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Influence of Topsoil Depth on Plant and Soil Attributes of 24-Year Old Reclaimed Mined Lands

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Topsoil replacement on reclaimed mine lands is vital for improved infiltration, plant rooting media, enhanced nutrient cycling, and as a potential source of plant propagules to increase plant community diversity. Varying topsoil depth may influence reclamation success. This study assessed the long-term (24 years) effects of four topsoil replacement depths (0, 20, 40, and 60 cm) on plant community attributes (species richness, diversity, canopy cover, and production) and soil characteristics [organic carbon (C), total nitrogen (N), available phosphorus (P), pH, soluble cations, electrical conductivity (EC), and cumulative water infiltration]. Species richness and diversity were highest at the 0 cm topsoil depth and lowest at the 60 cm topsoil depth. Percent canopy cover of grasses was highest (25%) at 60 cm and lowest (15%) at 0 cm topsoil depth. Percent forb cover was highest (6%) at the 0 cm depth and lowest (2%) at 60 cm topsoil depth. Seeded species cover was highest (12%) at the 40 cm depth, but was not significantly different from the other depths. Aboveground biomass was similar between the 40 (727 kg ha^{-1}) and 60 cm (787 kg ha^{-1}) topsoil depths and higher than the 0 (512 kg ha^{-1}) and 20 cm (506 kg ha^{-1}) replacement depths. Plant species richness and diversity decreased with increasing topsoil depth, while biomass increased. Organic C mass in the soil profile (75 cm) was greatest in the 60 cm topsoil replacement (18.7 Mg C ha^{-1}) and lowest in the 0 and 20 cm treatments (11.3 and 10.5 Mg C ha^{-1}, respectively).

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N mass (75 cm profile) exhibited a similar pattern with 60 cm of topsoil having the highest (1.9 Mg N ha^{-1}) and the 0 and 20 cm the lowest (0.8 Mg N ha^{-1} and 0.9 Mg N ha^{-1}, respectively). Cumulative water infiltration was highest (134 mm) for the 40 cm topsoil depth followed by 60 cm (116 mm), and lowest (61 mm) for the 0 cm treatment. Soil N, organic C, and infiltration data indicate topsoil replacement depths of 40 and 60 cm provide the best nutrient status and water storage potential for sustainable reclamation. Placement of shallow topsoil replacement depths should be carefully planned to ensure topsoil thickness is adequate to sustain a vegetative community capable of protecting the soil surface against erosion. Variable topsoil replacement depths can be used in reclamation to manipulate plant community characteristics and create a mosaic of vegetation types. However, the reduced vegetation cover observed at the shallower topsoil depths may not protect against soil erosion; therefore, using variable topsoil depth replacement as a reclamation practice will require careful planning and implementation.

Keywords mine reclamation, plant diversity, topsoil replacement depth, long-term soil study

Topsoil salvage and replacement strategies and practices to ensure successful reclamation of mined lands has been discussed among scientists, reclamationists, and regulatory agency staff for nearly three decades. Two hypotheses have been proposed. One states that topsoil replacement should be uniform and deep (based on available soil resources) to ensure good water infiltration, water storage, plant productivity, and promote stabilization of the soil. In contrast, others believe that topsoil depth replacement should reflect the natural landscape shaped by centuries of erosion and deposition.

In some cases, topsoil depth replacement has been influenced by subsoil and spoil material quality used in reconstructing the plant growth medium profile (Barth & Martin, 1984; Merrill et al., 1985; Power et al., 1976). However, by the early 1980s scientists proposed replacing topsoil to more closely reflect that observed on natural landscapes (Schafer & Nielson, 1979; DePuit, 1984; Munshower, 1982). Researchers believed that varying topsoil depth on the reconstructed landscapes may enhance plant community diversity by simulating natural edaphic diversity created by erosion and deposition. These hypotheses stimulated research to assess the effects of various topsoil depths on plant community composition, productivity, and succession (Redente & Hargis, 1985; Schuman et al., 1985; Pinchak et al., 1985). These short-term (3–5 years) studies were inadequate to assess long-term successional processes.

The objective of this research was to evaluate effects of topsoil replacement depth on plant community richness, diversity, cover, production and soil characteristics after 24 years.

Methods and Materials

Study Site

The study site was established in the spring 1977 at Pathfinder Mining Corporation's Shirley Basin uranium mine, approximately 64 km north of Medicine Bow in south-central Wyoming (42° 21′ N; 106° 10′ W). The climate is cold and semiarid, with an average annual maximum temperature of 11.6°C and minimum of –4.4°C. Average annual precipitation is 271 mm with approximately two-thirds as snowfall (Western

Regional Climate Center, 2001), and 88 average annual frost-free days (Schuman et al., 1985). Precipitation in 2000 and 2001 was 251 and 288 mm, respectively.

Topography consists of rolling hills at an elevation of 2,117–2,151 m. Livestock grazing and wildlife habitat were premine land uses. *Artemisia tridentata* ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush), *A. frigida* Willd. (fringed sagebrush) *Pascopyrum smithii* (Rydb.) A. Löve (western wheatgrass) *Pseudoroegneria spicatum* (Pursh) A. Löve (bluebunch wheatgrass), *Stipa comata* Trin. & Rupr. (needleandthread), and *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama) comprise the dominant plant species on the landscape.

Experimental Design

Direct-hauled topsoil (a mixture of A and B horizons) was spread in a wedge, ranging from no topsoil to a depth of 60 cm over regraded spoil (Figure 1), resulting in a level surface. Topsoil was a fine-loamy, mixed Borollic Haplargid (Young & Singleton, 1977). Spoil was ripped to a depth of 45 cm before topsoil replacement. The reconstructed overburden/spoil consisted of a 1 m layer of White River spoil material placed over several meters of Wind River spoil. The White River spoil is composed of bentonitic arkosic sands interbedded with fine silts and montmorillinitic clays formed during the Oligocene Epoch. The Wind River spoil (Eocene Epoch) is characterized by high silt and clay with scattered lenses of arkosic sands in the upper portion of the formation (Schuman et al., 1985). Both spoil materials were deficient in soil organic matter, N and P but neither contained any elements at toxic levels. Topsoil and White River material physiochemical characteristics are presented in Table 1.

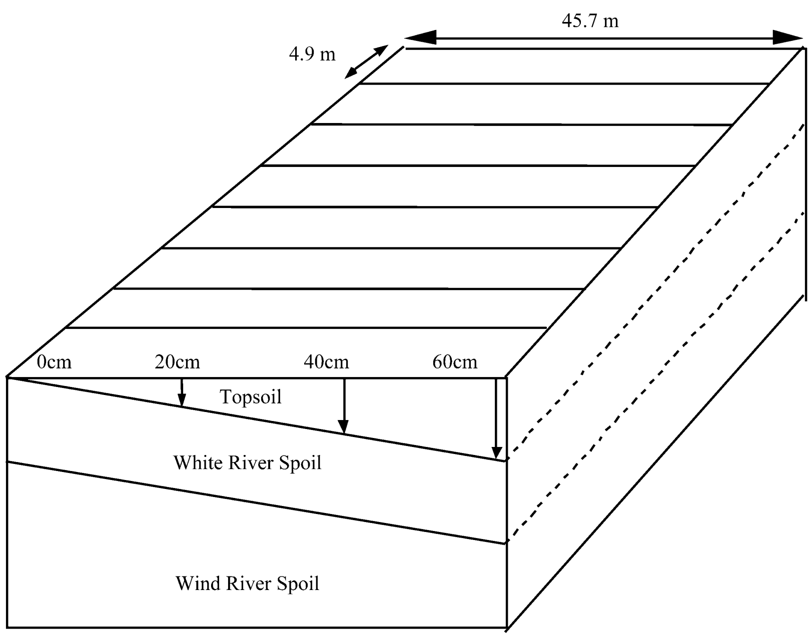

Figure 1. Diagram of the research plot design showing variable topsoil replacement depths (0, 20, 40, and 60 cm), Pathfinder Uranium mine, Shirley Basin, Wyoming (from Schuman et al., 1985).

Table 1. Chemical and physical characteristics of topsoil used in construction of the various topsoil depths and White River spoil used as 'subsoil' material, Shirley Basin, Wyoming (Schuman et al., 1985)

Characteristic	Topsoil	Spoil
pH	7.2	7.0
EC (dS m^{-1})	2.47	0.40
Organic C (%)	1.1	0.1
Kjeldahl-N (mg kg^{-1})	900	180
$NaHCO_3$-P (mg kg^{-1})	4.4	0.7
Water soluble cations (meq/L)		
Na	9.41	2.36
K	0.80	0.18
Ca	12.60	1.07
Mg	1.75	0.35
Particle size separates (%)		
Sand	57	45
Silt	30	38
Clay	13	17
Saturation percentage (%)	39	58

Experimental design was a completely randomized, split plot in time (Milliken & Johnson, 1996) with topsoil depth as factor A and two mulch treatments (straw mulch and stubble mulch), as factor B. The area was divided into 20 plots (4.9×45.7 m), running parallel to the topsoil depth gradient. In spring 1977, half of the plots were seeded to a dryland variety of barley, *Hordeum vulgare* L., to establish the stubble mulch. The remaining 10 plots were fallowed. Plots received fertilizer at rates of 67 kg P ha^{-1}(treble superphosphate) and 315 kg N ha^{-1} (ammonium nitrate) at establishment.

In October 1977, the plots were seeded with a perennial grass and shrub mixture composed of *Elymus dasystachyum* (Hook.) Scribn. (thickspike wheatgrass), *Stipa viridula* Trin. (green needlegrass), *Elymus trachycaulum* (Link.) Gould ex Shinners (slender wheatgrass), *Pascopyrum smithii*, *Artemisia tridentata*, and *Chrysothamnus nauseosus* (Pallas ex Pursh) Nesom & Baird (rubber rabbitbrush). The grass mixture and shrub component were drill seeded at a rate of 15.5 kg pure live seed (PLS) ha^{-1} and 0.5 kg PLS ha^{-1}, respectively. Straw was hand scattered on the fallowed plots at a rate of 5 Mg ha^{-1} and crimped into the soil surface to reduce loss from wind. In 1979, two nitrogen (N) fertilizer treatments were added to assess a single large application (268 kg N ha^{-1}) compared to four annual applications of 67 kg N ha^{-1} (total 268 kg N ha^{-1}) on forage production. Other details of the study design and plot construction can be found in Schuman et al. (1985).

Vegetation Sampling

In June 2001, plant canopy cover, frequency, and aboveground biomass were evaluated by species within three, 0.18 m^2 quadrats systematically located at each topsoil depth (0, 20, 40, and 60 cm) within each mulch by fertilizer treatment plot to assess long-term plant community development. A 0.3 m buffer was maintained between quadrats and plot borders. Percent cover (vegetation canopy, litter, bare ground) was estimated in each quadrat using a modified Daubenmire (1959) procedure, and frequency of occurrence was recorded for each species. Live aboveground plant biomass was assessed by clipping (by species) all live plant material at ground level within each quadrat. Clipped plant material from each of three quadrats was combined by species (three quadrats per treatment plot) and placed in paper bags, dried at 65°C for 48 h, and weighed to determine live aboveground biomass.

Relative percent cover, biomass, and frequency were calculated for each plant species within each topsoil depth and mulch by fertilizer treatment, and summed to provide an "importance value" (IV) (McCune & Grace, 2002). Importance values identify dominant species and illustrate composition of a plant community (Curtis & McIntosh, 1951).

Importance values were also used to calculate Shannon-Wiener diversity indices, Equation 1, (Krebs, 1999), which assesses proportional equivalence of species in a community and overall heterogeneity of the community (Whittaker 1977, Krebs, 1999). The Shannon-Weiner diversity index was selected because of its sensitivity to rare species in a community (McCune & Grace, 2002).

$$\underset{i=1}{\overset{S}{H'}} = -\sum(p_i)(\ln p_i) \qquad \text{(Eq.1)}$$

where H' = index of diversity, S = number of species present, P_i = relative importance value of species "i" expressed as a decimal.

Soil Sampling

Three randomly selected stubble mulch by 268 kg N ha^{-1}, crimped mulch by 268 kg N ha^{-1}, stubble mulch by 67 kg N ha^{-1} yr^{-1} and crimped mulch by 67 kg N ha^{-1} yr^{-1} treatment plots were soil sampled in August 2001, resulting in sample collection from 12 of the 20 plots. Within each plot, four soil cores (one at each topsoil depth) were taken to a depth of 75 cm. These soil cores were divided into four depth increments (0–5, 5–20, 20–40, and 40–75 cm) for the 0, 20, and 40 cm topsoil depths. The 60 cm topsoil depth treatment was separated in the same manner except the deepest increment was separated at the topsoil/spoil interface, approximately 60 cm, to separate the spoil from the topsoil. This separation of soil and spoil was achieved on all of the topsoil treatments by the selected sampling increments. There was some variability in the location of this soil-spoil interface due to settling and deposition/erosion over the past 24 years. To ensure adequate collection of sample material, the 0–5 cm sample depth was collected using a trowel. A small excavation was made with a spade to a depth slightly deeper than 5 cm, and a trowel was used to remove the 0–5 cm sample. This design resulted in 192 total soil/spoil samples, 96 from the barley stubble and 96 from the crimped straw mulch treatment. Soils were placed in plastic bags and air-dried to a constant weight. Samples were also collected for bulk density measurements from two of the three sample sites using the core method described by Blake & Hartage (1986). Samples were placed in plastic bags and dried at 105°C and bulk density calculated by dividing the dry weight of the sample (g) by the sample volume (cm^3), resulting in a mass per volume value (g cm^{-3}). Bulk density data was used to convert soil C and N concentrations to a mass basis (Mg ha^{-1}).

Total soil C and N were determined by dry combustion using a Carlo-Erba C/N analyzer (Nelson & Sommers, 1982). Organic C was calculated by subtracting inorganic C, as determined by the modified pressure-calcimeter method (Sherrod et al., 2002), from total carbon. Available P was assessed using the Na-bicarbonate method of Olsen and Sommers (1982). Soil pH and electrical conductivity were analyzed on a 1:1 soil:water extract (United States Salinity Laboratory Staff, 1954). Soluble cations (Na, Ca, Mg, K) were determined using an atomic absorption spectrometer (Rhoades, 1982).

In June 2002, water infiltration was evaluated using the double-ring infiltrometer method (Haise et al., 1956) on the same plots soil sampled in 2001. Water infiltration was measured over a 2 h period to assess equilibrium water infiltration rates in order to compare to data collected in 1979 and 1982.

Data Analysis

A three-way analysis of variance was used to evaluate the effects of topsoil depth, mulch, and N fertilizer treatment on plant species richness, diversity, cover, litter, bare ground, and aboveground biomass (SAS Institute, 1999). Analysis of variance was also used to evaluate the treatment effects on soil organic C, total N, available P, pH, EC and infiltration (SAS Institute, 1999). Mean separation was accomplished using the least significant difference method (SAS Institute, 1999). All statistical analyses were evaluated at $P \leq 0.05$.

Results and Discussion

Topsoil depth significantly influenced plant species richness, diversity, grass and forb cover, litter cover, bare ground, and aboveground biomass, as well as soil organic C, total N, available P, and water infiltration rates. There were no significant differences in plant or soil attributes due to mulch type and N fertilizer treatments imposed during establishment and early years of the study.

Plant Community Responses

Species Richness and Diversity. Deeper topsoil depths resulted in significantly lower species richness and diversity than shallower topsoil depths (Figure 2). Both species richness and diversity progressively declined as topsoil depth increased for 0 to 60 cm. The 20 and 40 cm topsoil depths were significantly greater in species richness and diversity than the 60 cm topsoildepth. Likewise, there was significantly greater species richness and diversity in the 0 cm topsoil depth treatment compared to the 40 cm treatment. Based on importance values, *Agropyron cristatum* (L.) Gaertn. (crested wheatgrass) and *Pascopyrum smithii* were the dominant grass species on the 0 (16.2, 35.2), 20 (21.3, 32.6), 40 (28.7, 34.2), and 60 cm topsoil treatments (45.9, 27.6), respectively. Sandberg bluegrass (11.6) was found on the 20 cm topsoil treatment only. The dominant forb, *Alyssum desertorum* Stapf (desert madwort), was found on the 0 (12.2), 20 (11.5), and 60 cm topsoil treatments (10.7).

These results concur with Redente et al. (1997), who also found higher species richness at shallower topsoil depths (15 cm). The increased number of species at shallower topsoil depths may be due to increased interspace, which favors species recruitment (Peart, 1989). However, as topsoil depth increased, total vegetation cover and

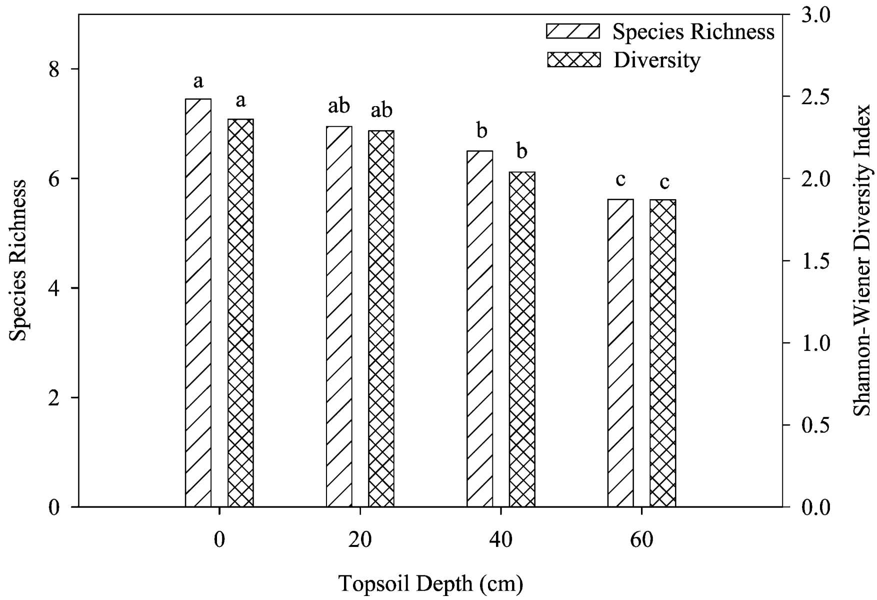

Figure 2. Species richness and diversity in response to topsoil depth, Shirley Basin, Wyoming, 2001. (Bars with the same letter within a variable, across topsoil depths are not significantly different, $P \leq 0.05$.)

biomass also increased, limiting potential recruitment of additional species. The dominate plant species were cool-season grasses, which responded to increased soil moisture stored at the deeper topsoil depths. Syndor & Redente (2000) reported similar results in northwestern Colorado. Increased competition for resources and space at deeper topsoil depths probably limited species richness over time due to competitive exclusion (Huston, 1979).

However, Pinchak et al. (1985), after only five years on this same study site, reported lower species richness where no topsoil was replaced compared to the 20, 40, and 60 cm topsoil depths. Limited cover and the addition of N fertilizer in 1979 likely caused the noted flush of observed annual forbs they reported. Vegetative cover, primarily cool-season grasses, was greater at deeper topsoil depths, where a deeper rooting zone, more stored soil water, and higher fertility provided a more competitive environment for these species, leading to the exclusion or suppression of less competitive species (Huston, 1979).

With respect to diversity, in 1981, Pinchak et al. (1985) found significantly higher diversity on the 40 cm depth compared to the 0 cm treatment and 20 and 60 cm replacement depths were not significantly different from each other or from other treatments. Their data, collected five years after seeding, included many "annual weedy forbs," indicating inadequate time for species dominance or natural recruitment to occur. Huston (1979) found that the rate of species increases in a community directly affects establishment competitive exclusion. Evidently in this study, from 1981 to 2001 was sufficiently long enough for seeded and nonseeded cool-season grasses to competitively exclude other species. Decreased diversity at deeper topsoil depths after 24 years was probably related to the limited interspace area between plants, characteristic of a dominant cool-season grass community.

Decreased diversity may be inversely related to increased competition for resources and space (Huston, 1979). According to West (1993), diversity helps maintain stable ecological communities, atmospheric gas composition, alleviates adverse climate conditions, stabilizes soils, promotes waste dispose, ensures nutrient cycling, and provides pathogenic and insect resistance.

Grass and Forb Cover. Mean percent grass cover progressively increased with increased topsoil depth replacement while forb cover decreased (Figure 3). Grass cover was significantly lower at 0 and 20 cm topsoil depths compared to the 40 and 60 cm topsoil depths, probably in response to higher nutrient levels and water holding capacity at the deeper depths. However, forb cover was significantly higher at the 0 cm topsoil depth, but progressively decreased on the 20, 40, and 60 cm topsoil depths, though these differences were not significant (Figure 3). This inverse relationship between grasses and forbs is related to the increased competition from grasses, and is expressed through greater natural recruitment of forbs where more bare ground and plant canopy openings exist (Peart, 1989). Although not originally seeded, *Agropyron cristatum* was a codominate species on the 40 and 60 cm topsoil depth treatments and was seeded on the mine in the early 1970s about a km away from the research site and invaded the 40 and 60 cm plots through natural seed dispersal. *Agropyron cristatum* produces a very vigorous and competitive seedling. Schuman et al. (1982) found *Agropyron cristatum* comprised over 95% of a stand, 4–5 years after seeding with a mixture of *Elymus trachycaulum, Elymus dasystachym*, and *Pascopyrum smithii*, and *Stipa viridula*, even though *Agropyron cristatum* only made up 25% of the seed mixture (seed number basis). These results corroborate the findings by DePuit & Coenenberg (1979) that seeding even a small amount of an aggressive, introduced species could ultimately result in a plant community

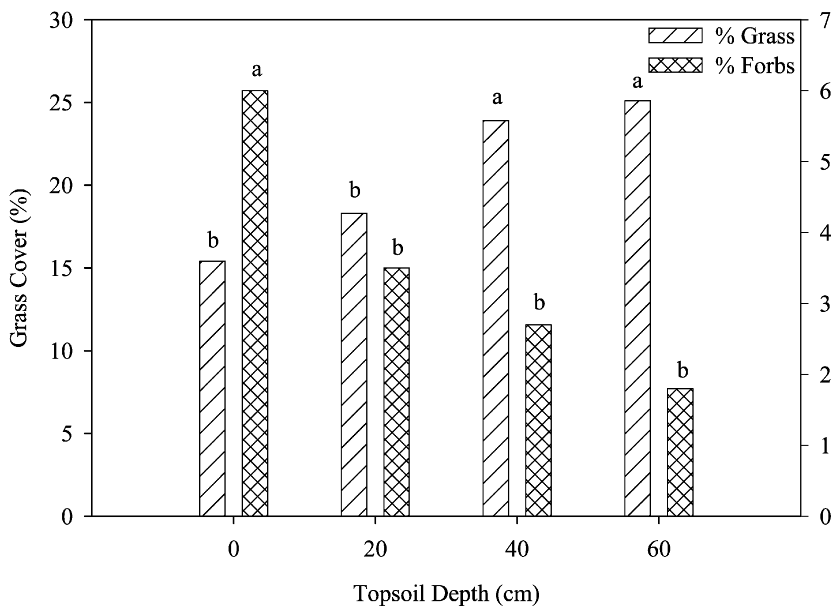

Figure 3. Percent cover of grasses and forbs in response to topsoil depth, Shirley Basin, Wyoming, 2001. (Bars with the same letter within a variable, across topsoil depths are not significantly different, $P \leq 0.05$.)

dominated by those species. Reclamationists should avoid using introduced species, such as *A. cristatum*, in mined land reclamation where plant community diversity is desired.

Depuit & Coenenberg (1979) and Doerr & Redente (1983) found that forb biomass increased and perennial grass biomass decreased on revegetated lands when N and P fertilizers were applied. Vicklund et al. (2004) reported no difference in aboveground biomass of grasses with seeding rates of 2–14 kg PLS ha^{-1} (2–3 years after seeding); therefore, higher grass seeding rates typically used by reclamationists could be reduced. Reduction in grass seeding rates should enhance species diversity in early stages of reclamation by reducing competition. Vicklund et al. (2004) found sagebrush canopy volume was enhanced at lower grass seeding rates compared to high grass seeding rates. This increase in sagebrush canopy volume is related to less resource competition by grasses during the early stages of site establishment and more open space in the plant community (Peart, 1989; Huston, 1979).

Seeded Species Cover. Mean seeded species cover ranged from 8% (20 cm) to 12% (40 cm) across topsoil depth treatments. There were no statistical differences across topsoil depth treatments. *Pascopyron smithii* accounted for the greatest cover (7.5%) across all topsoil depths among seeded species though not significantly greater. In 1985, *Elymus dasystachym* (12.4%, 14.6%) and *Stipa viridula* (4.2%, 4.0%) exhibited significantly higher cover at the 40 and 60 cm topsoil depths than at the 0 (8.3%, 7.2%) and 20 cm (0.8%, 2.6%) topsoil depths, respectively. *Elymus trachycaulum* cover was not significantly different among topsoil depths in 1981, and this species was not observed in 2001. Limited cover of seeded species at shallow soil depths is probably due to limited nutrient and water availability. At deeper soil depths, increased competition by *Agropyron cristatum* probably limited cover of the seeded grasses (Huston, 1979).

Only three of six seeded species were observed during 2001: *Elymus dasystachym*, *Pascopyron smithii*, and *Stipa viridula*. *Elymus trachycaulum* has a stand life of only 3–4 years, explaining its absence 24 years after seeding (Smith et al., 1997; Hanson, 1972). *Artemisia tridentata* ssp. *wyomingensis* and *Chyrsothamnus nauseosus* were originally seeded on the plots by drilling with the grass seed. However, Gores (1995) reported that *Artemisia tridentata* germinates and establishes best when seeded on the soil surface or at extremely shallow depths (3 mm) and light has also been shown to significantly increase germination (Weldon et al., 1959). For this reason broadcast seeding is preferred and is the most successful seeding method for many shrub species (Long, 1981; Hansen & Kleinman, 1996).

Aboveground Biomass. Total mean aboveground biomass was significantly higher at the 40 and 60 cm topsoil depths compared to the 0 and 20 cm topsoil depths. The 40 and 60 cm depths produced 727 and 787 kg ha^{-1} of live vegetation compared to 512 and 506 kg ha^{-1} for the 0 and 20 cm depths, respectively. Increased nutrient levels, as indicated by higher N, soil organic C, and available P, and available water holding capacity probably account for this response (Redente & Hargis, 1985). However, these production levels are 50% lower than 1981 for the 40 and 60 cm depths, and more than 65% less for the 0 and 20 cm depths (Pinchak et al., 1985). The decreases in live aboveground biomass observed from 1981–2001 are related to N fertilizer applications in the early study years.

Litter and Bare Ground. Mean percent litter cover progressively increased and bare ground cover decreased with increasing topsoil depths (Figure 4). There was significantly less litter cover at 0 (17%) and 20 (17%) cm topsoil depths compared

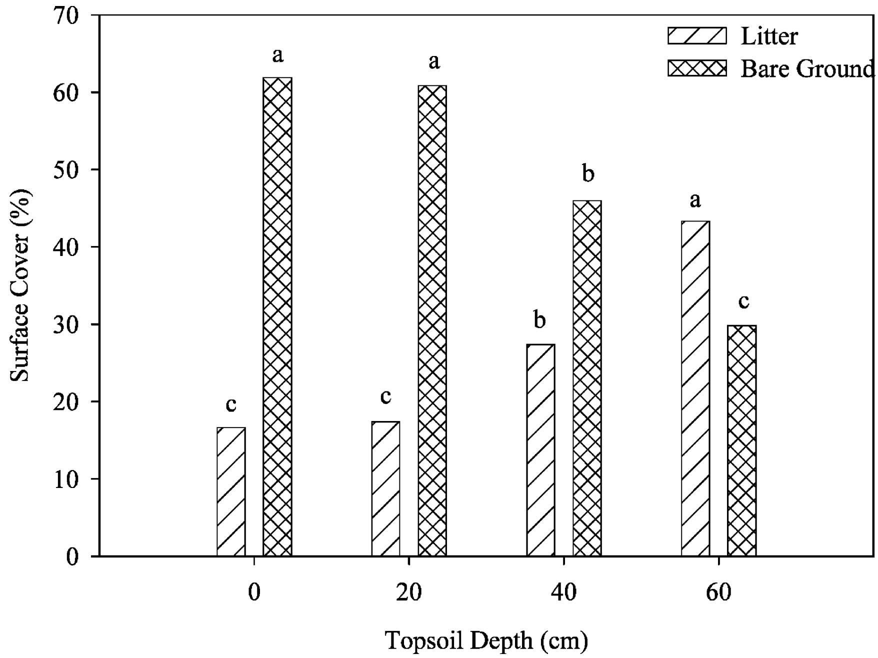

Figure 4. Percent litter and bare ground cover in response to topsoil depth replacement, Shirley Basin, Wyoming, 2001. (Bars with the same letter within a variable, across topsoil depths are not significantly different, $P \leq 0.05$.)

to 40 (27%) and 60 (43%) cm topsoil. Likewise, mean percent bare ground was significantly higher at 0 (62%) and 20 (61%) cm soil depths compared to 40 (46%) and 60 (30%) cm soil depth. Trends in litter and bare ground cover across soil depths are consistent with higher grass cover and greater total aboveground biomass reported earlier for deeper topsoil depths.

Dense cover and aboveground biomass of grass species at deeper soil depths, resulted in greater litter accumulation, which is important for reducing soil erosion from raindrop impact (Hofmann et al., 1983). Litter is also an essential component of nutrient cycling (Brady & Weil, 2002; Sylvia et al., 1998).

However, heavy litter accumulations could limit natural recruitment by preventing seed from contacting the soil. Schuman et al. (1998) found excessive rates of surface mulch reduced initial sagebrush establishment when seed was broadcast over a heavy mulch layer. High litter cover also reduces water evaporation and soil temperature, which favors cool-season species production.

The increased percent bare ground at the 0 (62%) and 20 (61%) cm depths, probably enhanced higher species richness and diversity at these topsoil depths due to more available interspace for plant species recruitment and establishment. However, there are concerns over potential wind and water erosion with higher percentage of bare ground. Hofmann et al. (1983) reported a positive correlation between percent bare ground and runoff from reclaimed lands. In their study, reclaimed lands with 54% vegetative cover (46% bare ground) exhibited soil loss to runoff ratios of 1 to 0.44 and plots with 72% vegetative cover (28% bare ground) exhibited ratios of 1 to 0.12. Therefore, the 0 and 20 cm topsoil depth treatments with >60% bare ground in this study may be prone to erosion. Although soil texture, structure, and topography strongly influence erosion potential, these shallower topsoil replacement depths may be more susceptible to erosion.

Soil Responses

Organic C and Total N. Soil organic C (SOC) and total N mass were higher in the 40 and 60 cm topsoil treatment sampling profiles (0–75 cm), compared to the shallow replacement depth profiles, 0 and 20 cm (Figure 5). This increase of SOC and N is partially due to additional topsoil applied at the 40 and 60 cm depths, which contained greater inherent levels of SOC and N than the spoil material comprising the remainder of the 0–75 cm profile (Table 1). However, increased vegetation production at these deeper topsoil depths over 24 years has also contributed considerable C. Inputs and decomposition of the greater above- and belowground residues at these depths represents a significant contribution to the observed increases in SOC and N at 40 and 60 cm topsoil depths. Reeder et al. (2001) concluded that plant residues (above-and belowground) are the largest source of organic C entering the soil. Reeder et al. (1998) reported that increased plant production and litter accumulation was responsible for C and N increases in the top 10 cm of a sandy loam soil that was reseeded to native grasses six years earlier after being wheat-fallow cropped for 60+ years in Wyoming. Bendfeldt et al. (2001) found organic C levels in revegetated, unamended plots comparable to those amended with sawdust, sewage sludge, and native soil with lime, 16 years after establishment. They also found that even though amended plots exhibited higher N levels five years after establishment, the

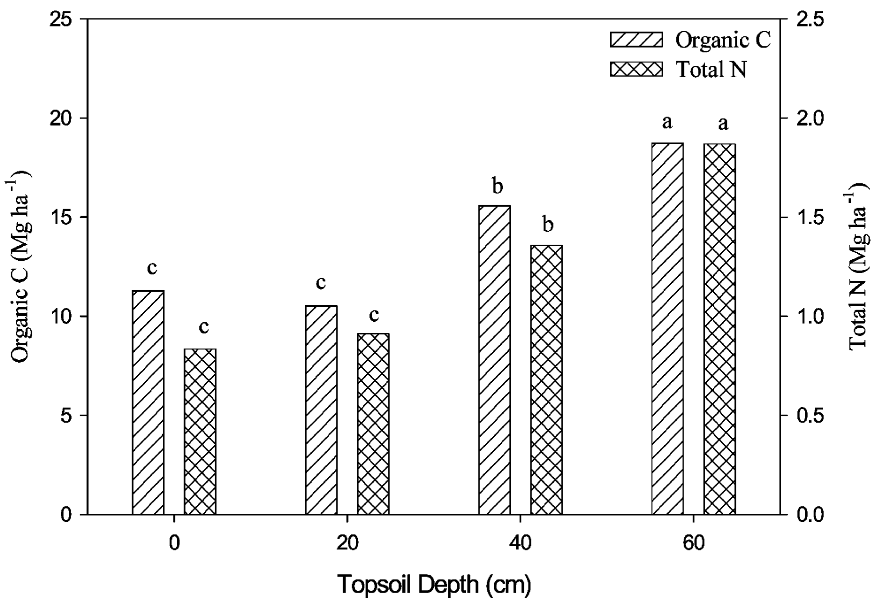

Figure 5. Mass of soil organic carbon and total nitrogen by topsoil replacement depth for soil profile (0–75 cm), Shirley Basin, Wyoming, 2001. (Bars with the same letter are not significantly different, $P \leq 0.05$.)

revegetated unamended plots, native soil with lime, and sewage sludge amended plots (112 Mg ha^{-1}) exhibited the highest levels of mineralizable N after 16 years.

Woods and Schuman (1986) and Ingram et al. (2003) found that mineralizable N levels increased with increasing SOC. In addition, Woods and Schuman (1986) found microbial biomass C and N levels in mine soil were strongly correlated with increased organic matter concentrations, and reported that SOC levels of 0.1% were unable to support adequate microbial biomass (microbial community) to provide sustainable nutrient cycling. Their work showed that between 0.1–0.7% SOC is required for sustainable plant communities. Peterjohn and Schlesinger (1990) found a strong linear relationship between increases in SOC and total N. This emphasizes the importance of additional plant biomass inputs at deeper topsoil replacement depths. Increased SOC and total N concentrations in the upper 20 cm of the profiles from 1981 to 2002 supports the hypothesis that greater vegetative biomass at greater topsoil depths over time has contributed considerable organic C to the soil system (Table 2). Nitrogen fertilizer added at study initiation and after 1981 sampling as part of the N fertilizer treatments also contributed to increased N levels from 1981 to 2001. In addition to N being cycled back into the soil system through organic matter decomposition, wet and dry atmospheric deposition may also have influenced N levels. Peterjohn and Schlesinger (1990) reported that as much as 2.99 kg N m^{-2} yr^{-1} has been deposited in southwestern desert soils of the United States. With few legume species located on these plots, N inputs from N-fixation are presumed to be low and N increases are attributable to fertilizer additions and atmospheric deposition.

Available Phosphorus. Available P in the 0–5 cm increment was highest in the 60 cm topsoil depth and lowest where no topsoil was replaced (Figure 6). The 5–20 cm sample depth increment of the 60 cm topsoil depth had the highest concentrations of P and the 0 and 20 cm depth the lowest. The 40 cm depth was not significantly different from any other topsoil depth. Higher concentrations are partially due to higher concentrations of P in the topsoil, 4.4 mg kg^{-1}, compared to 0.7 mg kg^{-1} for the spoil (Table 1). Phosphorus concentrations in 2001 were, in most instances, greater than those in 1981 (Table 2), especially in the upper portions of the profile. Increased microbial decomposition of organic matter in deeper topsoil plots due to increased root biomass and plant residue is most likely responsible for increased available P levels over time (Brady & Weil, 2002). Increased production of acid phosphatases by microbes strongly influences the availability of P, due to their ability to mineralize P bound in various compounds (Schlesinger, 1997). In addition, as soil organic matter content increases, increased microbial biomass and microbial phosphatases will occur, which results in increased available P (Polglase et al., 1992).

Water Infiltration. Cumulative infiltration, as measured over a 2 h period, exhibited a significant response to topsoil replacement depth in 2002 (Figure 7). The 40 cm replacement depth had the highest cumulative water infiltration, 134 mm, though not significantly higher than the 60 cm depth and similar to infiltration rates reported by Schuman et al. (1985) on these plots in 1982. Infiltration was lowest (61 mm) where no topsoil was replaced.

Lower infiltration at shallower topsoil depths is expected due to the higher clay content of the spoil material that represented the majority of the sampled profile in these treatments. Clay typically has a lower bulk density than sand, indicating a higher porosity in clay, but its porosity is comprised of small pore spaces with lower

Table 2. Concentrations of organic carbon (C), total nitrogen (N), and available phosphorus (P) by topsoil replacement depth and core increment depth for 2001 and 1981, Shirley Basin, Wyoming (Values with the same letter within the same year and soil depth increment are not significantly different, $P \leq 0.05$)

	Depth increment (cm)	Topsoil depth (cm)			
		0	20	40	60
Organic Carbon (%)					
2001	0–5	0.8c	1.1ab	1.0b	1.3a
	5–20	0.7a	0.5a	0.6a	0.8a
	20–40	0.4b	0.3b	0.6a	0.7a
	40–75	0.3a	0.3a	0.4a	0.2a
1981	0–15	0.3a	0.5a	0.6a	0.6a
	15–30	0.2a	0.2a	0.6a	0.7a
	30–60	0.3a	0.2a	0.3a	0.6a
	60–90	0.3a	0.2a	0.2a	0.3a
Total Nitrogen (%)					
2001	0–5	0.084c	0.119a	0.102b	0.132a
	5–20	0.036c	0.046c	0.063b	0.079a
	20–40	0.027b	0.020b	0.058b	0.065a
	40–75	0.023a	0.024a	0.027a	0.021a
1981	0–15	0.028c	0.048b	0.043b	0.060a
	15–30	0.016b	0.013b	0.051a	0.064a
	30–60	0.022b	0.019b	0.024b	0.052a
	60–90	0.021a	0.018a	0.014a	0.016a
Available Phosphorus ($mg\ kg^{-1}$)					
2001	0–5	6.0c	11.8b	11.5b	20.5a
	5–20	2.6b	1.7b	2.9ab	4.6a
	20–40	4.3a	2.3a	2.3a	3.3a
	40–75	2.8a	8.0a	2.6a	1.8a
1981	0–15	2.1c	3.5ab	3.1c	4.4a
	15–30	1.6b	1.3b	3.2a	4.2a
	30–60	1.3a	1.8a	1.0b	3.1a
	60–90	1.4a	1.4a	1.3a	1.2a

hydraulic conductivity under saturated conditions than sand which results in lower infiltration amounts and rates (Osterkamp & Joseph, 2000). Bare ground could also have reduced the infiltration rate due to surface sealing (Wangemann et al., 2000). Conversely, increased vegetation cover and production at the deeper topsoil depths facilitated water infiltration due to the improved soil structure and aggregation by plant roots (Brady & Weil, 2002). Macropores formed by live and decaying plant roots facilitate infiltration and percolation of water in deeper topsoil profiles (Beven & Germann, 1982). The increased aboveground vegetation cover and production at deeper soil replacement depths is assumed to have more plant root biomass, which

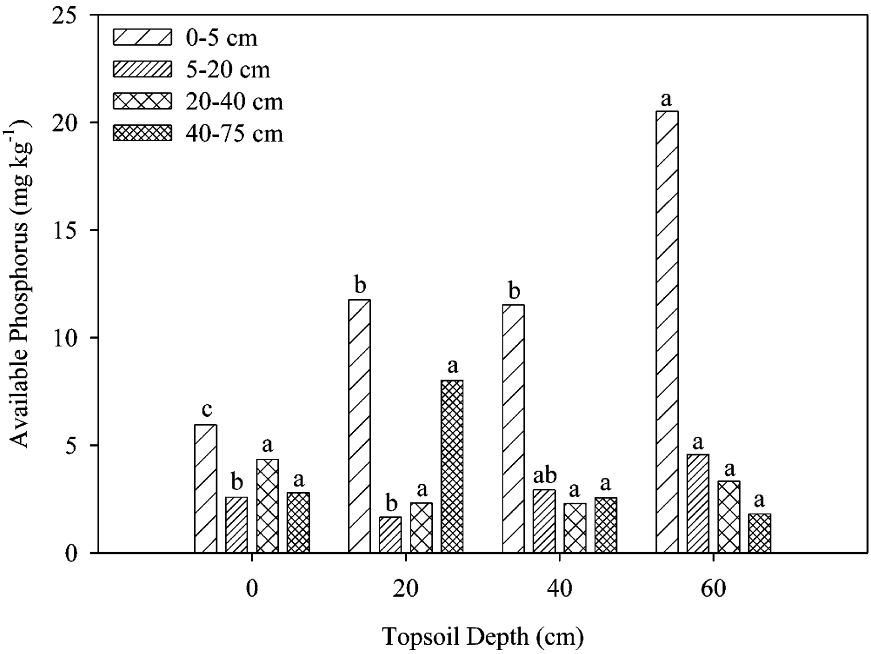

Figure 6. Available P by core increment depth in response to topsoil replacement depth, Shirley Basin, Wyoming, 2001. (Bars with the same letter within a soil core depth increment across topsoil depth are not significantly different, $P \leq 0.05$.)

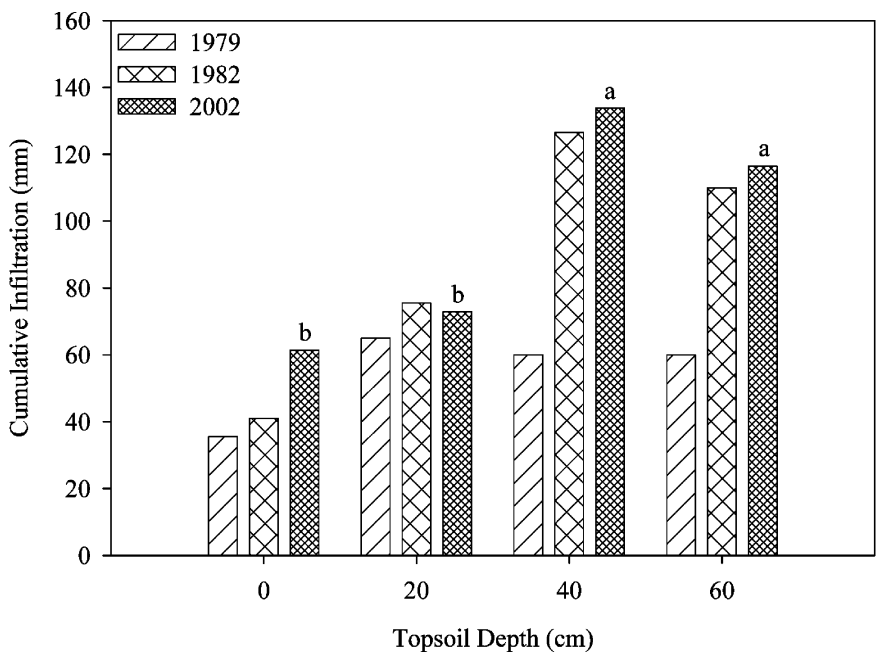

Figure 7. Cumulative infiltration in response to topsoil depth at Shirley Basin for 1979, 1982, and 2002. Data for 1979 and 1982 taken from Schuman et al. 1985. (Bars with the same letter are not significantly different, $P \leq 0.05$.)

will contribute to increased macroporosity. Gulick et al. (1994) found perennial and winter cover crops increased cumulative infiltration 250% over bare soil in irrigated croplands. Higher organic matter at deeper topsoil depths also enhances water infiltration, resulting in greater water holding capacity (Brady & Weil, 2002). Increased absorption and water storage by organic matter also favors infiltration (Brooks et al., 1997).

Conclusions

This research clearly shows the importance of long-term studies to evaluate plant community development in response to topsoil depth replacement on mined lands. Species richness, diversity, and forb cover were enhanced by shallow topsoil replacement ($\leq$20 cm). Natural recruitment and establishment of native species was greater in the open interspaces of the 0 and 20 cm topsoil replacement depths. Natural recruitment on this reclaimed mine site was undoubtedly also limited by the distance from native rangeland ($>$1.5 km), and the height of the reclaimed mine dump (several hundred meters high). Limited nutrients at shallower topsoil depths (Woods & Schuman, 1986) also limited natural recruitment. Plant communities on the 40 and 60 cm topsoil depth treatments were dominated by highly competitive cool-season perennial grasses (native and an introduced invader) that limited natural recruitment of native species. The competitive exclusion hypothesis proposed by Huston (1979) supports the observed stability of this reclaimed mine land community when topsoil depths $>$20 cm were utilized. Deeper topsoil depths provided a conducive environment for cool-season grass species, increasing resource and space competition while limiting diversity and richness (Huston, 1979). This study clearly demonstrates that variable topsoil replacement depths on mined lands can significantly influence plant species richness, diversity, and production. Therefore, to achieve a diverse plant community, variable topsoil depth replacement should be incorporated into reclamation planning in a way that limits erosion potential during the early years of plant establishment.

Soil attributes were influenced by topsoil replacement depth. This was the result of greater inherent inputs of SOC, N, and P and the impact of those benefits on aboveground production and hence organic matter inputs through plant residue and root residues available for decomposition. Greater aboveground production exhibited at greater topsoil replacement depths also greatly influenced water infiltration and stored water available for plant growth.

When using topsoil replacement depth as a tool to enhance plant community richness and diversity, care must be used to ensure that the newly established plant community is adequate to stabilize soil resources during the early years of reclamation. The high levels of bare ground measured on the 0 and 20 cm topsoil replacement depths have been shown in other research to have a high erosion potential.

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