Long-Term Plant Community Development on Topsoil Treatments Overlying a Phytotoxic Growth Medium

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ABSTRACT

The application of topsoil over phytotoxic mine waste materials is often the most effective method for establishing plant communities and protecting these communities from the inimical properties of such waste materials. However, long-term data on the effectiveness of this type of remediation, as well as on cultural treatments used to enhance vegetation establishment on topsoil cover treatments, are lacking. Therefore, we evaluated long-term plant community development on study plots where 60 cm of Paraho retorted oil shale was covered by various depths of topsoil. The study plots were drill seeded with native, introduced, or a combination of native and introduced species, and fertilized with one of three rates of nitrogen (N) and phosphorus (P) fertilizer following construction of the plots in 1977. Data collected 20 yr after seeding showed that total aboveground biomass was greatest on deeper topsoil depths and on plots seeded with introduced plant species. However, when considering the interaction between these two variables, we found that native species were as productive as introduced species on deeper topsoil depths and on the control. Relative plant species composition and plant species richness were greatly influenced by seed mixture treatments. Plots seeded with a particular seed mixture in 1977 were still highly dominated by those species originally seeded, and native seed mixture plots were more species rich than introduced seed mixture plots. Chemical analysis of the soil covers and underlying retorted shale suggests that leaching processes have moderated the once adverse chemical characteristics of the retorted shale.

MINING activities that produce phytotoxic waste materials occur throughout the western USA. Elevated concentrations of certain salts and trace elements in mine waste materials, and the movement of these elements via capillary rise, leaching, diffusion, and plant uptake and cycling (biocycling) may hinder reclamation efforts by inhibiting the satisfactory establishment of vegetation (Stark and Redente, 1990). In order to protect establishing plant communities from the upward movement of salts and trace elements, several researchers have advocated the placement of topsoil over such phytotoxic waste materials as retorted oil shale (Harbert and Berg, 1978; Harbert et al., 1979; Redente et al., 1982), trona tailings (Barth and Martin, 1981), molybdenum mill tailings (Trlica et al., 1994), and alumina refinery wastes (Bell and Meecham, 1978). Despite the addition of topsoil, the upward movement of soluble salts and/or trace elements due to capillary rise or diffusion (Bell and Meecham, 1978; Harbert and Berg, 1978; Stark and Redente, 1986; Trlica et al., 1994) and biocycling (Stark and Redente, 1990) has been reported. Accordingly, some researchers have investigated the use of capillary barriers, in conjunction with a topsoil covering, as a means of reducing the upward movement of salts and trace elements (Bell and Meecham, 1978; Barth and Martin, 1981; Redente et al., 1982). Unfortunately, few studies have examined the movement of salts and trace elements out of topsoil-covered phytotoxic waste materials over longer time scales (i.e., greater than 5 yr). Thus, the long-term effectiveness of topsoil coverings in containing phytotoxic materials in underlying mine waste and limiting capillary rise, leaching, and biocycling processes is unknown.

Many mining reclamation laws throughout the western USA require salvage and replacement of topsoil and the establishment of diverse, self-sustaining plant communities following reclamation. However, all of the above-mentioned research dealing with phytotoxic waste materials, with the exception of studies by Stark and Redente (1986, 1990), has been short-term in nature (i.e., less than 5 yr). Furthermore, long-term reclamation research has only been conducted on topsoil treatments overlying nonphytotoxic mine spoils (Chambers et al., 1994; Redente et al., 1997) and on intensively disturbed soils associated with mining activity (Newman, 1999). As a consequence, long-term plant community development on topsoil treatments overlying phytotoxic mine waste materials is poorly understood. Thus, it is difficult to make recommendations on the reclamation of phytotoxic waste materials that will promote diverse and self-regenerating plant communities over longer time scales.

These deficiencies in research led us to revisit the Retorted Shale Successional Study (RSSS), which was established in 1977 and described by Redente et al. (1982). The objectives of the current study were to (i) evaluate the effects of topsoil, seed mixture, and fertilization treatments on plant community development after 20 growing seasons and (ii) to determine if soluble salts and trace elements have migrated from retorted oil shale layers into overlying topsoil. Results of this study should prove useful in the reclamation of phytotoxic materials that may require soil covers for successful reclamation.

MATERIALS AND METHODS

This study was conducted in the Piceance Creek Basin of northwestern Colorado in Rio Blanco county (39°54′13″ N, 108°24′02″ W), approximately 65 km northwest of Rifle, CO. The study plots are situated on level ground at an average elevation of 2020 m. The climate of the area is semiarid. Mean annual precipitation (MAP) is 282 mm; winter and spring

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Abbreviations: EC, electrical conductivity; RSSS, Retorted Shale Successional Study; SAR, sodium adsorption ratio; TRT-30, 30 cm of topsoil over retorted shale; TRT-60, 60 cm of topsoil over retorted shale; TRT-90, 90 cm of topsoil over retorted shale; TRT-60CB, 60 cm of topsoil over a 30-cm rock capillary barrier over retorted shale.

(November–April) precipitation contributes roughly half of MAP and is received mainly as snow. Mean annual temperature (MAT) is approximately 6.8°C. Temperatures can often reach a maximum of 38°C in the summer and a minimum of −40°C during winter months.

The study area was classified within the Mid-Elevation Big Sagebrush/Moderately Deep Loams Phyto-edaphic Unit as described by Tiedeman and Terwilliger (1978). Big sagebrush (*Artemisia tridentata* var. *tridentata* Nutt.) is the dominant species in undisturbed plant communities. Common understory species include prairie junegrass [*Koeleria macrantha* (Ledeb.) Schult.], needle-and-thread (*Stipa comata* Trin. & Rupr.), carpet phlox (*Phlox hoodii* Richards.), scarlet globemallow [*Sphaeralcea coccinea* (Pursh.) Rydb.], and prickly pear cactus (*Opuntia polycantha* Haw.). Native reference plots adjacent to the study were found to support approximately 150 g m^{-2} of aboveground biomass averaged over a 4-yr period (McLendon and Redente, unpublished data, 1992). Loamy soils of the Yamac series (mixed Borollic Camborthids) are common in the vicinity of the study site (Mount, 1985). Depth to bedrock is highly variable on these soils and averages approximately 50 cm (Redente et al., 1982).

The RSSS was initiated in the summer of 1977 to examine three main treatments common in the reclamation of retorted oil shale with respect to their effects on plant establishment and succession, and to determine the movement of trace elements and salts contained in soil-covered retorted oil shale. The study was established as a split-split plot design with five topsoil treatments (whole-plot treatment), three seed mixtures (subplot treatment), three fertilizer treatments (sub-subplot treatment), and three replications. A total of 135 study plots (experimental units) were established with each measuring 7 × 11.5 m. It should be noted that the three seed mixtures and three fertilizer treatments were truly replicated throughout the study; however, since logistics required long, continuous pits in the construction of the topsoil treatments, these treatments were pseudoreplicated.

Topsoil used in this study was obtained on-site during the construction of the experiment, and the retorted oil shale (produced by the Paraho method) originated from the Anvil Points retorting facility near Rifle, CO. In all topsoil treatments except the control, a 60-cm layer of retorted oil shale was placed at an appropriate depth such that the surface of the various topsoil treatments would be level with the existing soil grade. Also, the lower 15 cm of the 60-cm layer of retorted shale was compacted to limit the percolation of soil water through the shale. The five topsoil treatments included:

(i) 30 cm of topsoil over retorted shale (TRT-30).
(ii) 60 cm of topsoil over retorted shale (TRT-60).
(iii) 90 cm of topsoil over retorted shale (TRT-90).
(iv) 60 cm of topsoil over a 30-cm rock capillary barrier over retorted shale (TRT-60CB).
(v) Soil control without retorted shale, which involved mechanically removing vegetation and ripping remaining soil to a depth of 30 cm (control).

A visual representation of topsoil treatments and the experimental layout of study plots is presented in Fig. 1.

Each topsoil treatment was then drill seeded with three different seed mixtures in November 1977. The seed mixtures consisted of a diverse mixture of either all native, all introduced, or a combination of native and introduced grasses, forbs, and shrubs (Table 1). In addition, three fertilizer treatments were applied: (i) 112 kg N ha^{-1} and 56 kg P ha^{-1}, (ii) 56 kg N ha^{-1} and 28 kg P ha^{-1}, and (iii) a control consisting of no fertilization. Phosphorus was applied as triple superphosphate (0–46–0) prior to seeding and was incorporated into the soil using a tractor-mounted rototiller to a depth of 30 cm. The application of N, in the form of ammonium nitrate (33–0–0), did not occur until the end of the first growing season (1978) in an attempt to limit the invasion of weedy annual plant species (Mount, 1985).

During June and July of 1997, we sampled each of the 135 study plots for aboveground biomass by harvesting vegetation within randomly placed 0.5-m^2 quadrats. Six quadrats were sampled within each study plot. Plants within the quadrat volume were clipped at ground level and separated by species. Plant samples were oven-dried at 55°C for 48 h and then weighed to determine aboveground biomass.

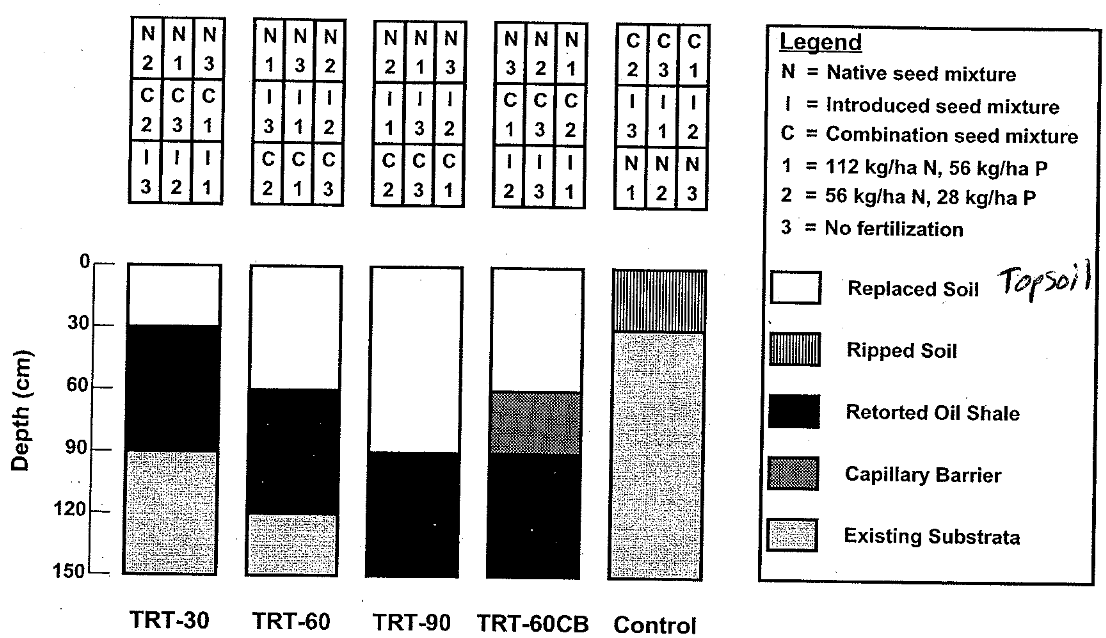

Fig. 1. Overhead view of the experimental layout of study plots (top) and side view of topsoil treatments (bottom). Only one replication is shown for study plot layout.

Table 1. Seed mixtures and rates used on the Retorted Shale Successional Study in 1977.

Common name	Scientific name	Seeding rate kg PLS ha^{-1}†
Native mixture		
1. Western wheatgrass 'Rosana'	*Agropyron smithii* Rydb.	1.1
2. Streambank wheatgrass 'Sodar'	*Agropyron riparium* Scribner & J.G. Smith	1.1
3. Beardless bluebunch wheatgrass	*Agropyron spicatum* (Pursh) Scribn. & J.G. Sm. var. *inerme* (Scribn. & J.G. Sm.) Heller	1.1
4. Indian ricegrass	*Oryzopsis hymenoides* Roemer & J.A. Schultes Ricker ex. Piper	1.1
5. Green needlegrass	*Stipa viridula* Trin.	1.1
6. Durar hard fescue	*Festuca ovina* L. var. *duriuscula* auct. non(L.) W.D.J. Koch	0.6
7. Big bluegrass 'Shermans'	*Poa secunda* J. Presl.	1.1
8. Alkali sacaton	*Sporobolus airoides* (Torr.) Torr.	0.6
9. Globemallow	*Sphaeralcea munroana* (Dougl. ex. Lindl.) Spach ex. Gray	0.6
10. Northern sweetvetch	*Hedysarum boreale* Nutt.	1.1
11. Palmer penstemon	*Penstemon palmeri* Gray	0.6
12. Stansbury cliffrose	*Cowania mexicana* D. Don *var. stansburiana* (Torr.) Jepson	2.2
13. Green ephedra	*Ephedra viridis* Coville	1.1
14. Fourwing saltbush	*Atriplex canescens* (Pursh) Nutt.	1.1
15. Winterfat	*Ceratoides lanata* (Pursh) J.T. Howell	1.1
16. Antelope bitterbrush	*Purshia tridentata* (Pursh) DC.	1.1
	Total	16.7
Introduced mixture		
1. Crested wheatgrass 'Nordan'	*Agropyron desertorum* (Fisch. ex. Link) J.A. Schultes	1.1
2. Siberian wheatgrass	*Agropyron sibericum* (Willd.) Beauv.	1.1
3. Tall wheatgrass 'Jose'	*Agropyron elongatum* (Host) Beauv.	1.1
4. Pubescent wheatgrass 'Luna'	*Agropyron trichophorum* (Link) Richter	1.1
5. Intermediate wheatgrass 'Oahe'	*Agropyron intermedium* (Host) Beauv.	1.1
6. Smooth brome 'Manchar'	*Bromus inermis* Leyss.	1.1
7. Meadow brome 'Regar'	*Bromus biebersteinii* Roemer & J.A. Schultes	1.1
8. Russian wildrye 'Vinal'	*Elymus junceus* Fisch.	1.1
9. Alfalfa 'Ladak'	*Medicago sativa* L.	0.6
10. Yellow sweetclover 'Madred'	*Melilotus officinalis* (L.) Lam.	0.6
11. Cicer milkvetch 'Lutana'	*Astragalus cicer* L.	0.6
12. Sainfoin	*Onobrychis viciaefolia* Scop.	0.6
13. Bouncing bet	*Saponaria officinalis* L.	1.1
14. Small burnet	*Sanguisorba minor* Scop.	2.2
15. Siberian peashrub	*Caragana arborescens* Lam.	1.1
16. Russian olive	*Elaeagnus angustifolia* L.	2.2
	Total	17.8
Combination (native and introduced) mixture		
1. Crested wheatgrass 'Nordan'	*Agropyron desertorum*	1.1
2. Siberian wheatgrass	*Agropyron sibericum*	1.1
3. Thickspike wheatgrass 'Critana'	*Agropyron daststachyum* (Hook.) Scribn. & J.G. Sm.	1.1
4. Streambank wheatgrass 'Sodar'	*Agropyron riparium*	1.1
5. Slender wheatgrass	*Agropyron trachycaulum* (Link) Malte ex H.F. Lewis	1.1
6. Meadow brome 'Regar'	*Bromus biebersteinii*	1.1
7. Indian ricegrass	*Oryzopsis hymenoides*	1.1
8. Green needlegrass	*Stipa viridula*	1.1
9. Hard fescue 'Durar'	*Festuca ovina* var. *duriuscula*	0.6
10. Yellow sweetclover 'Madrid'	*Melilotus officinalis*	0.6
11. Northern sweetvetch	*Hedysarum boreale*	1.1
12. Globemallow	*Sphaeralcea munroana*	0.6
13. Lewis flax	*Linum lewisii* Pursh	0.6
14. Arrowleaf balsamroot	*Balsamorhiza sagittata* (Pursh) Nutt.	1.1
15. Fourwing saltbush	*Atriplex canescens*	1.1
16. Stansbury cliffrose	*Cowania mexicana* var. *stansburiana*	1.1
17. Winterfat	*Ceratoides lanata*	1.1
18. Green ephedra	*Ephedra viridis*	1.1
	Total	17.8

† PLS, pure live seed.

Vegetation data were analyzed using a three-way analysis of variance (SAS Institute, 1998). The dependent variable was aboveground biomass (g m^{-2}), whereas independent variables included topsoil depth, seed mixture, and fertilization rate. The three main treatment effects, as well as any interactions, were tested for significance within grass, forb, shrub, and total aboveground biomass at the $\alpha = 0.05$ level. Means separation tests were performed using LSD at the $\alpha = 0.05$ level. The most important independent variables included topsoil and seed mixture treatments, as well as the interaction between these two variables. Fertilization rate, represented by the one-time application of N and P, was no longer significant; therefore, this treatment will not be discussed in further sections of this paper.

In September 1997, we excavated a soil pit in one of the native seed mixture plots in TRT-60CB. Our objective was to qualitatively observe the integrity of the capillary barrier 20 yr after construction. Of most importance was to determine if the large pore spaces of the capillary barrier had filled with soil over the past 20 yr thus allowing plant roots to grow through the barrier and into the underlying shale layer, or potentially allowing the upward movement of trace elements and salts from the retorted shale layer.

Soil samples were taken in May 1998 using a truck-mounted hydraulic soil corer. Overall, we sampled three soil cores from each of the five topsoil treatments. The soil cores varied in depth according to the corresponding depth of topsoil overlying retorted shale. Each soil core included the depth of topsoil overlying retorted shale plus the top 15 cm of the underlying retorted shale layer. Exceptions to this existed in TRT-60CB in which the soil core included only 60 cm of topsoil, as the soil corer would not penetrate the rock capillary barrier, and the control treatment in which a 60-cm soil core was taken. Also, in TRT-90, a 90-cm core was obtained as the soil corer would not penetrate to a depth of 105 cm due to mechanical difficulties. When the soil cores were extracted in the field, the top 3 cm (in height) of each core was removed and placed in a ziplock bag; a 3-cm subsample was then removed 15 cm below the soil surface, followed by 3-cm subsamples at 15-cm intervals until the bottom of the soil core was reached. These subsamples were placed in separate ziplock bags. In each topsoil treatment, each subsample at a particular depth was pooled with the other two subsamples corresponding to the same depth. In all, 27 composite subsamples encompassing all five topsoil treatments were analyzed for pH, electrical conductivity (EC), and sodium adsorption ratio (SAR). Total soil concentrations of boron (B) and molybdenum (Mo) were determined using inductively coupled plasma–atomic emission spectroscopy (ICP–AES) following acid digestion (USEPA Method 3050).

RESULTS AND DISCUSSION

Results from the 1980 growing season were published by Redente et al. (1982); data from the 1978, 1979, and 1980 growing seasons and then for all growing seasons between 1978 and 1983 were also compiled and submitted as progress reports to the United States Department of Energy (Redente and Cook, 1981, 1984). Data were not collected on RSSS study plots from 1984 to 1996.

Effect of Topsoil Depth

After 20 yr of plant community development, variations in topsoil depth (when averaged over seed mixture treatments) continued to influence total aboveground biomass. Overall, deeper topsoil depths supported greater aboveground biomass, being greatest on TRT-60CB (139 g m^{-2}) and TRT-90 (131 g m^{-2}), and lowest on TRT-30 (116 g m^{-2}), TRT-60 (116 g m^{-2}), and the control (102 g m^{-2}) (Fig. 2). Increased productivity of grasses, especially on TRT-60CB, was mostly responsible for greater total aboveground biomass on deeper topsoil depths (Fig. 2). Forb and shrub biomass did not respond as consistently to variations in topsoil depth, but both were generally lowest on TRT-60CB and the control (Fig. 2).

The depth of topsoil needed to maximize aboveground biomass on reclaimed mined land has been widely studied (Harbert and Berg, 1978; Bell and Meecham, 1978; Power et al., 1981; Redente et al., 1982; Barth, 1983; Schuman et al., 1985; Trlica et al., 1994; Redente et al., 1997). In general, these authors reported that productivity increased, especially with respect to grass biomass, as topsoil depth increased. The topsoil depth at which aboveground biomass is maximized is site-specific (Schuman and Power, 1981), and depends greatly upon (in order of importance) the characteristics of the underlying mine waste material, regional climatic conditions, and topsoil quality (Hargis and Redente, 1984). With respect to the characteristics of the waste

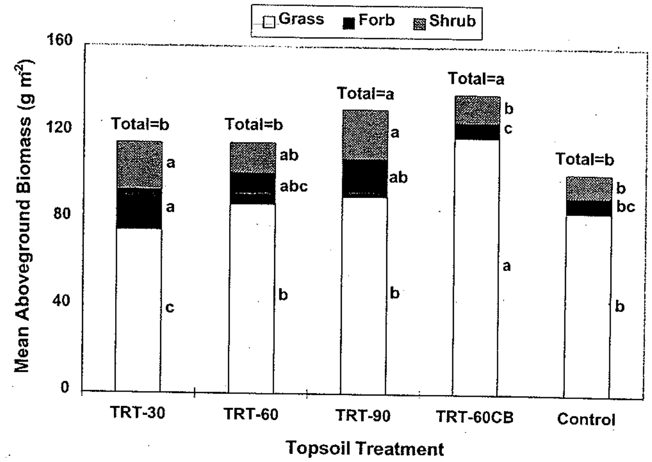

Fig. 2. Mean aboveground biomass (g m^{-2}) by topsoil treatment. Each mean for a given life form or total value within a topsoil treatment represents data taken from 27 plots (n = 27). Comparisons are made within each life form or the total of all three life forms across topsoil treatments. Means with the same letter within life forms or the total of all three life forms are not significantly different (α = 0.05).

material to be covered, Hargis and Redente (1984) recommended that deeper depths of topsoil are necessary when underlying mine waste or spoil material is phytotoxic, as compared with nonphytotoxic materials. In support of this statement, Barth (1983) found that the productivity of perennial grasses was maximized on the following topsoil depths over mine spoils (with chemical characteristics of spoil in parentheses): 50 cm (slightly saline), 71 cm (sodic), and more than 100 cm (acidic). In contrast, Schuman et al. (1985) reported that 40 cm of topsoil overlying nontoxic spoil from a uranium mine supported equal amounts of aboveground biomass as did 60 cm of topsoil. Likewise, Redente et al. (1997) reported that 15 cm of topsoil overlying nonphytotoxic coal spoil supported as much total aboveground biomass as 60 cm of topsoil. Deeper depths of topsoil overlying phytotoxic waste materials apparently benefit plant communities by isolating plant roots from the inimical properties of mine waste materials and limiting the upward movement of salts and trace elements (Barth, 1988).

Despite supporting equal amounts of aboveground biomass, relative production of grasses on TRT-60CB plots was approximately 25% greater than on TRT-90 plots. Furthermore, the relative production of forbs and shrubs on TRT-90 plots was nearly twice as great when compared with TRT-60CB plots (Sydnor, 1999). Relative production of grasses, forbs, and shrubs on TRT-60CB plots may have been influenced by the physical presence of the capillary barrier. Redente and Cook (1984) hypothesized that the abrupt textural change at the topsoil–capillary barrier interface disrupted the downward movement of soil water on TRT-60CB plots during the first six growing seasons (1978–1983), leading to greater soil moisture in topsoil overlying the barrier and more favorable growth conditions, especially for grasses. Upon examination of the capillary barrier in 1997, we observed that the large pore spaces that once existed in the rock barrier have filled with soil since the 1983 growing season. However, Barth (1988) suggested that large rocks present in capillary barriers, even when void areas within these barriers are filled with soil particles, may continue to disrupt the movement of soil water by interrupting pore continuity of soil present in the capillary barrier. Thus, the downward movement of soil water through the capillary barrier may still be obstructed, leading to greater soil moisture in overlying topsoil and helping to explain the continued dominance of grass species on TRT-60CB plots relative to the other topsoil treatments (Fig. 2).

Effect of Seed Mixtures

Barth (1986) stated that many of the plant species used to revegetate disturbed areas should be transitory and that their use should not compromise secondary successional processes by preventing or hindering the establishment of colonizing, nonseeded species. However, our long-term data revealed that study plots seeded with a given seed mixture in 1977 have tended to remain dominated by those species originally seeded (Table 2). Other long-term studies have reported similar findings 14 to 23 yr after seeding (Jordan and Dewar, 1985; Chambers et al., 1994; Walker et al., 1995; Newman, 1999). Furthermore, in support of our study, these same authors reported that the colonization of native, nonseeded species (especially shrubs) was slow in the presence of introduced species, possibly due to competition with introduced grasses. For example, colonizing, nonseeded native shrubs contributed 1% of total production in the introduced seed mixture in 1983 (Redente and Cook, 1984) and by 1997 were contributing only 3% (Sydnor, 1999); conversely, colonizing, nonseeded native shrubs represented only a trace amount of total production in 1983 on plots seeded with the native mixture (Redente and Cook, 1984), but contributed 8% of total production by 1997 on these same plots (Sydnor, 1999). Given that seeded species were initially favored by a well-prepared seedbed, we feel that the long-term dominance of seeded species has been maintained over time by interspecific competition among these species for limited resources, which has slowed the colonization of nonseeded species.

Table 2. Relative species composition of each seed mixture based on aboveground biomass and averaged over topsoil treatment. Only dominant species (≥5% relative biomass) are included. Out of the three seed mixtures, only one dominant species, rubber rabbitbrush (*Chrysothamnus nauseosus*), in the native seed mixture, was not originally seeded in 1977.

Seed Mixture	Species	Relative production
		%
Native	Big bluegrass 'Shermans'	5
	Western wheatgrass 'Rosana'	14
	Beardless bluebunch wheatgrass	44
	Fourwing saltbush	6
	Rubber rabbitbrush	5
	Other	26
Introduced	Tall wheatgrass 'Jose'	7
	Russian wildrye 'Vinal'	7
	Intermediate wheatgrass 'Oahe'	27
	Crested wheatgrass 'Nordan'	35
	Alfalfa 'Ladak'	15
	Other	9
Combination	Western wheatgrass 'Rosana'	6
	Meadow brome 'Regar'	27
	Crested wheatgrass 'Nordan'	42
	Fourwing saltbush	7
	Winterfat	6
	Other	12

Our results also indicated that the choice of seed mixture may affect the long-term productivity of restored plant communities. In the current study, the introduced seed mixture (134 g m^{-2}) supported greater aboveground biomass than either the native (120 g m^{-2}) or combination (108 g m^{-2}) seed mixtures, when averaged over topsoil depth (Fig. 3). This result contradicts Newman (1999), who found that a native seed mixture was more productive than an introduced seed mixture after 21 growing seasons; this response was partially due to the effects of an initial, 2-yr irrigation treatment. However, when we considered variations in topsoil depth, we found that the native seed mixture was as productive as the introduced seed mixture on deeper topsoil depths (TRT-60CB and TRT-90) and the control (Table 3). Conversely, the introduced seed mixture was more productive than both the native and combination mixtures on shallow topsoil depths. This trend suggests that the use of a native seed mixture may result in a plant community as productive as one resulting from a seed mixture containing all introduced species, over longer time scales, when well isolated from a phytotoxic growth medium (i.e., with the use of deeper topsoil depths). Overall, the results of this study indicate that the selection of a seed mixture for reclamation projects may have long-lasting effects on the resulting plant community in terms of plant species composition and productivity.

Effect of Treatments on Plant Species Richness

Overall, changes in topsoil depth did not affect plant species richness. This result contradicts Huston's (1979)

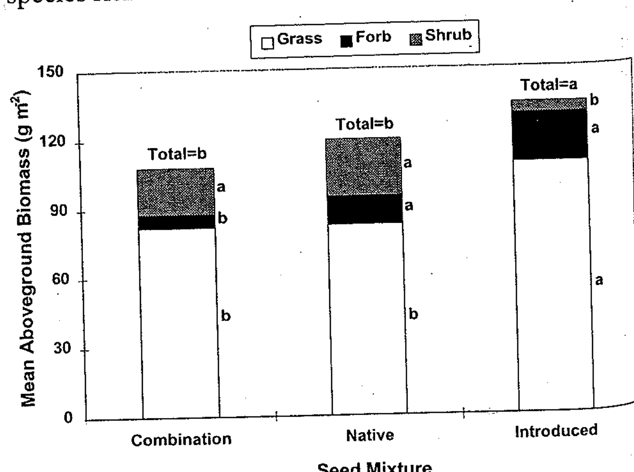

Fig. 3. Mean aboveground biomass (g m^{-2}) by seed mixture. Each mean for a given life form or total value within a seed mixture represents data taken from 27 plots (n = 27). Comparisons are made within each life form or the total of all three life forms across seed mixtures. Means with the same letter within life forms or the total of all three life forms are not significantly different (α = 0.05).

hypothesis concerning the relationship between diversity (which included the concepts of species richness and evenness) and productivity: "[d]iversity is determined not so much by the relative competitive abilities of the competing species as by the influence of the environment on the net outcome of their interactions." Put another way, conditions that enhance the rate at which certain plant species' competitive abilities are expressed will tend to lower diversity (or richness) as less competitive species are excluded. However, on deeper topsoil treatments, the increased productivity of grasses did not appear to heighten competitive exclusion of other species or limit colonization of species from the neighboring species pool.

Despite the fact that the introduced seed mixture was generally the most productive in the current study, this mixture had the lowest species richness. Overall, plots seeded with the introduced mixture contained an average of 2.7 species m^{-2}, whereas native and combination seed mixture plots supported an average of 4.3 and 3.7 species m^{-2}, respectively (Sydnor, 1999). As a comparison, undisturbed reference plots adjacent to the study site were found to contain 5.6 species m^{-2} on average (McLendon and Redente, unpublished data, 1992). In support of the current study, Redente et al. (1984) reported that seed mixtures containing all introduced species were generally less diverse than native seed mixtures, based on the Shannon–Weiner index. There may be several reasons why species richness or diversity is generally lower on sites seeded with introduced species mixtures. The most plausible explanation for this phenomenon in the current study may be attributed to the lack of introduced shrub establishment during the initial phases of this study (Redente et al., 1982). Thus, competition between introduced shrubs and grasses for resources on introduced seed mixture plots was nonexistent during early plant community development. This lack of competition, coupled with favorable growing conditions for several of the introduced grasses, probably enhanced the growth rates and competitive abilities of introduced grasses, thus allowing them to dominate the introduced mixture, exclude other less competitive species, and lower species richness (Huston, 1979).

Table 3. Mean aboveground biomass (g m^{-2}) by life form within a given seed mixture and topsoil treatment. Each mean represents data taken from nine plots (n = 9). Comparisons are made within a life form (or the total of all three life forms) *and are among seed mixtures.* Values followed by the same letter within a column are not significantly different ($\alpha = 0.05$).

Life form within seed mixture	TRT-30	TRT-60	TRT-90	TRT-60CB	Control
	g m^{-2}				
Native					
Grass	61b	67c	78b	113b	94a
Forb	13a	17a	13ab	11a	7a
Shrub	28a	21a	38a	22a	15ab
TOTAL	102b	105b	129a	145a	116a
Introduced					
Grass	102a	110a	109a	132a	90a
Forb	32a	25a	31a	10ab	7a
Shrub	11b	2b	7b	0b	4b
TOTAL	145a	137a	147a	142a	101ab
Combination					
Grass	62b	84b	86b	111b	68b
Forb	11a	2b	8b	1c	7a
Shrub	26a	19a	24a	17a	15a
TOTAL	99b	105b	118a	128a	90b

Reclamation of mined lands in the western USA must achieve specific goals in terms of total production and plant species diversity; however, research has shown that productive yet diverse plant communities are difficult to recreate (DePuit, 1984; Stark and Redente, 1985; Biondini and Redente, 1986). Some authors have successfully obtained both by increasing the number of species in an all-native seed mixture (DePuit and Coenenberg, 1979) or by using irrigation to manipulate composition of the seeded community (Redente and DePuit, 1988). Other authors (DePuit, 1984; Stark and Redente, 1985) have suggested the application of various depths of topsoil across the landscape as a potential strategy for obtaining productive and diverse plant communities. The results of the current study indicate that productive and relatively species-rich native plant communities can be established and maintained over phytotoxic mine waste materials with the use of at least 30 cm of topsoil, a diverse seed mixture of native species, and no initial fertilization. In addition, deeper topsoil coverings may be used to increase the productivity of a native seed mix without compromising plant species richness.

Chemical Analysis of Topsoil and Retorted Shale

Results of the chemical analysis of soil and retorted shale from 1998 are summarized in Table 4. Also included in Table 4 are average pH, EC, and SAR values of retorted shale and soil prior to the construction of study plots in 1977. Our chemical analysis revealed elevated SAR and/or EC values in deeper topsoil depths of the control, TRT-60, and TRT-90 (Table 4). Native soils of the study area typically have high concentrations of salts (especially Na^+) at deeper soil depths, as reported by Tiedemen and Terwilliger (1978). Also, Redente (unpublished data, 1977) found that, despite the average EC and SAR values for topsoil in 1977 (prior to plot construction), these values ranged as high as 8.2 dS m^{-1} and 17.6, respectively, at deeper soil depths. Our data also suggest that the chemical characteristics of the underlying retorted shale have been moderated over the past 20 growing seasons, as seen by reduced pH, EC, and SAR values (as compared with data from the beginning of the study). We hypothesize that these reductions are probably the result of the deep percolation of soil water and leaching of soluble salts. Deep percolation of soil water at the study site in early spring can occur following snowmelt and thawing of soils but before plants begin growing and actively taking up water. For example, Stark and Redente (1986) measured soil moisture recharge to a depth of 120 cm on the control plot of the RSSS following the winter of 1983–1984. Thus, the movement of soil water through the soil profile in early spring, coupled with the coarse texture (gravelly silt loam) and low cation exchange capacity (CEC) (6.0 meq 100 g^{-1}) of the underlying retorted oil shale (Redente et al., 2000), may have caused the

Table 4. pH, EC†, SAR‡, B, and Mo values for the five topsoil treatments by depth. Original data on pH, EC, and SAR for the retorted shale and topsoil used in the study was taken prior to construction of study plots and is listed at the bottom of the table (data from Redente et al., 1982).

Topsoil treatment	Substrate	Depth of Sample	pH	EC	SAR	Total B	Total Mo
		cm		dS m^{-1}		mg kg^{-1}	
Control	soil	0–3	7.9	0.4	0.4	36.6	<0.5
	soil	15–18	8.0	0.7	6.0	38.7	<0.5
	soil	30–33	8.4	1.0	9.5	36.6	<0.5
	soil	45–48	8.5	2.3	16.1	24.7	<0.5
	soil	60–63	8.0	7.9	10.3	32.5	<0.5
TRT-30	soil	0–3	7.8	0.8	0.8	43.3	<0.5
	soil	15–18	8.0	0.4	0.6	40.0	<0.5
	soil/shale	30–33	8.8	0.8	1.9	55.4	3.2
	shale	45–48	8.7	3.0	2.3	75.4	11.8
TRT-60	soil	0–3	7.8	0.5	0.2	33.7	<0.5
	soil	15–18	8.1	0.5	0.8	32.9	<0.5
	soil	30–33	8.3	0.5	4.4	27.6	<0.5
	soil	45–48	8.6	0.8	10.8	33.3	<0.5
	soil/shale	60–63	8.8	1.1	11.2	37.9	<0.5
	shale	75–78	8.8	3.8	4.8	74.1	11.2
TRT-90	soil	0–3	7.8	0.5	0.1	40.0	<0.5
	soil	15–18	8.1	0.5	0.8	42.5	<0.5
	soil	30–33	8.2	0.5	5.2	43.8	<0.5
	soil	45–48	8.7	0.8	9.4	36.3	<0.5
	soil	60–63	9.1	1.0	14.9	39.2	<0.5
	soil	75–78	8.8	2.3	16.4	39.6	<0.5
	soil/shale	90–93	8.2	6.7	9.6	47.5	<0.5
	shale	105–108§	–	–	–	–	–
TRT-60CB	soil	0–3	7.8	0.5	0.2	27.6	<0.5
	soil	15–18	8.0	0.4	0.5	30.9	<0.5
	soil	30–33	8.2	0.4	2.5	35.8	<0.5
	soil	45–48	8.3	0.5	6.7	30.9	<0.5
	soil	60–63	8.3	0.8	7.2	30.0	<0.5
Retorted shale	shale	averaged over depth	9.6	18.2	14.0	N/A (not available)	N/A
Topsoil	soil	averaged over depth	8.0	4.2	6.8	N/A	N/A

† Electrical conductivity.
‡ Sodium adsorption ratio.
§ Soil samples were not taken from the 105–108 cm depth in the 90-cm topsoil treatment due to mechanical difficulties.

leaching of soluble salts to depths beyond which we sampled. Also, the finer texture (clay loam) and higher CEC (18.3 meq 100 g^{-1}) of soil covers (Mount, 1985) may help to explain why SAR values are higher in soil just above underlying retorted shale in TRT-60 and TRT-90. Given that Na^+ is one of the most weakly held cations, it may be more readily leached from retorted shale than from soil.

Overall, our data suggest that the net movement of water through the soil profiles of study plots has been downward over the past 20 yr. It should be noted that our chemical analysis data may not be representative of drier soil conditions in late summer when hydraulic lift (Richards and Caldwell, 1987) and evaporation processes may cause the upward movement of water and soluble salts. However, Berg et al. (1983) reported an overall downward movement of soil water over a 6-yr period on study plots that consisted of a 30-cm layer of soil over a fine-textured retorted shale. Despite an initial upward movement of salts into overlying soil during the first growing season, chemical analysis of soil and retorted shale performed in the spring and fall of subsequent growing seasons showed a lowering of salt concentrations throughout soil profiles by the sixth year (Berg et al., 1983).

Our soils data also indicated elevated total concentrations of B and Mo in underlying retorted shale as compared with overlying topsoil (Table 4). Higher levels of B in retorted shale do not appear to be of any consequence from a plant growth perspective as field observations during biomass sampling did not reveal any symptoms associated with B toxicity, such as chlorotic leaves, scorched leaf margins, or premature leaf drop (Barth et al., 1987). Furthermore, soil and plant tissue analyses done by Schwab et al. (1983) and Stark and Redente (1986) on RSSS plots revealed soil and plant tissue concentrations of B that were below values listed as toxic to cultivated plant species. Soluble forms of B are relatively mobile in soils (Barth et al., 1987), and leaching with low B water is often used to remove excess B from soils (Peryea et al., 1985). We did not observe any upward movement of B into overlying soil (Table 4) and we did not measure any potential leaching of B into deeper soil layers.

Elevated concentrations of Mo under field conditions are not directly toxic to plants (Neuman et al., 1987), but may become harmful to herbivores when assimilated in plant tissue. Plant tissue Mo concentrations of between 10 to 20 mg kg^{-1} (Kubota, 1975) and Cu to Mo ratios of 2:1 (cattle) and 5:1 (sheep) and below in forage plants (Neuman et al., 1987) can lead to the onset of molybdenosis in grazing livestock. Leguminous species are most vulnerable to these critical values as they accumulate Mo in plant tissue at higher concentrations than nonleguminous species (Neuman et al., 1987). Several leguminous species, such as northern sweetvetch (*Hedysarum boreale* Nutt.), alfalfa (*Medicago sativa* L.), and yellow sweetclover (*Melilotus officinalis* Lam.), are present on the study plots; however, alfalfa is the only legume present in large enough quantities (15% of biomass in the introduced seed mixture) (Table 2) that could cause potential problems with herbivores. Most importantly, Schwab et al. (1983) and Stark and Redente (1990) found that during the 1980 and 1983 growing seasons, respectively, several species growing on study plots of the RSSS had elevated plant tissue Mo concentrations and Cu to Mo ratios within or below the critical values listed previously. Stark and Redente (1986) reported that Mo is relatively immobile under field conditions, and we did not detect any upward movement of Mo into overlying soil layers (Table 4).

CONCLUSIONS

The lack of long-term data on the effectiveness of treatments used in the reclamation of phytotoxic waste materials is apparent in the literature. In an attempt to fill this void of knowledge, the current study shows that initial treatments may have long-lasting effects on the productivity, species composition, and plant species richness of plant communities 20 yr after establishment. For example, the use of topsoil overlying retorted oil shale has resulted in plant communities that are as or more productive than the control, depending on the depth of topsoil used. Also, the long-term maintenance of native, species-rich plant communities may be achieved on topsoil treatments by initially seeding with a diverse mixture of native species. Thus, productive and species-rich native plant communities may be supported over longer time scales with the use of a topsoil covering over a phytotoxic mine waste material and a native seed mixture. However, if greater productivity or increased isolation of plant roots from waste materials is a goal of reclamation, then deeper depths of topsoil or the use of a capillary barrier in conjunction with a topsoil covering may be used without compromising plant species richness.

In spite of the results reported on long-term plant community dynamics, questions still remain regarding the chemical characteristics of the underlying retorted shale. Use of a rock capillary barrier in between overlying soil and underlying retorted shale may prevent roots from coming into contact with retorted shale or limit any potential upward movement of Mo. Our observations of the capillary barrier used in this study showed that the large pores that once existed in the barrier have since filled with soil and that roots are growing through the soil-filled capillary barrier into underlying retorted shale. This treatment and other similar treatments should be analyzed further to determine plant uptake of potentially harmful trace elements. Another issue that was not considered in the current study deals with the ultimate fate of salts and trace elements originally contained in phytotoxic waste materials. Our results indicated that salts may have leached within the underlying retorted shale over the past 20 yr to the point that the retorted shale may no longer be considered phytotoxic, at least to the depth in which we sampled. However, we did not determine the extent of this leaching. Further research into the effectiveness of treatments used to reclaim phytotoxic waste materials should not only concentrate on long-term plant community dynamics, but should also consider the long-term movement of salts and trace elements within and outside of the soil–waste system.

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Interactive Effects of Soil Amendments and Depth of Incorporation on Geyer Willow

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ABSTRACT

A greenhouse study was initiated to determine the effect that depth of incorporation of soil amendments had on growth of Geyer willow (*Salix geyeriana* Andersson) planted in fluvial mine tailing. Lysimeters were constructed to simulate a 60-cm tailing profile with a static water table established at a depth of 62 cm. The amendment treatments (lime, organic matter, and lime plus organic matter) were each applied at three depths of incorporation (0–20, 0–40, and 0–60 cm). Aboveground current-year's growth (CYG) from willow cuttings grown in treatments that contained lime was more than eightfold greater than that from willows grown in treatments that did not contain lime. Willows grown in the 0- to 60-cm treatments produced 36% more aboveground CYG than those grown in 0- to 20-cm treatments and 27% more than those grown in the 0- to 40-cm treatments. Belowground CYG, averaged across all amendment treatments, also increased with depth of incorporation. Chemical analyses of the growth media indicated that the lime amendment increased pH of the mine tailing such that trace metals were made less bioavailable and, therefore, not phytotoxic. The addition of organic matter to the lime amendment proved to be beneficial for plant growth and reduced bioavailability of some metals. Willows from all treatments accumulated high concentrations of the metals Cd and Zn in aboveground CYG. Results from this study suggest that increased depth of incorporation of soil amendments into mine tailing can significantly enhance vegetative production of willow cuttings.

THE extent of mining impacts to riparian ecosystems is vast. More than 19 000 km of rivers and streams in the United States alone have been adversely affected by mining activities (National Research Council, 1992). Given the high species and functional diversity present in riparian ecosystems (Kauffman et al., 1997; Belsky et al., 1999), restoration of riparian habitats affected by mining often requires the reestablishment of diverse forms of flora.

Establishment of woody plant species is a vital component of the restoration of many riparian areas (Volny, 1984; Conroy and Svejcar, 1991). Willows (*Salix* spp.) have been identified as keystone species in riparian areas (Kauffman et al., 1995) and are important to ecosystem structure and function for many reasons. Willows provide critical habitat and resources for a broad range of organisms (Sommerville, 1992), stabilize stream banks, and help regulate stream temperatures (McCluskey et al., 1983). Additionally, willows have some tolerance to heavy metal–enriched soils (Pushon, 1996), which makes them ideal candidates for restoring these disturbed systems.

Creating a growth medium that supports the key elements of the ecosystem is essential for successful restoration (Sengupta, 1993; Munshower, 1994). The conditions necessary for establishment and survival of willows may differ from those needed for herbaceous vegetation. Willows are obligate phreatophytes (Busch et al., 1992; Smith et al., 1998) and occupy a deeper rooting zone than most herbaceous species. Subsequently, willows are more likely to be dependent on resources (e.g., nutrients and water) from lower portions of the soil profile for their survival than herbaceous species. Therefore, the depth to which a contaminated profile is amended becomes of paramount concern in the design of restoration projects that include phreatophytic species such as willows.

A greenhouse study was designed to investigate the response of Geyer willow to soil amendments incorporated into mine tailing at three depths. Geyer willow was chosen for study because it is an early colonizer of

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Abbreviations: CYG, current-year's growth; ICP–AES, inductively coupled plasma–atomic emission spectroscopy.