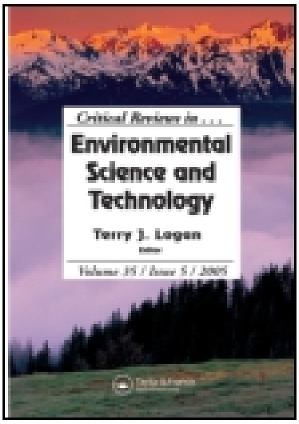

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Use of municipal sewage sludge to reclaim mined land

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USE OF MUNICIPAL SEWAGE SLUDGE TO RECLAIM MINED LAND

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I. INTRODUCTION*

Revegetation of disturbed lands is currently an area of environmental concern and active research, as well as practical application, particularly since the 1977 federal Surface Mining Control and Reclamation Act established strict regulations for the revegetation of currently mined land. The act (PL 95-87, Sec. 515) requires that a diverse, effective, and permanent vegetative cover of the same seasonal variety native to the area of land to be affected must be established and must be capable of self-regeneration and plant succession at least equal in extent of cover to the natural vegetation of the area. In March 1982 amended regulations were published. These rules are currently set forth in 30 CFR 816 and 817.[1] Specifically, they state that:

1. The permanent vegetative cover of the area must be at least equal in extent of cover to the natural vegetation of the area and must achieve productivity levels compatible with the approved postmining land use. Both native and introduced vegetation species may be used.
2. The period of responsibility initiates after the last year of augmented seeding, fertilizing, irrigation, or other work which ensures revegetation success.
3. In areas of more than 66 cm of average annual precipitation, the period of extended responsibility will continue for not less than 5 years. In areas with 66 cm of precipitation or less, the period of responsibility will continue for not less than 10 years.
4. Normal husbandry practices essential for plant establishment would be permitted during the period of responsibility so long as they can reasonably be expected to continue after bond release.
5. In areas of more than 66 cm of precipitation, the vegetative cover shall be equal to the success standard only during the growing season of the last year of the responsibility period unless 2 years would be required by the regulatory authority. In areas with less than 66 cm, the vegetative cover must be equal to the success standard for the last 2 years of the responsibility period.
6. The ground cover, productivity, or tree stocking of the revegetated area shall be considered equal to the success standard approved by the regulatory authority when the parameters are fully equivalent with 90% statistical confidence.

* A list of common and scientific names of vegetation discussed appears at the end of this article.

It will be difficult to meet these requirements using current reclamation techniques. New methods will have to be developed and larger amounts of lime, fertilizer, and seed will undoubtedly be needed. Soil amendments, mulching, and even irrigation may be required on some sites.

In addition to land disturbed by coal mining, other areas continually in need of reclamation in the eastern U.S. include borrow pits, dredge spoils, construction sites, quarries, gravel pits, clear-cut and burned forests, and shifting sand dunes.[2]

The problem of disposing of ever-increasing amounts of municipal sewage sludge is one which must be faced by many U.S. municipalities, particularly with the increasing cost of incineration, the decreasing land available for landfills, and the current controversy and concern over ocean dumping. In fact, about 42% of current U.S. sludge production is being land applied.[3] Both problems, that of devastated lands and that of sludge disposal, may be alleviated by sludge utilization and recycling, i.e., using sewage sludge to aid revegetation.

During the past decade, extensive research has been carried out in the eastern U.S. on the feasibility of reclaiming disturbed land with sludge. The research as well as large-scale practical projects and commercial ventures have shown that stabilized municipal sludge is an excellent soil amendment and chemical fertilizer substitute. Consequently, there has been considerable use of sludge for the production of agricultural crops. One disadvantage, however, is that sludge may contain every element or compound found in wastes from domestic and industrial sources. Thus, some concern has been raised about the potential introduction of these elements, particularly heavy metals, into the human food chain. The U.S. Environmental Protection Agency as well as some states have developed guidelines and regulations governing sludge applications in agriculture.[2]

Most of these guidelines set limits on sludge application rates based on nitrogen and other plant nutrient requirements of the vegetation as well as trace metal loadings. For instance, the U.S. Environmental Protection Agency has developed guidelines concerning the maximum amounts of Pb, Zn, Cu, Ni, and Cd allowable on agricultural land used for growing food-chain crops.[4] Food-chain crops are typically defined as those crops that can enter the human diet either with (wheat, corn) or without (leafy vegetables) processing. Researchers in the USDA and Agricultural Experiment Stations have proposed similar trace metal limits which would allow the growth of all crops after termination of sludge applications, provided the soil pH is maintained at 6.5 or above.[5] No federal guidelines have been issued specifically governing the use of sludge for reclamation proposes. Although the above guidelines were developed for agricultural applications, it is suggested that they also be considered for reclamation applications unless there are more specific state regulations.

The metal loadings suggested by the U.S. Environmental Protection Agency are given in Table 1. They are based upon the soil cation exchange capacity (CEC). The use of soil CEC was based on the assumption that metal solubility and thus plant availability tend to decrease with increasing CEC in most soils of the northcentral U.S.

These are *guidelines* and not *regulations*. The U.S. Environmental Protection Agency has only issued *regulations* for cadmium as part of the requirements under the Resource Conservation and Recovery Act of 1976 and the Clean Water Act of 1977.[6] These regulations are specifically for cadmium additions to cropland and can be summarized as follows:

1. The pH of the soil must be $\geq$6.5 at the time of sludge application.
2. Annual cadmium additions are limited to 0.5 kg/ha/year if leafy vegetables or tobacco are grown.
3. For other food-chain crops, the annual cadmium additions follow a phased reduction from 2 (present to 6/30/84) to 1.25 (7/1/84 to 12/31/86) to 0.5 kg/ha/year (after 1/1/87).
4. The cumulative cadmium applied must be <5 kg/ha if the background soil pH is $\leq$6.5.
5. The cumulative cadmium applied is as shown in Table 1 for soils with a background

Table 1
EPA RECOMMENDED MAXIMUM AMOUNTS OF TRACE METAL LOADINGS FOR AGRICULTURAL CROPLAND[4,5]

	Soil cation exchange capacity (meq/100 g)		
Metal	**<5**	**5—15**	**>15**
	Amount of metal (kg/ha)		
Pb	560	1120	2240
Zn	280	560	1120
Cu	140	280	560
Ni	140	280	560
Cd	6	11	22

pH ⩾6.5 and for soils with a background pH ⩽6.5 provided the pH is 6.5 at the time food-chain crops are grown.

The U.S. Environmental Protection Agency has also recently recommended that cumulative additions of lead to agricultural soils be limited to a maximum of 800 kg/ha rather than the values shown in Table 1.[7]

For soils used for growth of animal feed only, neither annual nor cumulative cadmium application limits have been established, but soil pH must be 6.5 and a plan is needed to show that the crop will not directly enter the human diet.

A general statement of federal policy and guidance in relation to land application of municipal sewage sludge for the production of fruits and vegetables has also been recently published.[7] The three federal agencies agree that the use of high quality sludges, coupled with proper management procedures, should safeguard the consumer from contaminated crops and minimize any potential adverse effect on the environment.

In addition, some states have even more stringent guidelines concerning sludge application on the land. For instance, in 1977 the Pennsylvania Department of Environmental Resources (PDER) issued *Interim Guidelines for Sewage Sludge Use for Land Reclamation.*[8] These guidelines state that due to the high permeability of mine spoils and low retention of organic matter, sufficient nitrogen in excess of the crop requirement must be provided in order to establish growth. To provide sufficient nitrogen a maximum application rate of 134 metric tons/ha may be utilized for land reclamation. In addition, the application is further limited according to the trace metal content of the sludge and application rates may not exceed the limits given in Table 2.

The state guidelines further require that the soil pH be adjusted to 6.0 during the first year of sludge application and maintained at 6.5 for 2 years following final sludge application. Liming is required to immobilize the trace metals in order to reduce their availability for plant uptake and to prevent their leaching into groundwater.

Other requirements include the following:

1. Sludge is to be incorporated within 24 hr after application.
2. Sludge is not to be applied when the ground is saturated, snow covered, frozen, or during periods of rain.
3. Sludge is not to be applied within 30 m of streams, 90 m of water supplies, 8 m of bedrock outcrops, 15 m of property lines, or 90 m of occupied dwellings.

Table 2
PDER RECOMMENDED MAXIMUM TRACE ELEMENT LOADING RATES FOR LAND RECLAMATION

	Maximum loading rate (kg/ha)	
Constituent	Land reclamation	Land reclamation for farming
Cd	3	3
Cu	112	67
Cr	112	67
Pb	112	67
Hg	0.6	0.2
Ni	22	13
Zn	224	134

4. Sludge for revegetation of inactive mines or active coal refuse piles is not to be applied to slopes exceeding 15%.
5. Dairy cattle must not be allowed to graze land for at least 2 months after sludge application.

In addition to guideline requirements, PDER uses several policies and procedures for permitting of land reclamation sites. The most important of these is the requirement of two on-site investigations prior to the spreading of sludge. The first investigation is made by the Department regional soil scientist and hydrogeologist during the application review process. The second investigation is made prior to sludge application, but after all proposed erosion and sedimentation control and monitoring devices are in place. PDER feels that control of surface water runoff is the most important aspect of land reclamation projects. Detailed erosion and sedimentation control plans must be included as a part of the application to keep sludge and soil on the site until the seed has a chance to germinate. In many cases, mulching is required to prevent sludge runoff and erosion of particularly steep or critical areas.

The second investigation usually is performed jointly with the Bureau of Mining and Reclamation and the consultants for the applicant. Critical areas of concern can be pointed out at this time to eliminate the costly time involved with the exchange of written review comments by the Department and responses from the applicant.

After a site has been recontoured and meets all the reclamation requirements of the Bureau of Mining and Reclamation, the permit is issued for sludge application by the Bureau of Solid Waste Management. This is another critical phase in the land reclamation process. Since most permits are issued for one application of sludge followed by seeding of the site, a large amount of sludge must be applied in a short period of time. In most cases, this requires stockpiling sludge at a particular site, and assembling the necessary manpower and equipment for the sludge spreading and seeding process, which may only last a few days.

The storage areas must be approved by the Department. Minimum requirements to be met for storage are diversion of surface water above and below the area and berms constructed around the area.

The sites are then inspected monthly to determine whether there is evidence of erosion channels being formed. Erosion and sedimentation control facilities are also inspected at this time. Where evidence of erosion exists, the area must be filled, reseeded, and mulched. The progress of germination and growth of vegetation is also checked during these inspection visits.

An extensive monitoring program is required for all reclamation projects using sludge. It was decided that since reclamation involved single applications of large volumes of sludge it would be necessary to collect documentary evidence to alleviate any public concerns over potential adverse environmental effects.

On each site less than 100 acres, at least one downgradient groundwater well is drilled. Four pairs of suction lysimeters for the collection of soil percolate water are installed at the 90-cm depth at locations considered to be representative of overall site conditions. Private water supplies from nearby homes are also sampled. A minimum of three samples is collected from the groundwater wells, lysimeters, and homes prior to sludge application in order to obtain background data. After sludge is applied, water samples are collected monthly for a period of 1 year. The background samples from lysimeters and private homes and those collected the first 3 months and the 12th month after sludge application are analyzed for pH, Cl, NO_3-N, NH_4-N, organic-N, Fe, Al, Mn, Cu, Zn, Cr, Co, Pb, Cd, Ni, and total and fecal coliform bacteria. Water samples collected during the 4th to 11th months are analyzed for pH, NO_3-N, NH_4-N, Cu, Zn, Cr, Co, Pb, Cd, Ni, and total coliforms. If total coliforms are found, samples are analyzed for fecal coliforms. Ground-water samples from the monitoring well are similarly analyzed with the exception of total coliforms. Since the equipment used to collect groundwater samples is not sterilized, the results of such analyses would be meaningless. Water sampling is terminated after 1 year unless data indicate a need to continue sampling, in which case samples are collected quarterly until a solution to the problem is found. The monitoring well remains on the site after the first year for additional sampling, if considered necessary by PDER.

Background soil samples are collected prior to sludge application. Surface soil samples (0 to 10 cm) are analyzed for pH and buffer pH to determine the amount of lime required to raise the soil pH to 6.5, and for cation exchange capacity to determine sludge application rate. While lysimeters are being installed background samples from the complete soil profile are collected at the 0- to 15, 15- to 30-, 30- to 60-, and 60- to 90-cm depths. These are analyzed for pH, Bray P, Ca, Mg, K, Na, Fe, Al, Mn, Cu, Zn, Cr, Co, Pb, Cd, Ni, and Kjeldahl nitrogen. One year after sludge application, soil samples from the 0- to 15-, 15- to 30-, and 30- to 60-cm depths are analyzed for these same constituents. The second year after sludge application, surface soil is again analyzed to determine if the pH is still 6.5.

To determine heavy metal content of the vegetation, samples of the seeded species are collected at the end of the first growing season following sludge application. For each of the species, foliar analysis for N, P, K, Ca, Mg, Fe, Al, Mn, Cu, Zn, Cr, Co, Pb, Cd, and Ni is performed. If a site is seeded in the fall, vegetation is collected and analyzed at the end of the following growing season.

One alternative, which may alleviate some of the food-chain concerns, is to use the sludge to reclaim marginal, unproductive lands and barren land devastated by mining activities. The potential for successful reclamation with municipal sludge is tremendous. Most of the highly beneficial properties of sludge as a soil amendment come from its high organic matter content. Although it has long been shown to increase productivity on good agricultural soils, sludge organic matter is extremely important where topsoil is inadequate in amount or quality, e.g., on sites that were previously in forest, and especially for areas mined and left barren for many years before the 1977 act, where no topsoil exists. It is on land like this that the benefits of sludge are most evident. The establishment as well as the continued maintenance of cover for the minimum required 5 years is difficult on acid, eroded, infertile, compacted, and stony spoils that have no buffering capacity for temperature extremes and are incapable of retaining sufficient moisture for plants during periods of water stress. Although organic matter is the single most important component in the improvement of soil physical properties, sludges also contain neutralizing compounds and fertilizer elements that improve spoil pH and fertility.

While the benefits of using sludge to reclaim land seem obvious, there is still some reluctance on the part of landowners, local citizens, and local government officials to accept

Table 3
STATUS OF LAND DISTURBED BY SURFACE MINING IN THE EASTERN U.S. AS OF JULY 1, 1977[11]

State	Unreclaimed land (ha) Coal mines	Sand and gravel pits	Other mined areas	Reclaimed land	Total disturbed land reclaimed (%)
Alabama	29,278	8,954	10,603	34,697	35
Connecticut	—	6,780	319	1,859	21
Delaware	—	1,179	25	607	33
Florida	—	5,883	103,932	24,813	18
Georgia	990	3,230	15,301	9,415	33
Illinois	64,642	11,709	7,593	35,988	30
Indiana	40,688	6,501	3,408	26,208	34
Kentucky	103,621	1,328	3,034	62,570	37
Maine	—	12,606	1,214	2,751	17
Maryland	4,906	6,954	1,180	8,029	38
Massachusetts	—	12,977	4,184	4,759	22
Michigan	57	22,310	11,135	11,178	25
Missouri	32,181	2,235	13,868	8,931	16
New Hampshire	—	5,154	169	221	4
New Jersey	—	9,967	2,256	3,346	21
New York	—	18,993	9,837	7,483	21
North Carolina	—	7,697	3,524	2,835	20
Ohio	100,872	15,908	11,077	77,184	36
Pennsylvania	121,500	10,530	18,427	101,250	40
Rhode Island	—	1,050	—	1,405	57
South Carolina	—	5,451	2,155	3,975	34
Tennessee	13,247	2,333	1,393	42,361	71
Vermont	—	1,723	866	622	19
Virginia	12,938	3,125	1,318	28,374	62
West Virginia	37,473	1,844	403	55,527	58
Wisconsin	—	21,664	4,220	8,750	25

Table 4
PROJECTED REGIONAL LAND USE FOR COAL PRODUCTION FROM SURFACE MINING[9]

Region	Hectares 1975	1977	1980	1985	1990
Northern Appalachia	8,019	8,302	9,396	10,813	14,013
Southern Appalachia	5,508	5,710	6,804	8,505	10,287
Midwest	7,209	7,411	8,302	9.922	11,704
Gulf	810	1,417	3,888	5,791	7,209

its use for reclamation. Due to the nature of devastated lands, larger amounts of sludge are used than for established farmlands, but usually only a single application is made which allows the vegetation to become self-sustaining. The greatest obstacle appears to be the lack of knowledge on the part of the general public about the possible impacts of sludge on soils, plants, groundwater, and surface water, and animal and human health. These impacts must be known in order to make rational decisions concerning the benefits and risks.

There is a large amount of research and demonstration experience and information available on all types of land application projects, initiated to address public concerns. The increasing

Table 5
FEDERAL AND
NONFEDERAL FOREST
LAND IN EASTERN U.S.[11]

Region	Total forest area (ha)
Northeast	30,873,555
North Central	31,364,010
Southeast	33,622,290
South Central	42,927,975
Total	**138,787,830**

number of successful projects across the country clearly shows the value of using sludge as a resource rather than disposing of it as a waste.

Considerable detailed information is available on the planning, economics, social and legal problems, engineering, agricultural, ecological, and health-related aspects of reclaiming disturbed land with sludge over a wide range of situations. Although most of the basic concepts and practices are applicable to land reclamation in the U.S. as a whole, this paper focuses on the eastern U.S. only due to considerable differences in climate, especially rainfall, as well as spoil chemistry, mining operations, and plant species used in revegetation.

II. DISTURBED LAND IN THE EASTERN U.S.

Disturbed land resulting from both surface and underground mining can result in major water quality problems as well as being unsightly and unproductive. The U.S. mining industry has disturbed over 1.48 million ha between 1930 and 1971, and only 40% of this has ever been reclaimed.[9] Besides coal, sand, gravel, stone, clay, copper, iron ore, phosphate rock, and other minerals account for most of the mining. Table 3 shows the status of lands in the eastern U.S. disturbed by surface mining, including both land requiring reclamation by law and abandoned mine lands for which there is no legal requirement for reclamation. Pennsylvania, Ohio, Ketucky, and Illinois each have over 40,500 ha and West Virginia, Alabama, and Missouri over 20,250 ha of unreclaimed coal-mined land. Florida has more than 81,000 ha of unreclaimed land after phosphate and other mining activities.

Surface mining, half of which is for coal, has disturbed over 1.6 million ha in the U.S.[10] In the populated eastern half of the U.S., additional thousands of hectares will be disturbed each year (Table 4).

Although most of the legislative and technical experience in land reclamation has involved land surface mined for coal, the information may be applied, with modifications, to other types of disturbed or marginal land. Forestry-related activities, roadway and other construction, and deposition of dredge materials and fly-ash from coal-fired power plants create large tracts of wasteland which are often difficult to reclaim with conventional techniques and offer considerable potential for municipal sludge amendments. The eastern U.S. has over 138 million ha of forest (Table 5). Large acreages of forest are harvested or devastated by forest fires, landslides, and other natural disasters each year which require reestablishment of trees for return to productivity.

About 400 million m^3 of sediment is dredged each year in the maintenance and establishment of waterways and harbors. Many sites where dredge spoils are deposited are highly acidic and of low productivity. Eroding sediment pollutes nearby waterways. Municipal sludge has been successfully used to stabilize and revegetate acidic dredge spoils along the Chesapeake and Delaware Canal.[12]

Nearly 700 million metric tons of fly ash, cinders, and bottom ash from coal-fired power plants has been produced since the end of World War II,[12] and with the increasing construction of new power plants, it is estimated that about 70 million metric tons of ash and 10 million metric tons of flue gas desulfurization sludge per year[13] will be produced. Fly ash contains some essential plant nutrients, and studies have evaluated the waste material in combination with municipal sludge for reclaiming derelict areas.[14,15]

Another area where sludge could be beneficially used is near construction sites and roadways. Over 10 million ha is occupied by public roads and highways in the U.S. Some work has been done using sludge to stabilize and revegetate these often eroded and unproductive soils,[16,17] and sludge appears to have potential as an amendment along roads and right of ways.

III. LAND RECLAMATION PROJECTS USING MUNICIPAL SLUDGE

Many of the ongoing land application projects, including research, demonstration, and practical application are described in the proceedings of two symposia held in Philadelphia in 1977 and Pittsburgh in 1980.[18,19] Table 6 summarizes these and other studies. Some of the largest projects include the acid spoils of the Palzo tract in southern Illinois,[20-24] Chicago's Prairie Plan in Fulton Co., Illinois,[25-30] and the Philadelphia program in the bituminous region of western Pennsylvania.[31,32] In addition, numerous projects on a smaller scale have evaluated land reclamation with sludge under many different geographical, environmental, and agricultural conditions.

IV. EFFECTS ON VEGETATION

A. Cover Species

The productivity and fertility of disturbed lands have in most cases been substantially improved by the addition of sludge, as reflected in large yield increases on sludge-amended land compared to the same type land amended with inorganic fertilizers.

In the midwest, nine grass species were seeded on calcareous strip mine spoil with pH between 6.0 and 7.5, with tall fescue, perennial ryegrass, and western wheatgrass showing the most rapid establishment and most vigorous growth where relatively high sludge loading rates were applied.[25] In a green-house study, four different sludges were applied to acidic spoils. Tall fescue yield increased with increasing rate of two of the sludges, but high metal concentrations of the other two sludges inhibited fescue growth.[52] Stucky and Newman[36] in another greenhouse study grew tall fescue and alfalfa for 2 years using 314 and 627 mt/ha of sludge in acidic spoils. The high treatment significantly increased yields, especially for alfalfa. Where sludge was applied on Ohio mine spoil at 658 mt/ha without lime, forage yield the first growing season was greater than 4.5 mt/ha.[40] On the Palzo strip mine site in Illinois, 16 seed mixtures were evaluated.[23,67] Perennial rye was a very successful initial cover crop, while Bermuda, orchard, reed canary, and tall fescue grasses were recommended for permanent cover along with the legumes red clover, lespedezas, and birdsfoot trefoil. Boesch[37] gives a vivid description of the devastated Palzo site and the sequence of events that led to large-scale reclamation with Chicago sludge. In 1970, demonstration plots were seeded with tall fescue and weeping lovegrass, which did not germinate on control plots, but produced a complete ground cover in 2 months where 271 dry mt/ha of sludge was applied. On coal refuse in Illinois, Joost et al.[38] observed a more than adequate cover with tall fescue, redtop, and reed canary grass 2 months after seeding even with high rates of high metal sludge. Redtop was most successful.

In the east, Kardos et al.[43] tested ten grass and ten legume species in boxes of bituminous mine spoil and anthracite refuse amended with liquid-digested sludge. Sludge and effluent

Table 6
RECENT LAND RECLAMATION PROJECTS WITH MUNICIPAL SLUDGES

		Sludge				
Type of disturbed land	State	Type[a]	Application rates (dry mt/ha)	Plant/animal studied	Parameters tested[b]	Ref.
Strip mine spoil	IL	Dig.—D	0,224—896	Grass species Corn Rye	GR PA SA	25
Acid strip mine spoil	IL	Dig.—L	448—997	5 tree species	PA SA	35
	IL	Dig.—L	336, 672	Annual Rye Orchardgrass Tall fescue	WA	21
Calcareous strip mine spoil	IL	Dig.—L	0—453	Corn	GR PA WA	27
Strip mine spoil	IL	Dig.—L	0, 11—45	Grasses Legumes Cattle	GR PA SA AH PO	33
	IL	Dig.—L, D	—	—	Application techniques	34
Calcareous strip mine spoil	IL	Dig.—L	0.8—85.8	Corn	GR PA SA WA	26
Acid strip mine spoil	IL	Dig.—L	448—997	8 herbaceous species 18 tree species	WA	22
	IL	Dig.—L	448—997	7 legumes 10 grasses	GR PA SA	23
	IL	Dig.—L	448—997	12 tree species	GR	20
	IL	Dig.—L	448—997	8 tree species	PA	24

Table 6 (continued)
RECENT LAND RECLAMATION PROJECTS WITH MUNICIPAL SLUDGES

Type of disturbed land	State	Sludge: Type[a]	Sludge: Application rates (dry mt/ha)	Plant/animal studied	Parameters tested[b]	Ref.
	IL	Dig.—L	0,314,627	Tall fescue	GR	36
				Alfalfa	PA	
	IL	Dig.—L	0, 31—121	Tall fescue	GR	37
				Weeping lovegrass	WA	
Coal refuse	IL	D	225—900	Tall fescue	GR	38
				Redtop	SA	
				Reed Canary Grass		
Acid strip mine spoil	IL	Dig.—L	0, 78—304	Tall fescue	GR	39
				Weeping lovegrass	SA	
					WA	
	OH	D	658	Forage	GR	40
					PA	
Strip mine spoil	IL	Dig.—L	NI	Corn	Operations	29
	IL	Dig.—L	56	Corn	PA	41
Acid strip mine spoil and deep mine refuse	PA	Dig.—D, L, C	7—202	Tall fescue	GR	31, 42
				Orchardgrass	PA	
				Birdsfoot trefoil	SA	
				Crownvetch	WA	
	PA	Dig.—L + effluent	0—51 cm	8 tree species	GR	43
				8 grass species	WA	
				8 legume species	SA	
	PA	Dig.—D, L, C	0, 11—202	Birdsfoot trefoil	PA	32
				Tall fescue		
				Orchardgrass		
Deep mine anthracite refuse	PA	Dig.—D	0, 40—150	10 tree species	GR	44
				5 grass species	PA	
				5 legume species	SA	
					WA	

Acid strip mine spoil and deep mine refuse	PA	Dig.—D, L, C	0, 7—202	Tall fescue Orchardgrass Birdsfoot trefoil Crownvetch	GR PA SA WA	45
Acid strip mine spoil	PA	Dig.—D + effluent	2—8 in.	Ryegrass Hybrid poplar	WA	46
	PA VA	Dig.—L, D	198—730	Tall fescue Red top Ladino clover Birdsfoot trefoil Ryegrass	GR	47
	VA	C	0, 159—412	Virginia pine Tall fescue Perennial ryegrass Annual ryegrass	GR SA	48
	VA	Dig.—D	Various (NI)	NI	SA	49
	WV	Dig.—D, C	Various (NI)	Blueberries	GR PA	50
	WV	D	0—224	Tall fescue	GR PA SA	51
	OH	Dig.—D	11—716	*Tall fescue*	GR PA SA WA	52
	MD	*Dig. composted*	0, 56—224	Tall fescue Birdsfoot trefoil	GR PA SA	53
	KY	NI	0, 100—345 kg/ 36 m² plot	European alder Black locust Cottonwood Loblolly pine Northern red oak	GR PA SA	54
	KY	Dig.—D	0, 34—269	Corn Soybeans	GR PA SA	55

Table 6 (continued)
RECENT LAND RECLAMATION PROJECTS WITH MUNICIPAL SLUDGES

Type of disturbed land	State	Sludge: Type[a]	Sludge: Application rates (dry mt/ha)	Plant/animal studied	Parameters tested[b]	Ref.
Iron ore tailings	WI	Dig.—D	42, 85	5 native prairie grasses	GR	56
				4 prairie forbes		
				Foxtail		
Taconite tailings	WI	Dig.—D	28, 115	4 grass-legume mixtures	GR	57
Abandoned Pyrite mine	VA	Dig.—D	82—260	Tall fescue	GR	58
				Lespedeza	PA	
				Weeping lovegrass	SA	
				Wheat, rye, oats	WA	
Gravel spoils	MD	C	0, 40—160	Corn	GR	59
				Beans	PA	
					WA	
Copper mine	TN	Dig.—D	0—275	Pine species	GR	60
Borrow pit	GA			Sweetgum		
Kaolin spoil						
Marginal land						
Zn smelter surroundings	OK	Dig.—L + effluent	2.5—34 cm	10 grass species	GR	61
				1 legume	PA	
					SA	
Strip mine spoil	IL	Dig.—L	NI	NI	PO	62
	IL	Dig.—L	NI	NI	SO	63
	IL	Dig.—L	25—128/year	Corn	AH	64
				Pheasant, swine		

IL	Dig.—L	NI	Cattle	AH PO SA PA	65
IL	Dig.—L	0—997	Blackbirds	AH	66

[a] Dig., digested; L, liquid; D, dewatered; C, composted; NI, no information.

[b] GR, growth responses; PA, plant tissue analysis; SA, soil analysis; WA, water analysis; PO, pathogenic organisms; AH, animal health; SO, soil organisms.

irrigation at 2.5 and 5 cm/week, totaling 59 to 147 cm, detoxified the highly acidic materials and resulted in vegetative cover establishment. The most successful species were weeping lovegrass, ladino clover, Iroquois alfalfa, sericea lespedeza, and red clover. Subsequently, Sopper and Kerr[31] grew a lush cover of tall fescue, orchardgrass, birdsfoot trefoil, and crownvetch on several 4-ha demonstration sites in Pennsylvania amended with several different types of municipal sludge applied at rates ranging from 7 to 202 mt/ha. The rationale for the mixture is that the grasses provide quick cover, while the legumes eventually take over to provide the permanent cover. Following the demonstration, over 1000 ha was successfully reclaimed using composted Philadelphia sludge, with phenomenal annual increases in dry matter production, surpassing the Pennsylvania strip mine revegetation requirements.

Yields of tall fescue on sludge-amended mine spoil in West Virgina were over 11,000 kg/ha, an 818% increase over controls. Both Mathias et al.[51] and Hinesly[25] observed some yield decreases over three growing seasons when sludge was applied only once and the crop was harvested annually with no additional amendments. If the vegetation is not harvested, however, the recycling of nutrients and buildup of organic matter can result in annual yield increases.[45] The slow-release fertilizing action of sludge provides a "residual effect" for forage species. On anthracite refuse, dry matter production was greatest the first growing season with 40 to 75 mt/ha applications of sludge, but by the third growing season the 150 mt/ha sludge treatment, with its added residual effect, gave the best herbaceous cover.[44] Composted Washington, D.C. sludge at 112 mt/ha produced forage cover in accordance with Maryland strip mine laws, i.e., 80% cover and 10% legume species after 2 years. Rates lower than 112 mt/ha were not as effective, but rates greater than 112 mt/ha resulted in superior performance.[53] In Virginia, the same sludge grew a very successful tall fescue and weeping lovegrass cover on two abandoned pyrite mines,[58] but a less than adequate cover on another site[47] due to low pH and drought conditions. The same author, however, observed threefold yield increases over plots amended with a standard inorganic fertilizer when Pennsylvania coal spoils were amended with Williamsport sludge at 730 mt/ha.

In Virginia, 159 and 412 mt/ha of composted sludge without limestone amendments put a good cover of tall fescue and perennial and annual ryegrass on the strip mine spoil, along with volunteer native species. By the fourth growing season results were excellent, while those on plots amended with inorganic fertilizer were poor. In another study, tall fescue, annual rye-grass, and sericea lespedeza produced a significantly denser cover with sludge than with inorganic fertilizer. Again, volunteer species were more abundant on the sludge plots. At 58 mt/ha, the sludge was more effective than at 31 mt/ha, which points out the need to supply sufficient plant nutrients.[48]

Two studies on iron ore tailings revegetation in Wisconsin found sludge far superior to inorganic fertilizers. Some of the successful species included sideoats grama grass, Canada wild rye, foxtail grass,[56] smooth brome grass, alsike clover, and alfalfa.[57] Soil contaminated in the vicinity of a zinc smelter in Oklahoma was successfully revegetated with sludge reinforced with urea-N, while inorganic fertilizer was ineffective. Switch-grass and kleingrass showed excellent response over three growing seasons.[61]

Nurse crops including wheat, rye, oats,[58] and barley[57] have been shown to significantly promote vegetative cover.

In general, studies show that good plant cover can be established on many types of disturbed land using municipal sludge, which is superior to inorganic fertilizer in such situations. Of course, plant performance varies considerably with species, and an appropriate seed mixture should be carefully chosen. Planting date is also crucial. On the Palzo site, winter rye seeded 1 month late resulted in a significant decrease in forage yield measured the following spring.[23] Table 7 lists some successful plant species used in various sludge-reclamation projects. Differences in soil, climate, etc. also dictate mixtures chosen for

Table 7
SOME SUCCESSFUL PLANT SPECIES AND SPECIES MIXTURES USED IN VARIOUS SLUDGE RECLAMATION PROJECTS

State	Species	Seeding rate (kg/ha)	Ref.
VA	Tall fescue[a]	8.4	48
	Perennial ryegrass[a]	8.4	
	Annual ryegrass[a]	8.4	
	Tall fescue[b]	22	
	Perennial rye[b]	22	
	Sericea lespedeza[b]	22	
	Black locust[b]	0.84	
IL	Tall fescue	25	25
	Perennial ryegrass	25	
	Western wheatgrass	25	
OH	Tall fescue	Unknown	52
PA	Weeping lovegrass	Unknown	43
	Ladino clover		
	Iroquois alfalfa		
	Sericea lespedeza		
	Penscott red clover		
	Tall fescue[a]	22	31
	Orchardgrass[a]	22	
	Birdsfoot trefoil[a]	11	
	Crownvetch[a]	11	
	Reed canary grass	224	44
	Tall fescue		
	Orchardgrass		
	Birdsfoot trefoil		
	Crownvetch		
WV	Tall fescue	Unknown	51
MD	Tall fescue	40	53
	Birdsfoot trefoil	10	
VA	Tall fescue	67.3	58
	Weeping lovegrass	22	
	Korean lespedeza	11.2	
WI	Sideoats grama	Unknown	56
	Canada wild rye		
	Foxtail grass		
OH	Fall Balbo rye	9.6(bu/ha)	40
	Spring K-31 tall fescue[a]	11	
	Korean lespedeza[a]	3.4	
	Sweet clover[a]	3.5	
	Orchard grass[a]	3.3	
IL	K-31 tall fescue	22	37
	Weeping lovegrass	7.8	
WI	Canada bluegrass[a]	11	57
	Red clover[a]	9.7	
	Smooth brome[b]	15.2	
	Alfalfa[b]	11	
	Western wheatgrass[c]	9.7	
	Alsike clover[c]	11	
	Barley[d]	16.5	
	Japanese millet (added to above mixtures)[d]	8.6	

Table 7 (continued)
SOME SUCCESSFUL PLANT SPECIES AND SPECIES MIXTURES USED IN VARIOUS SLUDGE RECLAMATION PROJECTS

State	Species	Seeding rate (kg/ha)	Ref.
OK	Switchgrass	154	61
	Kleingrass		
VA	K-31 tall fescue	67	47
PA	Red top	5.6	
	Ladino clover	5.6	
	Same as above plus Korean lespedeza and weeping lovegrass	Unknown	
IL	Tall fescue	22	39
	Weeping lovegrass	8	
	Common bermudagrass[a]	11	23
	Sericea lespedeza[a]	28	
	Kobe lespedexa[a]	11	
	Perennial ryegrass[a]	22	
	Potomac orchardgrass[b]	17	
	Sericea lespedeza[b]	22	
	Kobe lespedexa[b]	11	
	Potomac orchardgrass[c]	22	
	Penngift crownvetch[c]	17	

Note: Species with same superscript letter represent a seeding mixture.

revegetation. For example, tall fescue is an excellent choice on highly acidic strip mine spoil in Pennsylvania,[31] but that species failed completely on sludge-amended soils contaminated by a nearby zinc smelter in Oklahoma.[61] There, kleingrass and switchgrass were most successful.

B. Field Crops

Several studies have looked at yields of corn, beans, and even blueberries grown on sludge-amended disturbed land. On sand and gravel spoils of low pH and a heterogeneous profile, sweet corn, field corn, and bush bean biomass were significantly increased by applications of Washington, D.C. sludge. In general, bean yields were increased by 40 to 80 mt/ha sludge applications, but corn ear yields were not.[59] In Illinois, the yields of corn, soybeans, small grains, and forages over 2 to 7 years were highly variable where Chicago sludge at rates up to 453 mt/ha were applied to strip mine soils. Yields ranged from poor to excellent, with moisture stress and nutrient availability being the controlling factors.[27] Yield fluctuations in corn were not related to heavy metal concentrations in the plants.[64] In another study, an increase in corn production of 2666 kg/ha was observed when Chicago sludge was applied to strip mine soils at 56 mt/ha.[41] Spoil pH appeared to be the major factor governing yield of corn and soybeans on mine sites in Kentucky amended with 15 to 120 mt/ha of sludge. Some varieties of soybeans yielded twice that of others; corn varietal differences were not as dramatic.[55]

In a greenhouse study, Tunison et al.[50] grew high bush blueberries using a low-metal sludge from Waynesburg, Pa. composted with bark. Without composting, the plants were severely chlorotic and mortality was high, but composting resulted in healthier plants and increased berry production.

C. Trees

While ground cover is the crucial element in initial site stabilization, the potential of woody species for use in sludge management schemes is great, due to their relatively small input into the human food chain, and their ability to differentially accumulate metals in specific plant organs.[54] In general, establishment of woody vegetation is enhanced by sludge. At the Palzo tract in Illinois[35] where 12 tree species were planted, survival rate was 53% with sludge compared to 19% on the untreated area. On Illinois strip mines and Pennsylvania anthracite refuse, hardwood survival was greater when trees were planted along with herbaceous vegetation but conifers did better without herbaceous cover.[34,43] Ground cover competition with conifers usually occurs when the cover species are planted along with the trees, but Berry[60] found no weed competition problems with conifer establishment when sludge was applied at 34 mt/ha on barren land in the southeast. It was recommended that grass planting be delayed until seedlings are established. Virginia pine was successfully established at a seeding rate of 1.4 kg/ha where there was no herbaceous cover,[48] and the height of the trees was increased with increasing applications of composted sludge. The pines grown on spoils amended with ammonium nitrate fertilizer were markedly chlorotic, while those grown in composted sludge-amended spoils were green.[48]

Of ten tree species planted in sludge-amended spoils in Pennsylvania, hybrid poplar, black locust, and European alder gave the best results for survival and growth.[43] After 5 years of growth, the potential woody biomass produced was directly related to the amount of sludge applied, and was 10 times greater than trees not grown with sludge.[44] Hinkle[58] noted a significant establishment of volunteer hybrid poplar on sludged pyrite mine refuse in Virginia, after the unsuccessful planting of loblolly pine during a period of drought.

Seedlings of four hardwood species and one pine, usually good performers on reclaimed sites, were grown in spoils amended with a high and a low metal sludge (Cd 710 vs. 7 ppm; Zn 8010 vs. 1075 ppm). Growth, vigor, and survival the first year were highest with the high metal sludge, probably due to the higher amounts of organic matter and soil conditioning, since that sludge was put on at a higher rate. The species performance was in the order: European alder > black locust > red oak > cottonwood > loblolly pine.[54]

D. Plant Analysis

1. Macronutrients

Increases in the major plant nutrients, N, P, K, Ca, and Mg, are usually observed for crops grown in sludge-amended spoils,[25,53,32] but the effects are not always consistent. For example, Mathias[51] found that foliar P was always increased, K was decreased, and N was not much different in plants grown on sludged spoils compared to nonsludged controls. Sludges are often deficient in K. Even 224 mt/ha of sludge did not increase foliar K concentrations, but there was sufficient native K for plant growth in acidic Maryland spoils.[53] In Pennsylvania, where native feldspars and micas provide K, mine spoils have been successfully revegetated with municipal sludge without additional K, and no deficiency symptoms or yield reductions of forages have been observed in five growing seasons.[32]

Nitrogen levels in sweetcorn grain grown on sludge-amended sand and gravel spoils were significantly greater than fertilizer controls,[59] but sludge did not affect P, K, Ca, or Mg concentrations. Whole corn and soybean plants grown with sludge on acid spoils had higher levels of N, P, K, and Ca than controls.[55] If treatment differences are small (2.5 vs. 5.0 cm sludge), there may be no difference in forage growth response or in concentrations of N and P in the leaves. Differences in sludge type and treatment affect the availability of nutrients to plants. For example, where composted sludge is used, total soil N remains high over a long period of time due to its organic nature and slow mineralization over time, 10 to 20% the first year,[53,42] while N applied in liquid sludges is more readily available (up to 40% the first year).

Rock phosphate additions increased yields of fescue and birdsfoot trefoil on Maryland spoils in conjunction with one-time sludge applications,[53] but after repeated annual applications of sludge in Fulton Co., Illinois, a buildup of P in the soil to 15 times the optimum level reduced soybean yields.[64] Limestone incorporation along with sludge may increase concentrations of foliar Ca.[51] In most cases, the macronutrient concentrations of forages and other crops grown on sludge-amended spoils are within the range of concentrations in forages grown with inorganic fertilizers on agricultural soils.

2. Trace Metals

It is generally agreed that municipal sludge improves the capacity of spoil material to support vegetation, but questions often arise about the uptake of trace metals from sludges by forages, corn, trees, and other plants, which may be involved in food-chain dynamics.

a. Cover Species

Several studies indicate that a decrease in trace metal concentrations of sludge-grown vegetation over time may occur where a single application of sludge is used. Metal concentrations in tall fescue from Ohio mine spoils amended with up to 716 mt/ha of sludge were considerably lower the third growing season than the first.[52] On anthracite refuse in Pennsylvania, an initial increase in Cu, Zn, and Cd in reed canarygrass tissues occurred the first growing season after sludge was applied, but by the second and third years, with few exceptions, metal concentrations decreased to control levels or below.[44] As part of an extensive demonstration program in Pennsylvania, tall fescue and birdsfoot trefoil from two sludge-amended bituminous coal sites were analyzed for 7 trace metals over 2- to 3-year periods.[31] Results show a definite decrease in heavy metal concentrations over time. With few exceptions, Cu, Zn, Cr, Pb, Co, Cd, and Ni remained well below suggested tolerance levels for agronomic crops.[68,69] Seaker and Sopper[32] found the same trend occurring on 5 sites monitored for periods of 2 to 5 years. Other studies show no decline in metal concentrations, but these are often cases where sludge was applied annually for a number of years. In Illinois, metals in forage did not appreciably change even after 4 successive years of Chicago sludge applications, although values were higher than on control plots.[33] Hinesly et al.,[25] believe Cu and Zn may become less available with time because plant uptake decreased after sludge applications were terminated.

Several reasons may account for decreasing metal concentrations over time. Iron and phosphorus added in sludge may complex with metals, forming sparingly soluble precipitates.[70] Metals may bind with the humic fraction of sludge in the spoil-sludge mixture.[52] Although composted sludge additions increased Cu and Ni in forages after 2 years growth on an abandoned strip mine, the foliar concentrations decreased as compost application increased from 56 to 224 mt/ha, due to increased pH. The addition of rock phosphate or limestone along with sludge decreased uptake of Ni, Cu, Zn, and Cd.[53] In another study, increasing sludge rate from 314 to 627 mt/ha resulted in a decrease of Mn, Zn, Ni, and Cd in tall fescue and alfalfa over 2 years. Cd and Zn reductions may be attributed to increased pH, and Mn and Ni reductions to the additional organic matter supplied. Another important factor involved in metal concentrations in plant tissues is the possible ''dilution'' effect that occurs as a result of increased biomass production where sludges are used.[44] Sampling date determines in part the concentrations of metals in plants, and seasonal differences may be greater than treatment differences. For example, in one study Pb concentrations of tall fescue were four times higher in January than they were the previous October.[51] Forages collected in the fall had Mn and Al concentrations high enough to be considered potentially toxic, but the following June the levels were safe for animal rations.[40] This emphasizes the importance of sampling plant material at a predetermined growth stage or time of year. Part of the plant analyzed also influences metal concentration values. For example, significant differences in metal concentrations existed between grain and stover of winter rye for Cu, Pb, Zn, Mn, and Cd, but not for Ni and Cr.[23] There are often differences in metal concentrations of different species grown under the same sludge regime, but this is not always the case. Stucky and Bauer[23] observed little difference in Cu, Zn, Ni, Cd, Cr, Mn, or Pb among switchgrass, orchardgrass, and tall fescue, and Seaker and Sopper[32] found no consistent differences in concentrations of the same elements in tall fescue, orchardgrass, and birdsfoot trefoil. McBride et al.,[71] on the other hand, reported definite differences in Cd uptake between rye, Sudan grass, tall fescue, and reed canary grass.

In general, sludge-grown vegetation usually contains higher concentrations of metals like Cu, Zn, Cr, Pb, Cd, and Ni than plants grown without sludge. The heavy metal increases are of varying degrees, however, and in most cases are not great enough to be a threat to human or animal health. Control of sludge application rate and diagnostic soil testing and plant analysis are management tools used to monitor the metal distribution in the environment.

Within three growing seasons on sludge-amended spoils in Pennsylvania,[32] concentrations of six metals in forages were continually below the suggested tolerance levels for agronomic crops.[68,69] Annual mean concentrations from 5 sites over 2 to 5 years showed Cu and Zn concentrations in the forage below the required concentrations for total dairy rations. In other studies, Mn and Al accumulated to potentially harmful levels in forages the first year after sludge, but decreased to safe levels at the start of the second growing season.[61] Cadmium concentrations in tall fescue grown with 224 mt/ha sludge reached 2.3 ppm vs. 0.5 ppm suggested-safe food level.[73,51] On two sites near zinc smelter operations in Oklahoma, Cu concentrations of sludge-grown grasses were consistently below suggested tolerance levels, but Cd concentrations were usually in the potentially yield-reducing range. The major source of metals, however, may not have been the sludge.[61] In most cases, plant toxicity symptoms do not appear and metals are below suggested tolerance levels.[32,36,58,48]

b. Trees

Only a limited number of studies have been done with metal uptake by trees. Trees are beneficial for sludge-amended sites because they are not a significant food source, and due to their large biomass, tend to retain heavy metals on the site through biotic storage in plant parts not grazed by herbivores, thus limiting their entry into food chains.[35,72] Two studies looked at accumulation of metals by component tree parts. Patterns of accumulation by roots, stems, and leaves varied with the metal and the tree species. Eastern white pine, silver maple, and green ash, e.g., tended to accumulate Cu, Zn, and Cd in their roots as opposed to foliage and stems.[24] Roots and leaves were higher accumulators than stems.[35,72] Concentrations of metals were increased in trees grown with sludge[24] in one study. In a study using a high metal sludge, metals were sometimes lower in the leaves of sludge-grown trees than in the fertilizer controls, except Cd in hardwoods which was consistently higher when sludge was used.[54] Roth et al.[35] observed lower metal concentrations the third growing season after sludge application compared to the first, but still some third-year concentrations exceeded those considered to be toxic. For example, the maximum Cd concentration of combined tree parts was 950 ppm. The ability of the tree to tolerate such high metal levels may be due to a tie-up of metal ions in plant tissues in forms not readily moveable throughout the plant. Sludge-borne metals in the soil may inhibit soil microbial activity, resulting in slower breakdown of organic matter, accumulation of metals in the litter layer, and a decline in the recycling of metals back into trees.[35]

c. Field Crops

Although field crops are not often grown on reclaimed sites, some studies have been made to assess metal uptake in such cases where sludge is used as an amendment. Hundreds of hectares in Fulton Co., Illinois, that were once strip mined for coal, were returned to corn production after the soil was reconditioned with sludge from Chicago, resulting in Cd loadings as high as 135 kg/ha on some fields. Cd concentrations were increased in corn grain, with maximum values in 1979 of 0.46 ppm in controls and 0.81 ppm in treated corn. Such crops are used only for animal feed.[26,27] In a similar study[25] with high sludge loading rates, Zn, Cd, and Ni were increased in corn grain and leaves, but Cu, Cr, and Pb were not. Plant-soil concentration ratios indicated that metals were less readily available from the sludge than from the original spoil material. Even though the grain accumulated more Cd and Zn than controls, there was no increase in concentration of these elements over seven growing seasons due to repeated annual applications.[64] On sludge-amended spoils in Kentucky, Ni, Cr, Cu, Cd, Mn, and Fe concentrations were not significantly increased in corn and soybean plants at 112 or 269 mt/ha sludge rates,[55] nor did Cu and Zn in corn and bush beans increase as sludge rates increased on sand and gravel spoils;[59] Cu and Zn values were similar to controls, but Cd increased with sludge rate. All values for corn grain were well below suggested tolerance levels (Cd 0.27 vs. 3.0 ppm; Zn 32 vs. 300 ppm; Cu 4.5 vs. 150 ppm),[59] and corn was considered a better metal excluder than soybeans.[55] In another study, corn grown on spoils amended with 56 mt/ha of sludge showed no increased accumulation of Hg or Pb in the grain, and the protein content was increased over the control corn. Controls had higher Zn concentrations in the grain than the treated corn. Most of the metals are concentrated in the germ fraction rather than the endosperm, and the corn products produced were found to add only minor quantities of Cd, Pb, and Hg to the human diet.[41]

Few attempts have been made to produce horticultural crops on spoils, but Tunison et al.[50] grew highbush blueberries on spoils amended with sludge containing 1250 ppm Zn. High Zn levels and low Mg foliar levels resulted in severe chlorosis, but when the sludge was composted with bark, the symptoms were alleviated. The berries showed no significant accumulation of Cd, Cr, Cu, Ni, Pb, or Zn and these elements were within limits considered safe for human consumption.[74]

Table 8 lists some effects of sludge applications on the levels of trace metals in plant tissue found in various studies.

V. EFFECTS ON SOIL

A. Physical Properties

The high organic matter of sludge improves the physical condition of barren spoils tremendously. Parameters that benefit from sludge incorporation include water-holding capacity, bulk density, and surface temperatures. Organic-C content, water-stable aggregates, and water-holding capacity were increased with increasing sludge rates from 0 to 896 mt/ha, which resulted in increased corn yields during growing seasons when rainfall was sparse.[25] Composted sludge additions of 160 mt/ha doubled the moisture percentage in sand and gravel spoils,[59] and increased water retention of coal refuse[38] and mine spoils.[54] Increased volumes of percolate water were reported on the Palzo mine site in Illinois after liquid sludge was disked 15 cm into spoils.[21] On Ohio strip mine spoils,[52] however, the opposite effect occurred due to the rapid uptake and transpiration of soil water by increased plant biomass. In fact, the volume of percolate water was indirectly proportional to sludge loading rate. Because sludge is about 50% organic matter (dry weight basis), it can improve water infiltration and retention.[53] Younos and Smolen[49] found that the rate of water infiltration, accumulative infiltration, and hydraulic conductivity was increased in mine spoil by addition of anaerobically digested sewage sludge in amounts representing 1 or 5% of the weight of the soil-sludge mixture.

Sludge additions have resulted in decreased bulk density in Illinois mine spoils high in compacted clay[26,27] and coal refuse;[38] in decreased temperatures on sand and gravel spoils;[59] and reduced runoff, erosion, and sedimentation from coal mine spoils.[40] Soil physical condition is usually related to sludge application rate.[54]

Table 8
ELEMENTAL CONCENTRATIONS IN PLANTS IN RELATION TO SUGGESTED TOLERANCE LEVELS FOR AGRONIOMIC CROPS[a]

		Tolerance level in agronomic crops[68,69]			
Years	Species	Below	Above	Variable	Ref.
3	Tall fescue	Cd, Cu, Ni	Zn		52
	Tall fescue Orchardgrass Birdsfoot trefoil	Al, Zn, Cu, Co, Pb, Ni, Cd		Cr	32
	Reed canary grass	Cu, Zn, Cd	Ni		44
4	Forages	Cu, Ni, Zn	Cd, Cr	Pb	33
—[b]	Corn leaf	Ni, Zn, Cu, Cr, Pb		Cd	25
—	Tall fescue Birdsfoot Trefoil	Cu, Ni, Zn, Cd			53
	Tall fescue Switchgrass Orchardgrass	Cu, Ni, Pb	Zn, Cr	Cd	23
	Tall fescue	Cu, Zn, Cd, Ni		Pb, Cr	51
3	Korean lespedeza Tall fescue Weeping lovegrass	Cu, Cr, Cd, Ni, Pb, Zn			58
2	Bermudagrass Switchgrass Kleingrass Bluestem	Cu	Zn, Cd		61
	Alfalfa Tall fescue	Ni, Cd, Zn, Cu, Pb, Cr			36
—	Corn grain	Cd, Zn, Cu			59
	Blueberries	Zn, Cu, Cr, Ni, Pb, Cd			50
	Corn plant Soybean plant	Ni, Cu, Cd, Mn	Cr		53
	Hardwood leaves Pine needle	Cu, Zn, Ni	Cd		54

[a] See Table 13 for tolerance level values.
[b] Length of study uncertain.

B. Chemical Properties

When sludges are applied to land an increase in soluble salt content of the growing media may result. At a sludge application rate of 896 mt/ha and an electrical conductivity (EC) of 6.6 mmho/cm, a 50% reduction in corn yield resulted compared to the 224 mt/ha rate. High soluble salts may also affect the establishment of some grass species.[25] On another site, however, EC was significantly reduced after sludge incorporation in very stony spoil that was high in Fe, Al, and Mn.[54] After sludge incorporation into coal refuse,[38] EC at the 0- to 30-cm depth was decreased. Haynes and Klimstra[75] reported EC greater than 1.5 mmho/cm may be damaging to crops, and most of the sludge treatments were below this level. In another study, EC of sludge-amended spoils ranged from 0.68 to 2.80 mmho/cm, but vegetative cover was not as affected by EC as it was by pH.[23] Potential soluble salt problems can usually be avoided by proper management techniques. Maximum effective loading rates should be based on the constituents in the sludge and the crop that is to be grown.[25]

Limed sludges have a neutral to alkaline pH and can raise the pH of acid spoils.[53] The pH of coal refuse gob was increased from 2.6 to 5.3 even without limestone when sludge was incroporated at rates of 450 to 900 mt/ha. Sludge was more effective than 180 mt/ha limestone at raising pH.[38] Sludge applied at 67 to 269 mt/ha with lime increased pH considerably, but 34 mt/ha sludge, with lime, had no effect.[55] Even after 195 mt/ha of lime plus commercial fertilizer was applied to spoils in Ohio with pH 2.3, rye cover was considerably poorer than adjacent plots amended with sludge only.[40] When anthracite refuse was irrigated with liquid-digested sludge and sewage effluent, significant increases in pH to a 76-cm depth occurred.[43] After 6 consecutive lime and sludge applications in 4 years, pyrite mine spoils increased in pH from 2.4 to 3.6 to 5.0, and after the 7th application to 6.1 to 6.6.[58]

Limestone initially increases the pH of acid spoils, but the pH eventually declines as sulfur-bearing minerals are oxidized.[40] When commercial fertilizer plus lime was applied on Virginia acid mine spoils, pH remained below 4.0 for 4 years, but where municipal compost (pH 8.5) was added once without any lime, pH ranged from 4.9 to 7.4 through the 4-year period.[48] Sludge applications of 314 and 627 mt/ha increased the pH of strip mine spoil from 3.5 to 5.2-6.7 in the top 10 cm 2 months after application, and the higher pH was maintained for 2 years.[36] Where sludge and lime were applied on Pennsylvania strip-mined sites, pH was increased above 6.0 and maintained for up to 5 years without any additional amendments,[31] with good grass and legume cover. Sludge alone significantly raised the pH of spoils in West Virginia, and sludge plus lime was even more effective. Initial pH values of 3.0 to 4.0 were increased above 5.0 and usually above 6.0, with no decline after 3 years.[51] On Ohio strip mine spoil where two sludges were applied each at two rates, the pH did not decline over a 3-year period.[52] When Chicago sludge was applied annually to strip mines over a 6-year period, the pH decreased slightly the first 3 years, due mainly to nitrification and organic acid production in the soil. The decrease was minimal, however, and the pH appeared to stabilize during the next 3 years.[27] Hinesly et al.,[25] however, observed a drop in pH from 7.5 to 6.0 in calcareous spoil amended with 896 mt/ha of Chicago sludge. In a zinc smelting area, lime and sludge raised soil pH, and an increase from 5.8 to 6.5 occurred within 2 years of the application.[61] Soil pH is a critical factor for plant growth and complete mixing of the lime and sludge is essential for uniform vegetative cover.[40] Fibrous root systems, such as produced by tall fescue, may have a stabilizing effect on pH, according to Stucky and Newman.[36]

Some trials have attempted to assess the effect of deep incorporation of sludge on plant establishment and growth, but results are vague. Incorporation of sludge to 60 cm did not result in better vegetative cover the first year compared to 30-cm incorporation.[38] In another study, incorporation from a 15- to a 40-cm depth increased pH at the deeper level, and deeper root penetration plus better root quality appeared to be the result.[55] Root systems are often confined to nontoxic or treated layers when sludge is incorporated into spoils.[40] but are usually much more prolific and deeper than when inorganic fertilizer is used.[48]

Cation exchange capacity is normally improved by sludge addition to spoils due to the high CEC of organic matter.[22,36,54] Cation exchange capacity is an important factor in determining the availabilty of cations added to soil as constituents of soluble salts, but may not significantly affect the uptake of essential and nonessential trace elements by plants when they are added to soils as constituents of digested sewage sludge. Where Cd was added to soils as a constituent of digested sludge, differences in soil CEC did not affect uptake of the metal by soybeans[76] and corn.[77]

Effects of sludge incorporation on the amount and availability of major plant nutrients vary. In general, sludges supply considerable N and P, but little K. The Ca, Mg, and S contribution varies with the composion of the sludge. Peterson et al.[27] used soil N, P, and K as an index of soil rejuvenation by sludge, and found that over a 4-year period repeated application of Chicago sludge increased available N, P, and K each year on both agricultural soils and mine spoil. Significant increases in Kjeldahl-N and Bray-P occurred in spoils where sludge was applied in Pennsylvania. Total-N in control spoils was 0.01 to 0.07 vs. 0.21 to 0.32% in treated spoils. Phosphorus concentration was 122 to 266 ppm in controls vs. 391 to 472 ppm in treated spoils.[44] On abandoned pyrite mines, commercial fertilizer and sludge applied together increased spoil phosphate and K_2O, but K availability was much greater where good vegetative cover existed than where the site was bare, indicating the importance of plants in the uptake and recycling of nutrients.[58] Sludge additions increased spoil P, Ca, and Mg, but not K in West Virginia.[51] Spoil K decreased after 3 years, probably due to removal by vegetation. At the Palzo mine site, only K remained deficient after sludge application.[22] Total and extractable N and P were increased by four different sludge application rates in Kentucky spoils, but there was no change in K content.[54] Sutton and Vimmerstedt,[40] however, observed a 3-fold increase in available K and an 18-fold increase in available P from sludge. In another study, extractable P was greater in sludge-amended spoils than in controls, but an increase in sludge loading from 112 to 224 mt/ha did not further increase P. It is possible that the increased Ca at the higher rate neutralized some of the acid in the P extractant, since both Ca and Mg were markedly increased by sludge additions.[51]

Interpretation of reports on metal loadings to disturbed land after sludge is applied is difficult due mainly to the inconsistency in analytical methods used to determine metal concentrations. Values for extractable vs. total metals are quite different, as are those for HCl- vs. DTPA-extractable metals. Roth et al.[35] found that Cd, Cu, Mn, and Ni concentrations were significantly different when 4 extractants were compared: DTPA (pH 7.3; pH 4.9) and 0.1 *N* HCl (pH 1.3; pH 4.9). No extraction method has yet been found that adequately indicates the amount of metals that is available to plants. Plant uptake may be much less than indicated by DTPA extraction.[53] Factors such as pH, organic matter content, metal concentration of the sludge, phosphorus and iron concentrations, and CEC all contribute to plant availability of trace metals, and further complicate the matter. For any one study, however, comparison of spoil metal concentrations before and after sludge additions, based upon a single known method of analysis, can be made.

Sludge addition usually results in increases in spoil heavy metal content, but which metals increase depends on the particular sludge, and in many cases, the increases are not significant. Sludge organic matter and pH effects often cause a decrease in availability of Fe, Al, and Mn which are already found at extremely high concentrations in most acidic spoil materials. On anthracite refuse, liquid sludge irrigation greatly increased phosphorus, which tended to tie up and detoxify Fe, Al, and Mn in the upper root zone.[43] In Pennsylvania bituminous spoil and anthracite refuse, sludge incorporation of 75 to 184 mt/ha reduced extractable Fe, Al, and Mn in the plow depth, but increased Cu, Zn, Cr, Pb, Cd, and Ni. The increases were minimal, however, and sludge did not affect concentrations below the 15-cm depth.[31,44] Cadmium and Cu, but not Ni and Zn, exceeded the normal soil ranges[78] on sludge-amended spoils on the Palzo site.[35]

In Fulton County, Ill., Peterson et al.[27] reported that Chicago sludge, considerably high in metals, increased soil Cd, Zn, Ni, and Cu. When applied annually, however, only Cd exceeded the values for normal ranges in agricultural soils reported by Allaway.[78] Another study[33] with the same sludge found large increases in Cd, Zn, Ni, Cu, Cr, Pb, and Hg in soils compared to controls. Cu, Zn, and Cd were at times above reported normal ranges. However, except for Zn and Pb, the concentrations did not appreciably increase over the 4 years of annual application. Unamended gob material may be high in Mn and Cr,[38] and sludge additions to gob were found to cause large increases in Cr, Mn, Cu, Zn, Cd, and Pb based on maximum soil concentrations reported by Yopp et al.[79] However, there were no apparent effects on grass establishment and growth. Extractable Cu, Ni, Zn,and Cd increased as compost rates increased in Maryland mine spoils.[53] Phosphate rock, which can contain significant trace metals, raised the values even higher, but limestone additions decreased them. Zinc, Cu, Pb, and Ni may increase in availability and potential toxicity as pH decreases.[68]

In some instances, the availability of metals in spoil was not increased by sludge additions, due to the metal composition of the sludge and increases in pH and organic matter. For example, in soils contaminated by zinc smelting, Zn, Cu, and Cd levels were extremely high and sludge addition improved plant cover without significantly adding to the metal load.[61] On abandoned pyrite mines, a dramatic drop in metal concentrations occurred as reclamation progressed, probably due to increases in spoil pH.[58] Concentrations of Cu, Fe, Mn, and Zn were within normal soil ranges reported by Allaway.[77] Hinesly et al.[25] observed no increase in As, Mo, or Mn in sludge-amended spoils, due to low concentrations of these elements in the sludge.

C. Biological Characteristics

Several studies have been made on the changes in soil microorganism populations after a tract of barren, devastated land has been conventionally reclaimed, but very little information is available on soil biotic changes resulting from addition of municipal sludge to such land. A study on the Palzo tract in southern Illinois[63] found fungal populations in unreclaimed spoil to be only 1 to 2% of those in unmined agricultural soils. Application of sludge, and particularly incorporation, resulted in a tenfold increase in fungal activity, due to the increase in pH and food supply, and better soil moisture retention. Some fungi are introduced with the sludge, but with improved chemical and physical condition of the spoil and a vegetative cover that recycles organic matter and nutrients, natural successional changes and eventual stabilization of the fungal populations should occur.

VI. EFFECTS ON WATER QUALITY

Much concern has been voiced over the effects of high rates of sludge application on the quality of groundwater and nearby streams, ponds, and reservoirs. The state of Pennsylvania, e.g., prohibits the use of sludge for land reclamation directly on a watershed area that supplies drinking water to a community. However, that is not to say that sludge application results in the deterioration of waters; in fact, the opposite is usually true. Stabilization of drastically disturbed lands with municipal sludge most often improves the quality of the surrounding area by the ameliorating effect it has on the ecosystem as a whole. Reports on the effects of sludge application on the concentrations of NO_3-N, trace metals, and indicator organisms in soil percolate water, groundwater, nearby streams and reservoirs, and surface runoff indicate that a properly managed land application program will not cause deterioration of water quality on or near the site.

A. Soil Water and Groundwater

1. Trace Metals

On anthracite refuse and bituminous strip mine spoils, leachate collected (107 cm) below a grass, legume, and tree seedling cover was lower in Fe, Al, and Mn where liquid sludge and sewage effluent were applied biweekly than in control spoils.[43] Satisfactory renovation of the major constituents of sludge through acidic strip mine spoil has been reported by McCormick and Borden.[46] The pH of the percolate water was related to sludge rate and application method. Initially high sulfur levels resulting from the sludge decreased to below those of control areas. In Ohio strip mine spoils amended with sludge at rates up to 716 mt/ha, leachate Cu, Ni, and Mn were not increased, and even decreased with time. Zn and Al initially increased, but then decreased, while Cd and P were below detection limits.[52] On a burned anthracite refuse bank, sludge applications of 75 to 150 mt/ha did not degrade the quality of percolate water 90 cm below the surface.[44] In fact, Zn and Cd concentrations were lower in the treated plots than in the control. Where sludge applications were monitored for 2 to 5 years on 3 4-ha sites in Pennsylvania, groundwater samples collected monthly showed no evidence of contamination.[80] Cu, Zn, Cr, and Pb were, with very few exceptions, well within safe drinking water standards established by the U.S. Environmental Protection Agency. Lead sometimes exceeded the limit by a minimal amount even on unsludged areas due to Pb-bearing minerals in the bedrock. In an ongoing program, over 400 ha of strip-mined land in Pennsylvania as reclaimed with Philadelphia sludge at 134 mt/ha, and over a 4-year period groundwater quality has met drinking water standards for metals and fecal coliform bacteria.[80-87]

Where liquid digested sludge was applied at the Palzo site, concentrations of Fe, Mn, Al, Zn, Cu, Pb, and SO_4 in subsurface drainage water were reduced.[37] Compared to control sites, the trace metals in the leachate were decreased during the 3 years following sludge incorporation. Plant cover plays an important role in replenishing organic matter as the sludge decomposes. The organic matter along with spoil pH partly control the solubility of metals in the soil water.[21]

2. Nitrate-Nitrogen

There is a potential for nitrate buildup and eventual leaching into groundwater when continual applications of sludge, particularly liquid sludge, are used.[21,43] Various degrees of increases in nitrate-N of percolate water after sludge application have been reported.[21,43,80] Liquid sludge plus sewage effluent irrigation at 2.5 and 5.0 cm/week, totaling 59 and 119 cm on bituminous spoil, and 74 and 147 cm on anthracite refuse, increased nitrate and ammonium in the leachate water, but nitrate-N did not exceed the drinking water limit of 10 mg/ℓ.[43] Nitrates below the drinking water limit were also reported for leachate 90 cm below the surface of a burned anthracite refuse bank amended with sludge at 40 to 150 mt/ha.[44] Some studies show an initial peak in nitrate-N concentration followed by a decrease to acceptable levels. Often peak nitrate-N levels occur in late winter and spring when plants are not utilizing the nitrogen for growth.[52] Under forage cover, nitrate-N increased with increasing rate of sludge and decreased with time; after 8 months, nitrate levels were at or below 10 mg/ℓ and remained there for 2 years.[52] Both Cl and nitrate levels in leachate from sludge-amended sand and gravel spoils were initially increased, but tended to decrease over an 8-week period.[59] The nitrate-N concentrations of groundwater collected from wells at various depths on sludge-amended mine spoils in Pennsylvania were consistently within safe drinking water standards when monitored monthly for periods of up to 6 years.[80] Again, an initial increase in nitrate-N may occur, but once a good vegetative cover is established, the concentrations decrease.

Evidently there is some renovation of soil water through the profile, and eventual dilution in the groundwater system. A good vegetative cover is essential for the uptake and utilization of NO_3-N to reduce downward nitrate movement. Lower sludge loading rates should be used where nitrate leaching may pose a problem.[21]

B. Surface Water

Surface water runoff and a stream adjacent to the Palzo site were monitored following applications of liquid sludge.[21,22] Reduction of surface runoff was directly related to the density of the vegetative cover. Ammonium-N, nitrate-N, and total-N concentrations were decreased in runoff analyzed 2 years after sludge application, compared to runoff from unsludged areas.[21] Iron, SO_4, Al, and Cd concentrations in a nearby stream were drastically increased as a result of strip mining, but reductions in ion concentrations during the course of sludge application revealed no degradation in water quality during that period.[22] The chemical and biological qualities of Contrary Creek, adjacent to an abandoned pyrite mine in Virginia, were not affected within a year after the site was revegetated using municipal sludge. It may take decades before the site stabilization exerts an effect on stream quality, due to runoff from barren areas and the toxic mine sediments already in the stream bed.[58] On the Fulton County project in Illinois, the water quality monitoring program calls for monthly sampling of 33 wells and nearby streams and reservoirs. Although sludge addition increased nitrate-N minimally, mean annual concentrations of nitrate-N, Cd, Zn, Cu, Cr, and Pb were within U.S. Environmental Protection-Agency drinking water limits in the two watershed reservoirs tested during the 2 years after sludge was applied. Fecal coliform counts were not increased by sludge application; in fact, they decreased, probably due to less livestock grazing on the site. The authors[26] concluded that a properly managed digested sludge application site will not adversely affect local surface waters.

Two lakes adjacent to an abandoned bituminous strip mine in Pennsylvania were monitored monthly for 5 years, after the site was reclaimed with liquid and dewatered sludges at rates of up to 184 mt/ha. For the entire 5-year period, nitrate-N, Zn, Cu, Cr, and Cd were below the U.S. Environmental Protection Agency maximum limits for drinking water. Nitrates were slightly increased the first several months after sludge application, but then decreased. Lead was often slightly above drinking water limits due to natural dissolution of Pb-bearing minerals in the underlying rock.[80]

VII. ANIMAL NUTRITION AND HEALTH

The quality of forage should be determined before livestock are grazed on lands reclaimed with municipal sludge, as it would be in the management of a normal farming operation. In a properly managed land application system, forages would be expected to be of good nutritional quality. On 5 4-ha sites in Pennsylvania where mine spoils were revegetated with several types of sludge at rates from 11 to 202 mt/ha, tall fescue, orchardgrass, and birdsfoot trefoil were of excellent quality, due to low trace metal concentrations and protein and fiber contents comparable to forages grown on agricultural land amended with inorganic fertilizers.[32] Sludge amendments on mine spoils in Illinois significantly improved corn grain quality as measured by protein content.[41] Two studies showed some potential problems that may be encountered. Nitrogen:sulfur ratios were low in tall fescue (5:1) grown in West Virginia strip mine spoils amended with up to 224 mt/ha of sludge, compared to recommended ratios of 10:1 to 15:1[51] On soil contaminated by a nearby zinc smelter, forages grown with municipal sludge were not considered suitable for feed due to high nitrates, Zn, and Cd the first two growing seasons.[61]

Plant uptake of metals and sludge deposits on leaves eaten by grazing animals can increase the potential for higher tissue concentrations. Proper use of sludge depends on the impact on soils, plants, and animals exposed to it. According to Fitzgerald,[33] animals exposed to excess heavy metals show toxic reactions rather quickly. In a study involving the Fulton County, Ill., project, the concentrations of seven trace metals in tissues from animals grazing sludge-grown forage were not significantly different from the controls, except for increased Cd, Pb, Cu, and Zn in the liver and Cd in the kidney. Lead levels in blood were increased fourfold. Diaphragm, heart, brain, bone, and milk showed no effect of sludge, nor was there any effect on reproductive rate or any evidence of disease. Growth of experimental cows was above average. In a similar study, pigs feeding in sludge-amended pens did not accumulate any more trace metals in diaphragm, heart, or bone than did control animals, but Cd was increased in liver and kidney tissue.

Another study with Chicago sludge assessed metal accumulations in various organs of pheasants and swine which were fed for 100 and 56 days, respectively, corn grain harvested from reclaimed areas where liquid sludge had been applied annually for 5 to 6 years. Annual loading rates ranged from 25 to 128 mt/ha. Because trace metal composition of muscle tissue was unaffected by a diet of sludge-grown corn, the authors concluded that the consumption of meat from these animals would present little, if any, potential health hazard to humans. Although Cd concentrations were increased significantly in the liver and kidney tissues of pheasants and swine fed the corn grain from the sludge fields compared to control animals, the maximum levels of Cd in the tissues were still comparable to those reported elsewhere for animals fed a normal diet.[64]

When red-winged blackbirds nesting on the sludge-reclaimed Palzo strip mine were analyzed for tissue Cd, Zn, and Pb, it was found that Pb in brain, liver, kidney, and muscle was no different than for birds living in undisturbed areas or on strip mine sites reclaimed with inorganic fertilizers.[66] Higher kidney Cd was observed on the sludged sites, but in some tissues, Cd tissue concentrations were higher in birds from natural areas than in birds living on the Palzo site. Interpretation of such data is complicated due to Cd-Zn interactions that may occur in animal tissues and to the lack of data base for normal metal levels in birds.

In addition to trace metal accumulation, another health-related subject of much concern is that of pathogenic organisms in sludge. There is considerable information available on the survival of pathogens in sludge and sludge-amended soils, but little on the occurrence of disease transmission to animals from organisms in sludge.[65] With anaerobically digested, and especially with composted sludge, pathogens have not been found to pose a serious health risk. Although pathogens contained in anaerobically digested sludge have not been shown to present a serious potential health risk, Sagik et al.[88] have shown that population densities of indicator and pathogenic organisms are high enough in sludges digested at mesophilic temperatures to warrant a great deal of caution in their use as soil amendments. While thermophilic digestion or composting of sludges may markedly reduce numbers of pathogenic organisms, these sludges must still be handled as potentially infectious materials. Very few pathogenic organisms survive anaerobic digestion at 35 to 38°C, and even fewer survive composting at temperatures above 55°C. However, with aerobically digested or raw sludge there may be problems. A 4-year study related to the Fulton County, Ill., project examined 100 cows that were grazed on anaerobically digested sludge-treated forage.[65] No bacterial, viral, or fungal infections were observed in live animals or in blood or tissues at parasites was the same in experimental and control animals. In a similar 4-month swine study, *Ascaris* species infected some of the pigs in the pens amended with 200 mt/ha of digested sludge, but the number of worms was small. No other parasites or disease organisms were found, indicating that the transfer of pathogens from anaerobic-digested sludge to grazing animals is "remote".

On the 6000-ha Fulton County project, land application of Chicago sludge resulted in no significant public health problems.[88] Actual cases of disease on such projects are extremely scarce, and problems can be eliminated with proper sludge processing and application. Four years of data on the project indicate no significant numbers of viruses or indicator organisms in groundwater or surface water; no differences in discharge of nematode eggs or coccidian oocysts from animals grazing on sludge-treated forage; and no significant difference in soil pathogen content from control and sludge areas. Health effects of digested sludge are quite different than those resulting from the application of raw sludge or of raw or treated wastewater effluents.

VIII. EXAMPLE PROJECT

The Venango County, Pa. demonstration project provides an example of a well-planned and managed reclamation project which used local small city sludges to reclaim a bituminous coal strip mine spoil bank that had been recontoured without topsoil replacement.[31] The postmining land utilization of the site was vegetation establishment to reduce soil erosion and sedimentation followed by natural succession leading to a mixed hardwood forest cover.

Table 9
CHEMICAL ANALYSIS OF DEWATERED SLUDGE APPLIED ON THE VENANGO COUNTY DEMONSTRATION PLOTS

		Range	
Constituent	**Mean**	**High**	**Low**
pH	**7.9**	**8.2**	**7.7**
		(ppm dry wt)	
Total P	4,624	6,327	2,701
NO_3-N	46	52	40
NH_4-N	727	839	635
Organic N	12,188	14,612	9,990
Total N	12,962	15,500	10,768
Ca	9,970	12,699	3,805
Mg	2,082	3,108	590
Na	286	350	235
K	93	142	44
Al	6,133	8,641	1,208
Mn	1,651	2,703	285
Fe	29,709	44,561	5,912
Co	22	34	13
Zn	811	1,008	295
Cu	661	967	471
Pb	349	377	302
Cr	413	665	180
Ni	69	111	55
Cd	3.2	4.1	1.2
Hg	0.6	0.9	0.4
PCB	1.2	1.4	1.0

A. Site Location

The site was mined by a coal company in 1965, and is located in Venango County, Pa. It was mined prior to the passage of the strict surface mining regulations (PL 95-87) that require topsoil replacement. Three previous attempts were made by the coal company to reclaim the area using lime, commercial fertilizer, and seed; however, these efforts were unsuccessful and the site was essentially barren. Four ha of the approximate 40-ha area was selected for sludge application in a demonstration project. To maximize the value of the project, both liquid and dewatered sludges at a high and low rate were applied. After completion of the demonstration project, it is planned to continue to use sludge to complete reclaiming the remaining 36 ha.

B. Pretreatment Soil Sampling and Monitoring System

Twenty-one soil pits were excavated on the demonstration site with a backhoe to a depth of 90 cm. Each pit was used for the collection of soil samples and for the installation of suction lysimeters for percolate water sample collection. Three soil pits were excavated in each sludge treatment subplot and in an adjacent control. Soil samples were collected at the 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depth form chemical analyses. On a practical application, not being used as a demonstration, only about three to four soil pits would need to be excavated for the installation of soil percolate sampling instruments for monitoring purposes if required. Surface soil samples were collected from the area for initial soil pH to determine liming requirements and the cation exchange capacity of the area.

Table 10
CHEMICAL ANALYSIS OF LIQUID DIGESTED SLUDGE APPLIED ON THE VENANGO COUNTY DEMONSTRATION PLOTS

Constituent	Mean	Range: High	Range: Low
pH	6.8	7.0 dry wt	6.6
		(ppm dry wt)	
Total P	5,883	7.293	4,819
NO_3-N	1,780	3,869	528
NH_4-N	4,217	6,295	2,633
Organic N	20,509	25,021	18,010
Total N	26,506	35,185	21,750
Ca	39,726	63,836	26,344
Mg	6,689	12,051	4,707
Na	6,264	8,734	3,935
K	407	542	304
Al	19,545	42,083	6,667
Mn	808	1,022	531
Fe	28,517	34,460	20,909
Co	21	25	19
Zn	1,796	2,138	1,031
Cu	1,750	2,481	793
Pb	999	1,201	741
Cr	1,560	2,521	409
Ni	113	129	95
Cd	8.8	14.1	5.7
Hg	0.9	1.6	0.4
PCB	1.5	2.7	0.1

A monitoring system was established as required in Pennsylvania to determine the effects of the sludge applications on groundwater and soil percolate chemical and bacteriological quality, on the chemical properties of the soil, and on the vegetation.

Two suction lysimeters were installed in the excavated soil pits at the 90-cm depth for the collection of percolate water samples. One was used specifically for the collection of percolate water for bacterial analyses (total and fecal coliform) and the other for routine chemical water quality analyses. Samples were collected biweekly for the first 5 months and then monthly thereafter. For large-scale projects in Pennsylvania, only monthly sampling is required.

Three 15-cm diameter groundwater wells were drilled to monitor the effects of the sludge application on groundwater quality. Groundwater well sites were located by geologists of the Pennsylvania Department of Environmental Resources to collect samples up- and downgradient of the sludged site. The depth of each well and the depth to the water level at the time of drilling were as follows:

Well no.	Total depth (m)	Depth to water level (m)
1 (Upgradient)	18.0	5.3
2 (Downgradient)	17.8	3.3
3 (Downgradient)	11.4	2.1

Table 11
AMOUNTS OF SELECTED NUTRIENTS AND TRACE ELEMENTS APPLIED BY EACH SLUDGE APPLICATION ON THE VENANGO COUNTY DEMONSTRATION PLOTS

	Sludge application rate (mt/ha)			
Constituent	184	90	11	7
	(kg/ha)			
Total N	2388	1165	284	187
P	918	448	63	41
K	18	9	4	2
Cu	129	63	21	13
Zn	147	72	21	13
Cr	74	36	16	10
Pb	55	27	10	7
Ni	12	7	1	0.7
Co	3	2	0.2	0.1
Cd	0.6	0.2	0.09	0.07
Hg	0.09	0.04	0.01	0.007

Note: Metric conversion factors: 1 kg/ha = 0.89 lb/acre; 1 mt/ha = 0.446 T/acre.

Groundwater well samples were collected on the same schedule as percolate water samples. Samples were collected with both a submersible pump and a Kemmerer water sampler. The pump was used to remove standing water and draw-down the well. After recovery, the sampler was used to obtain a sample of fresh water in the well. For large-scale projects in Pennsylvania, only one downgradient groundwater monitoring well is required.

Water samples were also collected from two lakes adjacent to the demonstration plots. The samples were analyzed for the same constituents as the soil percolate water samples.

C. Background Sludge Sampling

Sludge for the demonstration project was obtained from local wastewater treatment plants at the cities of Farrell, Franklin, and Oil City, Pa. Liquid sludge was obtained from Farrell and Oil City, and dewatered sludge from Franklin and Oil City. Analyses of the sludge constituents as they were applied to the site are presented in Tables 9 and 10. Sludge samples were collected from each plant and analyzed to determine the loading rates and acceptability of the sludges for land application.

D. Site Preparation

Four 1-ha plots were laid out and marked for sludge application. Prior to application, a portion of the demonstration area was scarified with a tractor and chisel plow. This was necessary because the surface spoil material had been compacted in the backfilling and leveling operation. In addition, the roughened surface would prevent sludge runoff should an unusually heavy rainfall occur during the sludge application operation. The 2.0-ha area to receive the dewatered sludge was completely scarified. However, the chisel plow dug up many large rocks and brought them to the surface. As a result, it was decided not to scarify the area to receive liquid-digested sludge. However, as a precaution against sludge runoff, the perimeter of the plot was scarified.

Analyses of surface soil samples indicated that the average soil pH was 3.9 (buffer pH

Table 12
COMPARISON OF TRACE METAL LOADINGS AT THE VENANGO COUNTY DEMONSTRATION PROJECT WITH EPA AND PDER RECOMMENDATIONS

Constituent	Sludge application rate (184 mt/ha)	Recommendations: EPA (CEC 5—15)[a]	Recommendations: PDER
	(kg/ha)		
Cu	129	250	112
Zn	147	500	224
Cd	0.6	10	3
Pb	55	1000	112
Ni	12	250	22
Cr	74	NR[b]	112
Hg	0.09	NR[b]	0.6

Note: Metric conversion factors: 1 mt/ha = 0.446 t/acre; 1 kg/ha = 0.89 lb/acre.

[a] Average CEC of site ranged from 11.6 to 15.2 meq/100 g.
[b] No recommendations given by EPA.

5.9) on the area to receive dewatered sludge. Therefore, agricultural lime was applied at the rate of 12.3 mt/ha. This amount of lime was sufficient to raise the soil pH to 6.5. Liming is a Pennsylvania regulatory requirement and is necessary to immobilize the heavy metal constituents in the sludge and prevent them from leaching into the groundwater.

Lime was also applied to the area to receive liquid-digested sludge. Average soil pH was 6.1 (buffer pH 6.6). Lime was applied at the rate of 4.5 mt/ha.

Diversion ditches were installed to prevent sludge runoff in the direction of the two lakes on the property. A berm was constructed on three sides of the dewatered sludge unloading and storage area to prevent any movement of sludge from the area and to prevent water running into the sludge unloading area from higher ground.

E. Sludge Application and Incorporation

Because of the diversity of waste treatment processes and the variation in concentration of constituents in the sludges, it was decided to mix the sludges on the site prior to application. Samples of the sludge mixture were collected as the sludge was applied on the demonstration plots. Six composite samples were collected as the dewatered sludge was applied and five composite samples were collected as the liquid sludge was applied. The results of these analyses are given in Table 9 (dewatered sludge) and Table 10 (liquid-digested sludge). Average solids content for the liquid-digested sludge was 3% and for the dewatered sludge was 52%. Average total nitrogen content was 1.3% for the dewatered sludge and 2.7% for the liquid-digested sludge.

Results of the sludge analyses were used to calculate the amounts of selected nutrients and trace elements applied in the various application rates. These amounts, expressed in kilograms per hectare, are given in Table 11.

A comparison of the maximum sludge application rate (184 mt/ha) with the EPA and PDER recommendations is given in Table 12. The amounts of trace metals applied in the

Table 13
COMMERCIAL FERTILIZER EQUIVALENTS OF THE SLUDGE APPLICATION RATES IN VENANGO COUNTY

Sludge application rate (mt/ha)	Amount (kg/ha)	Fertilizer equivalent (fertilizer formula) [kg/ha (%)] N	P_2O_5	K_2O
184	22,440	2,388 (11)	2,103 (9)	21 (0)
90	11,200	1,165 (10)	1,026 (9)	11 (0)
11	2,240	284 (13)	143 (6)	6 (0)
7	2,240	187 (8)	95 (4)	2 (0)

Note: Metric conversion factors: 1 mt/ha = 0.446 t/acre; 1 kg/ha = 0.89 lb/acre.

sludge were below the PDER recommendations with the exception of copper. The amount of copper applied slightly exceeded the PDER recommendation, but was well below the EPA recommendation.

The commercial fertilizer equivalents of the various sludge application rates are given in Table 13. The highest sludge application rate would be equivalent to applying 10 mt/ha of an 11-9-0 commercial fertilizer. The value of the sludge as a commercial fertilzer substitue is quite obvious.

1. Liquid-Digested Sludge

During the period of May 17 to 23, 1977, liquid-digested sludge was hauled in tank trucks (19,000 to 26,000 ℓ) from the cities of Farrell and Oil City. At the site, the liquid sludge was emptied from the tankers into a temporary small holding pond with a plastic liner. The pond provided a means for mixing the two sludges. A vacuum tank liquid manure spreader with a 5700-ℓ capacity pumped the sludge from the holding pond and spread it on the plots. One half of the demonstration area received liquid sludge at an application rate of 155 m^3/ha (equivalent to 11 dry mt/ha). The other half received sludge at the rate of 103 m^3/ha (equivalent to 7 dry mt/ha). It was not possible to apply the liquid-digested sludge at the proposed design rate of 20 mt/ha because of an extremely high solids content (approximately 17.2%) of the sludge from Oil City. After four areal applications with the liquid spreader, infiltration was restricted and no more sludge could be applied without the threat of producing surface runoff.

2. Dewatered Sludge

During the period of May 18 to 21, 1977, dewatered sludge was transported by coal trucks from the cities of Franklin and Oil City. A total of 588 wet mt of sludge was transported to the site. The sludge from the treatment plants was unloaded at the site and mixed with a front-end loader prior to application with a farm manure spreader. One half of the demonstration site (1.0 ha) received an application of dewatered sludge at the rate of 90 mt/ha and the other half (1.0 ha) received 184 mt/ha. Sludge spreading was completed by May 25, 1977. On May 26, 1977, a tractor with a 6.4-mt disc attachment was used to incorporate the sludge into the surface 10 cm of spoil material.

F. Seeding and Mulching

During the period of May 27 to 31, 1977, the sludge-treated areas were broadcast seeded with a mixture of two grasses and two legumes. The seed mixture used was as follows:

Table 14
VEGETATION HEIGHT GROWTH AND DRY MATTER PRODUCTION AT THE VENANGO COUNTY DEMONSTRATION PROJECT

Sludge treatment (mt/ha)	Height (cm)				
	1977	1978	1979	1980	1981
7	29	37	52	55	52
11—L	32	30	43	48	48
90—L	34	41	41	49	52
184—L	35	52	44	58	54
	Dry matter production (mt/ha)				
7	6.3	9.5	18.5	34.4	32.9
11—L	7.7	8.7	17.1	26.7	22.8
90—L	4.8	7.4	14.3	26.1	19.8
184—L	6.0	9.3	11.3	31.2	22.6

Note: Metric conversion factors: 1 mt/ha = 0.446 t/acre; 1 cm = 0.3937 in; 1 kg/ha = 0.89 lb/acre.

	kg/ha
Kentucky-31 tall fescue	22
Pennlate orchardgrass	22
Penngift crownvetch	11
Birdsfoot trefoil	11
Total	66

The rationale for the selection of this seeding mixture was that the two grass species would germinate quickly and provide a complete protective cover the first year allowing time for the two legume species to become established and develop into the final vegetative cover.

The seed of the two grass species was mixed together and applied with a tractor-mounted seeder. The seed of the two legume species was inoculated, mixed together, and broadcast seeded with hand-carried whirlybird seeders. On large-scale practical operations, the entire seed mixture can be broadcast seeded at one time with a tractor-mounted seeder. Immediately after seeding, the entire 4-ha demonstration site was mulched with straw and hay at the rate of 3.8 mt/ha. On a large-scale practical operation, mulching is not necessary unless required by state regulations.

G. Monitoring Program

Some of the monitoring data are presented here as an example of the type of information which must be collected on reclamation projects using sludge in Pennsylvania.

1. Vegetation Growth Responses

Vegetation growth responses were evaluated at the end of each growing season. The results of these measurements are given in Table 14. All sludge-treated areas had a complete cover of vegetation by August 1977, 3 months after sludge application. Both vegetation height growth and dry matter production continually increased during the following 4-year period with no additional treatments.

During the first two growing seasons, the two grass species were the dominant vegetation

FIGURE 1. Application of 184 mt/ha of dewatered sludge prior to incorporation on the Venango County demonstration plot.

type on all sludge-treated plots. During the second growing season, the two grasses (tall fescue and orchardgrass) produced prolific seed heads. By the third growing season, the two legume species were well developed and had become the predominant vegetation cover on the plots treated with liquid-digested sludge and the limed dewatered sludge-treated plots. The sequence of vegetation development is shown in Figures 1, 2, 3, and 4. The unlimed dewatered sludge-treated plots were still vegetated primarily by the two grass species with only a few sparse patches of legumes.

Samples of the individual grass and legume species were collected at the end of each growing season for foliar analyses. Results for tall fescue and birdsfoot trefoil for the highest sludge application rate are given in Table 15 for 1977 to 1981. Foliar trace metal concentrations generally decreased over the 5-year period. Overall, the trace metal concentrations were well below the suggested tolerance levels. These levels represent the level at which a yield reduction might occur and do not represent levels at which toxicity occurs. There were no phytotoxicity symptoms observed for any vegetation on the sludge-treated areas.

In general, the vegetation cover has improved over the five growing seasons (1977 to 1981) following sludge application. No deterioration in vegetation quality or yield has been measured or observed. In comparison, the remainder of the site, not treated with sludge, remains barren.

On a large-scale practical operation, this type of information on vegetation yield and quality would only have to be collected for the first year following sludge application.

2. *Soils*

To evaluate the affects of the sludge treatment on the chemical properties of the spoil, samples were collected at various locations and depths at the end of each year. Results of spoil pH for the highest sludge application (184 mt/ha) area are given in Table 16. Surface spoil pH generally increased over the 5-year period following sludge application. Results indicate that the lime and sludge applications did raise the spoil pH significantly and that

FIGURE 2. Same view showing the lush dense complete vegetative cover which was established 3 months after sludge application.

FIGURE 3. During the second growing season after sludge application the grass species produced proflific seed heads.

FIGURE 4. Five years after sludge application, the two legume species had replaced the grass species as the predominant permanent cover.

FIGURE 5. General view of the winter rye vegetative cover the following spring after a fall application of sludge on the Westmoreland County Demonstration plot.

Table 15
AVERAGE CONCENTRATION (μg/g) OF TRACE METALS IN THE FOLIAR SAMPLES COLLECTED FROM THE 184 mt/ha PLOT AT THE VENANGO COUNTY DEMONSTRATION SITE

Species	Year	Cu	Zn	Cr	Pb	Co	Cd	Ni
Tall Fescue	1977	9.4	44.4	0.8	4.5	1.5	0.20	9.8
	1978	8.6	44.4	0.8	4.5	1.6	0.41	3.7
	1979	9.2	72.5	0.5	1.8	0.6	0.08	2.5
	1980	3.5	41.9	1.1	3.8	1.8	0.73	7.3
	1981	12.7	34.8	0.1	1.9	1.0	0.50	0.7
Birdsfoot Trefoil	1977	13.9	95.9	1.0	7.4	2.1	0.43	6.3
	1978	7.7	30.4	0.3	8.5	3.0	0.07	4.8
	1979	9.2	41.5	1.7	1.8	0.3	0.04	6.3
	1980	8.2	45.3	1.9	4.5	1.4	0.08	6.5
	1981	11.6	40.9	0.1	1.5	0.9	0.37	3.3
Suggested tolerance level[69]		150	300	2	10	5	3	50

Table 16
RESULTS OF SPOIL pH FOR THE 184 mt/ha PLOT AT THE VENANGO DEMONSTRATION SITE

	Spoil pH				
Spoil depth (cm)	Before sludge	1977	1978	1979	1981
0—15	3.8	6.2	6.7	7.3	6.7
15—30	3.8	4.2	4.6	5.1	5.1

Note: Metric conversion factors: 1 mg/ha = 0.446 t/acre; 1 cm = 0.3937 in.

Table 17
ANALYSES OF SPOIL SAMPLES FOR EXTRACTABLE TRACE METALS ON THE 184 mt/ha PLOT AT THE VENANGO COUNTY DEMONSTRATION SITE

		(μg/g)						
Time of sampling	Spoil depth (cm)	Cu	Zn	Cr	Pb	Co	Cd	Ni
Before sludge applied	0—15	2.5	2.9	0.2	0.5	0.7	0.02	1.1
	15—30	3.0	2.4	0.1	0.6	0.7	0.02	1.0
	30—60	3.7	3.6	0.2	0.9	1.0	0.03	1.6
4 months after sludge applied	0—15	10.8	7.7	0.4	3.5	1.3	0.07	0.9
	15—30	4.0	2.0	0.1	1.3	0.2	0.01	0.4
	30—60	4.9	2.9	0.1	1.9	0.3	0.01	0.5
18 months after sludge applied	0—15	8.8	7.7	0.2	2.3	1.2	0.02	1.2
	15—30	2.5	1.7	<0.1	1.3	0.5	0.01	0.7
	30—60	1.8	1.8	<0.1	1.5	0.5	0.01	0.7
Normal range for U.S. soils[76]		2—100	10—300	5—3000	2—200	1—40	0.01—7.0	10—1000

Note: Metric conversion factors: 1 mt/ha = 0.446 t/acre; 1 μg = 2.2×10^{-9} lb.

Table 18
RESULTS OF ANALYSES FOR TRACE METALS AND NITRATE-NITROGEN FOR SOIL PERCOLATE AT THE 90-cm DEPTH FROM THE VENANGO COUNTY DEMONSTRATION SITE

Sludge application rate (mg/ha)	Year[a]	mg/ℓ							
		Cu	Zn	Cr	Pb	Co	Cd	Ni	NO_3-N
0	1977	0.63	2.75	0.23	0.07	0.67	0.005	1.37	1.8
	1978	0.14	1.20	0.05	0.10	0.22	0.002	0.33	0.7
	1979	0.10	0.68	0.05	0.05	0.12	<0.001	0.26	0.7
	1980	0.08	0.90	0.06	0.07	0.10	0.001	0.22	0.8
	1981	0.05	0.36	0.03	0.03	0.07	0.002	0.12	0.9
184	1977	0.24	5.91	0.04	0.05	1.50	0.011	2.82	7.3
	1978	0.04	1.16	<0.01	0.08	0.19	0.002	0.26	0.5
	1979	0.07	0.87	0.02	0.05	0.20	0.001	0.34	<0.5
	1980	0.02	0.51	0.01	0.03	0.06	0.001	0.11	0.6
	1981	0.03	0.36	0.02	0.02	0.07	0.001	0.07	0.7
EPA drinking water standard		1.00	5.00	0.05	0.05		0.010		10.0

[a] Values represent the mean of all samples collected from the plot for the year.

the higher pH was maintained. Under Pennsylvania guidelines, surface spoil samples must be collected at the end of the first and second year following sludge application to document that the pH has not dropped below pH 6.5. Should the pH drop below this level, lime must be applied to raise it to at least 6.5.

Spoil samples were also analyzed for trace metals. A comparison of trace metal concentrations before and after sludge was applied is given in Table 17. Even at the highest sludge application rate (184 mt/ha), the trace metal concentrations in the surface spoil (0 to 15 cm) were only slightly increased. In general, the trace metal concentrations in the spoil were all extremely low in comparison to published normal ranges for soils. On a large-scale practical operation, soil samples only need to be taken 1 year after the sludge application.

3. Water Quality

a. Soil Percolate

Results of the analyses of soil percolate water at the 90-cm depth for the highest sludge application and the control plot are given in Table 18. Average monthly concentrations of NO_3-N in the percolate during the summer months in the first year (1977) on the plots treated with the highest applications of dewatered sludge were only slightly above potable water standards (10 mg/ℓ). The highest monthly average was 13.0 mg/ℓ for the month of August. Percolate NO_3-N concentrations were surprisingly low during May and June immediately following the sludge application. This was probably due to the fact that rainfall during this period was below normal. As a result, there was little opportunity for leaching of nitrogen from the sludge to occur. By October, with the development of a complete vegetative cover, the concentrations of NO_3-N in the percolate decreased to levels below 10 mg/ℓ. Concentrations of NO_3-N in the percolate remained at low levels throughout 1978 to 1981.

Average monthly concentrations of NO_3-N in the percolate at the 90-cm depth on the areas treated with liquid-digested sludge were slightly higher than those measured on the dewatered sludge plots. The highest concentration was 33.9 mg/ℓ on the 11 mt/ha plot and occurred during the first month (June 1977) following sludge application. These higher concentrations were probably due in part to the fact that the NO_3-N concentrations were

Table 19
GROUNDWATER ANALYSES FOR TRACE METALS AND NITRATE-NITROGEN FOLLOWING SLUDGE APPLICATION AT THE VENANGO COUNTY DEMONSTRATION SITE

		mg/ℓ							
Well no.	**Year**[a]	**Cu**	**Zn**	**Cr**	**Pb**	**Co**	**Cd**	**Ni**	**NO_3-N**
1	1977	0.22	4.13	0.01	0.14	3.19	0.006	3.23	1.4
(Control)	1978	0.23	2.02	0.01	0.19	1.04	0.002	1.00	<0.5
	1979	0.17	1.48	0.03	0.13	0.58	0.002	0.50	<0.5
	1980	0.04	0.84	0.05	0.10	0.59	<0.001	0.51	0.6
	1981	0.06	0.83	0.03	0.04	0.46	0.003	0.31	0.7
2	1977	0.10	3.39	0.03	0.09	2.12	0.001	2.67	1.1
(Dewatered	1978	0.14	3.29	0.01	0.20	1.16	0.002	1.26	<0.5
sludge)	1979	0.18	1.83	0.03	0.13	1.92	0.001	0.97	<0.5
(184 mt/ha)	1980	0.03	1.01	0.05	0.10	0.82	0.001	0.72	0.7
	1981	0.05	0.57	0.02	0.04	0.42	0.001	0.31	0.6
EPA drinking water standard		1.00	5.00	0.05	0.05		0.010		10.0

[a] Values represent the mean of all samples collected from each well for the year.

higher in the liquid-digested sludge (1780 ppm) than in the dewatered sludge (46 ppm), and nitrate-nitrogen in the liquid sludge is more susceptible to leaching prior to vegetation establishment. Concentrations of NO_3-N in percolate water started to increase almost immediately after sludge application. By August 1977, after development of a complete vegetative cover, concentrations of NO_3-N in percolate decreased to levels well below 10 mg/ℓ and remained at low levels throughout the study period.

Results of the analyses for dissolved trace metals at the 90-cm depth for the highest sludge application as well as the control plot are also given in Table 18.

Results indicate that percolate water quality met EPA drinking water standards with only a few exceptions. During the first 3 months in the first year following sludge application, the concentrations of Zn and Ni significantly increased and exceeded drinking water standards at the highest sludge application rate (184-L mg/ha). Concentrations of Cr and Pb slightly exceeded drinking water standards on both the control and sludge-treated plots. During the second (1978) and third (1979) years, only concentrations of Pb exceeded drinking water standards at the highest sludge applications. These concentration increases were minimal and posed no threat to human or animal health. It would also be noted that the average monthly concentrations of Pb on the control plot also exceeded potable water standards during the study period (1977 to 1981).

Total and fecal coliform analyses were conducted on all soil percolate water samples collected during the period of May 1977 through October 1979. No fecal coliform colonies were observed for any sample.

b. Groundwater

Groundwater samples were collected biweekly from monitoring wells to evaluate the effect of the sludge applications on groundwater quality. Results of these analyses are given in Table 19. Well no. 1 was drilled as a control outside the area of influence of the sludge applications. Groundwater flow under the dewatered sludge-treated area is toward well no. 2, located approximately 11 m downslope from the plot. Results indicate that the high application of dewatered sludge did not significantly increase the concentration of NO_3-N in groundwater. Concentrations of NO_3-N were below EPA limits for potable water (10 mg/

ℓ) for all months sampled. It also should be noted that the average depth to groundwater in well no. 2 was only 3 m.

Results of analyses of groundwater samples for trace metals during the 4 years after sludge was applied are also given in Table 19. There appears to be no significant increase in any of the trace metal concentrations in well no. 2, which was influenced by the sludge applications. Average annual concentrations were below EPA drinking water standards.

All groundwater samples collected during the period, of July 1977 to July 1981 were also analyzed for coliforms. No fecal coliform colonies were observed for any sample.

IX. SUMMARY

In general, this review of the literature indicates that single applications of stabilized municipal sludge, applied at the proper rate, can be used successfully to facilitate revegetation of mined land and maintain it for a minimum of 5 years in an environmentally safe manner with no adverse effects on vegetation, soil, or groundwater quality and with little risk to animal or human health.

LIST OF COMMON NAMES AND SCIENTIFIC NAMES OF VEGETATION DISCUSSED IN THIS ARTICLE

Common name	Scientific name
Wheat	*Triticum aestivum*
Oats	*Avena sativa*
Canada bluegrass	*Poa compressa*
Red clover	*Trifolium pratense*
Smooth bromegrass	*Bromus inermis*
Alfalfa	*Medicago sativa*
Western wheatgrass	*Agropyron smithii*
Alsike clover	*Trifolium hybridum*
Barley	*Hordeum vulgare*
Japanese millet	*Echinochola crusgalli var. frumentacea*
Tall fescue	*Festuca arundinacea*
Orchardgrass	*Dactylis glomerata*
Birdsfoot trefoil	*Lotus corniculatus*
Kleingrass	*Panicum coloratum*
Switchgrass	*Panicum virgatum*
Fescue	*Festuca megalura*
Perennial rye	*Lolium perenne*
Bermudagrass	*Cynodon dactylon*
Reed canarygrass	*Phalaris arundinacea*
Weeping lovegrass	*Eragrostis curvula*
Redtop	*Agrostis gigantea*
Ladino clover	*Trifolium repens*
Serecia lespedeza	*Lespedeza cuneata*
Crownvetch	*Coronilla varia*
Annual ryegrass	*Lolium multiflorum*
Sideoats gramagrass	*Bouteloua curtipendula*
Canada wild rye	*Elymus canadensis*
Foxtail grass	*Setaria* spp.
Korean lespedeza	*Lespedeza stipulacea*

LIST OF COMMON NAMES AND SCIENTIFIC NAMES OF VEGETATION DISCUSSED IN THIS ARTICLE (continued)

Common name	Scientific name
Sweetclover	*Melilotus* spp.
Kobe lespedeza	*Lespedeza striata*
Corn	*Zea mays*
Soybean	*Glycine max*
Highbush blueberry	*Vaccinium corymbosum*
Bush bean	*Phaseolus vulgaris*
Virginia pine	*Pinus virginiana*
Hybrid poplar	*Populus* spp.
Black locust	*Robinia pseudoacacia*
European alder	*Alnus rugosa*
Red oak	*Quercus rubra*
Cottonwood	*Populus deltoides*
Sudan grass	*Sorghum vulgare sudanenese*
Eastern white pine	*Pinus strobus*
Silver maple	*Acer saccharinum*
Green ash	*Fraxinus pennsylvanica*
Loblolly pine	*Pinus taeda*

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