklahoma Department of Forestry, 1992).

Much of the 7.5 million acres of forestland in Oklahoma are likely unsuitable for sludge utilization due to physical, chemical, and ownership constraints. Bottomland forest species range from willows and cottonwoods in the west to gums, sycamores, bald cypress, and pecan in the east (OSDA Forestry Services, 1992). Bottomland forests are unsuitable for sludge utilization due to frequent flooding and high water tables in stream bottomlands. About 3% (0.23 million acres) of Oklahoma forestland is in the Ouachita National Forest. About 25% of the national forest is included in recreational, scenic, and wilderness areas such as the Indian Nations National Scenic and Wildlife Area, the Winding Stair Mountain National Recreation Area, and the Upper Kiamichi Wilderness Area. Sludge utilization is incompatible with management objectives in such areas. Nine percent (0.68 million acres) of Oklahoma's forestland is owned by other public agencies such as state parks and wildlife management areas. Sludge utilization in state parks is unlikely. Wildlife management areas may benefit from sludge application, but public concerns may preclude its use. However, the forest industry owns about 14% (1.1 million acres) of Oklahoma's forestland (Lewis and Goodier, 1990). Industry lands represent the best opportunity for sludge utilization. Much of Oklahoma's forest industry land is located in southeastern Oklahoma and is primarily Pine-Hardwood forest (Figure 3). Soils in this region are low in fertility and may receive the greatest benefit from sludge applications. Extensive industry road networks can provide access for sludge-spreading equipment. The forest industry's major objective of land management is the production of timber and fiber. Therefore, potential gains in tree growth from sludge application fit into the management objectives of the forest industry. The greatest portion of Oklahoma's forestland (74% or 5.6 million acres) is held by nonindustrial private forest (NIPF) landowners (Lewis and Goodier, 1990). About 2.1 million acres of Cross-Timbers forestland are located in western Oklahoma (Figure 3). This forest type has a low potential for wood products production and would probably benefit little from

sludge applications. The Cross-Timbers area is also used for rangeland and wildlife. Conflicts between sludge application and possible effects on livestock and wildlife would have to be resolved. The average forestland ownership size in Oklahoma is 48 acres. In a study of NIPF ownership in 18 eastern Oklahoma counties, Donovan (1988) discovered that out of 5.26 million acres of forestland, only 1.53 million acres are in ownerships of 40 acres or larger. Of the 1.53 million acres, 0.33 million acres (22%) are in ownerships of 40-101 acres in size. Another 0.36 million acres (24%) of the ownerships range in size from 101-250 acres in size. The size distribution of forestland ownership may be a constraint to sludge utilization. Small land ownerships present many obstacles to sludge application, such as lack of sufficient access, conflicts with neighbors in close proximity, and varying forest management objectives. NIPF forestland owners are a diverse group, consisting of ranchers, farmers, doctors, lawyers, blue-collar workers, and urban and rural inhabitants. Many of these owners are not interested in timber production from their land for various reasons (Donovan, 1988). It is also unlikely that these landowners would be interested in sludge utilization on their land. Donovan (1988) targets the 1000 largest forestland holdings in eastern Oklahoma as the forestland with the greatest potential for the development of timber resources on NIPF land. The 1000 largest land ownerships comprise about 0.82 million acres of land that ranges in ownership size from 250 to 23,500 acres. The purpose of this section is to roughly identify the forestland area in Oklahoma where sludge would be most likely and most effectively used. Based on the assumption that only the largest NIPF ownerships would be suitable for sludge utilization, 0.82 million acres of NIPF land is potentially available. Sludge may also be potentially used on 1.1 million acres of industrial land. Therefore, about 1.92 million acres of forestland are most likely available for effective sludge utilization. From this acreage, areas in bottomlands, stream riparian zones, steep slopes, or shallow soils would have to be subtracted.

Oklahoma Forest Vegetation, Climate, and Soils

Many of the previously cited studies were performed in regions characterized by cooler temperatures, higher rainfall intensities, and soils with greater quantities of organic matter at the soil surface than found in Oklahoma. Initial increases in nitrate found in soil solution below forest stands in northern Michigan were due to rapid nitrification of ammonia and mineralization of organic nitrogen (Hart et al., 1988). Nitrification and mineralization increase with increasing temperatures. Hot summer temperatures may cause greater releases of nitrate from sludge applied in Oklahoma forestlands than have been experienced in cooler regions. On the other hand, rapid oxidation of sludge organic matter may provide more nutrients for increasing tree growth and allow for more frequent applications. Average rainfall intensities in Oklahoma are higher than those encountered in Washington and Michigan, where much of the previously cited research on sludge utilization was performed. Rainfall intensities rarely exceed 0.6 in./h in Washington and 1 in./h in northern Michigan (Hershfield, 1961). Rainfall intensities in the forested counties of Oklahoma commonly exceed 1 and 2 in./h on the average of once a year. Although surface flow rarely occurs on undisturbed forestland in Oklahoma, the combination of surface-applied sludge and high rainfall intensities may cause surface flow to occur in situations where it was not a problem in regions with low rainfall intensities. Surface flow generated over applied sludge could pose a water

quality problem if it were to enter streams. Soil organic matter, either in the organic horizons (O1 and O2) or in the mineral soil has been identified as the location where heavy metals in sludge are immobilized (Campa et al., 1986; Hauefler and West, 1986). Soils in the Pacific Northwest where sludge studies were performed have organic layers ranging from 1 to 5 inches thick. Organic matter content in mineral horizons range from 1 to 8% (Wooldridge and Stednick, 1980). Organic horizons in forest soils in Oklahoma rarely exceed 1 inch in thickness. Organic matter in the mineral horizons typically range from 1 to 3% in the A horizons and average about 1% in the B horizons. Thin organic horizons and low organic matter content in mineral horizons found in Oklahoma forest soils may be less effective in immobilizing heavy metals than soils found in Michigan or Washington. Many forest soils in Oklahoma, especially those in the Ouachita Mountains, are very strongly acid and have low cation exchange capacities. If the thin organic horizons and underlying mineral soil horizons are incapable of immobilizing heavy metals, then a potential for movement of heavy metals into subsurface flow paths or groundwater exists.

Summary and Recommendations

Sludge utilization on Oklahoma's forestlands may represent a feasible alternative to incineration or disposal of municipal sludge in landfills. Approximately 1.9 million acres of industrial and nonindustrial forestland in eastern Oklahoma have the best potential for achieving the benefits of sludge utilization. No research data on sludge utilization on Oklahoma forestlands is currently available. Research performed in other forested regions in the United States provides good background for understanding potentials and problems that may be encountered in Oklahoma. Differences in soils, vegetation, and climate between Oklahoma and other regions of the United States where sludge utilization research has been performed raise some concerns. Any sludge utilization project should aim to maximize benefits while minimizing environmental effects. Based on this concept, the results of successful applications of sludge to forestlands in other regions of the United States, and the lack of specific data for Oklahoma, the following recommendations are offered:

- Applications should not exceed 20 dry tons/acre.
- Apply sludge only on slopes less than 30%.
- Application depth should not exceed 1 inch.
- Application frequency should range from 5 to 10 years.
- Apply sludge to infertile sites that have a high potential for vegetative growth improvement.
- Consider using sludge and tree plantings to rehabilitate old mine or highly disturbed lands.
- Conduct field trials in conjunction with tree growth, wildlife, and theoretical modeling studies.

- Determine appropriate application rates and frequencies.
- Identify and quantify forest soil properties that control the movement of nutrients and contaminants.
- Identify and map soils and land with high, low, or no potential for sludge utilization (GIS).
- Develop risk assessment techniques for predicting environmental effects.

LAND APPLICATION OF SEWAGE SLUDGE: IMPACT ON WATER QUALITY

by *Michael D. Smolen*

Many researchers have examined the effect of land application of sewage sludge because of the concern that it could contaminate surface or ground waters. Two comprehensive, long-term studies of sludge application and several shorter experiments, reviewed here, indicate that heavy metals, synthetic organic compounds, and microorganisms are not likely to reach ground water in a well-managed land application site. These same studies show that nitrate contamination of ground water and surface water is possible if application rates exceed crop nitrogen needs.

The long-term studies are (1) the City of Chicago's land application area in Fulton County, and (2) the Rosemont Experimental Watershed in Minnesota, operated by the University of Minnesota. Results from these studies are presented in the following sections.

Rosemont Watershed Study, Rosemont, Minnesota (Knuteson, et al. 1988)

Researchers at the University of Minnesota applied municipal sewage sludge from nine communities to the Rosemont Experimental Watershed specifically to determine the impacts on water quality. Soils of the site are typical of sloping, medium textured, terraced agricultural lands in Minnesota. Liquid sewage sludge was applied to corn and reed canarygrass plots with a traveling gun sprinkler or by knifing into the soil to a depth of 3 to 6 inches. Application rate and sludge characteristics are shown in Table 2.

The lower area of the watershed has a perched water table at the 2-ft depth. Runoff from individual plots could be captured, and all runoff was captured in a pond at the watershed outlet. Subsurface migration of nutrients and trace metals was evaluated by

Table 2. Characteristics of sludge applied to Rosemont Experimental Watershed.

Amount applied	800 m ³ on 35 acres (2.1 in/yr)
N : P : K analysis	6 : 2.6 : 0.5
Solids	3% dry matter; 61% organic matter
Heavy metal content	Cr 2500 ppm; Cu 770 ppm; Zn 950 ppm; Cd 8 ppm; Pb 850 ppm

Table 3. Nitrogen utilization and loss under sewage sludge- and commercial fertilizer-treated corn and reed canarygrass plots during the first seven years of study (excess nitrogen applied).

Treatment	Corn		Canarygrass	
	Sludge	Fertilizer	Sludge	Fertilizer
Total N applied (kg/ha)	577	252	1134	300
Removal efficiency in crop	35%	73%	30%	96%
Runoff losses (kg/ha)	11.3	2.2	9.4	3.4
Runoff NO ₃ -N (mg/l)	14.1	4.4	10.1	5.4
Shallow groundwater NO ₃ -N (mg/l)	48	27	40	27

sampling the unsaturated zone with lysimeters, the perched water table with shallow wells, and the regional ground water in a deep well. Surface runoff was sampled directly from each treatment area and combined in the pond at the watershed outlet.

Sludge was applied to corn and reed canarygrass plots at high rates, well above crop requirements, to evaluate the effect of sludge on crop yield, disposition of nutrients, and trace metals in soil, crop, and water. Commercial fertilizer was used as the control and applied on top of sludge to meet specific nutrient requirements and avoid any deficiencies. No distinction was made between total nitrogen and mineralizable nitrogen, assuming all of the nitrogen applied would eventually become available to plants. Water quality was evaluated as effect on runoff, shallow ground water (a perched water table), a reservoir at the watershed outlet, and regional ground water.

Plant Nutrients

Crop yields for both corn and reed canarygrass hay were typical of the area, and there was no significant difference in yield between sludge- and commercial fertilizer-treated plots. Although soil pH declined in plots treated with commercial fertilizer alone, no acidification was observed in receiving sewage sludge.

Nitrogen losses and utilization from sewage sludge-treated and commercial fertilizer-treated plots is shown in Table 3. The amounts of nitrogen removed by crops was virtually identical for sludge-treated and control plots. However, because more nitrogen was applied in sewage sludge-treated plots than in control plots, removal efficiency was much lower. Nitrogen also accumulated in the soils of sewage sludge plots during the first few years of the experiment. However, when sludge application rates were reduced in the later years of the experiment, accumulation ceased. The concentration of nitrate nitrogen in soil water, sampled by porous-cup suction lysimeters at 60 cm and 150 cm depths, was significantly higher for sludge-treated plots under both corn and reed canarygrass plots. Phosphorus and potassium levels, however, were not significantly different.

Differences in surface runoff losses and runoff concentrations between corn and canarygrass were attributed to method of application. In corn plots, sewage sludge was incorporated into the soil, but sludge was surface-applied in grass production plots. Plots treated by surface application of sewage sludge (grass plots) also lost more phosphorus and potassium than those treated by subsurface injection. Amounts of phosphorus and potassium lost were not considered excessive in either case, however.

As shown in Table 3, there was also evidence of nitrate movement to shallow ground water from both sludge- and commercial fertilizer-treated plots during the first seven years of the study. During this period, researchers were applying excess nitrogen, particularly in the sludge-treated plots. Later in the experiment, nitrogen application rates were reduced and ground water nitrate concentration declined. Very little water quality impact of sewage sludge treatment was noted in the reservoir at the watershed outlet, and no impact was detected at the regional ground water well.

Heavy Metals

In seven years of study, researchers found no significant increase in concentration of heavy metals (cadmium, chromium, copper, zinc, and lead) in soil water or ground water of the Rosemont watershed.

Metropolitan Sanitary District of Greater Chicago Study (Fulton County, Illinois)

This site consists of more than 5,000 acres of former strip mined land and has received rates of about 25 dry tons/acre/year. Extensive information on the environmental fate of heavy metals has been collected over the last few decades from this site. Extensive ground water and surface water monitoring has been conducted. Results show that both ground water and surface water quality has not been affected by heavy metals. Heavy metal concentrations in surface water has remained unchanged and ground water levels have actually decreased (Lue-Hing et al., 1986).

Related Water Quality Studies

Microbiological Contaminants

In a four-year study, Liu (1982) evaluated microbiological effects of land application of sewage sludge. In this study, very large amounts (5100 kg/ha) of sewage sludge were added to 66 1.8-m lysimeters. Leachate was sampled monthly and coliform and total heterotrophic bacterial populations were determined. Although application rates greatly exceeded normal application rates, bacteria did not move through the 1.8 m soil columns. Heterotrophic bacterial populations decreased two orders of magnitude in 40 cm of loamy sand and four orders of magnitude in 40 cm of silt loam. More than 90% of coliform bacteria were retained in the top 20 cm of the soil column and 92 to 98% perished in soil 4 years after application.

Survival of microorganisms, including pathogens like viruses and bacteria, decreases under hot, dry conditions but is prolonged under wet, cool conditions. Retention

of microorganisms on soil particles prevents movement to ground water. If they are retained near the surface, they may also be subject to desiccation.

Viruses, which are much smaller than bacteria, have greater potential mobility in soil. Their mobility is affected by soil properties such as clay content and pH. Gerba (1983) indicates that virus adsorption increases with clay content and decreasing pH. Virus inactivation during sewage sludge treatment and strong retention of virus by the sludge matrix dramatically reduces mobility of viruses in soil. Reviewers of these studies concluded “a hazard to humans from viruses in sludge has not been demonstrated, despite several studies designed to reveal such a hazard” (Bertucci et al., 1987).

Although there have been many reports of viral contamination of ground water from septic tank fields or direct land application of raw sewage (Gerba, 1983, 1987), in a very thorough review, Gerba (1987) only found one instance where viruses were detected in ground water several meters below land-applied sewage sludge. In the one cited example, ground water occurred in a diluvial sand with virtually no adsorption capacity to retain sludge-borne viruses. Results from many other studies have not detected movement of sludge-borne viruses to ground water (Gerba, 1987, Bertucci et al., 1987).

Heavy Metals

Many studies have reported the fate of trace metals in land application of municipal waste water (Page et al., 1983). Because of the large amounts of water applied in waste water treatment, land application of municipal waste water has a higher potential for more heavy metal movement than land application of sewage sludge. Chang and Page (1981) studied the feasibility of land-applying large volumes of waste water to recharge ground water. The large volumes of water in this study were well beyond a worse case scenario associated with land application of sewage sludge. All of the heavy metals introduced in slow-flow systems remained in the top 20 cm of soil and were not detected in ground water. However, rapid infiltration systems on soils with low adsorption capacity and high infiltration rates (e.g., sand) did result in a small but measurable movement (1.8 meter) of heavy metals. Heavy metal movement did not affect ground water quality.

Beneficial Use of Sewage Sludge

Land application has been used to reclaim degraded rangeland in New Mexico. The impact of sewage sludge on surface runoff was determined under natural and simulated rainfall conditions (Aguilar and Lofton, 1991). The study site was an alluvial fan within the Sevilleta National Wildlife refuge in New Mexico. Sewage sludge was applied to surface sites at a rate of 45 MT/ha (20 tons/acre). Sewage sludge treatment reduced the volume of surface runoff five- and thirty-fold under natural and simulated rainfall conditions. The reduction of surface runoff was attributed to absorption of water by land-applied sewage sludge. Sludge treatment did not increase nitrate, copper, or cadmium runoff.

LAND APPLICATION AND AGROECOSYSTEM/ WILDLIFE IMPACTS

by *Robert L. Gillen*

Native Plant Communities

Most of the research concerning land application of sewage sludge has considered cropland or introduced pasture land. Less interest has been shown in application on native ecosystems such as forests and grasslands. As with cropland, the focus has been on the use of sludge as a source of plant nutrients and as a soil amendment.

The most extensive results from grassland application are available from New Mexico. Dried, anaerobically digested sewage sludge was applied at rates of 10, 20, and 40 tons per acre to degraded rangeland dominated by shortgrasses (Fresquez et al., 1991). After five years, all soil nutrients increased as the rate of sludge application increased. Copper and cadmium levels in the soil were slightly above desirable levels in the 20 and 40 tons per acre plots, partly due to a decrease in soil pH from 7.8 to 7.0. Nitrogen, phosphorus, potassium, and trace mineral contents of the major grass species were higher on sludge-treated plots for two years but were equal to those on untreated areas after five years. Total plant production and ground cover were increased with sludge application for four years (Fresquez et al., 1990). Most of the increase in plant production came from the dominant grass, blue grama (*Bouteloua gracilis*), which is a highly desirable forage species. Broom snakeweed (*Gutierrezia sarothrae*), an undesirable invading shrub, had a complete die-off in the sludge plots after four years. Sludge application rates of 10 to 20 tons per acre were recommended to maintain optimum levels of soil nutrients and significant improvements in forage production (Fresquez et al., 1991).

Other studies in the same region concentrated on runoff quality and quantity. In the first four months after application, runoff from precipitation events was drastically reduced on plots that received 20 tons of sewage sludge per acre compared to untreated plots (Aguilar and Loftin, 1991). There were no differences in the levels of nitrate, cadmium, lead, or copper in the runoff from the two treatments. Applying sewage sludge at the relatively light rate of 0.5 tons per acre had no effect on soil microflora or microfauna after two years (Whitford et al., 1989).

The addition of nutrients such as nitrogen or phosphorus can have negative impacts on native grasslands. Fertilization sometimes causes increases in broad-leaved plants or annual grasses that are considered to be weeds (Elder and Murphy, 1958; Graves and McMurphy, 1969). This is most likely to happen on grasslands in fair to poor condition that already have a moderate to high population of weeds. Managers should be aware of potential weed increases, regardless of the source of added nutrients, and should be ready to apply weed control practices if increases occur.

Sewage sludge has also been used as a soil amendment on forested land. The nutrient content of tree foliage increased after sludge application in Canada and sulfur deficiencies were better alleviated by sludge than by inorganic fertilizers (Westman et al.,

1993). As a result, leader growth of trees was 50 to 300% greater on plots that received sludge. Volume growth of crop trees has increased dramatically after sludge application to forests (McLeod et al., 1986; U.S. EPA, 1989b). Thirteen years after application of 63 tons of sludge per acre, there were no differences in the rate of nitrogen cycling in forest soils compared to untreated plots in Washington (Prescott et al., 1993). This would suggest no impacts on soil microorganisms from sludge application. The only long-term change due to sludge application was improved phosphorus status in the soil and the tree foliage.

Recommendations for sludge application to cropland often include incorporation of the sludge into the soil by tillage or injection (Chaney, 1990). Native ecosystems are sensitive to mechanical disturbances and may show long-term effects of such treatments (Penfound and Rice, 1957). If sludge is mechanically incorporated into existing native plant communities, the negative effects of the tillage will likely outweigh any possible effects of the sludge itself. Mechanical disturbance will decrease soil cover, increase soil erosion, and allow an increase in annual weeds. To achieve the twin goals of sludge disposal and enhancement of native plant communities, sludge should be surface-applied. This option is currently not available in Oklahoma.

Effects on Wildlife (Movement through Food Chains)

Sludge application will most likely affect native animals by altering the quantity or quality of their food supply. The quantity and quality of vegetation will often increase after sludge application (Haufler and West, 1986; Fresquez et al., 1991; Westman et al., 1993). The major concern is the concentration of heavy metals in the plants and the effects these metals may have on food chains.

The soil-plant barrier (Chaney, 1990) is effective in minimizing the movement of metals along the grazing food chain. First, the soil and plant roots tightly bind some metals such as lead or mercury so the metals do not move into the above-ground portions of the plants. Second, although present in the foliage, some metals are not absorbed at high levels in the digestive system of animals and excess levels are excreted. However, the greatest exposure to heavy metals will come from direct consumption of sludge or soils amended with sludge (Chaney, 1990).

Earthworms on sludge-treated areas have shown elevated levels of metals in their tissues (Lue-Hing et al., 1986) but these levels of metals did not cause toxicity. Possible effects on predators of earthworms are not well documented.

On sludge-treated forest, small mammals feeding on insects had higher levels of metals in their tissues than seed-eating small mammals, but neither group had any detectable organ damage (Hegstrom and West, 1989). Voles living in old fields treated with sludge in Ohio had increases in cadmium levels in their livers and kidneys (Anderson et al., 1982). The elevated cadmium levels did not reduce survivorship, longevity, or recruitment rates of the vole populations and did not affect body or organ weights (Anderson and Barrett 1982, Anderson et al., 1982). Metal concentrations were monitored in cottontail rabbits taken from reclaimed strip mines with or without sludge application and in rabbits from unmined, untreated areas (Dressler et al., 1986). The grasses

and legumes on the sludge-treated site had higher levels of copper, zinc, and cadmium. The only differences in the rabbits were higher levels of zinc in the leg bones of rabbits from sludge-treated areas.

As metals are added to soils in sludge applications, it would be expected that metal levels would also increase in the plants and animals growing on those soils. Increases in metal levels in animals will most likely occur in the liver and kidneys. While increases in metals have been documented in some situations, these increases have not reduced the overall health and vigor of the monitored populations (Hanson and Chaney, 1984).

Metal levels in fish taken from lakes with and without sludge-applications within their watershed boundaries were monitored over seven years in Illinois (Lue-Hing, 1986). No changes attributable to sludge application could be detected. In New Mexico, runoff from sludge-treated plots had the same levels of metals as runoff from untreated plots (Aguilar and Loftin, 1991).

LAND APPLICATION AND HUMAN HEALTH: A CASE STUDY

by *Nicholas T. Basta*

Sewage sludge poses very low human health environmental risk according to EPA's risk analysis (U.S. EPA, 1993a,b). There has been no known outbreak of human disease attributed to land application of sewage sludge within practices mandated by U.S. EPA regulations. Nevertheless, the public perceives potential health problems associated with land application of sewage sludge to be of high concern. Such was the atmosphere in Ohio in 1977 when a comprehensive demonstration project of acceptable systems for land disposal of sewage sludge was initiated by Ohio State University, the Ohio Farm Bureau Federation, and the U.S. Environmental Protection Agency (U.S. EPA, 1985). The purpose of this project was to demonstrate management systems that would address the rural community's concerns and that would clearly define the health risks to local residents and their livestock. The project consisted of 15 separate studies on topics of concern. Results from a case study on the effect of land application on human health will be presented in this section.

The study areas included four communities representative of Ohio conditions—Columbus, Defiance, Springfield, and Medina County. Human health effects were studied on 47 farms that land applied sewage sludge compared with 46 control farms that did not land apply any sewage sludge for a five-year period. Health surveys and, more importantly, periodic collection of blood and stool samples for serological detection of infections in participating families provided an objective measure of human health effects. Specific health concerns investigated included respiratory illness, digestive illness, infection with *Salmonella*, *Shigella* sp., and *Campylobacter* sp., and general symptoms of illness. Neither incidence of disease nor evidence of viral infections differed between sludge-using and control farm households. Results clearly showed no negative human health effects associated with land application of sewage sludge. Also, fecal cadmium levels in humans were not affected by exposure of rural residents to sewage sludge. The study concluded that large municipalities can work with large numbers of farmers on a cooperative basis in a mutually beneficial sewage sludge land application program.

LAND RECLAMATION BY LAND APPLICATION OF SEWAGE SLUDGE

by *John J. Sloan and Earl R. Allen*

Land application is the best option for using sewage sludge, especially when it aids in the reclamation of disturbed land. It has been used to reclaim disturbed land in all regions of the United States and in many parts of the world. Examples of disturbed lands where sewage sludge has been used as part of the reclamation process include coal strip-mine spoils, gravel spoils, coal refuse, clay strip mine-spoils, iron ore tailings, abandoned pyrite mine spoils, and sites devastated by toxic fumes. A review of available literature indicates stabilized municipal sludge, if applied properly according to present guidelines and regulations, can be used to revegetate disturbed lands in an environmentally safe manner with no major adverse effects on vegetation, soil, or groundwater quality and does not pose any significant threat to animal or human health (Sopper, 1993).

Effects on Vegetation

The addition of municipal sludge to disturbed soils affects the growth, development, and vegetative quality of plants grown on those soils. Plant growth and development is generally greater on disturbed soils amended with municipal sludge than on those amended with inorganic fertilizer (Sopper, 1993). Grass and legume species become established more quickly on disturbed soils amended with sludge, and once established, they exhibit greater ground cover. Tree species, especially hardwood varieties, are established more quickly on disturbed soils that have been amended with municipal sewage sludge. Tree seedling survival is higher and annual growth is greater. Agronomic crops, such as corn, beans, small grains, and sorghum, generally exhibit higher yields on sludge-amended, disturbed soils.

Uptake of major nutrients (nitrogen, phosphorus, potassium, calcium, and magnesium) by grasses, legumes, trees, and field crops is increased on sludge-amended, disturbed soils. Uptake of trace elements may also increase, but total amounts are generally below levels which are considered safe for animal consumption. Uptake of trace elements is greatest the first year of sludge application and decreases in succeeding years.

Effects on Soil Physical Properties

Perhaps the greatest benefit of sewage sludge amendments to disturbed soils is the improvement in soil physical properties. Drastically disturbed soils, especially those resulting from mining activities, are greatly lacking in soil organic matter due to a loss of topsoil. Municipal sewage sludge typically contains more than 50% organic matter on a dry weight basis. Increased soil organic matter allows water to infiltrate the soil more easily and gives the soil greater water holding capacity. Soil aggregates in sludge-amended soils are more water stable and less susceptible to erosion. Bulk density of dis-

turbed soils is decreased by sludge amendments. This allows greater aeration of the soil and provides a better environment for root growth and activity of soil organisms.

Effects on Soil Chemical Properties

The effect of municipal sewage sludge on the chemical properties of disturbed soils depends on the original characteristics of both the sludge and the soil. The effects are mostly beneficial, and negative effects are insignificant. Soil pH increases when municipal sludge is amended to an acid disturbed soil, especially if the sludge was lime-treated or if limestone was applied to the soil concurrently with the sludge. Temporary decreases in soil pH may occur when sludge is applied to neutral or alkaline soil. This decrease is caused by mineralization of sludge organic matter. The pH stabilizes once the organic matter has decomposed to more stable forms. Cation exchange capacity (CEC) of sludge-amended disturbed soils increases due to addition of organic matter. A higher CEC allows the soil to retain more nutrient cations. The concentration of nutritional elements (nitrogen, phosphorus, and potassium) is generally low in disturbed soils, so additions of municipal sludge can greatly increase their concentration. Trace metal concentrations may initially increase in sludge-amended soils due to mineralization of sludge organic matter. Once the organic matter has decomposed to more stable forms, trace metals convert to mineral forms that are less available for plant uptake. Total trace metal concentrations in sludge-amended disturbed soils are normally within the range considered normal for unpolluted or unamended soil.

Effects on Soil Biological Properties

Adequate biological activity in soil is essential for normal cycling of nutrients from organic forms to plant-available, inorganic forms. Most soil microorganisms, such as bacteria, fungi, and actinomycete, require organic carbon compounds as a source of energy. Municipal sewage sludge can be a valuable source of organic carbon for disturbed soils which are typically lacking organic matter. Without a source of organic matter, drastically disturbed soils can take decades to reestablish a normal soil ecosystem. The use of municipal sewage sludge in a land reclamation project can shorten that period to less than five years. Microbial populations and activity quickly increase following application of sewage sludge to disturbed soils. Rapid decomposition of organic matter into more stable forms (humus) and recycling of nutrients into plant-available forms follow. Most research has shown trace metals in sludge have no adverse effects on microbial populations or activity.

Effects on Water Quality

Both ground water and surface water may potentially be affected when municipal sludge is used in the reclamation of disturbed soils. Leachate nitrate-nitrogen concentrations frequently increase following the application of municipal sludge to disturbed soils. These elevated concentrations rarely exceed acceptable levels and eventually return to background levels when no additional sludge is applied. Most studies show little or no movement of trace metals or fecal coliform bacteria into groundwater.

Application of municipal sludge to disturbed soils usually improves the quality of surface water runoff relative to unsludged soils. Vegetative growth is more vigorous and

more dense on sludge-amended soils. This reduces total runoff and results in greater plant uptake of inorganic nitrogen. Most studies show little or no change in concentrations of trace metals and fecal coliform bacteria in wells, streams, and reservoirs surrounding sludge-amended, reclaimed soils.

Effects on Animal Nutrition and Health

No significant difference in health has been shown between domestic animals grazing forages on sludge-amended, disturbed soils and animals grazing on unsludged soils. Most studies show no increase in trace element concentrations (e.g., Cd, Pb, Cu, Zn) in domestic animal muscle tissue and only slight increases in trace element concentration in the liver and kidneys. Wild animals and birds sampled from sludge-amended soils show little or no difference in trace metal content than those sampled from unsludged sites. Health risks from pathogenic organisms in sludge-amended, disturbed soils is minimal when the sludge was anaerobically digested, lime treated, or composted. Raw sludge or aerobically-digested sludge pose the greatest pathogenic risk.

Summary

When applied properly, municipal sludge can be an indispensable tool in the reclamation of disturbed soils. The greatest benefit is attributed to the high organic matter content of the sludge. Organic matter improves both the physical and chemical properties of the soil and provides a source of energy for soil microorganisms. Macronutrients are supplied by the sludge, and any adverse effects from trace metal contents or pathogenic organisms is minimal. The ultimate goal of soil reclamation is to reestablish a normal functioning soil ecosystem. Municipal sludge can accelerate that process by years and even decades.

REGULATIONS GOVERNING LAND APPLICATION OF SEWAGE SLUDGE

by *Nicholas T. Basta*

Land application of sewage sludge is regulated at federal and state levels. All aspects of sewage sludge disposal are regulated by the U.S. Environmental Protection Agency at the federal level. Although EPA requirements must be met throughout the United States, states may pass regulations that exceed EPA requirements. At present, 45 states (including Oklahoma) have passed laws that are more stringent than EPA regulations. New regulations governing land application have been promulgated by the U.S. EPA and the State of Oklahoma during the last few years. Detailed summaries of these new regulations are provided in the following sections.

Federal Regulations

Under authority of Sections 405(d) and (e) of the Clean Water Act (CWA), as amended (33 USCA, 1251, *et seq.*), EPA promulgates regulations to protect public health and the environment from any reasonably anticipated adverse effects of certain pollutants that may be present in sewage sludge. These regulations establish requirements for the final use and disposal of sewage sludge in three circumstances. First, the regulations establish requirements for sewage sludge when the sludge is applied to the land for a beneficial purpose (including sewage sludge or sewage sludge products that are sold or given away for use in home gardens). Second, the regulations establish standards for sludge when the sludge is disposed on land by placing it on surface disposal sites (including sewage sludge-only landfills). Third, the regulations establish requirements for sewage sludge when incinerated. The standards for each end use and disposal practice consist of general requirements, numerical limits on the pollutant concentrations in sewage sludge, management practices, and, in some cases, operational requirements. Also, these regulations specify monitoring, record keeping, and reporting requirements.

New regulations (The Standards for the Use or Disposal of Sewage Sludge—40 CFR, Part 503) were published in the Federal Register (U.S. EPA, 1993a) on February 19, 1993. These regulations govern all aspects of sewage sludge generation and disposal. Concepts and principles that govern only sewage sludge land application rates and site lifetimes will be presented in this paper. This paper is not a comprehensive review of all Part 503 regulations governing land application. The reader should refer to published regulations (U.S. EPA, 1993a) for regulations governing management practices and a comprehensive treatment of sewage sludge disposal.

Land Application—General Requirements 40 CFR, Part 503

Under Part 503, land application includes all forms of bulk or bagged sludge for beneficial uses at agronomic rates. These include application to agricultural lands (land used for production of food, feed, and fiber crops; pasture; and range land), non-agricultural land (forests, disturbed land such as mine spoils, construction sites, public sites

such as parks and golf courses, and home lawns and gardens), and the sale or giveaway of sewage sludge products. The regulations apply to the person who prepares sewage sludge for land application or applies sewage sludge to the land.

Part 503 establishes (1) two criteria for sewage sludge quality with respect to heavy metal content—the pollutant Ceiling Concentrations and “high quality” Pollutant Concentrations, (2) two levels of sewage sludge quality with respect to pathogen densities—Class A and Class B, and (3) two types of approaches for meeting vector (birds, insects, rats, and other animals that can cause transfer of pathogens and spread disease to humans) requirements. To qualify for land application, sewage sludge must

- (1) contain less heavy metal than the pollutant Ceiling Concentrations,
- (2) meet Class B pathogen reduction requirements, and
- (3) meet vector attraction reduction requirements.

Sewage sludges that do not meet these requirements cannot be land-applied and they must be incinerated or landfilled. Land-applicable sewage sludge may meet “Exceptional Quality” (EQ) or “Clean Sludge” standards and have fewer restrictions than lower quality land-applicable sewage sludge. In addition to meeting requirements necessary for land application (above), “Clean Sludge” must

- (1) contain less heavy metal than the “high quality” Pollutant Concentrations (more restrictive than the Ceiling Concentrations), and
- (2) meet Class A pathogen reduction requirements (more stringent than Class B).

“Bulk sewage sludge,” sludge land-applied in large amounts (not including sludge applied to home gardens or lawns), does not have to meet EQ requirements. Land that has received bulk class B sludge will have site restrictions that limit public access or harvesting of food for well-defined periods of time. The length of the site restriction depends on land use and type of crop grown (U.S. EPA, 1993a). Class A sludge is exempt from these site restrictions. Also, Class A sludge can be applied to home gardens or lawns and sold for other non-bulk (less than one metric ton) uses.

Land Application—Application Rates

Under Part 503, land application of sewage sludge shall not exceed the “agronomic rate.” Agronomic rate is defined as the whole sludge application rate designed (1) to provide the crop nitrogen requirement and (2) to minimize the amount of nitrogen that passes below the root zone of the crop or vegetation grown on the land to the ground water. The agronomic rate requires knowledge of the crop nitrogen requirement; the available nitrogen in the sewage sludge; soil conditions at the site, including available nitrogen content; and the geology of the site. Nitrogen is supplied from sewage sludge in readily available forms (nitrate and ammonium) and slow-release forms (organic forms). Available nitrogen from sewage sludge mineralization may provide the majority of the crop nitrogen requirement. The amount of available nitrogen released depends on the type of treatment process that produced the sewage sludge (e.g. aerobic, anaerobic, etc.)

Table 4. Pollutant limits and loading rates governing land application of sewage sludge in U.S. EPA regulations (40 CFR Part 503).

Pollutant	Table 1 Ceiling Concentrations (mg/kg)*	Table 2 Cumulative Pollutant Loading Rates (kg/ha)	Table 3 Pollutant Concentrations (mg/kg)*	Table 4 Annual Pollutant Loading Rates (kg/ha/365 day period)
Arsenic	75	41	41	2.0
Cadmium	85	39	39	1.9
Chromium	3,000	3,000	1,200	150
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum	75	18	18	0.90
Nickel	420	420	420	21
Selenium	100	100	36	5.0
Zinc	7,500	2,800	2,800	140

*Dry weight basis

and the number of years after land application. The amount of sludge-borne available nitrogen may be calculated by using the EPA's "Process Design Manual—Land Application of Municipal Sludge" (U.S. EPA, 1985). Crop nitrogen requirements and other information needed to determine the agronomic application rate is obtained from County Extension Service agents, State Extension soil fertility specialists, and Soil Conservation Service agents.

Agronomic rate as used in Part 503 regulation is based on beneficial use concept of land application of sludge. Application rate is based on providing beneficial fertilizer and minimizing the amount of nitrogen that passes below the root zone of the crop grown on the site to ground water beneath the application site. The sewage sludge application rate may be limited by the amount of heavy metals in the sewage sludge. The annual sewage sludge application must not exceed the Annual Pollutant Loading Rate (APLR) specified in Table 4 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4). The APLR is the maximum amount of a pollutant that can be applied to a unit area of land during a 365 day period. The basis for APLR values is discussed in the following section on annual pollutant loading rates.

Land Application of Sewage Sludge—Risk Assessment

Under Section 405(d) of the Clean Water Act, the EPA must promulgate regulations that are "adequate to protect human health and the environment from any reasonably anticipated adverse effect of each pollutant." Part 503 is a risk-based regulation designed to protect the public health and the environment from reasonable worst-case scenarios. The approach by EPA used in Part 503 involved pollutant identification, determination of pollutant exposure pathways, risk determination, and derived pollutant concentration limits.

Fifty pollutants of potential concern were evaluated. Fourteen organic pollutants and 10 inorganic pollutants were selected for risk assessment evaluation of land application of sewage sludge. They were

Organic pollutants	Inorganic pollutants
Aldrin/dieldrin	Arsenic
Benzene	Cadmium
Benzo(a)pyrene	Chromium
Bis(2-ethylhexyl)phthalate	Copper
Chlordane	Lead
DDT/DDE/DDD	Mercury
Heptachlor	Molybdenum
Hexachlorobenzene	Nickel
Hexachlorobutadiene	Selenium
Lindane	Zinc
N-Nitrosodimethylamine	
PCBs	
Toxaphene	
Trichloroethylene	

Toxic organic compounds were deleted from Part 503 if

1. The pollutant has been banned for use in the United States, has restricted use in the United States, or is not manufactured in the United States; or
2. The pollutant has a low percent detection limit in sewage sludge; or
3. The pollutant limit in the exposure assessment is not expected to exceed that in sewage sludge used or disposed.

After identification, the EPA evaluated 14 pathways of potential exposure to pollutants in sewage sludge for the final Part 503 rule:

1. Sludge-soil-plant-human (consumer)
2. Sludge-soil-plant-home gardener
3. Sludge-soil-child
4. Sludge-soil-plant-animal-human (farmer/hunter)
5. Sludge-soil-animal-human (farmer/hunter)
6. Sludge-soil-plant-animal toxicity
7. Sludge-soil-animal toxicity
8. Sludge-soil-plant toxicity
9. Sludge-soil-soil biota toxicity
10. Sludge-soil-soil biota-predator of soil biota
11. Sludge-soil-airborne dust-human (tractor driver)
12. Sludge-soil-surface water-fish-human
13. Sludge-soil-air-human
14. Sludge-soil-ground water-human

Risk assessment was conducted to determine the effect of each pollutant (separately) on highly exposed individuals (HEIs) and subpopulations as well as the population as a whole in each exposure pathway. Dose-response values were used to quantify injury levels between pollutants and HEIs and whole populations. Sewage sludge pollutant concentrations were derived from the most limiting (lowest) determined risk assessment value for each pollutant. Finally, pollutant concentration limits were derived by using the lower of two numbers derived either from risk assessment or from the National Sewage Sludge Survey (NSSS) 99th percentile concentration of pollutants (i.e. 99% of sewage sludges are lower in concentration).

Risk exposure methodology and NSSS data were used to derive pollutant limits in Part 503: Ceiling Concentration Limits, Cumulative Pollutant Loading Rates, Pollutant Concentration Limits, and Annual Pollutant Loading Rates (Table 4).

Ceiling Concentration Limits

Ceiling Concentration Limits are the maximum pollutant concentrations of inorganic pollutants allowed in land-applicable sewage sludge. To qualify for land application, all sewage sludge pollutant concentrations must be below the Ceiling Concentration Limits. Sewage sludges that contain pollutants that exceed the Ceiling values cannot be land-applied and must be disposed of by incineration or landfilling. The ceiling concentrations in Table 1 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) are the larger of two values. They are the concentrations calculated using the cumulative pollutant loading rules from the land application exposure assessment, an assumed 100-year site life, and an assumed annual sludge application rate of 10 metric tons per year (chromium, nickel, and selenium) or the 99th percentile concentration from the NSSS, whichever is larger.

Cumulative Pollutant Loading Rate

Cumulative Pollutant Loading Rate is the maximum amount of an inorganic pollutant that can be applied to an area of land. This loading rate is not an annual rate. Rather, it is the maximum amount of an inorganic pollutant that can be cumulatively applied to an area of land. When the cumulative pollutant loading rate for a pollutant is reached for a particular land application site, no more of that pollutant can be applied to the site in bulk sewage sludge (sewage sludge application ceases—site lifetime is reached). To comply with this requirement, the amount of each pollutant in the bulk sewage sludge applied to a site must be known. Records have to be kept of the amount of each pollutant applied to each site. When the cumulative pollutant loading rate for any of the pollutants in Table 2 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) is reached for a site, no more bulk sewage sludge may be applied to that site.

Pollutant Concentration Limits

Pollutant Concentration Limits are the maximum amount of inorganic pollutant allowed in Exceptional Quality (EQ) sewage sludge (sewage sludge that contains pollutants that exceed PCL values is not considered EQ). The pollutant concentration limits are monthly average concentrations. To be considered EQ, the monthly average concentration of the pollutant in the sewage sludge that is applied to the land cannot exceed

the Pollutant Concentration Limit values. Records do not have to be kept of the amount of each inorganic pollutant in the bulk Exceptional Quality sewage sludge applied to a site (i.e., no site lifetime).

Exceptional Quality sewage sludge pollutant limits are the more stringent (lower) of two values. The concentrations are calculated using the cumulative pollutant loading rules from the land application exposure assessment, an assumed 100-year site life, and an assumed annual sludge application rate of 10 metric tons per year or the 99th percentile concentration from the NSSS (chromium, nickel, and selenium), whichever is smaller (more stringent). EPA concluded that using a site life of 100 years is conservative because bulk sewage sludge most likely will not be applied to a site for 100 years.

Annual Pollutant Loading Rates (APLR)

The APLR is the maximum amount of a pollutant that can be applied to a unit area of land during a 365-day period.

Application of Sewage Sludge and Site Lifetime

Heavy metal pollutants in sewage sludge may limit the amount of sewage sludge that can be applied to a unit area of land. There are two types of land-applicable sewage sludges with respect to site lifetime. Pollutant content of sewage sludge and pollutant limits are used to categorize these sludges.

Sewage sludges with one or more pollutants with concentrations that are below Ceiling Concentration Limits but are above EQ Pollutant Concentration Limits are subject to cumulative loading limits and finite site lifetimes. Records are kept until the Cumulative Pollutant Loading Rate of the first pollutant is reached. At this point, the site lifetime has been reached and land application of sewage sludge must cease.

Exceptional Quality sewage sludge is not subject to site lifetimes—it can be land-applied indefinitely. EQ sewage sludge is not subject to cumulative loading rates and pollutant loading records are not required by the EPA. The EPA's rationale is that Cumulative Pollutant Loading Rates in Table 2 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) will never be reached through land application of EQ sludge with very low pollutant contents.

Figure 4 summarizes EPA regulations on pollutant content of sewage sludge and land application.

State of Oklahoma Regulations

State regulations cannot be less stringent than U.S. EPA regulations governing land application of sewage sludge. Many states, including Oklahoma, have passed regulations that are more stringent than federal regulations. In response to new U.S. EPA regulations, promulgated in February of 1993, the Oklahoma Department of Environmental Quality (ODEQ) drafted new state regulations governing land application of sewage sludge (ODEQ, 1994). These regulations will become effective in October, 1994.

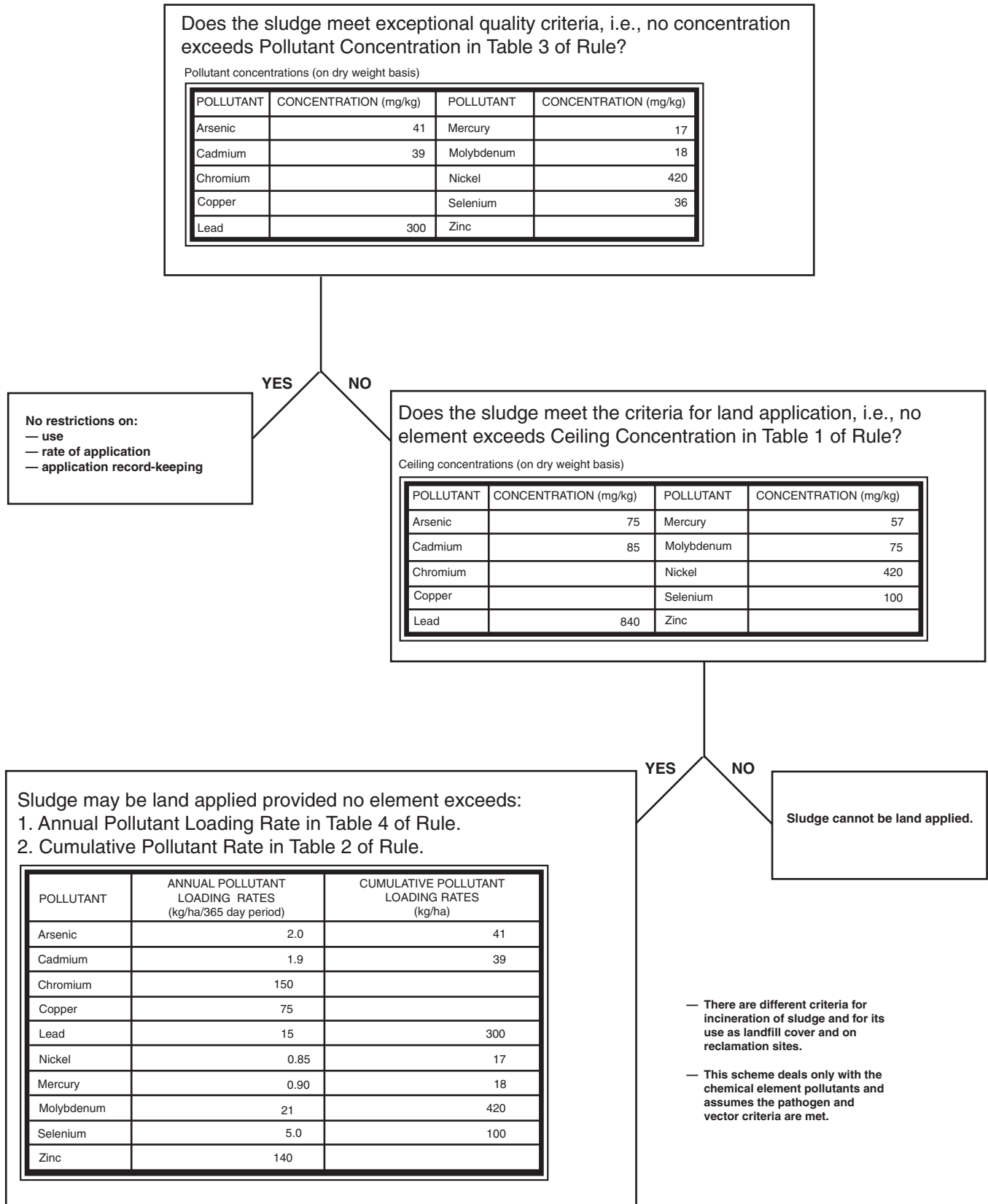


Figure 4. Decision scheme for land application of sewage sludge based on U.S. EPA regulations (40 CFR Part 503). This scheme assumes pathogen and vector criteria are met.

		U.S. EPA	STATE OF OKLAHOMA
P O L L U T A N T	↑	TABLE 1 U.S. EPA 40 CFR Part 503	CANNOT BE LAND APPLIED
			SUITABLE FOR LAND APPLICATION SITE LIFETIME SUBJECT TO CUMULATIVE POLLUTANT LOADING RATES (TABLE 2)
		TABLE 3 U.S. EPA 40 CFR Part 503	CANNOT BE LAND APPLIED
			SUITABLE FOR LAND APPLICATION PENDING APPROVAL OF CORRECTIVE ACTION PLAN SITE LIFETIME SUBJECT TO CUMULATIVE POLLUTANT LOADING RATES (TABLE 2)
		EXCEPTIONAL QUALITY SLUDGE NO LIMIT ON SITE LIFETIME IF OTHER EQ PARAMETERS ARE MET	EXCEPTIONAL QUALITY SLUDGE NO LIMIT ON SITE LIFETIME IF OTHER EQ PARAMETERS ARE MET

Figure 5. Comparison of State of Oklahoma and U.S. EPA regulations (40 CFR Part 503) governing land application of sewage sludge.

Although they are similar, State of Oklahoma proposed regulations meet and exceed federal regulations. Notable differences between state and federal regulations include land application exceptions regarding metal concentration limits (252:647-5-5), pH limits (252:647-5-7 (a)), and restrictions on phosphorus loading (252:647-5-7 (b)).

Sewage sludge that exceeds Pollution Concentration Limits of Exceptional Quality sewage sludge listed in Table 3 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) cannot be land-applied in Oklahoma without approval of a “corrective action plan for the reduction of heavy metals to the normal concentrations” (252:647-5-5 (a) (2)) by the Oklahoma DEQ.

State of Oklahoma regulations promote beneficial use of sewage sludge. Sewage sludge with heavy metal concentrations below the U.S. EPA’s Ceiling Concentration Limits listed in Table 1 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) must be land-applied. Disposal alternatives (i.e., landfilling or incineration) can be used for sewage sludge with metal levels below Table 1 of 40 CFR Part 503 (U.S. EPA, 1993a) (Table 4) if a “cost effectiveness analysis demonstrating that the benefits of land application are less than the costs associated with disposal alternatives” is approved by the Oklahoma DEQ.

Figure 5 compares federal and state regulations concerning heavy metal concentrations in sewage sludge.

State of Oklahoma regulations should increase beneficial use of “cleaner sewage sludge” in the future. Oklahoma is the first state to simultaneously increase beneficial use of sewage sludge through land application and significantly reduce heavy metal content of sewage sludge through regulation.

Results from many research studies show that plant uptake and mobility of heavy metals are decreased by increasing soil pH (Basta and Tabatabai, 1992a,b,c; Chaney et al., 1987; Dowdy and Volk, 1983; Logan and Chaney, 1983). Previous federal regulations required maintenance of soil pH at 6.5 (U.S. EPA, 1979). New federal regulations (U.S. EPA, 1993b) do not require adjustment of soil pH. Under State of Oklahoma regulations, soil pH must be at least 5.5 before sewage sludge is land-applied (252:647-5-7 (b)). Recently reported results from research on heavy metal availability in Oklahoma soils amended with sewage sludge show maintenance of soil pH above 5 provides additional assurance against heavy metal mobility and availability (Sloan and Basta, 1993).

Excessive amounts of phosphorus nutrients and excessive soil erosion may lead to surface water contamination and degradation of water quality. State regulations limit sludge application to soils that contain excessive amounts of available phosphorus and have significant erosion potential.

FUTURE DIRECTIONS

Nicholas T. Basta

Many of the trends associated with land application of sewage sludge established during the last 25 years are likely to continue. Land application will increase, and incineration, landfilling, and other alternative sludge disposal methods will decrease. Municipal land application programs have been proven by the test of time. Land application has become a routine practice and will continue to gain acceptance by the public. Alternate disposal costs will continue to increase and discourage landfilling and incineration practices. Pretreatment programs will continue to produce a “cleaner sludge” that contains lower amounts of heavy metals and undesirable chemical and biological constituents.

New products derived from sewage sludge, biosolids, will be land-applied in increasing amounts. Biosolids will be designed to provide more agronomic benefits, thereby making sewage sludge a more beneficial land treatment. Products such as N-Viro that have both lime and fertilizer value provide an example of materials with combinations of agronomic benefits. Development and manufacturing of “Designer Sludges” (sewage sludges with very low heavy metal bioavailability) has been advocated (Chaney, 1993).

The next 25 years will bring an increase in beneficial land application of a variety of new waste materials including municipal solid waste (MSW). The annual production of MSW in the United States is 180 million tons, much larger than the 5 million tons of sewage sludge produced annually in the U.S. (Barkenbus, 1993). Knowledge gained from sewage sludge research and methods used to regulate land application will be essential for beneficial land application of new materials.

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