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Ecological Studies of Natural and Established Ecosystems on Energy Related Disturbances in Colorado

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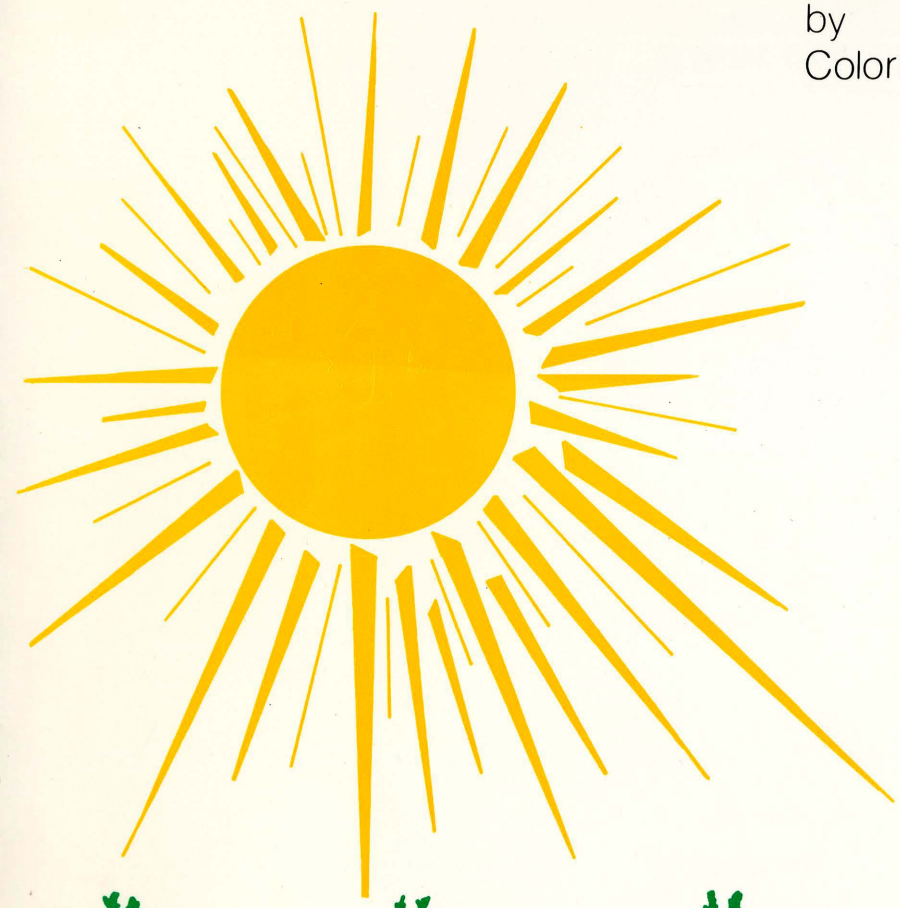

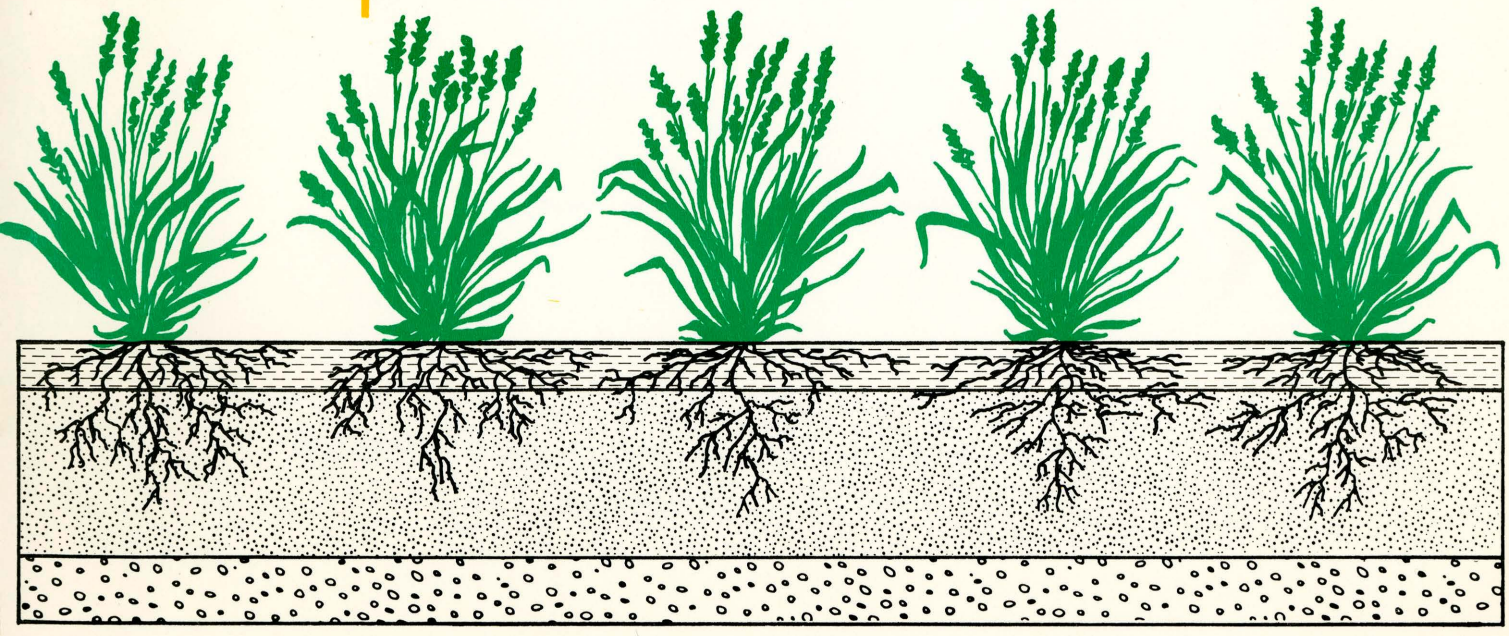

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Ecological Studies of Natural and Established Ecosystems on Energy Related Disturbances in Colorado

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Abstract

During this research period studies have concentrated on soil, plant, and microbial interactions to gain a better understanding of plant community changes over time on perturbed systems. These studies have shown that disturbance and revegetation practices influence vegetation structure and succession primarily in two ways: (1) by modifying chemical, physical, and biological properties of the soil and (2) by influencing the initial floristic composition of the plant community.

Both the intensity and the type of disturbance, through their effect on soil chemical and physical properties have been shown to influence aboveground vegetation structure and succession. These studies show that types of disturbances which create highly productive soil conditions result in low plant diversity, while disturbances which create less productive soil conditions result in high diversity. In addition, very intense disturbances which increase the rockiness of the surface soil have been shown to not only alter the rate of succession but also the direction of succession.

Similarly, the nature of the disturbance can have major effects on soil biological properties. Disturbed and revegetated soils continue to have markedly higher microbial activity and organic matter contents than undisturbed native soils. Where topsoil has been stockpiled, however, microbial activity is generally reduced. Stockpiling affects various microbial populations differently, depending on the length of the stockpiling period and whether or not the stockpile is vegetated. When the stockpile is vegetated, there is a relative increase in bacterial and fungal populations while when a stockpile is not vegetated actinomycetes show greater relative abundance. When topsoil is stored for a period of four years, significant and predictable declines in Mycorrhiza Inoculum Potential (MIP) of the soil occur. However, the MIP of the upper levels (<90 cm) of topsoil can be preserved and enhanced by seeding with plant species that host VAM fungi.

Certain reclamation practices may temporarily influence soil chemical and physical characteristics and thus affect biological structure and succession in the above- and belowground compartments. Fertilization, for example, continues to have a positive influence on plant production in some studies. Its influence on plant species diversity, however, has been negative. The effect of fertilizer on the belowground compartment is most apparent with fungal populations. In general, fertilization causes reduced fungal hyphal lengths and a reduction in MIP values.

When disturbance results in a material such as retorted oil shale being used as a growth medium, the chemical, physical, and biological properties are drastically altered. Few plant species have been shown to perform well on this material and as a result, plant communities established on Paraho retorted shale are low in diversity and canopy cover. In the belowground compartment, retorted shale has a negative effect on phosphatase activity and nitrogen fixation and seems to prevent mycorrhizal formation. Mixing retorted shale with topsoil ameliorates these effects somewhat. Mycorrhizal formation is not inhibited until the amount of added shale exceeds 50%.

The negative effects of retorted shale are primarily due to its high salt content and its high pH which results in a high availability of toxic elements and poor nutrient availability. The chemical equilibria involved in producing the high pH in oil shale have been studied. During the processing of oil shale at high temperatures, carbonate minerals are often destroyed and silicate minerals such as $CaSiO_3$ (pseudowallastonite) and $MgSiO_3$ (clinoenstatite) are formed. These minerals buffer the pH of spent shale near 12. When processed Lurgi shale is recarbonated by bubbling CO_2 through suspensions of spent shale, the pH is decreased from 11.6 to 7.9. The result is a disappearance of the silicate minerals and formation of $CaCO_3$ (calcite) and $MgCO_3$ (magnesite).

In addition to modifying soil properties, these studies show that the second major way that disturbances and revegetation practices affect vegetation structure and succession is by influencing the initial floristic composition of the plant community. By initially seeding grasses and forbs alone, shrubs can be prevented from invading the stand in spite of the fact that shrubs are well adapted to the site and there is a ready seed source. Including adapted shrub species in the initial seed mixture on the same sites, however, can result in greater total biomass without significant reductions in grass and forb biomass. Since results of another study on competition among woody plants offer no support for the hypothesis that intensity of competition between shrubs is correlated with the abiotic environment, planting densities for the shrubs studied may be selected without consideration of shrub competition.

Once the initial floristic composition of the community is determined, changes in species composition may occur due to competitive

interactions. The competitive interactions among four native grass species occurring on the site have been studied. Competitive relationships among species are discussed in terms of the effect of fertilizer, soil depth, and phenologic stage on biomass and gross energy content of competing pairs.

Identification of adapted species for use in revegetation is often difficult since ecotypes of the same species can be quite variable. Therefore, the ecogenic variation within eight native species (five shrubs, one forb, and two grasses) has been studied and adaptive advantages of the genetic differences are discussed.

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VEGETATION STRUCTURE AND SUCCESSION AS THEY RELATE TO SOIL DISTURBANCE AND RETORTED OIL SHALE

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DIRECT REVEGETATION OF PARAHO RETORTED OIL SHALE

Introduction

The objective of this study was to establish a diverse, self-sustaining plant community on Paraho retorted oil shale with a minimum of cultural inputs. Initial attempts to establish plants directly on retorted shale using only fertilization in 1977 proved unsuccessful (Redente et al. 1981). In 1979 new seed mixtures and fertilizer treatments were applied with straw mulch in a second attempt to establish functional plant communities.

Methods Used in 1979

The three seed mixtures used were composed of either all native, all introduced, or a salt-tolerant species mixture (Table 1). The following three combinations of phosphorus and nitrogen were applied: (1) 672 kg P/ha, 56 kg N/ha; (2) 488 kg P/ha, 56 kg N/ha; and (3) 244 kg P/ha, 56 kg N/ha. These three rates were chosen because greenhouse studies revealed that Paraho retorted oil shale was phosphorus and nitrogen deficient, which severely limited plant growth (Redente, unpubl. data). The phosphorus was incorporated into the upper 15 cm of the profile using a tractor-mounted rototiller prior to seeding. The nitrogen was applied during the spring of the first growing season following seedling emergence. Seeds were hand-broadcasted and covered by raking. Finally, seed-free straw mulch was applied at 2.2 MT/ha to reduce the high surface temperatures and to increase available moisture for germinating seeds.

Results of the 1979 Seeding

Generally, individual plants growing on Paraho retorted shale were low in stature, vigor, and biomass; chlorotic in color; and lacked reproductive structures. Open spaces of the seeded communities had become dominated by invading plants, particularly Russian thistle (Salsola iberica) and kochia (Kochia scoparia). After two growing seasons invading weeds accounted for over 70% of the total biomass, and seeded species production was less than 120 kg/ha. Since establishment of the seeded species was so poor, following the 1981 growing season the Shale-to-Surface plots were further modified in an attempt to produce a more desirable plant community.

Methods Used in 1981

Each of the three replicates of the original experimental design underwent different treatments following the 1981 growing season. This allowed a broader range of treatments to be applied to the Shale-to-Surface Study, with each of the 27 subplots of this study now representing an individual treatment without replication.

One-third of the Shale-to-Surface area was left intact without further modification to monitor the change in existing species composition through time and to determine the effects that Russian thistle, the major plant component, would have on modifying the retorted shale as a plant growth medium. On the second one-third of the area the existing vegetation was left intact, but the growth medium was modified by leaching with 75 cm of water applied during six consecutive nights of irrigation in August 1981. This area was then fertilized by surface applications using the same rates applied in 1979. The final one-third of the Shale-to-Surface area received the most intensive modification beginning with an application of glyphosate to kill all existing vegetation. Following the herbicide treatment, 75 cm of water was applied in a similar fashion as on the area described above. The same fertilizer rates were also applied. The surface 15 cm were cultivated using a rototiller, and the area was then reseeded using the same seed mixtures and rates as in the 1979 planting. Following seeding, a seed-free straw mulch was

Table 1. Seed mixtures and rates used on the Retorted Shale-to-Surface Study.

Common Name	Scientific Name	Seeding Rate (kg/ha)
Mixture A--Salt-tolerant species		
1. Jose tall wheatgrass	Agropyron elongatum	4.5
2. Rosana western wheatgrass	Agropyron smithii	2.2
3. Critana thickspike wheatgrass	Agropyron dasystachyum	1.1
4. Oahe intermediate wheatgrass	Agropyron intermedium	2.2
5. Slender wheatgrass	Agropyron trachycaulum	2.2
6. Vinal Russian wildrye	Elymus junceus	1.1
7. Madrid yellow sweetclover	Melilotus officinalis	1.1
8. Ladak alfalfa	Medicago sativa	1.1
9. Strawberry clover	Trifolium fragiferum	1.1
10. Fourwing saltbush	Atriplex canescens	4.5
11. Shadscale saltbush	Atriplex confertifolia	4.5
12. Mat saltbush	Atriplex corrugata	2.2
13. Castle Valley clover	Atriplex cuneata	3.4
14. Gardner saltbush	Atriplex gardneri	2.2
15. Winterfat	Ceratoides lanata	4.5
		37.9
Mixture B--Native species		
1. Beardless bluebunch wheatgrass	Agropyron inerme (spicatum)	2.2
2. Sodar streambank wheatgrass	Agropyron riparium	1.1
3. Rosana western wheatgrass	Agropyron smithii	2.2
4. Paloma Indian ricegrass	Oryzopsis hymenoides	1.1
5. Green needlegrass	Stipa viridula	1.1
6. Sweetvetch	Hedysarum boreale	6.7
7. Lewis flax	Linum lewisii	1.1
8. Palmer penstemon	Penstemon palmeri	0.6
9. Big sagebrush	Artemisia tridentata	0.1
10. Fourwing saltbush	Atriplex canescens	4.5
11. Curlleaf mountain mahogany	Cercocarpus ledifolius	4.5
12. Winterfat	Ceratoides lanata	4.5
		34.2
Mixture C--Introduced species		
1. Nordan crested wheatgrass	Agropyron desertorum	1.1
2. Jose tall wheatgrass	Agropyron elongatum	4.5
3. Oahe intermediate wheatgrass	Agropyron intermedium	2.2
4. Siberian wheatgrass	Agropyron sibiricum	1.1
5. Luna pubescent wheatgrass	Agropyron trichophorum	2.2
6. Regar meadow brome	Bromus biebersteinii	2.2
7. Vinal Russian wildrye	Elymus junceus	1.1
8. Lutana cicer milkvetch	Astragalus cicer	2.2
9. Ladak alfalfa	Medicago sativa	1.1
10. Madrid yellow sweetclover	Melilotus officinalis	1.1
11. Small burnet	Sanguisorba minor	4.5
12. Siberian peashrub	Caragana arborescens	13.4
13. Russian olive	Elaeagnus angustifolia	44.8
		81.5

applied at 2.2 MT/ha to promote successful plant establishment.

During 1983 a double sampling technique was used to collect vegetation data by species (Wilm et al. 1944) with nine randomly placed quadrats per subplot. Density, aboveground biomass, and percent canopy cover for each species were recorded. Vegetation data was analyzed using analysis of variance techniques to determine if differences in total aboveground biomass existed among seed mixtures or fertilizer treatments. Statistically significant differences among leaching treatments were not determined because of lack of treatment replication.

Nordan crested wheatgrass (Agropyron desertorum) and Siberian wheatgrass (A. sibiricum) were indistinguishable in the field, so for sampling purposes they were grouped together and are referred to in this report as the crested wheatgrass complex. Luna pubescent wheatgrass (A. trichophorum) and Oahe intermediate wheatgrass (A. intermedium), also indistinguishable in the field, will be referred to as the pubescent-intermediate wheatgrass complex. These species groupings apply only to the introduced seed mixture.

Results and Discussion of 1981 Seeding

Effects of Leaching Treatment

The 1983 vegetation data showed large differences among the three leaching treatments (Fig. 1). Seeded species in the leached/reseeded portion of this study failed to become established during the 1982 growing season. The data reflect this failure which resulted in invading forbs composing 89% of the aboveground production for this treatment. Because of this reseeding failure the vegetation data for the leached/reseeded section was omitted from the calculations concerning seed mixture and fertilizer effects. Only the data from the leached and unleached areas were used in these calculations.

The failure of seeded species to become established on the reseeded area is most likely due to the heavy annual weed competition which occurred during the summer immediately after seeding. Apparently kochia had a ready seed source and responded to the fertilizer and added leaching water by producing a dense stand. The few seeded species which did germinate and were observed early in the growing season lacked vigor, with virtually none surviving the hot, dry summer.

The leached treatment produced considerably more aboveground biomass than the unleached treatment (Fig. 1). The reason for this effect is most likely that leaching provided additional water for plant growth and also reduced salt concentrations in the retorted shale. In 1981 the retorted shale had an electrical conductivity (EC) of 18.2 mmhos/cm and a sodium adsorption ratio (SAR) of 9.5. Leaching with 75 cm of water improved the conditions for plant growth by reducing salt concentrations to an EC of 5.8 mmhos/cm and SAR of 5.0 in

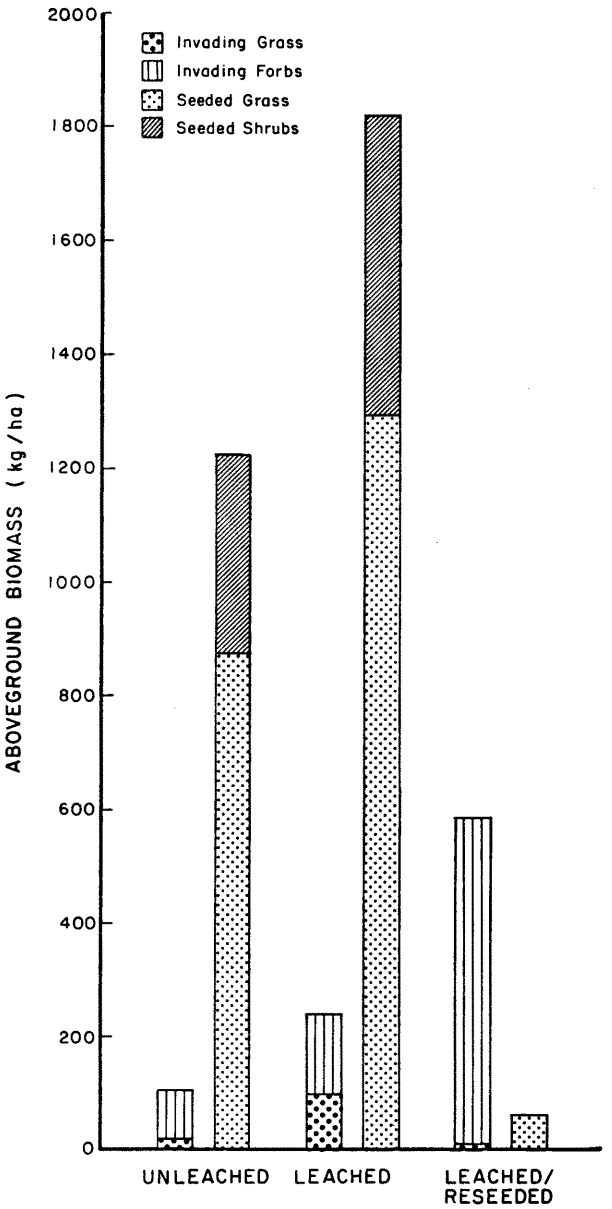

Fig. 1. Mean dry weight of aboveground biomass (kg/ha) by leaching treatment on the Shale-to-Surface Study in 1983.

1983. Most species responded to the more favorable conditions by increasing production approximately 50% over the unleached treatment. This increase was fairly even across seed mixtures and was not surprising since, in addition to leaching, this section was refertilized and was therefore operating on a richer nutrient supply than the unleached area. It should be noted, however, that in 1983 aboveground production on the unleached treatment increased 10-fold over the 1981 production. The two additional years of natural weathering lowered the EC and SAR of this treatment from 18.2 mmhos/cm and 9.5 in 1981 to 8.4 mmhos/cm

and 8.0 in 1983. This indicates an improvement in growing conditions brought about by natural weathering. Examination of plant roots on the Shale-to-Surface Study during 1983 revealed that roots of larger plants have entered the soil below the 60-cm layer of shale. This new source of water and nutrients may have been partly responsible, along with the lower salt concentrations, for the increased production over that of 1981.

Effects of Seed Mixture

The effects of seed mixture on aboveground production are shown in Fig. 2. The salt-tolerant mixture produced slightly more aboveground biomass than the introduced mixture, with both producing considerably more than the native mixture (Fig. 2). These differences however were not significant. Grass production in the salt-tolerant mixture was dominated by intermediate wheatgrass (moderately salt tolerant) which composed 80% of the aboveground biomass while thickspike wheatgrass (Agropyron dasystachyum) and Russian wildrye (Elymus junceus) made up 12% and 6%, respectively. All seed mixtures responded similarly to the leaching treatment with increased production compared to the unleached treatment.

Seeded grass production was greatest in the introduced mixture. This was probably due to the lack of shrub competition since no introduced shrubs became established on this study. The pubescent-intermediate wheatgrass complex composed 94% of the introduced grass production. These grasses had a very robust appearance, with individuals frequently being much larger than the same species in the nearby study containing topsoil. Densities of all grass species in the Shale-to-Surface study were low, allowing individual plants to occupy more space both above and below the ground than if densities were higher. The pubescent-intermediate wheatgrass complex apparently was able to utilize this growing space more effectively than other plants.

Figure 2 shows that the native grasses performed poorly on the Shale-to-Surface Study. The failure of the native grasses to become well established on the Shale-to-Surface plots was accompanied by a greater amount of invaders present. In fact, in 1983 the invading grasses, which were mostly species from the adjacent salt-tolerant or introduced mixtures, produced more biomass than the seeded native species. Streambank wheatgrass (Agropyron riparium) composed 75% of the seeded grass production in the native mixture, but since the total production of all seeded grasses was only 58 kg/ha, even this dominant species was not thriving. Because of their low production the grass species in the native mixture do not seem suited for rapid revegetation of retorted shale. The high salts, sodium, and pH apparently were more detrimental to native species than to the salt-tolerant or introduced species.

Seeded forbs failed to establish in any of the three seed mixtures. Forb species such as alfalfa (Medicago sativa), yellow sweetclover (Melilotus officinalis), sweetvetch (Hedysarum boreale), Lewis flax (Linum lewisii), and cicer milkvetch (Astragalus cicer), readily found in the adjacent Retorted Shale Topsoil Study, could not withstand the harsh growing conditions of the retorted shale.

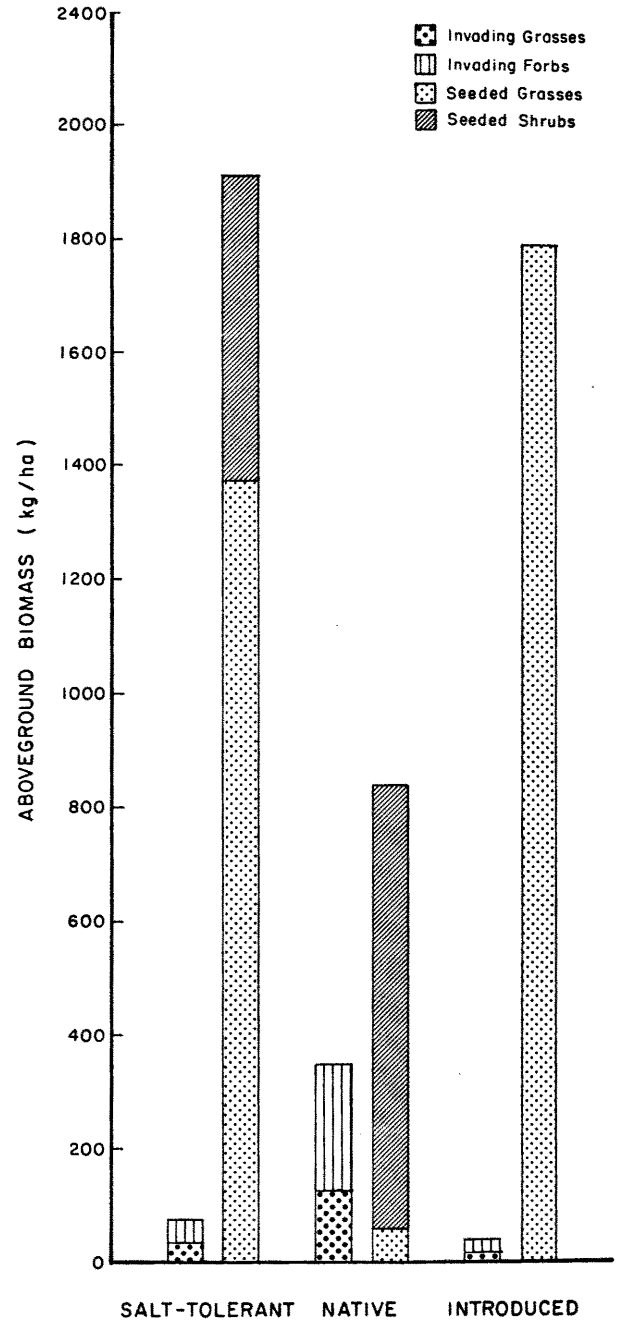

Fig. 2. Mean dry weight of aboveground biomass (kg/ha) by seed mixture on the Shale-to-Surface Study in 1983. Values are averages of leached and unleached treatments. Treatment means were not significantly different (α = 0.10).

Shrub production was greatest in the native seed mixture where winterfat (Ceratoides lanata)

and fourwing saltbush (Atriplex canescens) composed 55% and 45% of the shrub biomass, respectively. These same two species composed 90% of the shrub biomass in the salt-tolerant mixture. The higher shrub production in the native seed mixture was probabily due to the lack of grass competition. Siberian peashrub (Caragana arborescens) and Russian olive (Eleagnus angustifolia) failed to become established in the introduced mixture.

Effects of Fertilizer

The effects of fertilizer observed in the unleached and leached treatments are shown in Fig. 3. Both treatments were fertilized in 1979, but the leached treatment was again fertilized in 1981, two months after leaching. All fertilizer treatments received 56 kg N/ha; only the P application varied, so a differential response would indicate a P effect.

Total production among fertilizer treatments did not vary significantly. However, production was considerably higher on the high P treatment (672 kg P/ha) within the leached area than on all other treatments (Fig. 3). Production on the unleached plots did not vary greatly among fertilizer treatments and was actually highest on the low P treatment. This could indicate that the leaching treatment allowed the plants to respond to the higher P application, while the higher salt content on the unleached plots prevented a fertilizer response from occurring. This conclusion must be approached cautiously, however, because even on the leached treatment moderate P did not produce any more biomass than the low P application. It is also possible that the more recent fertilization of the leached area was responsible for the different response between leaching treatments.

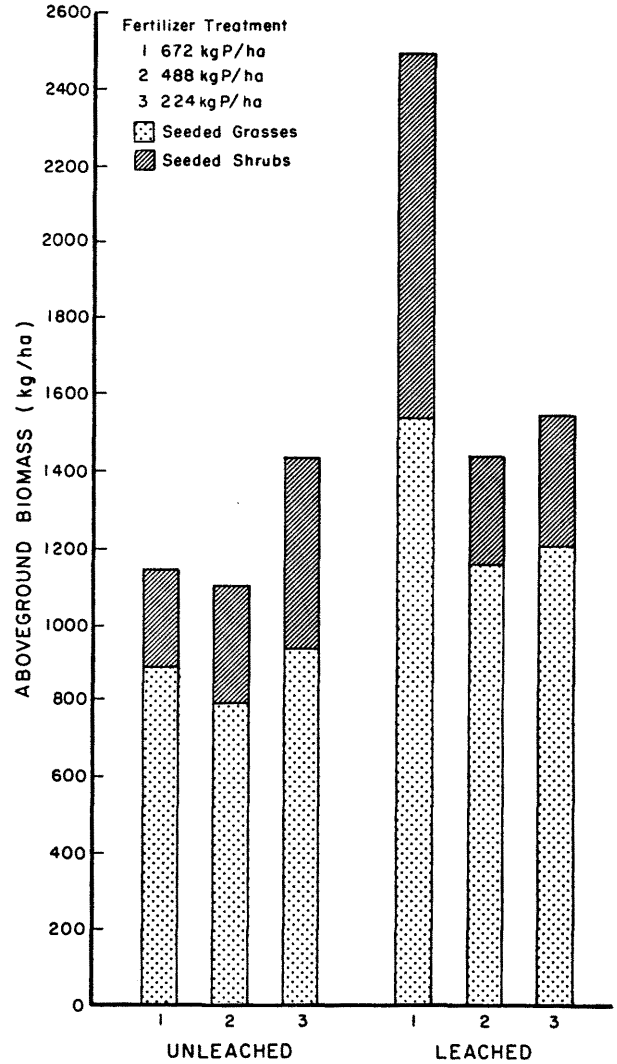

Fig. 3. Mean dry weight of aboveground biomass (kg/ha) by fertilizer rate within the unleached and leached treatments of the Shale-to-Surface Study in 1983.

Conclusions

Attempts to revegetate retorted shale without soil cover resulted in a plant community that was productive but low in canopy cover and diversity. On the unleached portion of this study, after six years of natural weathering, total aboveground biomass equaled 1335 kg/ha. This represents a 10-fold increase in production from 1981 to 1983. The leached portion of this study produced 50% more aboveground biomass than the unleached area. The 75 cm of leaching water lowered the salt content by approximately 30% compared to the unleached treatment, providing more favorable growth conditions. The high production on the Shale-to-Surface Study occurred in 1983 presumably because roots of the dominant plants have recently penetrated the 60 cm of retorted shale and have entered the underlying soil. This soil contained stored moisture which had not been removed by plants in previous years.

Vegetative production on the Shale-to-Surface Study was composed of a small number of dominant species. The pubescent-intermediate wheatgrass complex composed approximately 87% of the seeded grass biomass over all treatments. The large size and low densities of the pubescent-intermediate wheatgrass plants resulted in lower canopy cover than would have been present if a large number of smaller plants comprised the biomass, as seen on the topsoil treatments. High canopy cover is desirable in revegetation, especially on retorted shale when protection from water and wind erosion is essential. Native grasses used in this study generally lacked vigor, had low production, and were not able to close the area to invasion. If a successful native plant community is to be established directly on retorted shale, more native species must be found which can tolerate the adverse conditions of the shale. Winterfat and fourwing saltbush composed 95% of the shrub biomass of this study over all treatments. Since no seeded forbs became established, these two shrubs and the

pubescent-intermediate wheatgrass complex accounted for approximately 90% of the total production over all treatments. This low level of diversity is presently undesirable in land reclamation.

RETORTED SHALE SUCCESSIONAL STUDY

Introduction

The Retorted Shale Successional Study was begun in the summer of 1977 to evaluate plant growth and succession as affected by various topsoil depths over retorted shale along with the effects of a capillary barrier. To study this, several topsoil/shale profiles were constructed to simulate conditions that may result from various retorted shale disposal schemes. The dimensions of each profile treatment measured 23x109 m and varied in depth from 60 to 150 cm depending upon the treatment. The profile configurations are:

1. 30 cm topsoil over retorted shale
2. 60 cm topsoil over retorted shale
3. 90 cm topsoil over retorted shale
4. 60 cm topsoil over 30 cm rock capillary barrier over retorted shale
5. Control which consisted of disturbed soil with no retorted shale (vegetation removed and soil ripped to 30 cm)

All profiles containing shale received 60 cm of Paraho (direct mode process) retorted shale from the Anvil Points retorting facility near Rifle, Colorado. The lower 15 cm of retorted shale in each profile was compacted to reduce soil water movement through the material.

Following topsoil placement the five profiles were drill seeded with three seed mixtures which consisted of diverse combinations of grasses, forbs, and shrubs. The three mixtures contained either all native, all introduced, or a combination of native and introduced species (Table 2). Nitrogen (N) and phosphorus (P) were applied in the following combinations:

Treatment 1: 112 kg N/ha, 56 kg P/ha

Treatment 2: 56 kg N/ha, 28 kg P/ha

Treatment 3: no fertilizer

The study is a factorial design with three main factors: five topsoil depths x three seed mixtures x three fertilizer rates for a total of 45 treatments. All possible treatment combinations occur in each of three replications for a total of 135 subplots.

A double sampling technique (Wilm et al. 1944) was used to collect vegetation data with nine randomly placed quadrats per subplot. Vegetation data was analyzed by life form (grasses, forbs, and shrubs) using analysis of variance techniques to study main effects and interactions.

Treatment means were separated using least significant differences ($\alpha = 0.10$). All biomass figures are oven-dry weights. Several of the seeded grass species were indistinguishable in the field during the 1983 growing season. These species were combined and considered a two-species complex both during sampling and in this report. Nordan crested wheatgrass (Agropyron desertorum) and Siberian wheatgrass (A. sibiricum) were grouped together and referred to as the crested wheatgrass complex. Critana thickspike wheatgrass (A. dasystachyum) and Sodar streambank wheatgrass (A. riparium) were grouped together as the streambank-thickspike wheatgrass complex. In the introduced mixture, Luna pubescent wheatgrass (A. trichophorum) and Oahe intermediate wheatgrass (A. intermedium) were grouped and referred to as the pubescent-intermediate wheatgrass complex.

Results and Discussion

Each of the three treatments of topsoil depth, seed mixture, and fertilizer rate had a significant influence on aboveground production in 1983. Several significant interactions also occurred, most notably between seed mixture and fertilizer rate.

Effects of Topsoil Depth Over Retorted Shale

Aboveground biomass of seeded species was significantly greater on the 60-cm soil/capillary barrier treatment compared to all other topsoil treatments and the control (Fig. 4). Examination of the capillary barrier late in the 1983 growing season showed soil and plant roots entering the upper half of the gravel layer, with the lower half remaining essentially clear of soil and roots, thus retaining its large pore size. Gravel layers such as that used in the capillary barrier treatment have been shown to enhance the water storage characteristics of the overlying soil (Brady 1974). By disrupting the downward movement of water, the gravel layer can greatly increase the field capacity of the topsoil and thus increase plant available water. Preliminary studies have shown that this effect has been occurring on the 60-cm soil/capillary barrier treatment resulting in more favorable growth conditions. This would explain why the capillary barrier treatment consistently produced higher aboveground production than the others.

Seeded grass biomass was highest on the 60-cm soil/capillary barrier treatment, accounting for 93% of the total aboveground production in 1983 (Fig. 4). The introduced grasses that performed best on the capillary barrier treatments were the crested wheatgrass complex, pubescent-intermediate wheatgrass complex, and meadow brome (Bromus biebersteinii) which composed 28%, 18%, and 14%, respectively, of the grass biomass on this treatment. The native grasses showing good production on this treatment were the streambank-thickspike wheatgrass complex and bearded bluebunch wheatgrass

Table 2. Seed mixtures and rates used on the Retorted Shale Successional Study.

Common Name	Scientific Name	Seeding Rate (kg/ha)
Mixture A--Combination (native and introduced species)		
1. Nordan crested wheatgrass	Agropyron desertorum	1.1
2. Siberian wheatgrass	Agropyron sibiricum	1.1
3. Critana thickspike wheatgrass	Agropyron dasystachyum	1.1
4. Sodar streambank wheatgrass	Agropyron riparium	1.1
5. Slender wheatgrass	Agropyron trachycaulum	1.1
6. Regar meadow brome	Bromus biebersteinii	1.1
7. Indian ricegrass	Oryzopsis hymenoides	1.1
8. Green needlegrass	Stipa viridula	1.1
9. Durar hard fescue	Festuca ovina duriuscula	0.6
10. Madrid yellow sweetclover	Melilotus officinalis	0.6
11. Sweetvetch	Hedysarum boreale	1.1
12. Globemallow	Sphaeralcea munroana	0.6
13. Lewis flax	Linum lewisii	0.6
14. Arrowleaf balsamroot	Balsamorhiza sagittata	1.1
15. Fourwing saltbush	Atriplex canescens	1.1
16. Stansbury cliffrose	Cowania mexicana stansburiana	1.1
17. Winterfat	Ceratoides lanata	1.1
18. Green ephedra	Ephedra viridis	1.1
		17.8
Mixture B--Native species		
1. Rosana western wheatgrass	Agropyron smithii	1.1
2. Sodar streambank wheatgrass	Agropyron riparium	1.1
3. Bearded bluebunch wheatgrass	Agropyron inerme (spicatum)	1.1
4. Indian ricegrass	Oryzopsis hymenoides	1.1
5. Green needlegrass	Stipa viridula	1.1
6. Shermans big bluegrass	Poa ampla	1.1
7. Alkali sacaton	sporobolus airoides	0.6
8. Globemallow	Sphaeralcea munroana	0.6
9. Sweetvetch	Hedysarum boreale	1.1
10. Palmer penstemon	Penstemon palmeri	0.6
11. Stansbury cliffrose	Cowania mexicana stansburiana	2.2
12. Green ephedra	Ephedra viridis	1.1
13. Fourwing saltbush	Atriplex canescens	1.1
14. Winterfat	Ceratoides lanata	1.1
15. Antelope bitterbrush	Purshia tridentata	1.1
		16.1
Mixture C--Introduced species		
1. Nordan crested wheatgrass	Agropyron desertorum	1.1
2. Siberian wheatgrass	Agropyron sibiricum	1.1
3. Jose tall wheatgrass	Agropyron elongatum	1.1
4. Luna pubescent wheatgrass	Agropyron trichophorum	1.1
5. Oahe intermediate wheatgrass	Agropyron intermedium	1.1
6 Manchar smooth brome	Bromus inermis	1.1
7. Regar meadow brome	Bromus biebersteinii	1.1
8. Vinal Russian wildrye	Elymus junceus	1.1
9. Ladak alfalfa	Medicago sativa	0.6
10. Madrid yellow sweetclover	Melilotus officinalis	0.6
11. Lutana cicer milkvetch	Astragalus cicer	0.6
12. Sainfoin	Onobrychis viciaefolia	0.6
13. Bouncing bet	Saponaria officinalis	1.1
14. Small burnet	Sanguisorba minor	2.2
15. Siberian peashrub	Caragana arborescens	1.1
16. Russian olive	Elaeagnus angustifolia	2.2
		17.8

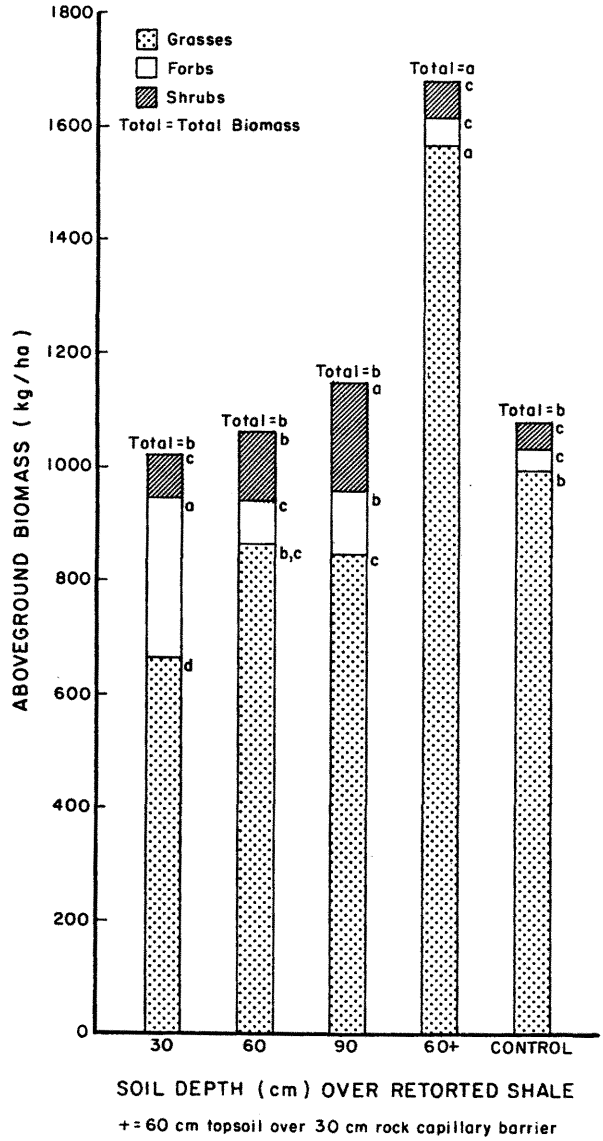

Fig. 4. Mean dry weight of aboveground seeded biomass (kg/ha) by soil treatment on the Retorted Shale Successional Study in 1983. Means with different letters within life forms are significantly different ($p = 0.10$).

(Agropyron inerme) which composed 13% and 12% of the grass biomass, respectively.

Generally, grass production as well as total production increased as topsoil depth increased. Seeded grass biomass was significantly greater on the control than on the 90-cm and 30-cm soil treatments. Grass production on the 60-cm topsoil treatment was not significantly different from either the 90-cm or control treatments. The greater space for root growth and water storage offered by the deeper soil is an important benefit under the climatic conditions of the Piceance Basin. Here plants rely on stored soil moisture during the growing season because summer precipitation is usually of short duration, only wetting the soil surface, and quickly lost by evaporation. For this reason, the deeper topsoil supports more biomass than shallower topsoil treatments. Seeded grass production was significantly lower on the 30-cm topsoil treatment where it accounted for only 65% of seeded species biomass, the lowest proportion of all the topsoil treatments.

Forb production, as affected by topsoil depth, generally showed the reverse of the grass response. Aboveground biomass of seeded forbs was significantly higher on the 30-cm soil treatment where they accounted for 27% of the total aboveground production, a much higher proportion than in the other treatments. Seeded forb production was significantly higher on the 90-cm soil treatment compared to the 60-cm, 60-cm/capillary barrier, and control treatments. Generally where grass production was low, more space, both above- and belowground, was available for forbs. The space preemption by grasses, especially on the 60-cm/capillary barrier treatment and the control, has kept the forb component relatively small resulting in lower diversity on these two treatments compared to the others.

Shrub biomass was significantly higher on the 90-cm soil depth compared to all other treatments, and significantly higher on the 60-cm soil depth compared to the 30-cm, 60-cm/capillary barrier, and the control treatments (Fig. 4). On all treatments, winterfat and fourwing saltbush together composed just over 80% of the seeded shrub biomass. The rooting morphology of these shrubs allows them to reach and absorb moisture at deeper soil depths compared to grasses (Stoddart et al. 1975). The deeper soil in the 90-cm soil treatment may have been vacant long enough for the shrub roots to initiate use of available resources before the grass roots could. This may explain why shrubs performed better on the 90-cm treatment than on any other topsoil treatment. Low shrub production on the control treatment may be partially due to an increase in bulk density just below the ripped soil layer that impeded root development and therefore limited deep soil moisture availability.

There was a significant interaction for total aboveground production between topsoil treatment and seed mixture ($p = 0.001$). This indicates that the effect of topsoil treatment on aboveground production is dependent upon the seed mixture involved. The clearest example of this interaction occurred on the 30-cm treatment where total aboveground production in the native seed mixture averaged 651 kg/ha while the introduced mixture averaged 1658 kg/ha. Other topsoil treatments did not show such a large difference among seed mixtures. There are several factors which may have caused this interaction to occur on the 30-cm soil depth. First of all, the low grass production on this treatment has allowed the alfalfa in the introduced mixture to gradually become established over the past several years. Alfalfa production on the 30-cm topsoil depth in 1983 was 656 kg/ha, much higher than the other topsoil depths. The vigorous growth of alfalfa may have contributed additional nitrogen through N_2-fixation, further stimulating total production. Another important factor which allowed the introduced species mixture to have such

high production on the 30-cm topsoil depth involves a change in the growth conditions on the treatment. During the six years since these soil/shale profiles were constructed some leaching of salts has occurred in the upper portion of the retorted shale, gradually making the upper 10-30 cm more hospitable to plant roots. By 1983, in the 30-cm topsoil treatment, roots often penetrated 25 cm into the shale layer. This resulted in a greater volume of stored water being available for plant growth compared to previous years when root penetration essentially stopped at the soil/shale interface. The introduced species, especially alfalfa which has the potential to produce an extensive root system, were most successful at utilizing this extra rooting space as it became available. This factor and the relatively high winter precipitation compared to the previous two growing seasons helped the introduced seed mixture produce two and one-half times the biomass of the native mixture: an effect unique to the 30-cm topsoil treatment.

Effects of Seed Mixture

The effects of seed mixture are shown in Fig. 5. The introduced seed mixture produced significantly more total aboveground production than the combination mixture which produced significantly more aboveground production than the native mixture in 1983. This was in reverse of 1981 results which represented a less favorable growing season caused by low winter and spring soil moisture recharge. One reason for the increase in introduced species during 1983 may be that introduced species seem to respond to the favorable growth conditions more rapidly than the native species. This is supported by the fact that within the combination mixture, introduced species accounted for a greater proportion of the total aboveground production in the 1983 growing season compared to the drier 1981 growing season. The relative composition of major species for each seed mixture are shown in Tables 3-5.

Seeded grass biomass was significantly greater in the introduced seed mixture than the combination or native mixtures. In the introduced mixture, the pubescent-intermediate wheatgrass complex and the crested wheatgrass complex were the dominant species composing 40% and 27% of the total aboveground production, respectively (Table 3). Both of these species had 100% frequency within this seed mixture, as did meadow brome which composed 10% of the aboveground biomass of this mixture.

In the native mixture (Table 4) bearded bluebunch wheatgrass and Sodar streambank wheatgrass produced 27% and 23% of the biomass, respectively. Other major native grasses were big bluegrass (Poa ampla) and western wheatgrass (Agroypron smithii) which produced 16% and 10% of the total aboveground production, respectively. Grass production in the combination mixture (Table 5) was dominated by the crested wheatgrass complex which composed 39% of the total aboveground biomass. Meadow brome and steambank-thickspike wheatgrass complex produced 19% and 14% of the aboveground production, respectively.

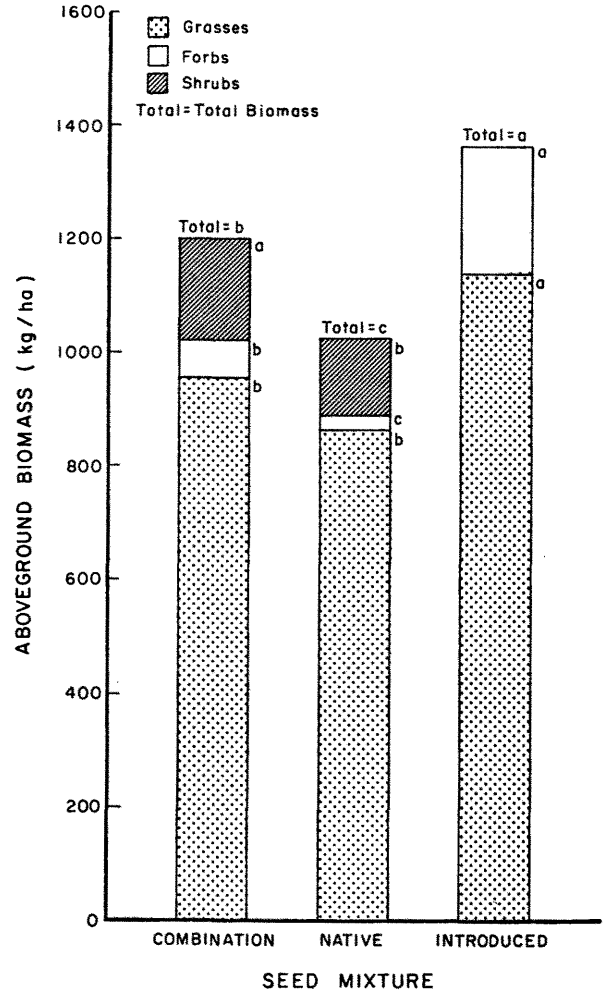

Fig. 5. Mean dry weight of aboveground seeded biomass (kg/ha) by seed mixture on the Retorted Shale Successional Study in 1983. Means with different letters within life forms are significantly different ($p = 0.10$).

Seeded forb production was significantly different among seed mixtures. It was greatest in the introduced, followed by the combination, with the native mixture having the lowest forb production (Fig. 5). Alfalfa composed 88% of the seeded forb biomass in the introduced mixture where the proportion of forbs has greatly increased over previous years (Table 3). The combination mixture, which did not contain alfalfa, showed considerable amounts of yellow sweetclover which composed 44% of the seeded forb biomass followed by Lewis flax and sweetvetch contributing 19% and 8%, respectively. Sweetvetch produced 74% of the forb biomass in the native mixture with Palmer penstemon (Penstemon palmeri) and globemallow (Sphaeralcea munroana) composing the remaining 26%.

During the winters of 1980-1981 and 1981-1982 a noticeable dieback of fourwing saltbush and

Table 3. Relative species composition (%) for introduced seed mixture on the Retorted Shale Successional Study from 1978-1983.

Species	Initial Seeding Densities (seeds/m^2)	Species Composition†					
		1978	1979	1980	1981	1982	1983
Crested wheatgrass complex	25.1	10.5	34.1	35.8	31.3	29.9	26.6
Pubescent-intermediate wheatgrass complex	10.6	35.6	37.3	38.8	47.9	46.9	39.6
Meadow brome	5.6	4.9	3.3	4.2	6.4	6.8	9.8
Smooth brome	7.0	1.5	3.0	1.8	1.6	0.9	0.8
Russian wildrye	9.5	1.2	1.7	0.4	3.7	5.8	4.6
Other grasses	4.4	29.5	6.5	9.2	1.8	1.4	1.1
Total grasses	62.2	83.2	85.9	90.2	92.7	91.7	82.5
Cicer milkvetch	3.4	0.6	0.4	0.9	0.2	0.2	0.2
Yellow sweetclover	7.3	6.9	9.9	0.5	0.1	T‡	0.1
Alfalfa	6.3	1.0	1.5	6.2	5.3	6.2	14.4
Sainfoin	0.5	0.8	0.9	0.4	1.0	0.6	0.4
Other forbs	18.7	7.2	1.3	1.6	0.3	0.2	1.4
Total forbs	36.2	16.5	14.0	9.6	6.9	7.2	16.5
Siberian peashrub	1.1	--¶	--	--	--	--	--
Russian olive	0.5	--	--	--	--	--	--
Winterfat		0.3	0.1	0.2	0.2	0.8	0.3
Other shrubs		T	T	T	0.2	0.3	0.7
Total shrubs	1.6	0.3	0.1	0.2	0.4	1.1	1.0
Total composition	100.0 0	100.0	100.0	100.0	100.0	100.0	100.0

†Aboveground biomass values were used to calculate relative species composition.

‡Trace amount: less than 0.05% of composition.

¶No aboveground biomass recorded.

winterfat occurred. These major shrub species collectively composed approximately 84% of the seeded shrub biomass in both the native and combination seed mixtures. Fourwing saltbush suffered more severe dieback than winterfat, the result being a relative increase in winterfat composition over the past three years (Table 5). Winterfat densities were greater in the combination mixture, while the native mixture had higher fourwing saltbush densities. For this reason the combination mixture, having more winterfat and therefore less overall shrub dieback, produced significantly more shrub biomass than the native mixture (Fig. 5).

The introduced shrubs, Siberian peashrub and Russian olive, did not become established in the introduced mixture (Fig. 5). Environmental conditions at the time of seeding, the lack of preseeding treatment of the seed, competition from rapidly establishing grasses, or a combination of these factors probably hindered the establishment of these two shrubs.

Effects of Fertilizer

Following the sixth growing season (1983), the response to N and P was still evident (Fig. 6). In general, total seeded aboveground production was significantly greater on the high fertilizer treatment (112 kg N/ha, 56 kg P/ha) than on the moderate fertilizer treatment (56 kg N/ha, 28 kg P/ha) or on the control. The overall fertilizer response in this study was primarily due to an increase in seeded grass production that was associated with high fertilizer rates. Grass species generally respond to nitrogen fertilizer better than other life forms (Wight and Black 1978). The crested wheatgrass complex, pubescent-intermediate wheatgrass complex, and bearded bluebunch wheatgrass showed the greatest biomass increase from N and P applications. Meadow brome and the streambank-thickspike wheatgrass complex composed larger proportions of total production under the lower N and P levels indicating they may

Table 4. Relative species composition (%) for native seed mixture on the Retorted Shale Successional Study from 1978-1983.

Species	Initial Seeding Densities (seeds/m^2)	Species Composition†					
		1978	1979	1980	1981	1982	1983
Agropyron spp.		28.7	1.4	5.7	0.6	0.7	0.2
Bearded bluebunch wheatgrass	4.1	2.3	14.9	8.6	20.9	35.3	27.4
Streambank wheatgrass	4.5	1.5	41.2	31.1	19.3	13.4	23.2
Western wheatgrass	3.7	0.4	6.4	4.1	4.7	7.2	10.4
Indian ricegrass	5.4	6.8	6.7	2.3	0.6	0.4	1.4
Big bluegrass	26.1	2.8	10.8	31.2	38.7	23.0	16.2
Alkali sacaton	27.6	--‡	--	--	--	--	--
Green needlegrass	5.2	2.0	2.3	1.7	3.3	4.1	3.5
Other grasses		0.9	1.7	3.4	2.1	2.2	2.2
Total grasses	76.6	45.4	85.4	88.1	90.2	86.4	84.5
Sweetvetch	2.6	1.6	1.4	1.9	1.4	1.6	2.5
Palmer penstemon	4.4	0.6	4.8	1.9	0.4	0.1	0.5
Globemallow	7.9	--	0.1	0.1	--	--	0.2
Other forbs		35.9	0.9	0.3	0.2	0.7	0.3
Total forbs	14.9	38.1	7.2	4.2	2.0	2.4	3.5
Fourwing saltbush	2.0	7.4	2.7	3.8	5.6	6.7	6.6
Winterfat	1.7	8.0	3.7	3.3	2.0	3.6	4.1
Stansbury clifforse	3.7	0.6	0.6	0.1	--	--	0.1
Green ephedra	0.7	0.3	0.2	0.2	0.2	0.4	0.9
Antelope bitterbrush	0.4	0.1	--	--	--	0.1	0.1
Other shrubs		0.1	0.2	0.3	--	0.4	0.1
Total shrubs	8.5	16.5	7.4	7.7	7.8	11.2	11.9
Total composition	100.0	100.0	100.0	100.0	100.0	100.0	100.0

†Aboveground biomass values were used to calculate relative species composition.

‡No aboveground biomass recorded.

be more effective competitors under these less fertile conditions.

There were significant interactions for grass ($p = 0.049$) and forb ($p = 0.001$) biomass between fertilizer and seed mixture. Forbs consistantly showed decreasing production with increasing fertilizer rates (Fig. 6). This was probably caused by the rapid response of grasses to the high fertilization rate during the early phase of the study which limited forb establishment.

Grass production showed a very consistant trend in both the combination and native seed mixtures where increasing N and P increased production (Fig. 6). Within the introduced seed mixture, however, the unfertilized treatment produced slightly more grass biomass than the moderate fertilizer treatment. The abundance of N_2-fixing legumes on the unfertilized treatment within this seed mixture may have compensated for the lack of N and P application. Unlike the other seed mixtures where increased forb production was accompanied by a decrease in grass production (Fig. 6), the unfertilized portion of the introduced seed mixture showed an increase in both grass and forb production over the moderate fertilizer treatment.

Shrub production varied only slightly among fertilizer treatments. Within the combination species mixture, a small fertilizer response by winterfat produced a significant difference between high and moderate fertilizer treatments within this seed mixture. However, this is probably not biologically significant. Generally the N requirements of the woody plants can be met by internal cycling and subsequent conservation of the nutrient. This translocation process within the shrubs has been estimated to satisfy 60% or more of the N requirements during growth (Charley 1977). Therefore shrub species do not rely as heavily on available N content in the soil as the grasses do, so significant responses to external inputs of N are not common.

Table 5. Relative species composition (%) for combination seed mixture on the Retorted Shale Successional Study from 1978-1983.

Species	Initial Seeding Densities (seeds/m^2)	Species Composition†					
		1978	1979	1980	1981	1982	1983
Agropyron spp.		22.5	0.5	3.4	1.0	1.6	0.2
Crested wheatgrass complex	16.0	11.5	35.9	51.4	45.5	50.1	39.1
Streambank-thickspike wheatgrass complex	12.6	0.6	19.5	11.1	20.6	8.2	14.2
Slender wheatgrass	5.7	10.6	7.7	6.8	1.8	2.1	1.6
Meadow brome	3.5	4.0	4.0	7.3	11.0	13.2	18.7
Indian ricegrass	8.3	3.3	2.0	1.1	0.4	0.3	0.1
Other grasses	16.5	2.5	1.7	1.2	4.7	5.6	4.2
Total grasses	62.6	55.0	71.3	82.3	85.0	81.1	78.1
Arrowleaf balsamroot	3.8	0.1	0.1	0.1	0.4	0.3	0.1
Sweetvetch	3.2	0.8	0.6	2.3	0.9	0.9	0.4
Lewis flax	7.5	1.9	2.9	2.2	1.0	1.1	1.0
Yellow sweetclover	4.6	14.2	17.1	1.1	0.3	T‡	2.4
Other forbs	8.9	3.1	1.7	1.2	0.9	0.5	2.2
Total forbs	28.0	20.0	22.4	6.9	3.5	2.8	6.1
Fourwing saltbush	1.1	11.1	2.7	4.9	6.0	7.0	4.6
Winterfat	5.3	13.0	3.4	5.6	5.2	8.3	8.1
Green ephedra	0.7	0.4	0.1	0.2	0.2	0.8	0.8
Stansbury cliffrose	2.3	0.2	0.1	T	T	T	T
Other shrubs		0.2	T	0.1	0.1	T	2.3
Total shrubs	9.4	24.9	6.3	10.8	11.5	16.1	15.8
Total composition	100.0	100.0	100.0	100.0	100.0	100.0	100.0

†Aboveground biomass values were used to calculate relative species composition.

‡Trace amount: less than 0.05% of composition.

Conclusions

After six years the 60-cm topsoil/capillary barrier treatment was the most productive with respect to total aboveground production. This trend is likely to continue until such time as the integrity of the capillary barrier is sufficiently reduced. This treatment is strongly dominated by grasses and may not be as desirable as a less productive topsoil treatment if a greater diversity of life forms is desired. Seeded shrubs appeared to increase with soil depth, and the greatest shrub biomass was recorded on the 90-cm topsoil treatment. The 30-cm topsoil treatment showed the greatest percentage increase in total aboveground production in 1983 compared with the previous two years, both of which were much drier. This greater increase was attributed to this treatment supporting a large forb component, specifically alfalfa, which responsed to the increased soil moisture in 1983 by tripling its production compared to 1982. Manipulation of topsoil depth and profile configuration have directly affected overall species composition and life form dominance. The alteration of topsoil depth and use of capillary barriers my ultimately prove useful as a managment tool in modifying ultimate plant community composition.

Precipitation at the study site is erratic and may have as much of an impact on the success or failure of a given species as man-imposed treatments. Winter and spring precipitation (November-April) previous to the growing seasons of 1981, 1982, and 1983 has been 63 mm, 41 mm, and 152 mm, respectively. Each seed mixture has responded differently to the variation in stored soil moisture that has resulted from the fluctuation in precipitation. Native species had more consistant production. Introduced species had the least consistent production with the lowest production in both dry years, but the greatest production in 1983 when conditions were most favorable. The combination seed mixture was out-produced by the native mixture in dry years and out-produced by the introduced mixture in 1983; however, it had the highest average production over the three-year

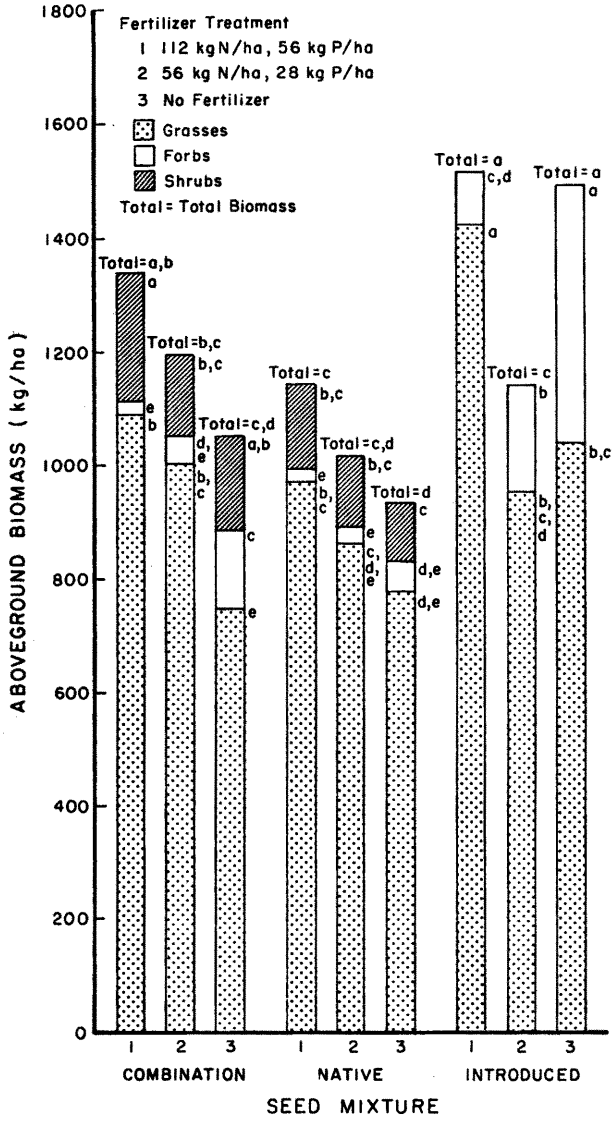

Fig. 6. Mean dry weight of aboveground biomass (kg/ha) for seeded species by fertilizer treatment within seed mixture. Means with different letters within life forms are significantly different (p = 0.10).

period. From this short period of time at least, it seems that the species mixture chosen for revegetation may determine the consistency of production in an area where precipitation patterns are erratic such as the Piceance Basin.

The rapid response of introduced species to the additional available water in 1983, especially in the shallow topsoil treatment, may be a desirable characteristic if the prevention of water movement into the underlying shale is a reclamation goal, as this increased production may indicate increased water removal.

Higher rates of N and P application increased the dominance of grass species and decreased the production of forbs. Introduced grass species such as crested wheatgrass, pubescent wheatgrass, and intermediate wheatgrass appear to be responding to increased soil fertility. Seeded forbs such as sweetvetch and alfalfa appear to be more competitive with other species at lower fertility levels. Shrubs, composed mainly of fourwing saltbush and winterfat, did not show a significant response to fertilizer and may be an especially important component when conditions of low fertility exist. These results indicate that fertilizer can be used to control individual species responses of grasses, forbs, and shrubs and alter short-term plant community composition.

TRACE ELEMENT AND SALT MOVEMENT WITHIN SOIL-RETORTED SHALE PROFILES

Introduction

The major problems associated with successful reclamation of retorted shale generally stem from its high trace element and salt content. That the trace elements and salts in buried retorted shale will migrate toward the soil surface, either by simple diffusion or capillary action, and prevent adequate plant establishment, or that they will be leached downward out of the profile and eventually contaminate ground water supplies are two primary concerns. This study was initiated to determine the extent of salt and trace element movement within soil-retorted shale profiles after six years in the field.

Methods and Materials

Seven different soil-retorted shale profiles were intensively sampled to determine the amount and direction of trace element and salt movement. The seven profiles consisted of the disturbed control, 30 cm, 60 cm, 90 cm, and capillary barrier treatments of the Retorted Shale Successional Study, and the unleached and leached treatments in the Shale-to-Surface Study (Fig. 7). One pit was dug in each of the above treatments and samples were taken to a depth of 3 m or to bedrock, whichever came first.

Soil and retorted shale samples were analyzed for extractable Mo and As, using the AB-DTPA method, and water soluble B and F, using saturation extracts. The samples were also analyzed for electrical conductivity (EC) and sodium adsorption ratio (SAR).

During the following discussion, it should be kept in mind that this study deals with a retorted shale layer 60-cm thick. Retorted shale piles constructed during commercial operations will be many times this thickness and thus will release much greater quantities of trace elements and salts.

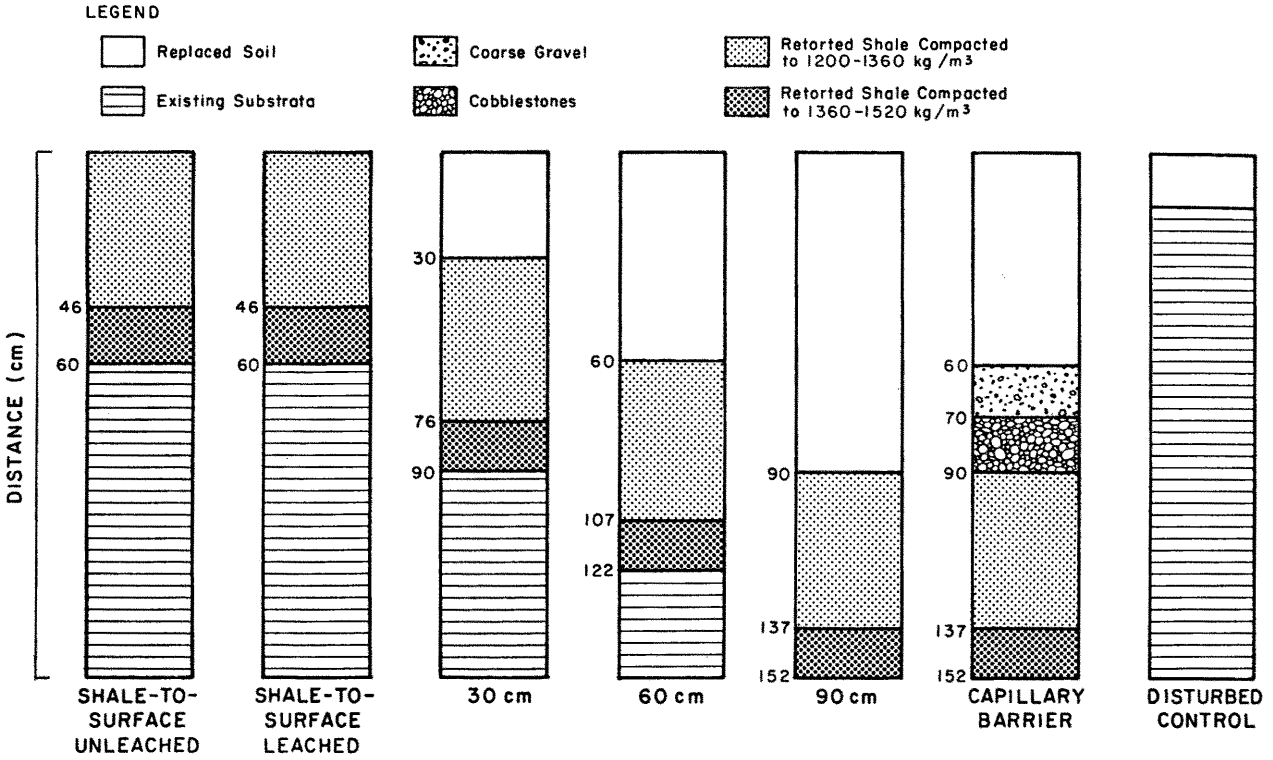

Fig. 7. Profile configurations of the Retorted Shale Successional Study.

Results and Discusson

Figures 8-10 show the distribution of SAR, EC, F, Mo, B, and As within each of the seven soil-shale profiles. The most interesting distribution patterns occurred with SAR and EC (Fig. 8). In the 30-cm, 60-cm, and 90-cm treatments, SAR is lowest at the soil surface and increases to a peak just above the upper soil-shale interface. Then in the upper portion of the shale, the SAR starts out low again and increases rapidly to a maximum near the lower shale-soil interface. Presumably these distribution patterns are primarily a result of leaching actions; however, there also appear to be interface effects, which are not completely understood. During the late fall, winter, and early spring, when precipitation exceeds evapotranspiration, water movement down through the soil leaches Na^+ and other highly soluble ions to greater depths. The abrupt textural change at the soil-shale interface may cause water to build-up just above the shale, resulting in a high concentration of Na^+ ions being deposited in this layer. Electrical conductivity also begins to increase in the 5-10 cm immediately above the shale, indicating an increase in soluble salts at this level. As water moves down through the shale layer, the same process repeats itself: soluble salts (especially Na^+) are leached out of the upper shale and redeposited in the lower shale layers. Processes such as salt sieving (Kemper 1960) and capillary rise may also be occurring at the soil-shale interfaces to produce the distributions shown here.

Of the trace elements considered in this study, fluorine presents perhaps the greatest hazard to groundwater contamination because of its high mobility. Runnells et al. (1979) found that F concentrations in Paraho retorted shale leachates contained two to five times the EPA standards for drinking water. Figure 9 shows that there has been considerable movement and redistribution of F within the seven soil-retorted shale profiles. This movement is most obvious in the 30-cm treatment. Fluorine has accumulated at both upper and lower soil-shale interfaces and has been reduced in the middle portion of the shale layer. This same effect is noticeable in the 60-cm treatment although it is not nearly as well developed. This redistribution pattern can be explained in terms of the two processes mentioned earlier, leaching and capillary rise. When precipitation exceeds evapotranspiration, the net downward movement of water through the shale leaches F (and other soluble constituents) deeper in the profile, resulting in a buildup of F at the lower shale-soil interface. Then when evapotranspiration increases, plant roots, which were observed to extend 10-20 cm into the shale, remove moisture from the topsoil and upper shale layers. This may result in movement of water from the moist middle shale layers to the dry upper layers by capillary action, depositing additional F near the upper soil-shale interface. The difference in distribution between F and SAR could simply be a result of differences in solubilities between the flourine and sodium compounds present.

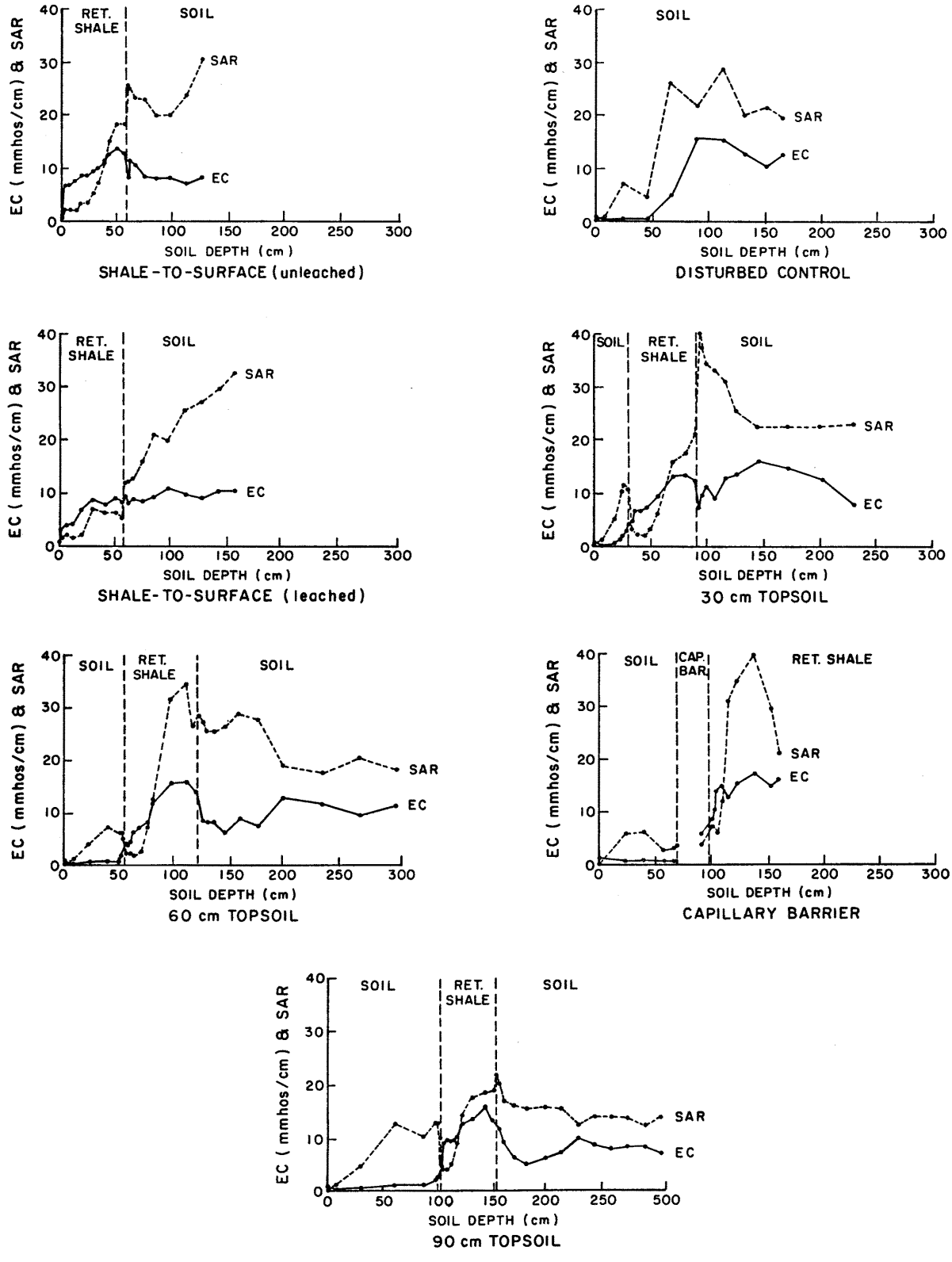

Fig. 8. Distribution of electrical conductivities (EC) and sodium adsorption ratios (SAR) within seven soil-retorted shale profiles.

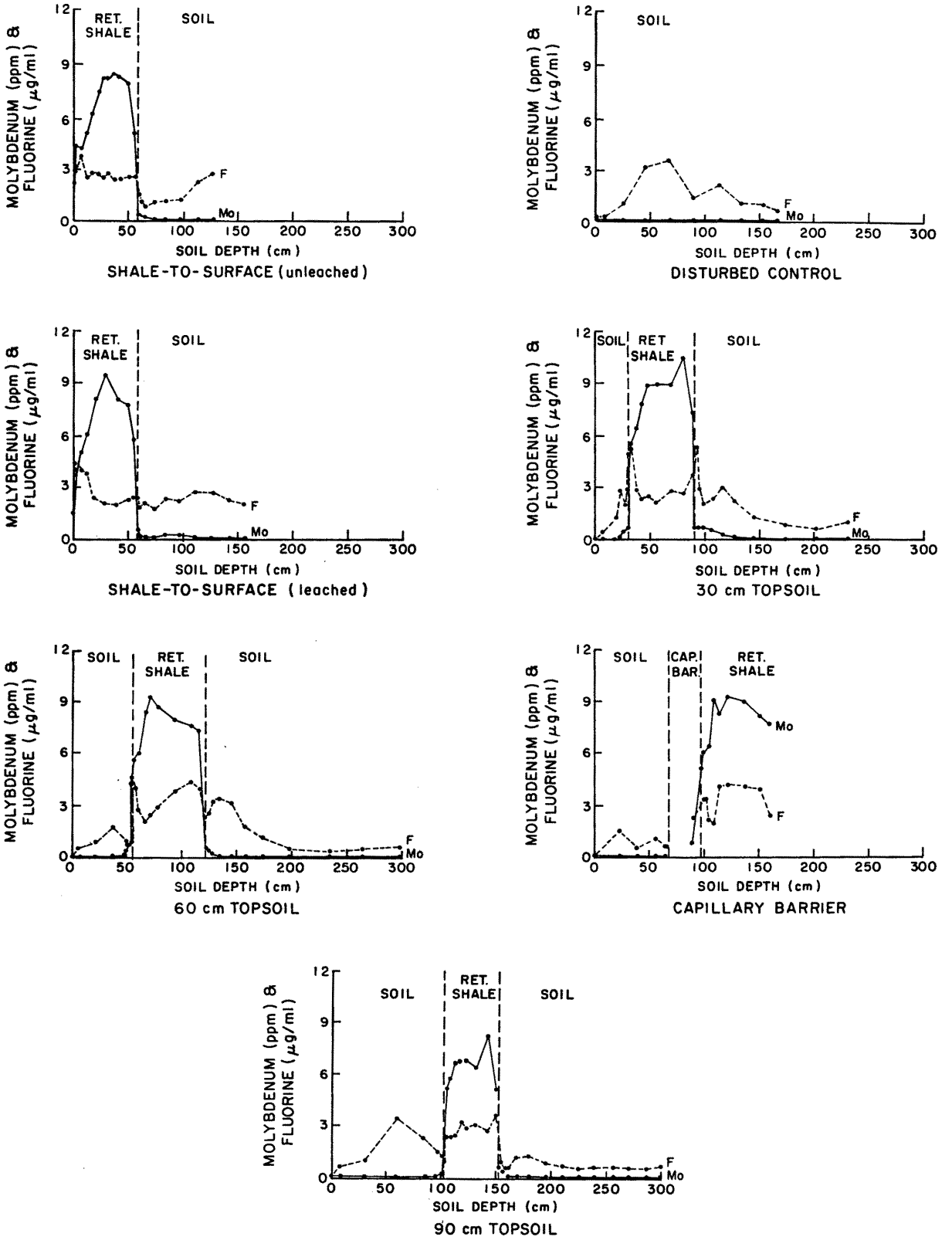

Fig. 9. Distribution of molybdenum and fluorine concentrations within seven soil-retorted shale profiles.

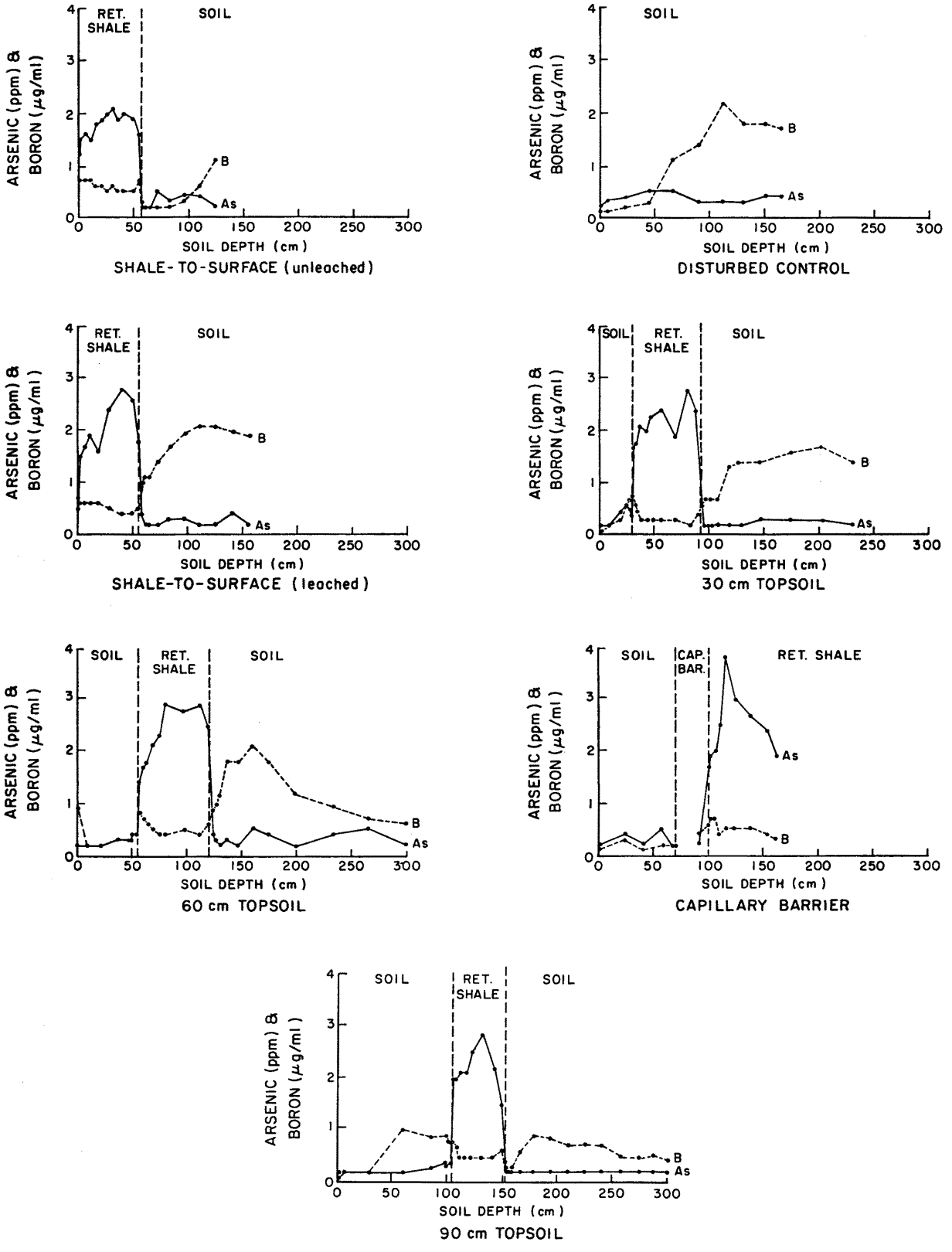

Fig. 10. Distribution of arsenic and boron concentrations within seven soil-retorted shale profiles.

Molybdenum showed only a slight redistribution within the profile (Fig. 9). Although Mo concentrations in the 8-28 cm of soil immediately adjacent to the shale increased from less than 0.1 ppm to about 0.7 ppm, the majority of the Mo remained within the shale layer itself. The lack of mobility of Mo shown here is surprising considering the observations made by Runnells et al. (1979). In laboratory studies, these researchers found concentrations of 2-5 µg/ml in leachates from Paraho retorted shale. This would lead one to suspect that Mo would be much more mobile under field conditions than it actually is. It is also interesting to note that the leached shale-to-surface treatment (leached with 75 cm water) had no greater movement of Mo than any other treatments. Apparently leaching has little effect on reducing Mo concentrations under field conditions.

Boron has been reported to be present in high concentrations in retorted shale and, thus, represents a potential hazard to plant growth (Schmehl 1971, Kilkelly and Lindsay 1979) and groundwater contamination (Runnells et al. 1979) because of its high mobility. All of the B concentrations found in the soil-shale profiles in this study, however, were relatively low (Fig. 10). In fact, the highest concentration of B was in the disturbed control treatment (2.2 µg/ml). The shale-to-surface treatments did have slightly higher B concentrations than the control in the upper 60 cm, but the concentrations are low enough that they probably do not represent much of a hazard to plant growth.

Arsenic was the least mobile of any of the trace elements studied. In spite of the observation made by Klein et al. (1981) that volatilization of As and subsequent movement of gaseous As represents a potential pathway for movement within the profile, and the findings of Runnells et al. (1979) that small amounts of As occur in leachates from Paraho retorted shale, there has been no observable movement of As out of the shale layer and into the adjacent soil after six years in the field.

Conclusions

Substantial salt and trace element redistribution appears to be occurring within the soil-retorted shale profiles for all elements studied except arsenic and molybdenum. While Mo has shown only slight movement out of the shale into the adjacent soil material, arsenic has remained entirely within the shale layer.

Movement of fluorine, boron, and soluble salts (primarily sodium salts) within the profiles has been both upward, either by capillary rise or simple diffusion, and downward by leaching. Of the treatments considered, the capillary barrier treatment was the most effective at preventing upward movement of salts and trace elements. Unfortunately, in this treatment the retorted shale rested directly on bedrock, so it was not possible to collect samples to determine the amount of downward movement. In general, the treatments which had the greatest topsoil depths had the least amount of salt and trace element movement in either direction in the profile. Apparently, the deeper the shale layer is buried, the less it is affected by leaching and capillary effects. After six years, the shale-to-surface treatments (both leached and unleached) continued to have the highest salt and trace element concentrations within the upper 60 cm compared to any of the other treatments.

These results indicate that both upward migration and downward leaching of salts and trace elements are occurring in soil-retorted shale profiles. The extent to which these processes will occur in commercial shale piles depends on the thickness of the retorted shale pile, the concentration and type of salts or trace elements in the retorted shale, and the thickness and nature of the soil used to cover the shale.

SOIL-PLANT DIVERSITY RELATIONSHIPS

Introduction

Obtaining adequate plant diversity on reclaimed sites is one of the major problems facing reclamation specialists today. Many studies dealing with the effects of cultural practices on reclamined sites indicate that these effects are relatively short-lived and it is primarily the environmental factors which determine the final nature of the plant community.

This study was initiated, therefore, to consider some of the environmental factors which influence plant diversity. More specifically, the effect of soil factors on diversity was considered and the results are used to suggest possible methods for increasing diversity on reclaimed sites.

Methods and Materials

The site selected for this study was the Shallowly Disturbed Successional Study. These plots were chosen because they occurred on a variety of soil types with widely varying properties. In addition, the ground surface is slightly undulating, providing variation in topographic position.

Plot Construction

The plots were constructed in the fall of 1976 by mechanically removing the native vegetation and top few centimeters of soil from a 2-ha site. The soil was then ripped to a depth of 30 cm. The following three rates of nitrogen and phosphorus fertilizer were applied:

1. 112 kg N and 56 kg P/ha
2. 56 kg N and 28 kg P/ha
3. Control (no fertilizer)

Six different seed mixtures were drill seeded on the site. The mixtures, which are listed in Table 6, included various combinations of native and introduced grass, forb, and shrub species. A split-plot consisting of 108, 9x18-m subplots was designed, with seed mixtures comprising the main plots and fertilizer treatments comprising the subplots.

The particular site that was chosen for this study consisted of five different soil types with widely varying properties. The center of the site was depressed where a small drainageway previously existed. Unfortunately, at the time the study was set up, the variation in soils was not recognized and thus seeding treatments were not distributed equally over all soil types. For example, while Seed Mixture D (Table 6) occurred on all of the soil types, Mixtures A and C occurred only on two soil types. Thus, certain seed mixtures were more valuable for studying the effect of soil properties on diversity than were other mixtures. Seed Mixture D, the introduced grass forb mixture, occurred on the broadest range of soil physical properties. Therefore, this seed mixture was used most extensively in studying the effect of physical properties on plant diversity. Seed Mixture C, conversely, occurred on the broadest range of salt contents, so it was used to study the effect of soil salts on diversity.

Vegetation Data

Vegetation data was collected using 10 randomly located 25x100-cm quadrats per subplot. Percent canopy cover and standing crop were estimated for each plant species during late June, 1981. Shannon-Weiner diversity indices were calculated for each subplot based on canopy cover data. In addition to the diversity index, a value of species richness was obtained for each subplot by traversing the entire subplot and recording which species were present.

Soil Data

Soil samples were taken from the major horizons in 77 soil pits located throughout the plots. A variety of chemical and physical analyses were performed on the samples. Chemical analyses included pH, electrical conductivity, percent organic matter, cation exchange capacity, extractable cations (Ca, Mg, Na, K, NH_4), and extractable anions (PO_4, SO_4, NO_3). From this data sodium adsorption ratios (SAR) and exchangeable sodium percentages (ESP) were also calculated. Physical analyses included coarse fragment content, bulk density, and particle density. Soil volume or "effective" depth was also calculated by subtracting the coarse fragment volume from the total volume. Data from the soil pits was used to map the gradients in soil properties across the site and to determine average soil property values for each subplot.

The effects of topography on the plant community were undoubtedly the most difficult to quantify. Although neutron probe data collected throughout the growing season showed few differences in soil moisture, it was obvious that the plants in the drainageway were receiving more water than those elsewhere: the plants were more robust and showed signs of senescence later during the growing season. Since the effect of topography appeared to be mainly the result of a change in water distribution, an index was designed which represented a gradient in soil moisture based on topographic position. Subplots were assigned index values based on their position in the landscape (Table 7). Although technically these index values are qualitative, they do represent a continuum with subplots having values of "1" being the driest and those having values of "5" being the wettest.

Statistical Methods

Simple and multiple regression techniques were used to determine correlations between plant diversity and each soil factor. Stepwise regressions were performed to determine which combination of soil properties had the highest correlation with diversity. In addition, regressions were calculated using the percent canopy cover of individual life forms and species to determine how soil factors affected species composition. When the effect of fertilizer on diversity was analyzed, dummy variables were used to adjust for seed mixture and soil type. To correct for heteroscedasticity, all cover values were transformed using arcsin transformations (arcsin $\sqrt{y}$). Transformations used on the independent variables included $\sqrt{x}$, log x, 1/x, x^2, and x^3.

Results and Discussion

In Seed Mixture D, the introduced grass-forb mixture, the soil properties which had the greatest correlation with seeded plant diversity were the percent large coarse fragments (>4.76 mm) within the rooting depth, the moisture index, and the depth to bedrock. Of these three properties, the percent large coarse fragments had the highest correlation with the Shannon-Weiner diversity index.

Figure 11 shows the relationship between coarse fragments and diversity. As the coarse fragment content of the soil increased, the diversity also increased. This rise in diversity as coarse fragments increased was a result of a reduction in abundance of the grass species, primarily Russian wildrye and an increase in all of the seeded forbs. The increase in the forb component at the expense of grasses may be a result of a greater efficiency of forb root systems in exploiting soil moisture under conditions of high rockiness. Forbs generally have root systems which consist of a large central taproot and smaller

Table 6. Mixtures seeded during November 1976 on the study area.

Common Name	Scientific Name	Seeding Rate (kg/ha)
Mixture A--Native grass mixture		
1. Bearded bluebunch wheatgrass	Agropyron spicatum	3.36
2. Rosana western wheatgrass	Agropyron smithii	4.48
3. Green needlegrass	Stipa viridula	3.36
4. Indian ricegrass	Oryzopsis hymenoides	2.24
5. Sodar streambank wheatgrass	Agropyron riparium	3.36
Mixture B--Introduced grass mixture		
1. Nordan crested wheatgrass	Agropyron desertorum	3.36
2. Luna pubescent wheatgrass	Agropyron trichophorum	4.48
3. Vinal Russian wildrye	Elymus junceus	3.36
4. Oahe intermediate wheatgrass	Agropyron intermedium	4.48
Mixture C--Native grass-forb mixture		
1. Critana thickspike wheatgrass	Agropyron dasystachyum	3.36
2. Green needlegrass	Stipa viridula	2.24
3. Bearded bluebunch wheatgrass	Agropyron spicatum	2.24
4. Indian ricegrass	Oryzopsis hymenoides	1.12
5. Sodar streambank wheatgrass	Agropyron riparium	2.24
6. Northern sweetvetch	Hedysarum boreale	1.12
7. Crownvetch	Coronilla spp.	1.12
8. Lewis flax	Linum lewisii	1.12
9. Palmer penstemon	Penstemon palmeri	1.12
Mixture D--Introduced grass-forb mixture		
1. Vinal Russian wildrye	Elymus junceus	3.36
2. Nordan crested wheatgrass	Agropyron desertorum	3.36
3. Luna pubescent wheatgrass	Agropyron trichorphorum	3.36
4. Ladak alfalfa	Medicago sativa	1.12
5. Bouncing bet	Saponaria officinalis	1.12
6. Small burnet	Sanguisorba minor	1.12
7. Lutana cicer milkvetch	Astragalus cicer	2.24
Mixture E--Native grass-forb-shrub mixture		
1. Indian ricegrass	Oryzopsis hymenoides	2.24
2. Bearded bluebunch wheatgrass	Agropyron spicatum	2.24
3. Rosana western wheatgrass	Agropyron smithii	4.48
4. Crownvetch	Coronilla spp.	1.12
5. Northern sweetvetch	Hedysarum boreale	1.12
6. Stansbury cliffrose	Cowania mexicana stansburiana	1.12
7. Green ephedra	Ephedra viridis	1.12
8. Fourwing saltbush	Atriplex canescens	2.24
9. Winterfat	Ceratoides lanata	1.12
Mixture F--Native and introduced grass-forb-shrub mixture		
1. Green needlegrass	Stipa viridula	2.24
2. Bearded bluebunch wheatgrass	Agropyron spicatum	2.24
3. Nordan crested wheatgrass	Agropyron desertorum	2.24
4. Luna pubescent wheatgrass	Agropyron trichophorum	2.24
5. Lutana cicer milkvetch	Astragalus cicer	1.12
6. Sweetvetch	Hedysarum boreale	1.12
7. Stansbury cliffrose	Cowania mexicana stansburiana	1.12
8. Green ephedra	Ephedra viridis	2.24
9. Winterfat	Ceratoides lanata	1.12

Table 7. List of the moisture index values assigned to the subplots.

Index Value	Relative Topographic Position	Effect on Moisture
1	Sloping erosional uplands	Net water loss
2	Flat uplands	No change or slight loss during intense storms
3	Flat lowlands	No change or slight gain during heavy storms
4	Axillary drainages	Net water gain
5	Main drainageway	Large gain in water

lateral roots which spread more horizontally. This type of root system is often referred to as an extensive root system because it is most effective at exploiting resources which are distributed throughout large volumes. The grasses' intensive root systems, however, being more fibrous in nature, are more adapted to exploiting resources which are concentrated in smaller volumes. Thus, where the soil material contains few coarse fragments, grass species outcompete the forbs and rapidly dominate the stand. In areas where the soil resources have been "diluted" by large coarse fragment contents, however, forb species are able to compete more effectively with grasses and thus comprise a greater portion of the stand.

Soil moisture had an effect on diversity that was opposite to the effect of coarse fragments. Figure 12 shows that as moisture increased, diversity decreased. Again the change in diversity was due to an interaction between the grasses, primarily Russian wildrye, and all of the seeded forb species. As moisture increased, the cover of Russian wildrye increased but the forb cover decreased. The reason for this shift toward grass dominance on the moister subplots may be that the competitive advantage that the grasses have over forbs is expressed more rapidly where growth rates are higher.

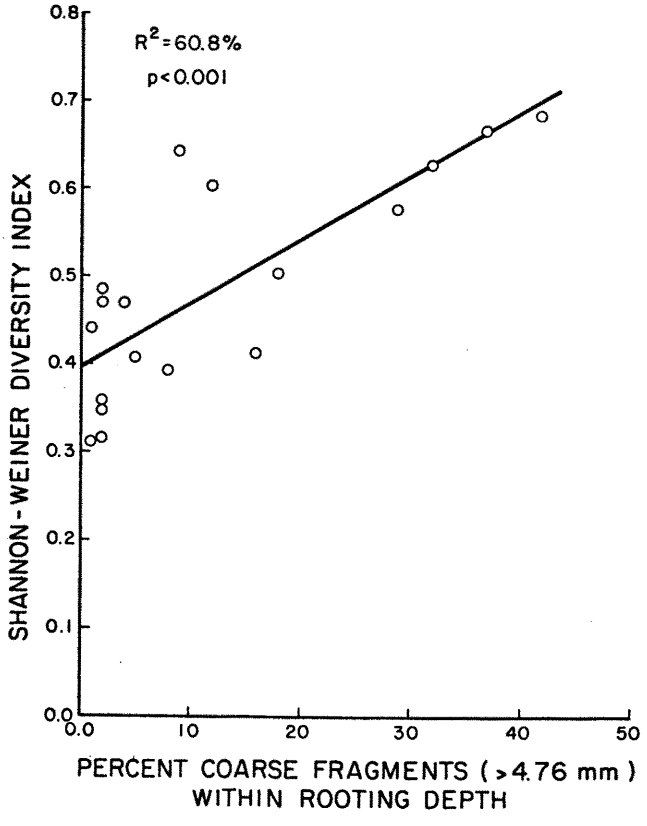

Fig. 11. Relationship between the Shannon-Weiner diversity index and percent large coarse fragments (>4.76 mm) within the rooting depth for the introduced grass-forb mixture (Mixture D).

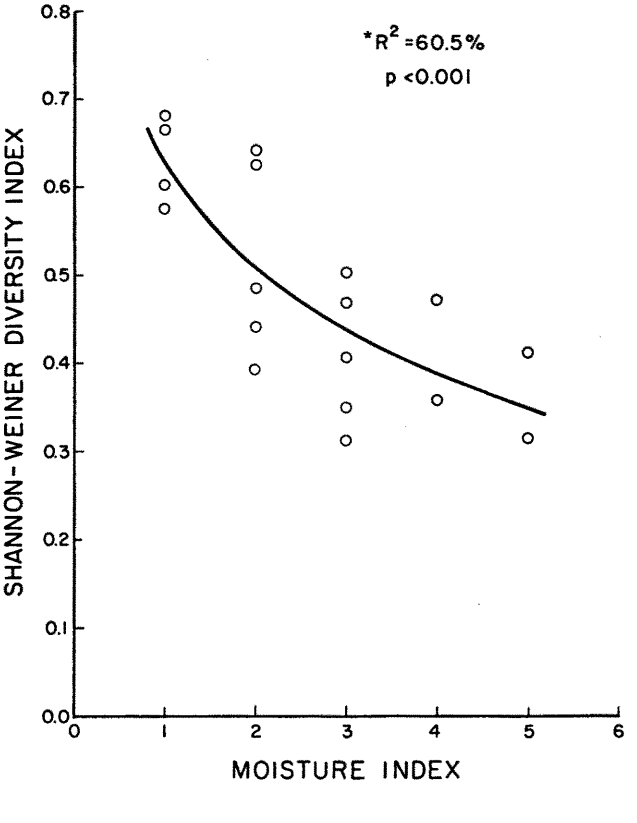

Fig. 12. Relationship between Shannon-Weiner diversity index and the moisture index for the introduced grass-forb mixture (Mixture D). *R^2 and p values are for transformed data (log x).

This explanation is consistent with models proposed by Huston (1979) and Grime (1979). Both researchers hypothesized that growth rates are one of the primary factors affecting the diversity of a site. Where growth rates are high, competitive advantages are rapidly expressed and displacement or exclusion of less competitive plants occurs in a short period of time. Conversely where growth rates are low, competitive advantages are slow to be expressed, displacement of poor competitors is less effective, and diversity remains high for a longer period.

The results from the stepwise regression showed that, for Seed Mixture D, the percent large coarse fragments within the rooting depth and the moisture index provided the best model for prediction of diversity. The regression model including these two variables had an R^2 of 74.1% and a p value of less than 0.001. The influence of coarse fragments and moisture on diversity, however, was mainly through their effect on evenness rather than species richness. Species richness actually had a poor correlation with these two factors (R^2 = 17.4% for coarse fragments and R^2 = 18.1% for the moisture index). The soil factor that was most closely correlated with species richness in Mixture D was the depth to bedrock (Fig. 13). As the depth to bedrock increased, species richness decreased. The decrease in species richness was caused entirely by forb species being eliminated from the stand on subplots with deeper soils. Two mechanisms may be involved here. Since the taproot system of the forbs is probably more effective at penetrating the fractures in the sandstone bedrock, forbs may gain some competitive advantage in obtaining water when bedrock occurs near the surface. On deeper sites, however, this competitive advantage is lost and grasses are able to successfully exclude forb species from the stand. The second mechanism probably involves the effect of soil depth on growth rates. The deeper soils are able to store more moisture than the shallow soils, resulting in higher growth rates and more rapid expression of the competitive advantage held by the grasses.

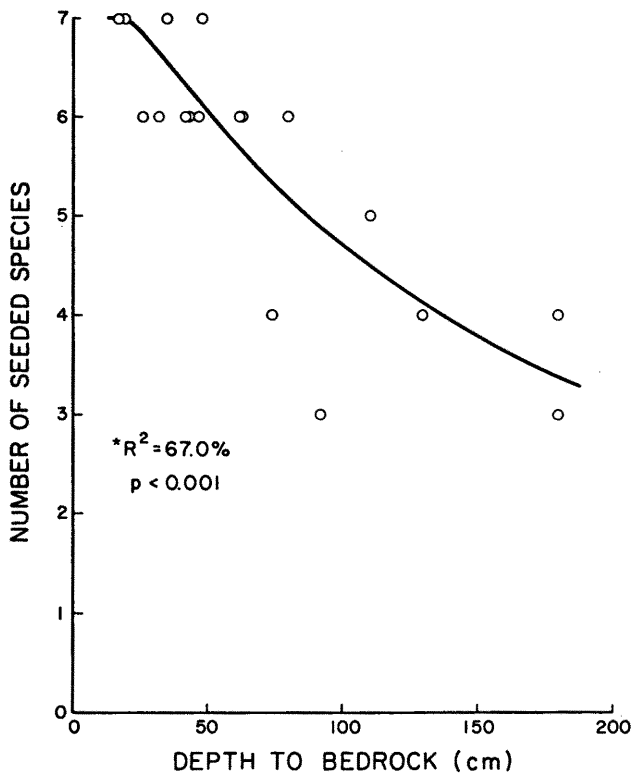

Fig. 13. Relationship between seeded species richness and depth to bedrock for the introduced grass-forb mixture (Mixture D). *R^2 and p values are for transformed data (log x and arcsin $\sqrt{y/7}$).

Since the chemical analyses indicated that there was little difference in fertility among soil types, the rate of fertilizer application was used as the best indicator of nutrient availability on the site. A multiple regression was performed using dummy variables to adjust for the six seed mixtures and five soil types. This regression showed that there was a highly significant inverse relationship between fertilizer rate and diversity (R^2 = 63.6% and $p < 0.001$). As fertilizer application was increased from 0 kg N and P/ha to 112 kg N and 56 kg P/ha, the Shannon-Weiner index dropped an average of 0.041 units. The cause of the negative effect of fertilizer on diversity was probably two-fold. Application of nitrogen fertilizer both reduced the advantage held by legumes in being able to fix nitrogen and increased growth rates, which allowed the most competitive plants to more rapidly dominate the stands.

The effect of soil salts on plant diversity was studied using Seed Mixture C, the native grass-forb mixture. This mixture was chosen because it occurred on soils which had the widest range of salt contents but which were fairly homogeneous with regard to other soil properties.

When only seeded species were considered, there was no significant relationship between the average salt content of the subplots and any measure of diversity. However, when all species were considered (seeded plus invading species), there was a highly significant positive correlation between diversity and SAR ($p < 0.001$). SAR affected diversity primarily by increasing the species richness (Fig. 14).

The mechanisms by which SAR increased diversity was most likely a result of an increase in environmental heterogeneity that was associated with higher values of SAR. High average SAR values were caused by the presence of small saline-sodic patches within the subplot. There were also areas within these subplots that were not affected by salt or only moderately affected. Subplots which had low average SAR values, conversely, occurred entirely on soils with no salt influence and thus were quite homogeneous. The environmental heterogeneity provided by the salt patches allowed additional plant species such as greasewood (*Sarcobatus vermiculatus*, tumbling saltbush (*Atriplex argentea*), and amaranth (*Amaranthus* spp.) to persist in the community. These species, which were able to tolerate extremely high sodium and salt levels, were able to persist on the isolated

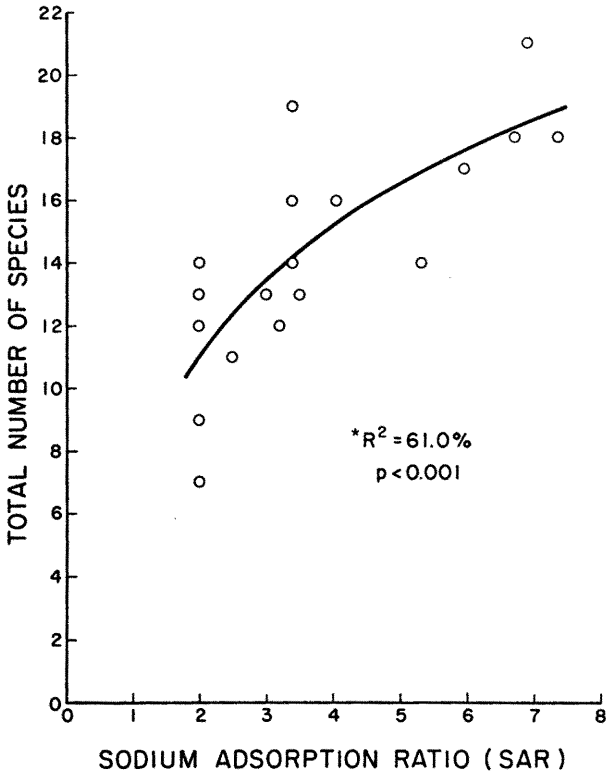

Fig. 14. Relationship between total species richness and the sodium adsorption ratio for the native grass-forb mixture (Mixture C). *R^2 and p values are for transformed data (log x).

salt patches whereas they ordinarily would not have remained in the plant community because of their low competititve abilities.

In addition to the effect of increased heterogeneity, the effect of growth rates on diversity may also be involved. At moderate SAR values (3.0-5.0) growth rates may have been depressed slightly, resulting in a slower expression of competitive advantages and a slower rate of competitive displacement.

In all cases there was an inverse relationship between growth rate and diversity. Soil properties which increased standing crop consistently resulted in a decrease in diversity and vice versa. Listed in Table 8 are the results of regressions performed on each soil property versus both standing crop and the Shannon-Weiner diversity index. In every instance, the effect of a soil property on diversity was opposite to its effect on standing crop. Moisture, soil volume, depth and fertilizer all had positive effects on standing crop but negative effects on diversity. Conversely, coarse fragment content and SAR had negative effects on standing crop but positive effects on diversity. These results suggest that the effect of soil factors on increasing growth rates and thus speeding up the process of competitive displacement may be quite important in controlling diversity on reclaimed sites.

Table 8. Correlation coefficients for regressions of Shannon-Weiner diversity index and aboveground standing crop versus various soil properties.

Soil Property	Shannon-Weiner Index	Standing Crop
Introduced grass-forb mixture		
Moisture index	-0.78	+0.54
Soil volume within rooting depth	-0.66	+0.42
Rooting depth	-0.60	+0.41
Total soil volume	-0.56	+0.42
Depth to bedrock	-0.52	+0.40
Coarse fragments	+0.78	-0.42
Native grass-forb mixture		
Sodium adsorption ratio	+0.59	-0.34
All seed mixtures		
Fertilizer rate	-0.80	+0.60

Conclusions

The inverse relationship between production and plant diversity suggested by the results of this study presents a dilemma to reclamation specialists. By law a vegetative cover must be reestablished that not only has equal or greater production than the original vegetation but also has equal or greater plant diversity. This study indicates, however, that it is not possible to obtain both high production and high diversity simultaneously. Therefore, it appears that the reclamation specialist is left with three alternatives: (1) to manage the site for high production at the expense of diversity (by using large topsoil thicknesses, high fertilizer rates, irrigation, etc.), (2) to manage for high diversity and sacrifice production (by withholding fertilizer, using shallow rocky topsoil, etc.), or (3) to achieve a compromise between the two and risk not meeting either production or diversity requirements (by using moderate to low fertilizer rates and topsoil thicknesses).

The results of this study indicate that there is also a fourth alternative. By increasing environmental heterogeneity a reclamation specialist could potentially increase diversity without radically influencing production. Heterogeneity could be increased by varying topsoil thickness across the landscape, reapplying soil which is high in coarse fragments on some locations while using soil which is low in coarse fragments on other areas. High rates of fertilizer could be applied across the site in strips with alternating strips left unfertilized. In addition, the land surface could be modified to increase variations in microtopography which would favor a variety of different plant species. If the above activities were properly coordinated, the reclamation specialist could create a site which would include both areas of high production and areas of high diversity.

ANNUAL DISTURBANCE STUDY

Introduction

Ecological theory has produced a wide variety of general hypotheses on vegetation succession. The hypothesis of community replacement driven by autogenic mechanisms (Weaver and Clements (1938); the individualistic theories of Gleason (1926), Whittaker (1975), and Glenn-Lewin (1980); and the initial floristic composition concepts of Egler (1954) are some of the traditional ones. More recent successional theories based on population dynamic concepts (Peet and Christensen 1980) and species life histories and vital attributes (Grime 1979, Noble and Slatyer 1980) have introduced new concepts. The problem with most of these theories lies in the fact that they are holistic in their approach, very general, and have low predictive value. Given the prospects for extensive energy development in the West, with its by-product of large ecosystem disturbances, more concrete data on succession is needed. Knowledge is needed, in particular, on the relationship between soil disturbance levels and patterns of secondary succession.

The present study was designed to address one main objective:

> To determine how incremental levels of soil disturbance can affect vegetation succession and rates of successional change.

Two hypotheses were experimentally tested in this study:

1. Increased levels of disturbance retard the rate of successional change by reducing the level of soil biological activity.

2. A severe soil disturbance, by an alteration of physical and soil biological characteristics, can alter the direction of secondary succession.

Materials and Methods

The study was initiated in the summer of 1976. Treatments consisted of four increased levels of soil disturbance:

Treatment 1: Vegetation was scraped off with as much topsoil as possible left.

Treatment 2: Vegetation was scraped off and the subsoil ripped to a depth of 30 cm.

Treatment 3: Topsoil and subsoil were removed to a depth of 1 m; the material was mixed together and replaced in the same area.

Treatment 4: Two layers of 1 m of soil were removed and stockpiled separately; the material was replaced in a reverse order with the second layer placed on the surface.

The experiment was arranged in a randomized block design with two replications. The plots were 6x8 m with a buffer zone 1.5-m wide left undisturbed between plots. The vegetation parameter measured was plant canopy cover. The plots were sampled once a year, at the end of the growing season, with ten 0.25-m^2 (25x100 cm) permanent quadrats randomly located within each plot. The cover values were then utilized to calculate species composition (as a percent relative cover).

Ordination techniques were utilized to summarize species composition data. Factor analysis (FA) was used, with the treatment of nonlinearlity cases (i.e., cases where one axis of ordination is a function of the other) by the techniques suggested by McDonald (1962) and Phillips (1978). The number of significant axes were determined by the use of Fisher's proportion test (Fisher 1958). The composition changes over time for dominant individual species or group of species were analyzed by regression analysis with the stand ordination scores. Multiple response permutation procedures (MRPP) (Mielke et al. 1981) were used for the statistical analysis of species composition and the rates of successional change (as measured by species composition changes.)

Results and Discussion

An ordination procedure was used to summarize the species composition for every treatment at different points in time. The initial step in the ordination analysis extracted two significant axes of variation from the stand-x-species matrix. The first axis accounted for 44.5% of the total matrix variance ($p < 0.001$) while the second extracted 28.4% ($p < 0.06$) of the variance. The independence of the axis was tested by a rigid rotation of the coordinates until the regression of the second axis on the first was maximized (McDonald 1962, Phillips 1978). A significant quadratic regression ($p < 0.05$) between the two axes was found after a rotation of 45°; this indicated that only one ordination axis (explaining 72.9% of the total matrix variation) was needed. The stands were ordinated through a projection onto the regression line as suggested by Phillips (1978) (Fig. 15).

Total grass composition increased in a linear manner along the ordination axis (Fig. 16a) with the dominant individual grass species (*Agropyron riparium*, *A. smithii*, *Koeleria cristata*, *Oryzopsis hymenoides*, and *Stipa comata*) following a similar trend (Table 9). The general pattern was an increase in grass composition as time elapsed and an inverse relationship between grass composition and the severity of the treatment. The grass component in Treatment 1 increased from 49.04% in 1977 to 62.15% in 1982 (Table 9). The vegetation of Treatments 2 and 3 began with a very low grass component (as indicated by their position in the ordination axis (Fig. 16a) but made a substantial

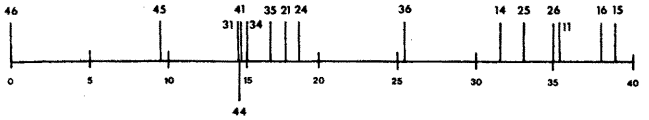

Fig. 15. Stand ordination: Ordination axis in which the relative position of the stands is based on their distance along the regression line between the original two FA ordination axes. **NOTE:** Each stand is identified by two numbers: the first number is the treatment, and the second number represents the years elapsed since disturbance. **Example:** "25" means Treatment 2 after 5 years of succession.

gain in the six-year period. Treatment 2 changed grass composition from 14.27% in 1977 to 38.07% in 1982 while Treatment 3 had an increase from 1.27% to 43.80% in the same period of time. The vegetation of Treatment 4, as indicated by its position in the ordination axis (Fig. 16a), did not change in the direction of Treatment 1. Its grass component increased from 0.04% in 1977 to only 5.44% in 1982 (Table 9).

Total forb composition also increased in a linear manner along the ordination axis (Fig. 16b) with the dominant individual forb species (Sphaeralcea coccinea, Erigeron engelmanii, Phlox longifolia, Senecio multilobatus, and Trifolium gymnocarpon) following a similar trend (Table 9). The general pattern was (a) an increase in the perennial forb composition as time elasped and

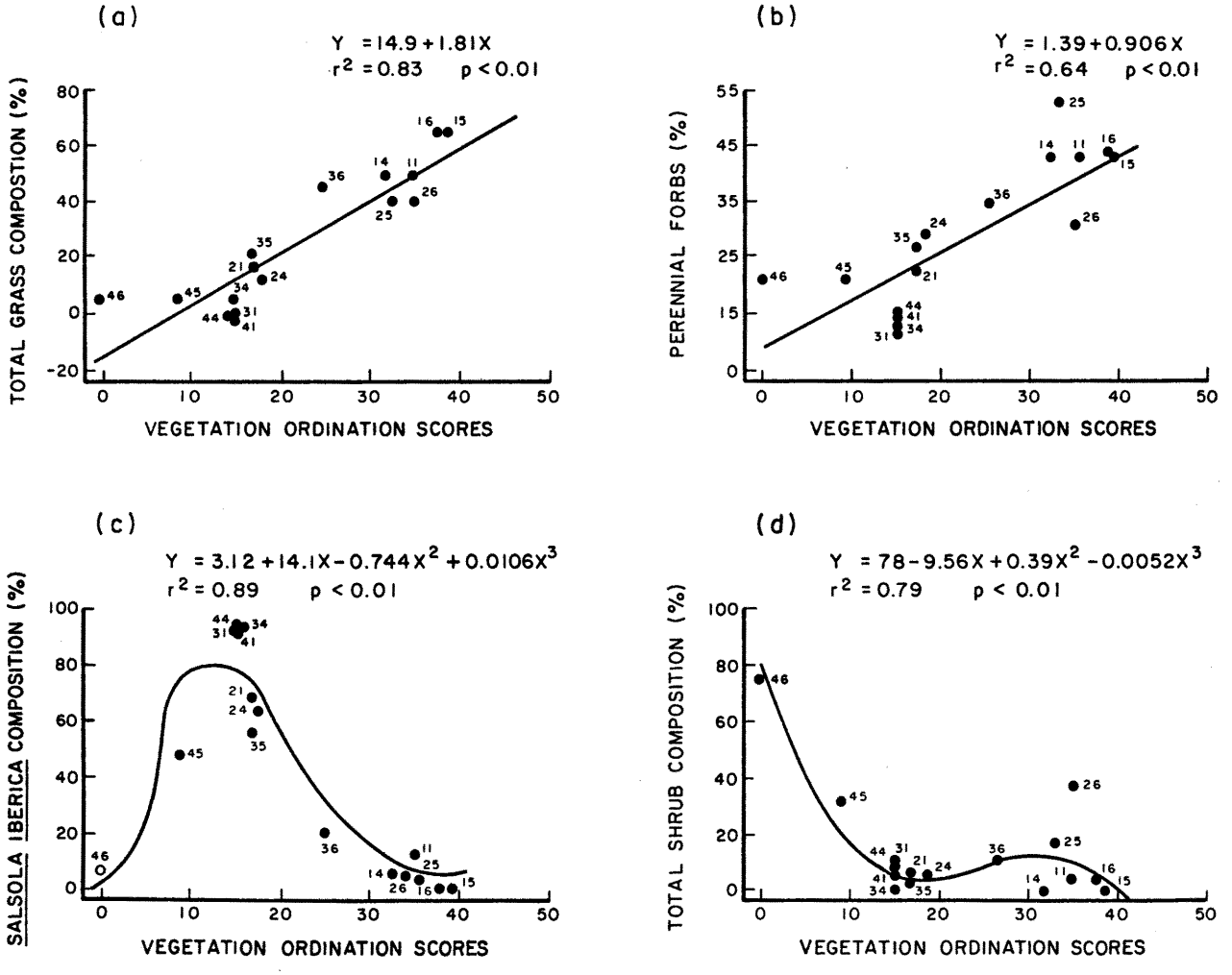

Fig. 16. Distribution of the dominant vegetation groups along the stand ordination axis. (a) Total grass composition. (b) Perennial forb composition. (c) Salsola iberica composition. (d) Shrub composition. **NOTE:** Each stand is identified by two numbers: the first number is the treatment, and the second number represents the years elapsed. **Example:** "25" means Treatment 2 after 5 years of succession.

Table 9. Percent composition for the dominant species in each treatment for Years 1, 4, 5, and 6 of succession.

	Treatment 1				Treatment 2				Treatment 3				Treatment 4			
	Year of Succession				Year of Succession				Year of Succession				Year of Succession			
Species	1	4	5	6	1	4	5	6	1	4	5	6	1	4	5	6
Grasses																
Agropyron riparium	2.73	6.75	29.87	26.24	2.61	3.59	21.90	19.62	0.001	0.001	10.18	21.95	0.001	0.001	0.47	0.68
Agropyron smithii	0.34	18.19	4.54	8.78	7.52	5.16	4.92	2.10	0.03	0.21	4.17	7.62	0.001	0.001	0.09	0.001
Koeleria cristata	17.05	11.93	18.29	9.32	2.61	1.60	2.72	6.29	0.001	0.001	0.001	0.51	0.001	0.001	0.001	0.68
Oryzopsis hymenoides	1.02	1.47	3.82	3.62	1.20	2.21	4.58	3.05	0.07	0.47	6.01	3.76	0.04	0.21	4.03	2.83
Stipa comata	6.62	6.60	4.01	14.12	0.05	0.74	4.67	6.95	0.34	1.11	0.001	9.96	0.00	0.00	0.00	1.25
Other grasses*	21.28	4.89	3.42	0.07	0.27	0.00	0.00	0.00	0.83	2.76	0.00	0.00	0.00	0.00	0.28	0.00
Perennial Forbs																
Sphaeralcea coccinea	26.74	28.36	22.37	22.81	11.87	17.77	32.51	9.62	1.01	2.11	3.98	4.07	1.48	2.16	4.31	3.17
Erigeron engelmanii	0.41	0.001	0.53	0.27	0.05	0.21	1.78	2.57	0.00	0.00	0.00	0.00	0.00	0.001	0.75	1.93
Phlox muscoides	6.34	3.81	5.92	8.33	1.14	1.44	3.74	7.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Senecio multilobatus	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.10	0.001	3.69	3.15	0.00	0.06	2.34	6.12
Trifolium gymnocarpon	0.41	0.20	2.89	1.18	0.33	0.19	1.61	1.24	0.03	0.001	0.29	0.00	0.00	0.00	0.00	0.00
Other perennial forbs	0.00	0.00	0.33	0.00	0.00	0.00	0.52	0.10	0.00	0.02	9.31	18.04	0.00	2.28	4.39	0.57
Annual Forbs																
Salsola iberica	11.73	13.40	1.58	0.09	66.12	62.20	6.03	2.29	91.56	91.38	54.70	21.04	92.62	90.82	47.85	6.57
Other annual forbs	2.90	3.60	1.00	2.45	0.00	0.00	0.00	0.00	0.00	0.00	4.01	0.00	0.00	0.00	0.00	0.00
Shrubs																
Artemisia tridentata	0.14	0.15	0.20	0.63	0.11	0.13	0.42	1.81	0.00	0.00	0.97	1.73	0.23	0.21	6.55	12.12
Chrysothamnus nauseousus	0.00	0.00	0.00	0.00	2.45	2.71	10.61	24.00	0.00	0.00	0.00	0.00	0.80	4.12	16.67	25.93
Chrysothamnus viscidiflorus	1.36	0.49	0.33	0.45	0.27	0.53	2.12	1.33	0.00	0.00	0.00	0.00	2.09	0.06	5.90	10.08
Xanthocephalum sarothrae	0.82	0.05	0.53	1.09	2.72	1.36	1.87	10.57	5.91	1.32	2.13	7.52	2.28	0.02	4.87	26.73

*In 1977 there was an invasion of Agropyron desertorum from an adjacent study on one of the replications of Treatment 1. That is the reason for the high values of the "Other grasses" category in Treatment 1 of Year 1.

(b) an inverse relationship between forb composition and the severity of the treatment. Perennial forb composition in Treatment 1 was virtually unchanged in the six-year period ranging from 33.90% in 1977 to 32.86% six years later (Table 9). The vegetation of Treatments 2 and 3 started with a low perennial forb component, but as time elapsed, they changed in the direction of Treatment 1 (Fig. 16b). The composition of perennial forbs in Treatment 2 increased from 13.39% in 1977 to 21.05% in 1982 while in Treatment 3 it changed from 1.14% to 25.31% in the same period of time (Table 9). Perennial forb composition also increased with time in Treatment 4 even though it remained below the level of the other three treatments. In the six-year period forb composition increased from 1.48% to 11.79% (Table 9).

Salsola iberica was a major species in the initial steps of succession, and Fig. 16c shows that it had a cubic relationship with the ordination axis. Salsola iberica contribution to the species composition of Treatments 3 and 4 was high in the first year of succession; it comprised 91.56% and 92.62% of the vegetation cover (Table 9). Treatment 2 had an initial Salsola iberica composition of 66.12% while Treatment 1 only had 11.73% (Table 9). Salsola iberica composition decreased sharply with time in all treatments (and that is the reason for the shape of the curve) in contrast to grasses and perennial forbs (Fig. 16c). Salsola iberica composition after six years declined to 0.09% in Treatment 1, 2.29% in Treatment 2, and 6.57% in Treatment 4 (Table 9). The only treatment with a sizable Salsola iberica component after six years was Treatment 3 with 21.04%.

Shrub composition made a substantial difference between the species composition of Treatments 1, 2, and 3 as compared with Treatment 4. It had a cubic relationship with the ordination axis (Fig. 16d). The dominant shrubs established were Artemisia tridentata, Chrysothamnus nauseosus, C. viscidiflorus, and Xanthocephalum sarothrae, and they individually followed a similar trend as total shrub composition (Table 9). The shrub component of Treatments 1 and 3 throughout the six-year period never surpassed 10.0% (Table 9). Treatment 2 showed a steady increase in shrub composition from 5.55% in 1977 to 37.71% six years later (Table 9). The biggest increase in shrub composition was observed in Treatment 4 (Fig. 16d). Shrub composition increased from 5.40% in 1977 to 33.99% in 1981 and 74.86% in 1982 (Table 9).

The location on the ordination axis of the different treatments and the species distribution along them tend to support the hypothesis that high levels of soil disturbance can alter the direction of secondary succession (as defined by species composition). The ordination axis shows that in the first year of succession Treatments 2, 3, and 4 were clumped together around the middle of the axis while Treatment 1 was located at the end of the axis (Fig. 15d). Six years after, the ordination

scores of Treatments 2 and 3 have changed in the direction of Treatment 1 while the ordination scores of Treatment 4 changed in the opposite direction (Figs. 15d and 17). The hypothesis was formally tested with MRPP. The dominant species shown in Table 9 were used as the multivariate observation which characterized the species composition of each treatment. Treatments were analyzed at two points in time: (1) one year into the succession and (2) six years into the succession. One year into succession, Treatments 2, 3, and 4 were shown to be significantly different ($p < 0.035$) in species composition from Treatment 1. No significant difference ($p < 0.11$) was found between Treatments 2, 3, and 4. Six years later, Treatments 1 and 2 had a similar species composition ($p < 0.15$); Treatment 3 had a probability value of less than 0.09 of being equal to Treatments 1 and 2 while Treatment 4 was shown to be significantly different from Treatments 1, 2, and 3 ($p < 0.001$). The hypothesis that increased levels of soil disturbance can alter secondary succession patterns was then accepted on two bases. (1) The species composition of Treatments 1, 2, and 3 converged after six years of succession. Treatment 4 in Year 1 was similar (in species composition) to Treatments 2 and 3 in Year 1. Six years later, however, the species composition of Treatment 4 became significantly different from that of Treatments 2 and 3. (2) Treatment 4 became a shrub dominated community while Treatments 1, 2, and 3 became grass-forb dominated communities.

The rate of successional change for each treatment was defined as the slope of the linear regression between the vegetation ordination scores and time elapsed (Fig. 17). Figure 17 shows that contrary to the proposed hypothesis the rate of successional change was not slowed down by the level of disturbance. Three analyses were done to formally test the hypothesis. The first test compared Treatment 1 against Treatments 2, 3, and 4. The slopes of the curves were shown to be significantly different ($p < 0.001$). The second test compared Treatment 2 against Treatments 3 and 4. The slopes of the curves in this case were shown to be equal ($p < 0.15$). The hypothesis of decreased rate of successional change with increased disturbance levels was rejected on the grounds that: (1) Treatments 2, 3, and 4 had steeper slopes than Treatment 1 and (2) Treatments 2, 3, and 4 did not differ significantly in their absolute slope value.

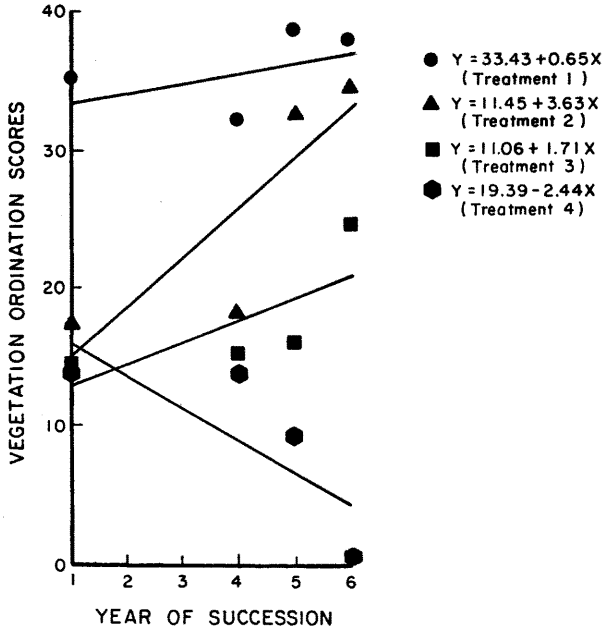

Fig. 17. Rate of successional change in each treatment as measured by the changes with time of the vegetation stand ordination scores.

The general pattern of succession observed in this experiment coincided with Grime's model for secondary succession (Grime 1979). The initial stages of the successional process were dominated by ruderals (Salsola iberica) while the latter stages were dominated by stress tolerators (rhizomatous grasses and perennial shrubs).

The rejection of the hypothesis of a decrease in vegetation successional rate with an increased soil disturbance could be related to the rapid recovery of two important parameters of soil biological activity: dehydrogenase enzymatic activity (which measures the capacity of the soil microflora to process carbon) and mycorrhizal infection potential (see Sections by Klein and Reeves in this report). This recovery in dehydrogenase activity and MIP was particularly unexpected in Treatment 4 where the horizons were reversed and the C horizon became the "topsoil." This operation, on the other hand, could have been the threshold in the disturbance gradient that allowed for a successful establishment of shrubs and altered the successional pattern. Shrubs, with their deep root system, are more adapted to soils with a coarse texture and precipitation that either takes place out of the growing season or consists of large but infrequent events (Neils and Tueller 1971). These two conditions were met in the study. The reversed horizons results in a new "topsoil" with a very rocky texture. Approximately 50% of the precipitation in the Piceance Basin occurs in the winter. The very low level of grass establishment in these plots (Table 9) could also have enhanced the probability of shrub establishment by a reduction in competition. The establishment of shrubs then could have created adequate rhizosphere conditions for microbial and mycorrhizal development. This could explain in part the rapid recovery of dehydrogenase activity and MIP.

Conclusions

From this study two main conclusions can be drawn which are applicable to reclamation practices.

1. The high rate of succession observed in the treatments with high soil disturbance indicate that these ecosystems have a good resilience level and because of this, they have the potential for being adequately reclaimed.

2. The dominance of shrubs on the treatments with a high soil disturbance indicates an ability of this life form to out-compete other life forms under that condition. From the practical point of view then, when shrub establishment is an important objective of the reclamation effort, surface soils should be left as coarse as possible.

REVEGETATION TECHNIQUES STUDY

Introduction

The Revegetation Techniques Study was established in the fall of 1976 to evaluate how various cultural practices influence the reestablishment of plant communities on intensively disturbed soils. The cultural treatments included four seeding techniques, three seeding mixtures, two fertilization rates, and two irrigation treatments.

To construct the plots, six panels measuring 16x92 m were scraper excavated to a depth of 1 m (Fig. 18). The excavated material, which included both the topsoil and the rockier subsoil, was then mixed and returned to the excavations.

Of the four seeding techniques being evaluated, two involved manipulation of grass, forb, and shrub seeding ratios, and the other two involved a comparison of drill and broadcast seeding methods.

Seeding ratios

Technique 1: Grass, forb, and shrub mixtures drilled at a rate of 17 kg/ha.

Technique 2: Grass, forb, and shrub mixtures drilled at a rate of 19 kg/ha with a decreased grass and forb seeding rate and an increased shrub seeding rate (Table 10).

Drill vs. Broadcast seeding

Technique 3: Grass and forb seed drilled at a rate of 17 kg/ha.

Technique 4: Grass and forb seed broadcasted at a rate of 29 kg/ha and lightly covered with soil.

Three seed mixtures of various combinations of grasses, forbs, and shrubs were evaluated in this study. They included a combination mixture consisting of both introduced and native species, a native mixture, and an introduced mixture (Table 10).

The two fertilization treatments used were:

1. 112 kg N/ha and 90 kg P/ha

2. control (no fertilizer)

Two irrigation treatments were applied. On half of the site, supplemental water was added on a weekly basis beginning in early June (1977), to bring the total water received (supplemental water + precipitation) up to 2.5 cm/wk. Irrigation water was applied for the first two growing seasons only (1977 and 1978). The other half of the study received approximately 2.6 cm of water between 26 and 29 June 1977 to prevent failure of seedling establishment during severe drought conditions. No additional water was applied to this portion of the study. The entire study was hydromulched with wood fiber at a rate of 2.2 MT/ha. The treatments were combined in a split-split plot design with three replicates of all possible treatment combinations (Fig. 18).

Vegetation data were collected using six randomly located 0.25-m^2 quadrats per subplot. Ocular estimates were made of aboveground biomass, canopy cover, and density for each plant species. All biomass data is reported on an oven-dry basis. The results discussed below are for the 1982 growing season.

Results and Discussion

Of the various cultural practices that were used on the revegetation technique plots in 1976, few have had lasting effects on the plant community. In most cases the effects of altering life form seed ratios, drill vs. broadcast seeding, fertilization, and irrigation were no longer significant by 1982. Instead, the type of species seeded and environmental factors appear to be having the major influence on the plant community.

Figure 19 shows the effects of altering life form seed ratios on life form biomass after six years. Some slight differences are noticeable. Reducing grass and forb seeding rates while increasing shrub seeding rates resulted in slightly lower biomass of grasses and forbs but higher biomass of shrubs. None of these differences are significant, however.

Figure 20 shows the effects of drill and broadcast seeding on biomass of seeded grasses and forbs and invaders. Both seeding methods resulted in equivalent amounts of grasses, forbs, and invaders.

Figure 21 shows the effects of irrigation and fertilizer on biomass of seeded grasses, forbs, and shrubs. All treatments produced essentially the same grass and forb biomass at the end of six years. Shrub biomass was highest on the unirrigated fertilized treatment and lowest on both irrigated fertilized and irrigated unfertilized treatments. The reason for the difference in shrub biomass among these treatments is not clear. Irrigation during the first two growing seasons may have stimulated grasses to such an extent that shrub establishment was reduced. Thus in subsequent years shrub biomass may have been limited by

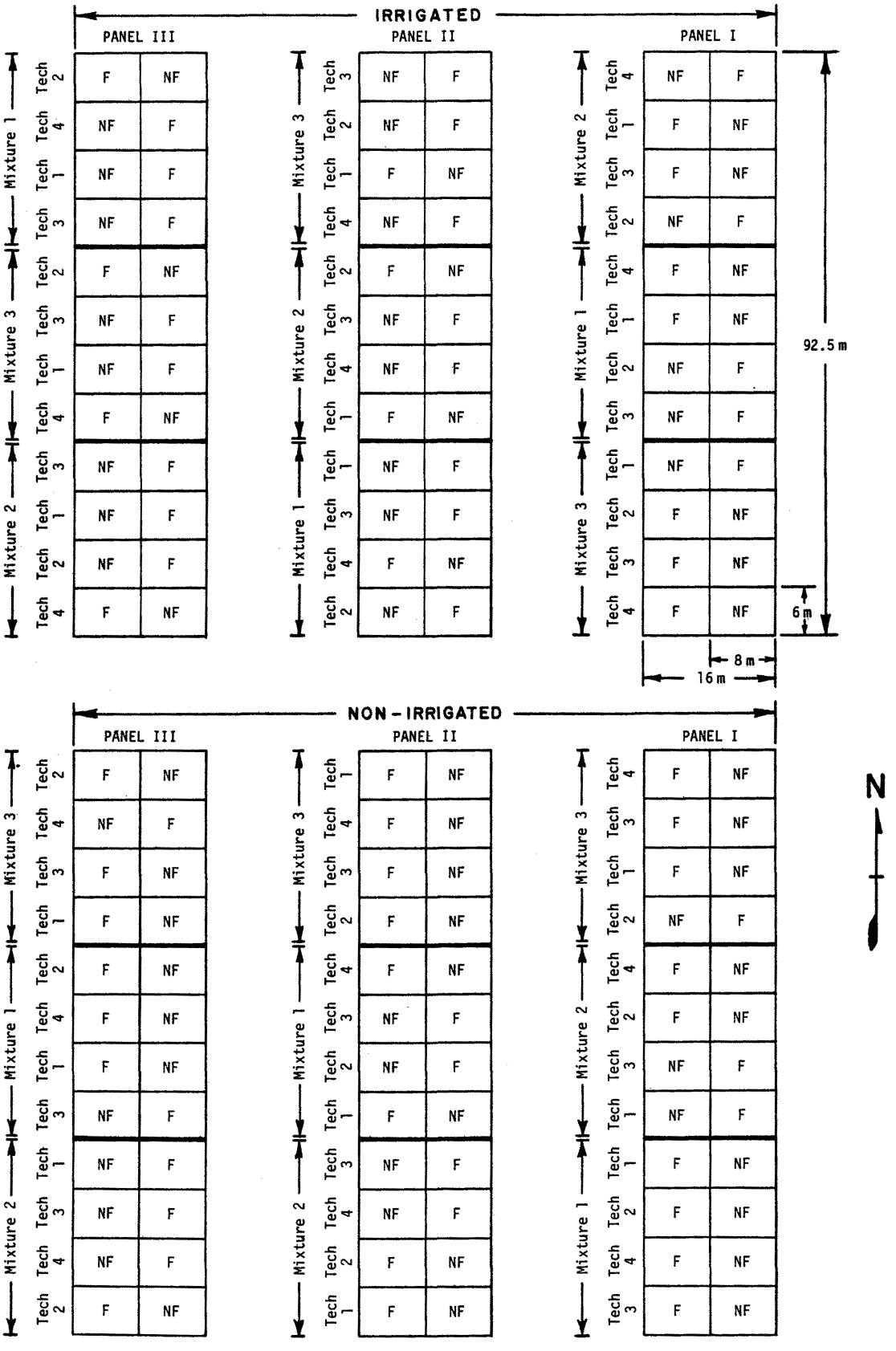

Fig. 18. Experimental design for the Revegetation Techniques Study on Intensively Disturbed Soils.

Table 10. Seeding mixtures and rates used on the Revegetation Techniques Study.

	Common Name	Scientific Name	Seeding Rate PLS (kg/ha) Tech 1	Tech 2	Tech 3	Tech 4
Mixture 1--Combination (native and introduced) species						
1.	Nordan crested wheatgrass	Agropyron cristatum	1.12	0.56	1.12	1.12
2.	Siberian wheatgrass	Agropyron sibiricum	1.12	0.56	1.12	2.24
3.	Critana thickspike wheatgrass	Agropyron dasystachyum	1.12	0.56	2.24	3.36
4.	Sodar streambank wheatgrass	Agropyron riparium	1.12	0.56	2.24	3.36
5.	Slender wheatgrass	Agropyron trachycaulum	1.12	0.56	2.24	3.36
6.	Regar meadow brome	Bromus biebersteinii	1.12	0.56	1.12	2.24
7.	Indian ricegrass	Oryzopsis hymenoides	1.12	0.56	2.24	2.24
8.	Green needlegrass	Stipa viridula	1.12	0.56	2.24	3.36
9.	Durar hard fescue	Festuca ovina duriuscula	0.56	0.28	0.56	1.12
10.	Madrid yellow sweetclover	Melilotus officinalis	0.56	0.28	0.56	0.56
11.	Sweetvetch	Hedysarum boreale	1.12	0.56	1.12	1.68
12.	Globemallow	Sphaeralcea munroana	0.56	0.56	0.56	1.12
13.	Lewis flax	Linum lewisii	0.56	0.56	0.56	1.12
14.	Arrowleaf balsamroot	Balsamhoriza sagittata	1.12	0.56	1.12	1.68
15.	Fourwing saltbush	Atriplex canescens	1.12	4.48	----	----
16.	Stansbury cliffrose	Cowania mexicana stansburiana	1.12	3.36	----	----
17.	Winterfat	Ceratoides lanata	1.12	2.24	----	----
18.	Green ephedra	Ephedra viridis	1.12	2.24		
		Total	17.92	19.60	19.04	29.68
Mixture 2--Native species						
1.	Rosana western wheatgrass	Agropyron smithii	1.12	0.56	3.36	4.48
2.	Sodar streambank wheatgrass	Agropyron riparium	1.12	0.56	1.12	2.24
3.	Bearded bluebunch wheatgrass	Agropyron spicatum	1.12	0.56	2.24	4.48
4.	Indian ricegrass	Oryzopsis hymenoides	1.12	0.56	2.24	4.48
5.	Green needlegrass	Stipa viridula	1.12	0.56	2.24	4.48
6.	Durar hard fescue	Festuca ovina duriuscula	0.56	0.28	0.56	1.12
7.	Shermans big bluegrass	Poa ampla	1.12	0.56	1.12	1.12
8.	Alkali sacaton	Sporobolus airoides	0.56	0.28	0.56	1.12
9.	Globemallow	Sphaeralcea munroana	0.56	0.28	0.56	1.12
10.	Sweetvetch	Hedysarum boreale	1.12	0.56	1.12	1.12
11.	Palmer penstemon	Penstemon palmeri	0.56	0.28	0.56	1.12
12.	Stansbury cliffrose	Cowania mexicana stansburiana	2.24	4.48	----	----
13.	Green ephedra	Ephedra viridis	1.12	3.36	----	----
14.	Fourwing saltbush	Atriplex canescens	1.12	3.36	----	----
15.	Winterfat	Ceratoides lanata	1.12	2.24	----	----
16.	Antelope bitterbrush	Purshia tridentata	1.12	3.36		
		Total	16.80	21.84	15.68	26.88
Mixture 3--Introduced species						
1.	Nordan crested wheatgrass	Agropyron cristatum	1.12	0.56	2.24	3.36
2.	Siberian wheatgrass	Agropyron sibiricum	1.12	0.56	1.12	2.24
3.	Jose tall wheatgrass	Agropyron elongatum	1.12	0.56	2.24	3.36
4.	Luna pubescent wheatgrass	Agropyron trichophorum	1.12	0.56	1.12	2.24
5.	Oahe intermediate wheatgrass	Agropyron intermedium	1.12	0.56	1.12	2.24
6.	Manchar smooth brome	Bromus inermis	1.12	0.56	1.12	2.24
7.	Regar meadow brome	Bromus biebersteinii	1.12	0.56	2.24	4.48
8.	Vinal Russian wildrye	Elymus junceus	1.12	0.56	1.12	2.24
9.	Ladak alfalfa	Medicago sativa	0.56	0.28	0.56	1.12
10.	Madrid yellow sweetclover	Melilotus officinalis	0.56	0.28	0.56	1.12
11.	Lutana cicer milkvetch	Astragalus cicer	0.56	0.56	0.56	1.12
12.	Sainfoin	Onobrychis viciaefolia	0.56	0.56	0.56	1.12
13.	Bouncingbet	Saponaria officinalis	1.12	1.12	1.12	2.24
14.	Small burnet	Sanguisorba minor	1.12	1.12	1.12	2.24
15.	Siberian peashrub	Caragana arborescens	1.12	4.48	----	----
16.	Russian olive	Elaeagnus angustifolia	2.24	4.48	----	----
		Total	16.80	17.36	16.80	31.36

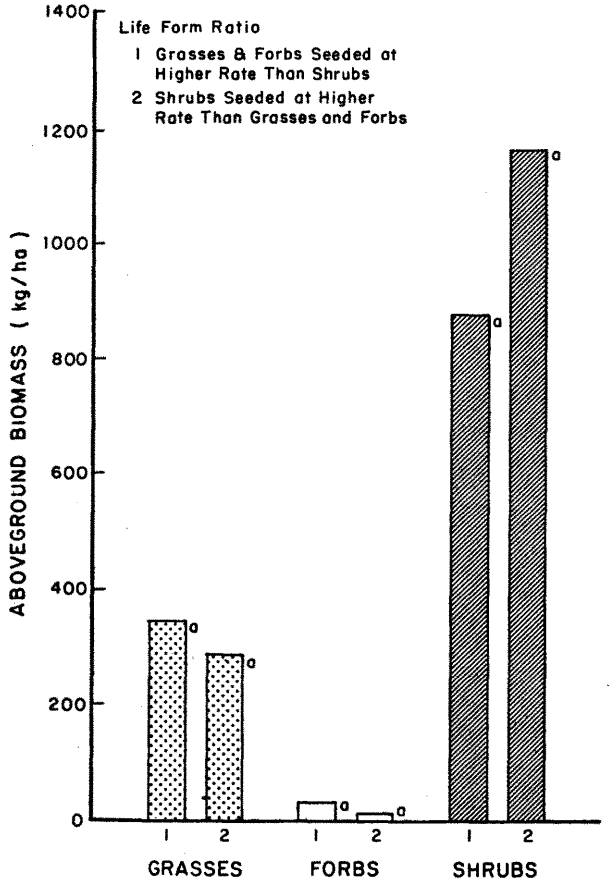

Fig. 19. Effect of altering seeding ratio on seeded grass, forb, and shrub biomass in 1982. Means with different letters within life forms are significantly different ($p = 0.05$).

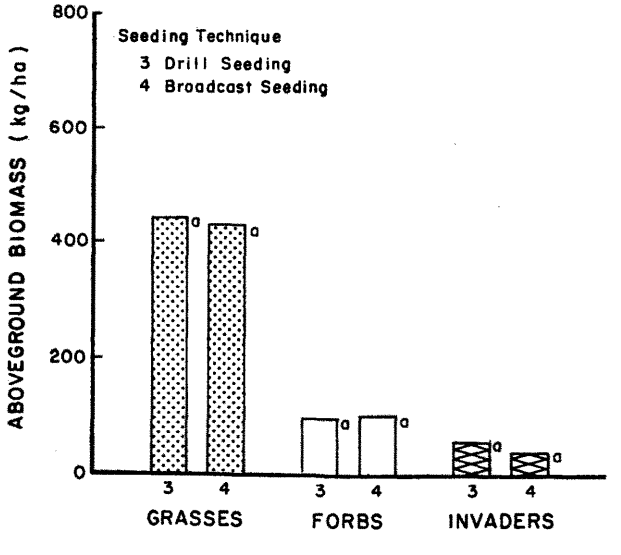

Fig. 20. Effect of drill versus broadcast seeding on biomass of seeded grasses and forbs and invaders in 1982. Means with different letters within life forms are significantly different ($p = 0.05$).

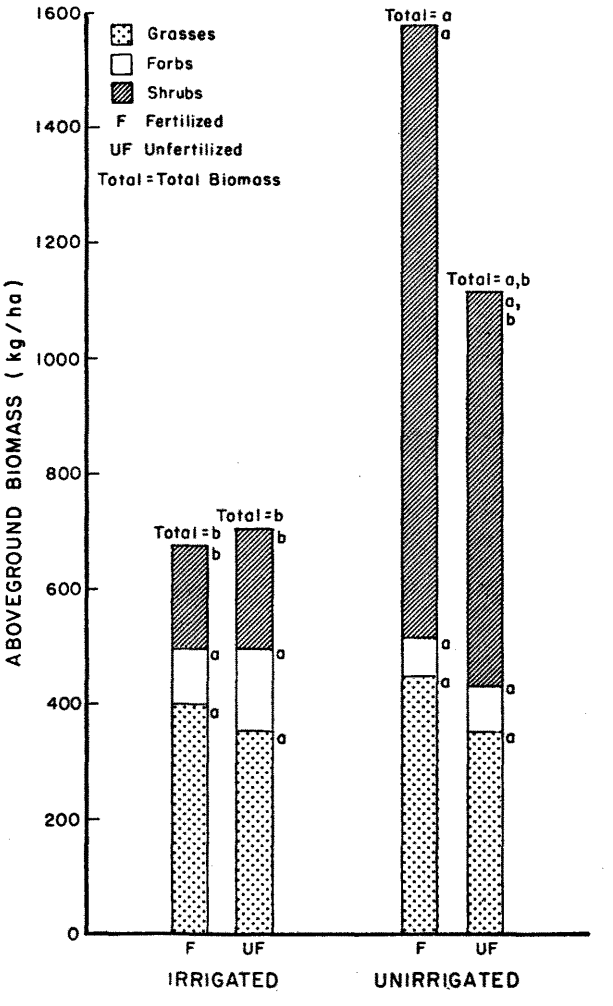

Fig. 21. Effect of fertilizer and irrigation on seeded grass, forb, and shrub biomass. Means with different letters within life forms are significantly different ($p = 0.05$).

low shrub densities. Soil rockiness may also be interacting with the effects of irrigation, however, since previous studies have shown the unirrigated and irrigated portions of the site to contain 23% and 41% coarse fragments, respectively (Redente et al. 1981).

The factor that had the greatest lasting influence on the plant community was the seed mixture. After six years the type of species seeded still had substantial effects on the nature of the plant community. Figure 22 shows how biomass was greatly increased whenever adapted shrub species were seeded. The two shrubs which comprised over 98% of the shrub biomass were fourwing saltbush and winterfat. The other shrub species either were only present in small amounts or failed to become established at all (as in the case of the two introduced species, Siberian peashrub and Russian olive) (Table 11). Where adapted shrubs were seeded, total biomass was two to three times higher than where shrubs were not

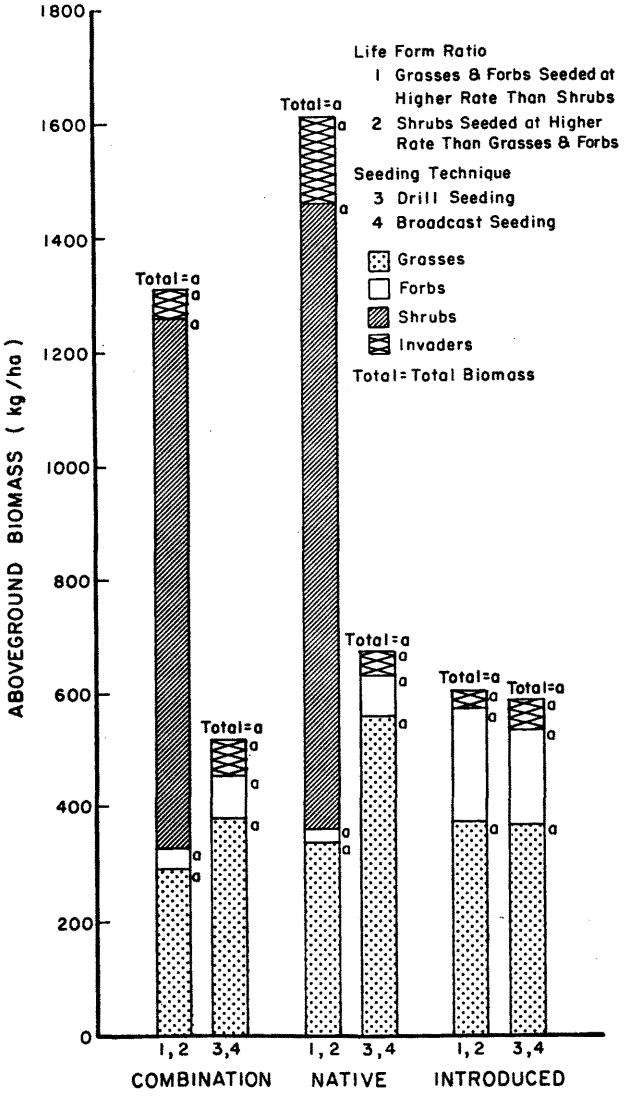

Fig. 22. Effect of seeding mixture on biomass of seeded grasses, forbs, and shrubs and invaders in 1982. Means with different letters within life forms are significantly different (p = 0.05).

seeded. This indicates that there are resources present at this site that can only be utilized by shrub species. Presumably, that resource is deep soil moisture. As mentioned earlier, on this particular site soil rockiness was relatively high. Since high coarse fragment contents result in lower soil water-holding capacities per unit volume, water will percolate to greater depths when rocks are present. This deep soil moisture may be beyond the reach of grass roots and only available to the deeper rooted shrubs. The fact that there is no significant reduction in grass and forb biomass when shrubs are present also implies that there is very little niche overlap between the shrub and grass species, and only a small overlap between shrub and forb species. On a less rocky site, however, this might not be the case. Water

Table 11. Species composition list† for each seeding treatment in the Revegetation Techniques Study.

Species	Techs 1 & 2 (%)	Techs 3 & 4 (%)
Combination Mixture		
Grasses		
Streambank/thickspike wheatgrass complex	18	44
Crested/Siberian wheatgrass complex	7	18
Bluebunch wheatgrass	--	7
Slender wheatgrass	1	2
Meadow brome	2	4
Green needlegrass	2	3
Forbs		
Sweetvetch	3	12
Yellow sweetclover	--	2
Shrubs		
Fourwing saltbush	57	‡
Winterfat	3	‡
Invaders		
Broom snakeweed (Xanthocephalum sarothrae)	1	3
Native Mixture		
Grasses		
Bluebunch wheatgrass	8	39
Streambank/thickspike wheatgrass complex	7	19
Western wheatgrass	4	10
Shermans big bluegrass	5	6
Green needlegrass	--	5
Forbs		
Sweetvetch	1	10
Shrubs		
Fourwing saltbush	56	‡
Winterfat	2	‡
Invaders		
Broom snakeweed	5	5
Alfalfa¶	3	--
Introduced Mixture		
Grasses		
Intermediate/pubescent wheatgrass complex	28	21
Crested/Siberian wheatgrass complex	13	14
Russian wildrye	14	20
Meadow brome	6	5
Smooth brome	2	2
Forbs		
Alfalfa	23	20
Cicer milkvetch	9	9
Shrubs		
No seeded shrubs became established		
Invaders		
Broom snakeweed	2	4
Thickspike wheatgrass	--	2
Winterfat	--	2

†Only species comprising 2% or more of the biomass are listed.

‡Not seeded.

¶Invaded from other plots.

percolation would not be as deep and therefore grass, forb, and shrub competition for moisture would be more intense.

Although there appears to be little competition between the shrub and grass species established on this site, it is interesting to note that shrub species have failed to successfully invade subplots where they were not initially seeded. On these sites, invading shrubs comprise less than 6% of the total biomass (Table 11). Apparently the resource partitioning of deep and shallow soil moisture only occurs after the shrub species have developed deep root systems. Since shrub seedlings must rely on shallow soil moisture until they can develop a deep root system, initially they must compete directly with grasses. For this reason, a well developed stand of grasses can prevent invasion of shrub species even on sites where shrubs have been shown to be well adapted.

There were no significant differences in total biomass among the native, introduced, or combination seed mixtures when shrub species were not included (Seed Techniques 3 and 4) (Fig. 22). Although grass biomass was highest in the native mixture (primarily due to bluebunch wheatgrass) and forb biomass was highest in the introduced mixture (primarily due to alfalfa), the differences were not significant. These results indicate that seeding of introduced species will not always result in greater production on reclaimed sites.

Conclusions

After six growing seasons the effects of fertilization, irrigation, drill vs. broadcast seeding, and manipulation of life form seeding ratios were no longer important. The only factor to have a major lasting effect on the plant community was the type of species seeded.

Although cultural practices such as fertilization, irrigation, and modification of seeding technique can be valuable in promoting rapid establishment of vegetative cover, they may be of little value for modifying the final nature of the plant community. Instead, it appears that the composition of the initial seeding mixture along with environmental factors such as soils and climate will be the most important variables.

On rocky sites or other sites where deep percolation of soil moisture is promoted, the addition of adapted shrub species in the seed mixture can result in increased production, with only slight reductions in grass and forb biomass. This has particular relevance on reclaimed areas that will be used to support a variety of animal species. On rocky sites, seeding of shrubs could supply browse and cover for a number of wildlife species without substantially reducing the value of the site for cattle grazing.

The results of this study indicate that native and introduced seed mixtures can perform equally well in terms of biomass production under ungrazed conditions. This seems to contradict the "conventional wisdom" held by many that introduced species are inherently more productive than native species. Although the introduced species became established faster and had higher biomass initially, after six years the native species produced biomass that was equal to or greater than the introduced species.

STUDIES IN PROGRESS

Wildlife Forage Quality and Availability

The Piceance Basin is critical wintering grounds for the largest migratory mule deer herd in North America. Oil shale mining and subsequent replacement of the existing plant communities with seeded stands of vegetation can have a large impact on forage resources and thus on mule deer populations. If the quantity or nutritional quality of winter forage supplied by reseeded areas is lower than that supplied by the natural plant community, mule deer populations could be substantially reduced.

Data is currently being collected so that the quantity and quality of winter forage produced on the revegetation plots can be compared with that produced in the natural big sagebrush communities. The total quantity of available forage is being estimated on three different dates during the period that the deer herds are in the basin (October-April). Plant samples are being collected and analyzed for gross energy, crude protein, and phosphorus content. Although the data collection will not be complete until April of 1984, it appears at the present time that the forage produced by the revegetation plots will compare quite favorably with that produced by the natural plant community.

Soil Moisture Budget

One of the major environmental concerns with regard to retorted oil shale disposal piles is that water percolating down through the retorted shale will leach salts and trace elements into the groundwater. As mentioned previously in the study on trace element and salt movement, the probability of this occurring is dependent on a variety of factors, including the nature and thickness of the shale, the nature and thickness of the soil material, the water-use characteristics of the vegetative cover, and the climate.

Two studies currently in progress are designed to more clearly define the nature of this problem and to propose methods by which it can be alleviated. The first study is concerned primarily with the water-use characteristics of plants in various seed mixtures and fertilizer treatments. The second study is concerned with developing water budgets for each of the six different soil-shale profiles located in the Retorted Shale Successional Study. The results of these two studies will allow us to make recommendations on the optimum topsoil depths, seeding mixtures, and fertilization rates that can be used to maximize evapotranspiration and

reduce deep percolation of water through retorted shale piles. Preliminary results from these studies indicate that more than 100 cm of topsoil may be required to prevent water movement into the retorted shale during a year of average rainfall.

Trace Element Uptake by Plants Growing on Retorted Shale

The amount of trace elements accumulating in tissues of plants growing on retorted shale is of concern to reclamationists because certain trace elements may reach phytotoxic levels, resulting in reduced vegetative cover, and because herbivores grazing on the plants may suffer adverse effects if plants contain elevated levels of certain elements. Studies done in the past have shown that certain plant species and topsoil treatments result in relatively high accumulations of trace elements in plant tissues (Kilkelly and Lindsay 1979, Schwab et al. 1983). The trace element content of the plants growing on retorted shale will continue to be monitored to determine if these accumulations increase over time.

Production Potential of Stockpiled Topsoil

Previous studies have indicated that the biological, physical, and in some cases the chemical properties of stockpiled topsoil degrades as the length of the stockpiling time increases. This study was initiated to determine if changes in these properties adversely affect subsequent plant production.

Soil samples were taken from four depth increments in vegetated and bare portions of a seven-year-old topsoil stockpile. Western wheatgrass, Indian ricegrass (Oryzopsis hymenoides), and bitterbrush (Purshia tridentata), are currently being grown in each of the soil samples under greenhouse conditions. In April 1984, above- and belowground portions of the plants will be harvested to determine the potential of each of the soil materials for plant production.

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SOIL MICROORGANISMS AND PLANT COMMUNITY DEVELOPMENT IN DISTURBED ECOSYSTEMS

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OBJECTIVES

The major goal during this study period was to begin to develop an understanding of mechanisms controlling plants in disturbed arid systems. Less emphasis, therefore, was placed on routine monitoring of seeding mixture, fertilization, irrigation, and seeding technique effects. Specific objectives included the following:

--To determine the effects of retorted shale on the microbiological characteristics of soil covering shale in relation to the development of plant communities on these materials.

--To evaluate rhizosphere microbial responses of selected range plants grown in soil, soil with overlying retorted shale, and retorted shale.

--To evaluate the effects of amendments to retorted shale on development of microbial populations and biogeochemical cycling processes.

--To study the effects of soil storage and disturbance on microbiological populations and on microorganism-related nutrient cycling processes.

METHODS

Study Site

Field sampling was completed at the intensive study site during the summer of 1982, using the annual disturbance, retorted shale successional, revegetation technique, and soil storage plots. In addition, samples were taken from the native soil plot, to provide a baseline to judge the development of microbiological processes on the experimental areas.

Soil Sampling

Soil samples were taken from the 5-10 cm depth from all plots to assure that effects of shorter-term variations in temperature and moisture would be minimized and to sample in the zone of maximum root activity. Triplicate samples of roughly 500 g each were taken from the 5-10 cm depth on each of the plots. Samples were sieved through a 2-mm mesh screen, mixed in a Patterson-Kelly twin shell dry blender for 20 minutes, returned to individual plastic bags, and stored at 6°C until analysis. The soils were double bagged with moist toweling to minimize soil water loss.

Analytical Procedures

The procedures used for soil organic matter measurement, microbial enumeration, nitrogen fixation, phosphatase and dehydrogenase activities have been described by Hersman and Klein (1979), Sorensen et al. (1981), and Sorensen (1982). The dehydrogenase assay was carried out using glucose amendments by adding 0.5 ml of a 1% solution in place of distilled water.

Nitrification

The status of autotrophic nitrifying microbial populations was determined using measurements of the ammonium oxidation rate and the nitrite oxidation rate. The analytical time frame was kept short enough to exclude the proliferation of the bacteria primarily responsible for this activity. In this way a measure of the preexisting enzymatic activity of these organisms was obtained (Belser and Mays 1980, E. L. Schmidt, pers. comm., 1980).

Ammonium Ion Oxidation

To measure initial potential ammonium oxidation activity, 12 g of soil were weighed into a 250 ml Erlenmeyer flask. Fifty milliliters of a 0.5 M ammonium phosphate-buffer solution (167 mg K_2HPO_4/l, 3 mg KH_2PO_4/l, 66 mg $(NH_4)_2SO_4$/l, pH 8) was added. To each flask 0.5 ml of 1 M $NaClO_3$ was added to block nitrite oxidation. The flasks were capped with aluminum foil and placed on an orbital shaker at 200 rpm at 24 ± 2°C. Over the next 24 to 30 hours, at 8-14 hour intervals, 5-7 ml samples of the soil slurry were poured from each flask into a test tube, $Ca(OH)_2$ (~0.1 g) was added to coagulate suspended clay, and the samples were centrifuged at 600 x g for 10 minutes. A 2 ml portion of the supernatant was diluted to 50 ml and analyzed for nitrite. At least three such analyses were completed for each flask. A least square linear regression line was calculated to fit the nitrite concentration of the slurry over time. The slope of the regression line represents the rate of nitrite production from ammonium.

Nitrite Oxidation

The initial potential nitrite oxidation rate was measured similar to the ammonium oxidation rate. To measure nitrite oxidation, however, 6.9 mg of $NaNO_2$ (0.1 mM) was substituted for the $(NH_4)_2SO_4$ in the buffer solution used for ammonium oxidation rate measurements. Chlorate ion was not added. Instead 10 ml of a 20% solution of nitrapyrine (2-chlor-6-(trichloromethyl) pyridine) was added to each flask to block the oxidation of indigenous ammonium to nitrite (Shattuck and Alexander 1963). Sampling frequency and sample preparation was the same as for ammonium oxidation, and nitrite content was again analyzed. A linear regression line was calculated to fit the nitrite concentration of the slurry over time.

Viable Enumerations

Viable counts of bacteria, actinomycetes, and propagules of fungi were counted using surface spread plates. Bacteria and actinomycetes were counted from decimal dilutions of soil on sodium caseinate agar (Society of American Bacteriologists 1957). Fungal propagules were counted on Martin's rosebengal medium (Martin 1950). Fungi were counted after one week incubation and bacteria and actinomycetes after two weeks incubation in the dark at room temperature.

Direct Microscopic Counts

Bacteria

Direct microscopic counts were done using fluorescein isothiocyanate (FITC) staining and epifluorescent microscopy. The method generally followed that of Babiuk and Paul (1970). A minimum of 200 cells were counted per well, and the count and number of fields counted were recorded. Knowing the area of the microscope field, the number of bacteria per gram of soil was calculated.

Fungi

Additional 1.0 ml subsamples were placed in individual tubes, stained with phenolic aniline blue (PAB), and placed as an agar-film onto a microscope slide for direct measurement of fungal hyphal lengths (Jones and Mollison 1948).

Chemical/Physical Analyses

Soil moisture content was calculated from the weight loss upon drying of about 6 g of soil at 105°C over night and is expressed as percent of dry weight.

Organic matter was determined using the method of Graham (1959). Three-tenths gram of soil, 3 ml of 1N potassium dichromate, and then 6 ml of concentrated H_2SO_4 were combined in a 35-ml prescription bottle and allowed to stand for 10 minutes. Thirty milliliters of deionized water were then added, and the bottle contents mixed. After standing overnight (to allow settling) or after standing 1 hour and centrifuging at 600 x g for 10 minutes, the supernatant was carefully decanted into a 1-cm cuvette and the absorbance at 610 nm read on a B&L spectronic 20. Reference soils, from which a standard curve was prepared, were supplied by the University of Missouri Soils Testing Laboratory, Columbia, Missouri.

Retorted Shale-Rhizosphere Studies

Plant Growth

In the summer of 1983 a greenhouse pot experiment was initiated to evaluate the effect of retorted shale on microbial development in the rhizosphere, rhizoplane, and free soil associated with selected reclamation plant species. The plant growth medium treatments were:

Treatment 1: Soil control

Treatment 2: Retorted shale

Treatment 3: 8.5 cm soil over 8.5 cm retorted shale

In addition, all plant growth media treatments received a 2.5-cm surface layer of vermiculite perlite-composited pine bark mixture that served as a germination bed. The seeded species used in this study were Rosana western wheatgrass (*Agropyron smithii*), Ladak alfalfa (*Medicago sativa*), and fourwing saltbush (*Atriplex canescens*). Control soil was obtained from the native soil plot at the Intensive Study Site.

Retorted shale was obtained from the Laramie Energy Technology Center, Laramie, Wyoming. The oil shale was mined at Anvil Points, Colorado, and retorted via a simulated vertical in situ batch process. After processing, the spent shale was passed through a hammermill and crushed to a size ranging from fine to 10 cm. The shale was leached in an attempt to reduce the electrical conductivity of the processed material. Plastic pots were surface-sterilized with Wescodyne. All seeds were surface sterilized for 3 minutes in a 10% Chlorox solution. Pots were maintained essentially at field capacity, and plants were grown for a period of three months.

Microbial Analyses

Microbial analyses were completed using free soil and material from the rhizosphere and rhizoplane. Dilutions of free soil were plated in triplicate on sodium caseinate agar at pH 7.0 for aerobic bacteria and actinomycetes, and Martin's medium (Martin 1950) was used for fungal enumerations. Plates were incubated at 25°C for two weeks. Rhizosphere and rhizoplane microorganisms were isolated following techniques similar to those recommended by Louw and Webley (1959) and Nakas and Klein (1980).

Microbial Development in Soil Systems

The effects of various amendments on the development of microbial populations and processes in retorted shales was also evaluated in a laboratory study. Three shales were used which have been described in previous reports including the Paraho material used by Hersman and Klein (1979), the Lurgi material previously studied by Hassler (1982), and samples of the Batch 7 material used in the retorted shale-rhizosphere studies described in this report. Due to limitations of material available, the Paraho material consisted of 30-g samples while the remaining materials were able to be used in 300-g amounts. All samples were amended with 0.1% K_2HPO_4 with two replicate samples prepared per variable. The amendments included, on a percentage weight-weight basis:

1.	Glucose	2.5%
2.	NH_4NO_3	0.25%
3.	Glucose + NH_4NO_3	2.5 + 0.25%
4.	Cellulose	2.5%
5.	Cellulose + NH_4NO_3	2.5 + 0.25%
6.	Casein	3.5%
7.	Soy bean meal	6.0%
8.	Control without amendments	

The samples were set up on 30 May 1983 and maintained at a water content of 60% based on the method of Peters (1965). On 1 November 1983 the samples were readjusted for water content to maintain approximately 16% by weight water. The samples were analyzed using previously described procedures.

Statistical Analyses

All data were analyzed using a multivariate analysis of variance statistical package (SPSS). Univariate means with significant F-statistics ($p \leq 0.05$) were further evaluated using the least significant difference (LSD) method.

RESULTS

Native Soil Study

Results from the native soil control study are summarized in Table 1. Ten samples were taken on 8 June 1982 and ten on 30 June 1982. Soil moisture decreased from an average 8.7% to 5.8% during the time interval between the two sampling dates. Zymogenous dehydrogenase activity, acetylene reduction, FITC bacteria, and nitrate oxidation all showed significant decreases from the 8 June to the 30 June sampling times, while PAB fungi and ammonium ion oxidation were not significantly different. Activity measurements of autochthonous dehydrogenase and phosphatase were inversely related to soil moisture, both being significantly higher during the latter sampling date when soil moisture was lower.

As has been seen in previous years, zymogenous dehydrogenase activity appears to be more sensitive to seasonal variations in abiotic conditions than the autochthonous dehydrogenase activity: zymogenase dehydrogenase activity decreased by 14.7 units while autochthonous dehydrogenase activity increased 6.8 units over the two sampling times. Also of interest is the inverse relationship that appears to exist between the activities of zymogenous dehydrogenase and phosphatase. This relationship has been described in previous progress reports.

Revegetation Technique Study

Irrigation completed during the first two growing seasons following seeding (1977 and 1978) continues to show a significant effect ($P < 0.01$), in comparison with fertilization of species on belowground processes. No significant interactions among treatment variables were observed.

Subplots which had been initially irrigated maintained a higher level of zymogenous dehydrogenase, phosphatase activity, N_2-fixation potential, NH_4^+ and NO_2^- oxidation potential, and organic matter compared to the nonirrigated subplot (Table 2).

Although not significant, interesting trends were noted for the response of the three species mixtures (native, introduced, and a combination of native and introduced) to irrigation. Irrigation leads to higher zymogenous and authochthonous dehydrogenase activity, phosphatase activity, N_2-fixation potential, and NH_4^+ and NO_2^- oxidation potential in introduced and combination

Table 1. Native soil study microbiological responses--1982.

Parameter	Unit	8 June Mean	8 June 95% CI	30 June Mean	30 June 95% CI	Sig. of F by Date
Zymogenous dehydrogenase	µg form. · g^{-1} · 24 h^{-1}	32.6	23.1 - 42.1	17.9	32.4 - 22.5	**
Autochthonous dehydrogenase	µg form. · g^{-1} · 24 h^{-1}	8.2	5.0 - 11.4	15.0	12.4 - 17.7	*
Phosphatase	µg PNP · g^{-1} · h^{-1}	128.9	100.1 -157.6	279.4	227.6 -331.2	**
Acetylene reduction	nmoles C_2H_4 · g^{-1} · h^{-1}	0.24	0.11- 0.37	0.09	0.04- 0.15	*
FITC Bacteria	x 10^8 · g^{-1}	27.9	23.1 - 32.7	19.8	17.8 - 21.9	**
PAB fungi	M · g^{-1}	12.0	7.4 - 16.6	9.8	6.8 - 12.9	NS
Ammonium oxidation	µg N · g^{-1} · h^{-1}	0.19	0.16- 0.23	0.33	0.0 - 0.77	NS
Nitrite oxidation	µg N · g^{-1} · h^{-1}	0.10	0.07- 0.13	0.06	0.03- 0.08	**
% organic matter	% dry weight	1.4	1.2 - 1.6	1.2	0.9 - 1.4	NS
Soluble inorganic P	µg P · g^{-1}	2.2	1.2 - 3.1			--
Hydrogen ion activity	pH	8.2	8.1 - 8.4	8.3	8.2 - 8.3	NS
% moisture	% dry weight	8.7	7.4 - 10.1	5.8	5.1 - 6.4	**

* = 5%

** = 1%

NS = not significantly different.

(native and introduced) species mixtures compared to the native species mixture. In nonirrigated subplots autochthonous dehydrogenase activity, N_2-fixation potential, NH_4^+, and NO_2^- oxidation were slightly higher with the native species mixture, whereas the zymogenous dehydrogenase activity and phosphatase activity were higher with the introduced species mixture.

A significant increase ($p < 0.01$) in NO_2^- oxidation potential was observed on fertilized treatments in 1982. The significant effect of fertilization on N_2-fixation potential, which has been observed in previous years, was not apparent in 1982. No fertilizer effects were observed for the other microbial parameters measured.

Species mixture had a significant effect on zymogenous dehydrogenase activity ($p < 0.01$). The introduced and combination mixtures maintained a higher zymogenous dehydrogenase activity compared to the native species mixture (Fig. 1). This trend has been observed previously; however, the absolute levels of activity have increased. Organic matter levels were similar in irrigated subplots planted with native or introduced species, both being slightly higher than the subplots planted with the combination mixtures. In the nonirrigated

Table 2. Irrigation effects on organic matter and microbial responses, Revegetation Technique Plot--1982.

Parameter	Unit	Irrigated Mean	Nonirrigated Mean	LSD ($p \leq 0.05$)
Autochthonous dehydrogenase	µg form. · g^{-1} · 24 h^{-1}	17.6	12.0	12.0
Phosphatase activity	µg PNP · g^{-1} · h^{-1}	87.5	29.4	14.7
Acetylene reduction	nmoles C_2H_4 · g^{-1} · h^{-1}	0.15	0.03	0.07
Ammonium ion oxidation	µg N · g^{-1} · h^{-1}	0.039	0.014	0.018
Nitrite ion oxidation	µg N · g^{-1} · h^{-1}	0.039	0.009	0.008
Organic matter	% dry weight	0.83	0.62	0.13

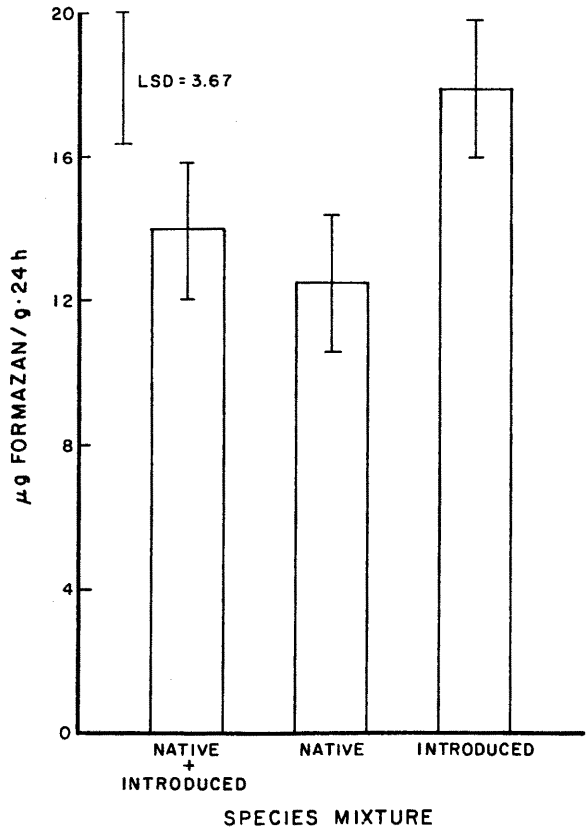

Fig. 1. Dehydrogenase Response-Planting Mixture Relationships, Revegetation Technique Plot--1982. (LSD range ($p \leq 0.05$) is given.)

subplots, organic matter levels were higher in the combination and introduced mixtures compared to the native mixture.

There was an apparent decrease in organic matter levels in irrigated subplots planted with native species from 1979 to 1982. This should be monitored in future years to determine if this trend continues to be observed. The earlier suggestion by Klein et al. (1981) that introduced species are able to fix more carbon for transport to the belowground compartment during initial growth on disturbed soil appears to be supported by the 1982 dehydrogenase and soil organic matter analyses.

Retorted Shale Successional Study

The retorted shale successional study, initiated in 1977, was designed to provide information concerning possible effects of retorted shale on the microbiological characteristics of various depths of topsoil placed over this material and to assess the performance of a capillary barrier under field conditions. Soil samples from this plot were taken on 8 June 1982.

Dehydrogenase Activity

A statistically significant ($p < 0.01$) soil treatment effect was observed in autochthonous dehydrogenase activity. The 90-, 60-, and 30-cm soil depths over retorted shale maintained statistically higher activity than the control and capillary barrier treatments (Fig. 2). Since 1980 there has been a decreasing trend in autochthonous dehydrogenase activity in the control panel; however, the 1982 sampling marks the first time that a reduction of activity also has been observed in the capillary barrier panel.

A significant soil treatment effect ($p < 0.01$) was also observed for the zymogenous dehydrogenase activity. The 90-cm depth of soil over retorted shale maintained the highest activity. The 60- and 30-cm depth of soil over retorted shale did not show activity different from the control or capillary barrier (Fig. 3).

The 1982 measurements indicate that autochthonous and zymogenous dehydrogenase activities in replaced soils over shales have recovered to levels equal to or greater than the control, while the effectiveness of the capillary barrier appears to be decreasing.

Phosphatase Activity

A significant soil treatment effect ($p < 0.01$) was observed for phosphatase activity, continuing the trend which has been observed since 1979, with the lowest activity being observed with 30 cm of soil over shale. All of the average activities from the disturbed plots were significantly lower compared to the native soil values (Table 1).

A significant three-way interaction ($p < 0.05$) between fertilizer, seed mixture, and soil depth in relation to phosphatase activity also was observed. Higher phosphatase activities were observed with the introduced speces mixture, in comparison with the native and mixed seeding mixtures.

Nitrogen Cycling Processes

Nitrogen Fixation

Nitrogen fixation activity showed a significant ($p < 0.01$) soil treatment effect for 1982. These results indicate that although activity levels were higher for all soil treatments except 30 cm soil over retorted shale when compared to 1981 results, soil over shale treatments were still significantly lower than the control (Fig. 4). No significant difference existed between the capillary barrier and 90- and 60-cm soil over retorted shale treatments, again suggesting that the barrier may be losing its effectiveness. All responses for soil over retorted shale treatments were within the 95%

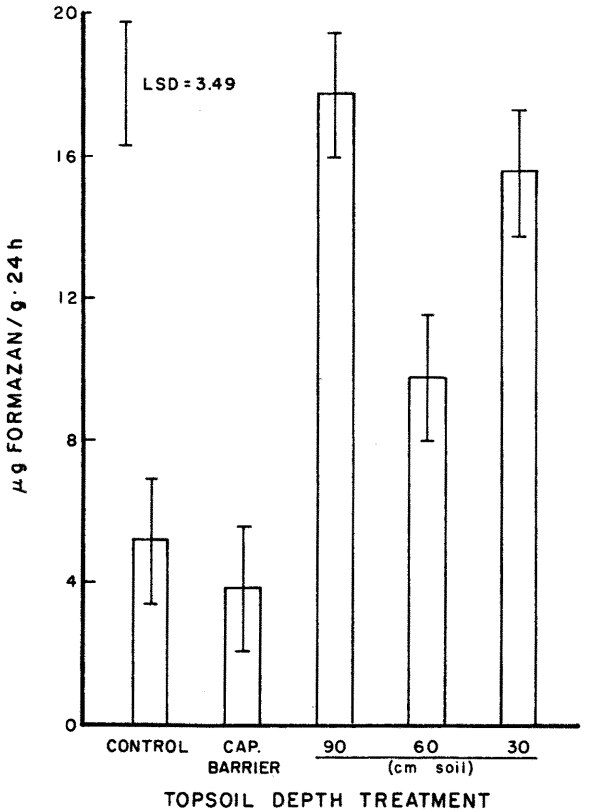

Fig.2. Autochthonous Dehydrogenase Responses, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

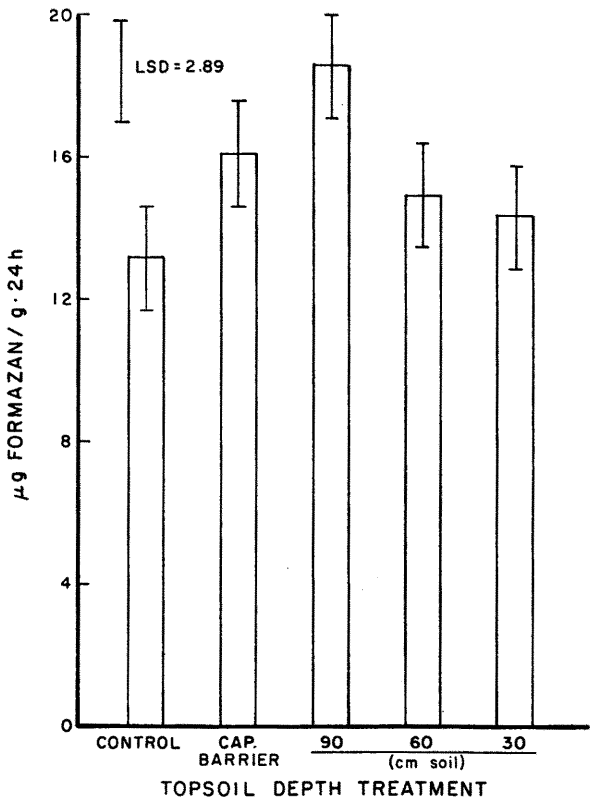

Fig. 3. Zymogenous Dehydrogenase Responses, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

confidence intervals of the native soil plot (Table 1).

Although not significant, the highest average N_2-fixation potential was observed on subplots receiving the highest fertilizer treatment and the lowest on the unfertilized subplots. This fertilizer effect was also observed in both 1980 and 1981.

Ammonium Ion Oxidation

The highest initial ammonium ion oxidation rate was observed in the disturbed control. It was significantly higher ($p < 0.01$) than the rates observed in all of the replaced soil over shale treatments. The average rate of oxidation in all replaced soil treatments was independent of depth of soil covering. Compared to the 8 June 1982 sampling of the native soil site (Table 1), the average soil treatment NH_4^+ oxidation rates on this plot were significantly lower.

The initial NH_4^+ ion oxidation rate also responded directly to fertilization ($p < 0.05$). Increased N fertilization resulted in a higher initial NH_4^+ ion oxidation rate, as noted in Fig. 5. These ammonia oxidation rate responses to soil treatment and fertilizer effects are similar to patterns observed in the 1981 sampling.

Nitrite Oxidation

A significant soil treatment effect ($p < 0.01$) was observed for the initial NO_2^- oxidation rate. The capillary barrier and 60 cm and 30 cm soil over retorted shale treatments had significantly lower values than the control and 90 cm soil over retorted shale treatments. All responses fell below the 95% confidence intervals for the native soil plants (Table 1). A fertilizer effect ($p < 0.05$), similar to that observed for NH_4^+ oxidation, was also observed for nitrite oxidation, and a higher fertilizer level resulted in a higher nitrite oxidation rate.

A species effect ($p < 0.05$) was also observed. The combination species mixture maintained a higher average initial NO_2^- oxidation rate, followed by the introduced mixture. Although lower, the NO_2^- oxidation rate observed in subplots planted with a native species mixture was not significantly lower than the introduced species mixture.

With the exception of the 90 cm over retorted shale treatment, initial NH_4^+ oxidation rates were always higher than initial NO_2^- oxidation rates. This trend was observed across all fertilizer levels. It is generally recognized (Focht and Verstraete 1977) that nitrite ion oxidizing organisms exhibit a higher sensitivity to environmental stresses.

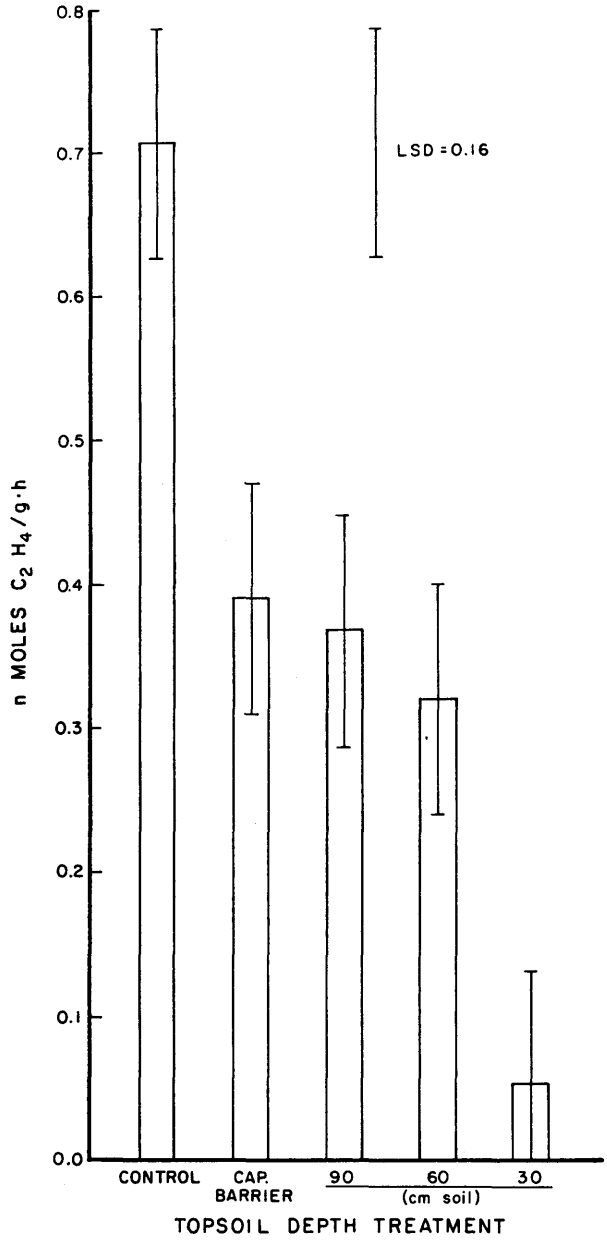

Fig. 4. Nitrogen Fixation Potential Responses, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

Microscopic Bacteria

The average number of FITC stained bacteria in the 90 and 30 cm replaced soil treatments was not significantly different from the control, whereas stained bacterial populations were significantly higher in the capillary barrier and 60 cm replaced soil treatments. There appears to be a significant decrease in direct counts of bacteria in the control from the previous year (1981 data), rather than an increase in numbers of bacteria in replaced soil treatments. Direct microscopic

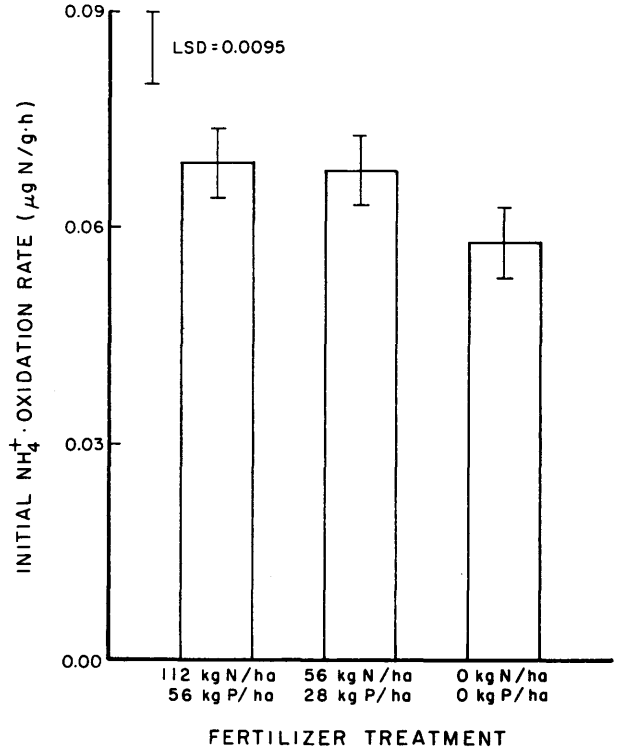

Fig. 5. Fertilization-Ammonium Ion Oxidation Potential Interactions, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

counts of the stained bacteria in all treatments fell below the 95% confidence interval for the 8 June sampling of the native soil plot (Table 1).

Fungal Hyphal Lengths

Results of direct microscopic observations of stained fungal lengths in composited samples from subplots on each of the treatment plots indicated a significant soil treatment effect ($p < 0.01$) existed. The control and capillary barrier treatments were not significantly different. The 90- and 30-cm soil depth over retorted shale values were significantly lower than the control, while the 60 cm soil over retorted shale, which also had the highest direct bacteria counts, was significantly higher than the control. With the exception of the 90- and 30-cm soil depth treatments, all other treatments are within the 95% confidence interval of measurements obtained from the sampling of the native soil plot (Table 1). A significant fertilizer effect ($p < 0.05$) also was observed. This inverse relationship between fertilizer level and PAB fungal hyphal lengths (Fig. 6) indicated that fertilizer presence can result in major changes in the belowground microbial community structure. No similar microscopic bacterial responses were detected.

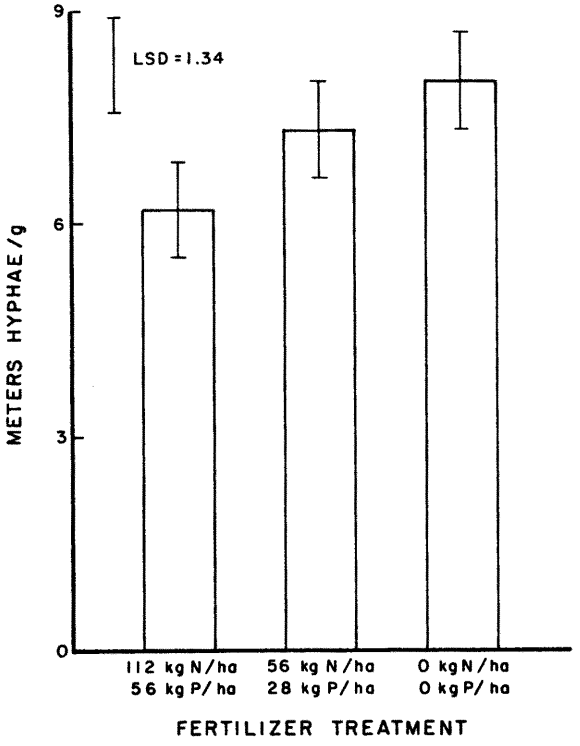

Fig. 6. Fertilization-Fungal Hyphal Length Interactions, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

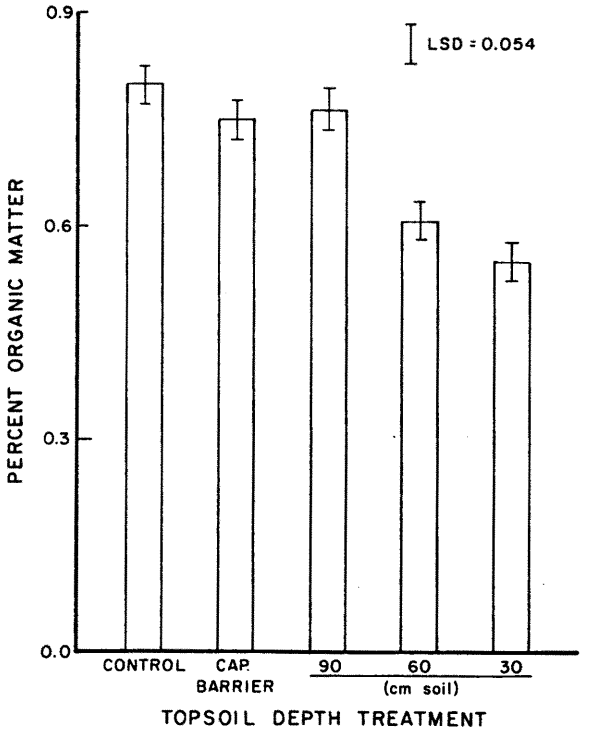

Fig. 7. Organic Matter Responses, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

Organic Matter Dynamics

The results from organic matter determinations on each of the soil treatments are shown in Fig. 7. The 60- and 30-cm soil depths over retorted shale treatments had average organic matter contents that were significantly lower than the control, while organic matter levels in the capillary barrier and 90 cm soil over retorted shale were not significantly different from the control. In comparison with the native soil plot values (Table 1), organic matter levels for all treatments were significantly lower. With the exception of the elevated organic matter level obtained from the 90-cm depth treatment in 1981, the most recent data follows a trend of consistent decline in organic matter content for all treatments observed since 1979.

Inorganic Phosphorus

A significant positive fertilizer effect ($p < 0.01$) on the extractable P level was observed for 1982 (Fig. 8). These results suggest that phosphorus, which was originally applied in the fall of 1977, is still available for plant uptake. Subplots that received P fertilizer are maintaining available P levels significantly higher than levels found in the native soil plots (Table 1).

Annual Disturbance Study

This study was initiated to determine the effects of different levels of disturbance on subsequent natural succession and on microbial processes. Four increasingly severe disturbances were created on replicate plots (see Redente et al., this report). The significant results which were observed in the 1982 sampling are summarized in Fig. 9. Organic matter levels in Treatments 3 and 4 were not statistically different from each other. However, both were significantly lower than the levels observed in Treatments 1 and 2, which were less severely disturbed (Fig. 9a). A trend of decreasing phosphatase activity with increasing soil disturbance was also apparent (Fig. 9b). Both organic matter levels and phosphatase activity in all soil treatments for the 1982 sampling did not differ significantly from the previous year's results, although decreased activities still were observed with more intensive disturbance. In addition, autochthonous dehydrogenase activity did not show the distinct response to soil disturbance in 1982 as shown in 1981. Although not significant, in all cases the least disturbed treatments (1 and 2) averaged higher zymogenous dehydrogenase activity, nitrogen fixation potential, and more FITC stained bacteria and

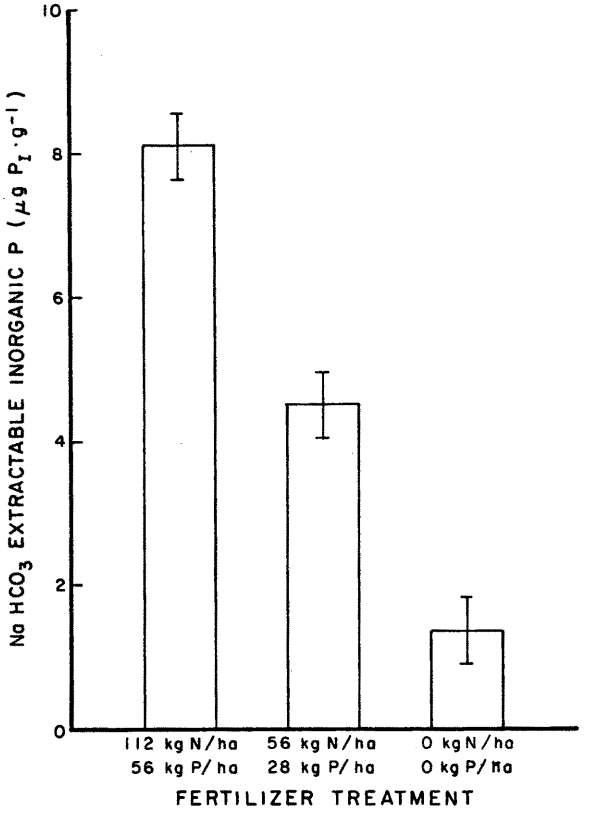

Fig. 8. Fertilizer-Inorganic Extractable Phosphorus Interactions, Retorted Shale Successional Plot--1982. (LSD range ($p \leq 0.05$) is given.)

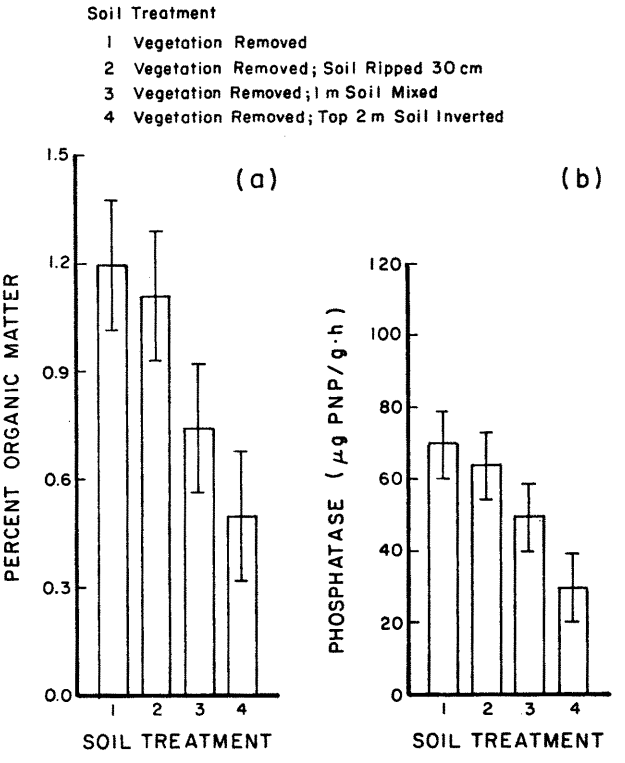

Fig. 9. Organic Matter and Phosphatase Responses, Annual Disturbance Study--1982. (LSD range ($p \leq 0.05$) is given.)

PAB stained fungal hyphae than the more extreme disturbance treatments (3 and 4).

Topsoil Storage Experiment

The stored soil experiment continued to provide valuable information. Significant differences ($p < 0.01$) were observed in 1982 for percent soil moisture and phosphatase activity between the vegetated and nonvegetated portions of the stockpile (Fig. 10). The vegetated portion had a lower percentage soil moisture, primarily in the top 122 cm which would be expected from plant uptake of water in the root zone. Vegetation had a direct effect on phosphatase activity in the stockpile. The vegetated half had an average phosphatase activity approximately three times that found in the unvegetated portion of the structure.

Significant depth effects across all cores were observed for autochthonous dehydrogenase activity ($p < 0.01$) and nitrogen fixation potential ($p < 0.05$). Dehydrogenase activity declined with depth (Fig. 11). Surface soils (0-60 cm) maintained higher nitrogen fixation potentials compared to soils from depths lower in the stockpile. These patterns have been observed in 1980 and 1981 data.

Viable counts across all sampling depths for bacteria, actinomycetes, and fungi do not differ statistically between vegetated and nonvegetated treatments. However, an interesting depth and vegetation interaction ($p < 0.01$) appears to exist for viable actinomycetes and fungi. Vegetation presence appears to result in relatively lower viable actinomycete counts in the upper 90 cm of the pile, while the nonvegetated area showed higher actinomycete populations. Vegetation appears to have had an opposite effect on viable fungi in the upper region of the stockpile. Viable fungal counts are consistently higher with than without vegetation in this depth interval. Below 90 cm and 120 cm, for actinomycetes and fungi, respectively, the interaction of depth by treatment is reversed. These results suggest that the vegetation on the stockpile is influencing the belowground microbial community structure. The fungi appear to be maintained at higher levels with plant root derived materials, while the actinomycetes appear to maintain dominance in soils where biologically more resistant soil organic matter must be utilized as a nutrient source.

Retorted Shale-Rhizosphere Interactions

In the summer of 1983 a greenhouse pot experiment was initiated to evaluate the effect

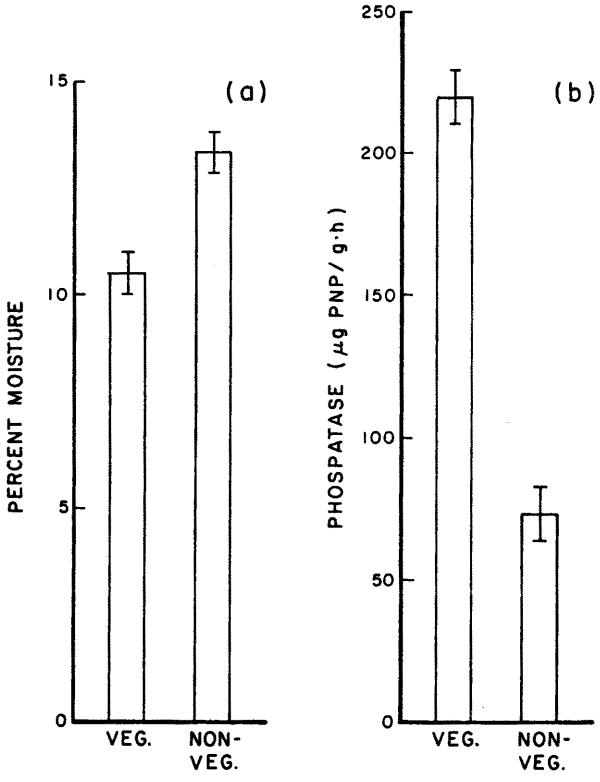

Fig. 10. Vegetation Effects on Soil Moisture and Phosphatase Activity, Topsoil Storage Experiment--1982. (LSD range ($p \leq 0.05$) is given.)

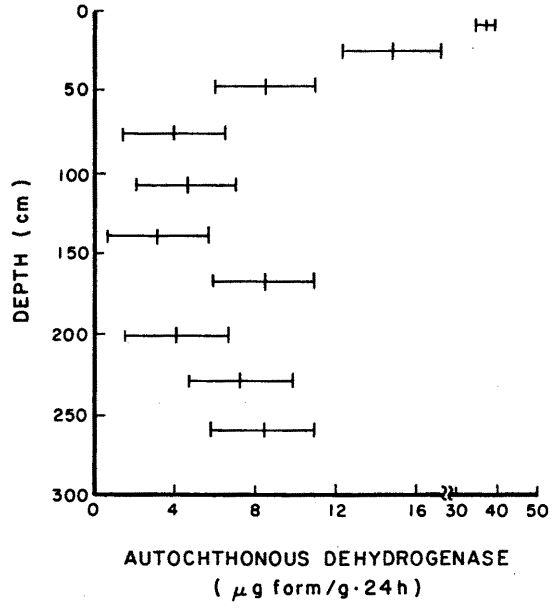

Fig. 11. Soil Depth Effect on Autochthonous Dehydrogenase activity, Topsoil Storage Experiment--1982. (LSD range ($p \leq 0.05$) is given.)

of retorted shale on microbial numbers in the rhizosphere, rhizoplane, and free soil associated with selected revegetation plant species. Chemical and physical characteristics of the soil and shale are given in Table 3.

A significant effect of the growth medium on free soil or shale viable populations for actinomycetes was observed (Fig. 12). The plants grown in the retorted shale had significantly reduced viable actinomycete populations in the free soil compared to the control and soil over shale treatments (Fig. 12a). No significant bacterial or fungal responses were observed in the free soil environment. Viable bacteria and fungal propagules in the rhizosphere showed a markedly increased level in the retorted shale treatment, which was independent of plant species, compared to the control soil and soil over shale treatments (Fig. 12b&c). This pattern was also observed for the rhizoplane bacteria and fungal propagules as shown in Fig. 13a&b, where increases in these populations were observed in plants grown in the retorted shale. Again, no parallel actinomycete responses were evident.

In addition, a plant species effect was observed for viable rhizosphere bacteria and fungi,

Table 3. Chemical and physical characteristics of control soil and retorted shale, Retorted Shale Rhizosphere Study--1983.

Measurement	Control Soil	Leached Shale
pH†	7.4	12.6
EC (mmhos/cm at 25°C)‡	0.45	15.4
SAR	0.38	66.8
Cations (meq/l)‡		
Ca	6.8	0.9
Mg	1.0	<0.1
Na	0.6	47.0
K	0.1	13.2
Anions (meq/l)‡		
HCO_3	5.6	3.8
CO_3	0.0	59.6
Cl	0.31	1.1
SO_4	ND¶	5.0
NO_3^--N (ppm)§	7.5	2.0
P (ppm)§	1.7	19.0
K (ppm)§	44.6	442.0
% organic matter	1.1	0.2

†Paste.

‡Saturation extract.

¶Not determined.

§NH_4HCO_3-DPTA extract.

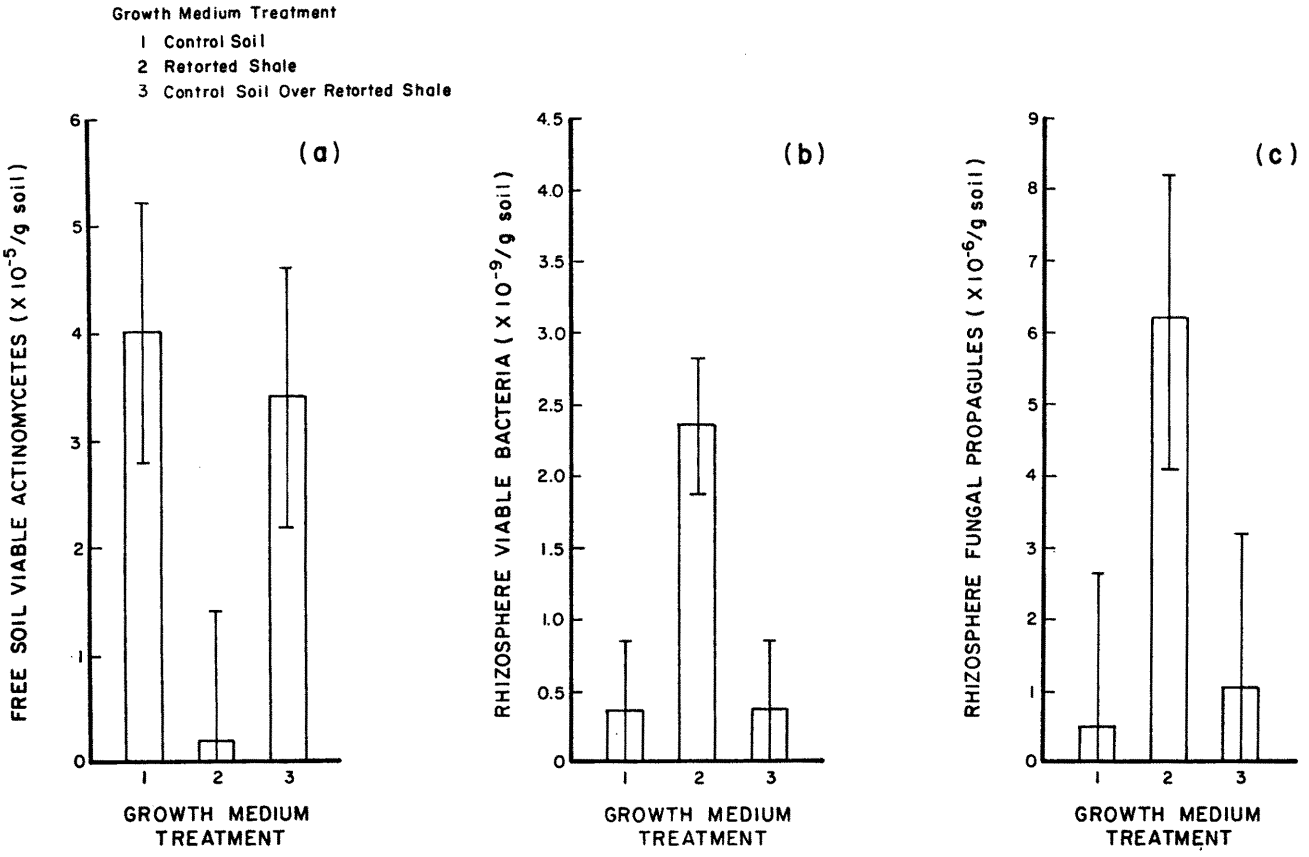

Fig. 12. Significant Plant Growth Medium Effects on Rhizosphere and Free Soil Microbial Responses, Retorted Shale Rhizosphere-Studies--1983. (LSD range ($p \leq 0.05$) is given.)

with higher populations of bacteria and fungi observed on the alfalfa roots, in comparison with the western wheatgrass and fourwing saltbush (Fig. 14). A possible explanation for this response might be related to root exudation patterns and microbial population distribution in microbiologically more active soils in comparison with shale materials. This could also be related to plant stress responses. Root exudation generally increases with increased plant stress. Plants growing on retorted shale might be expected to be under physiological stress, including higher pH and salinity. Based on studies of Polonenko et al. (1983), a balanced salt stress increased levels of soluble carbohydrates in root exudates of barley over the control by a factor of 20 under sterile growth conditions on semisolid agar. In the same study, a significant salt-induced decline in the free amino acid content of exudates was observed. Changes in the type and concentrations of root exudates can alter microbial activity and rhizosphere microbial populations (Bowen and Rovira 1976). In addition, it might be expected that the composition of root exudates differs among the species used in this study. It is interesting to note that, in all cases except one, the most salt tolerant species, i.e., fourwing saltbush, had the lowest populations of bacterial, actinomycetes, and fungal propagules in the rhizosphere and rhizoplane environments in comparison with the other plant types used in this study.

Microbial Development in Soil Systems

Initial results from the microbial development studies, where Lurgi, Paraho, and Batch 7 materials were used, suggest that the retorting process can have major effects on microbial community development, assuming similarity of beginning materials. The shale pH does not appear to be a controlling factor in these responses. After three months of simulated soil development, the Lurgi material, with a pH of 10.5-11.0, showed essentially no microbial development. The only response was with soybean meal presence where a pH shift to 8.6 occurred and an increased phosphatase activity was evident. In contrast, the Batch 7 materials, with a pH of 11.5-12.0, showed several significant responses to nutrient amendments. With glucose, casein, or soybean meal, but not with cellulose, increased zymogenous dehydrogenase activity occurred. Nitrification appeared to be stimulated by glucose plus nitrogen, but not with nitrogen alone. Essentially no nitrogen fixation potential responses to these nutrient amendments were observable.

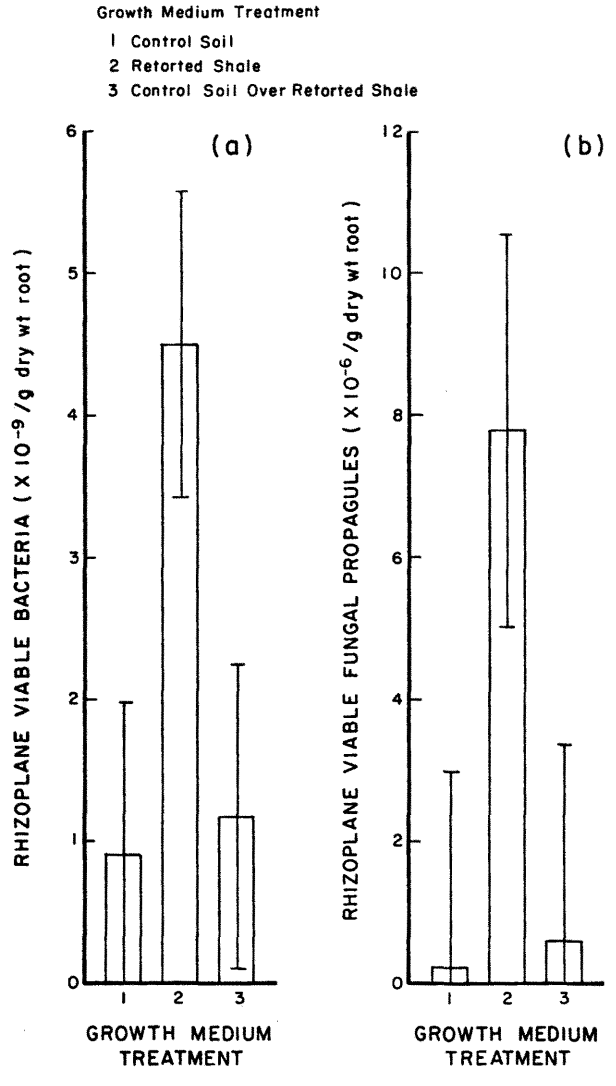

Fig. 13. Significant Plant Growth Medium Effects on Rhizoplane Microbial Responses, Retorted Shale Rhizosphere Studies--1983. (LSD range ($p \leq 0.05$) is given.)

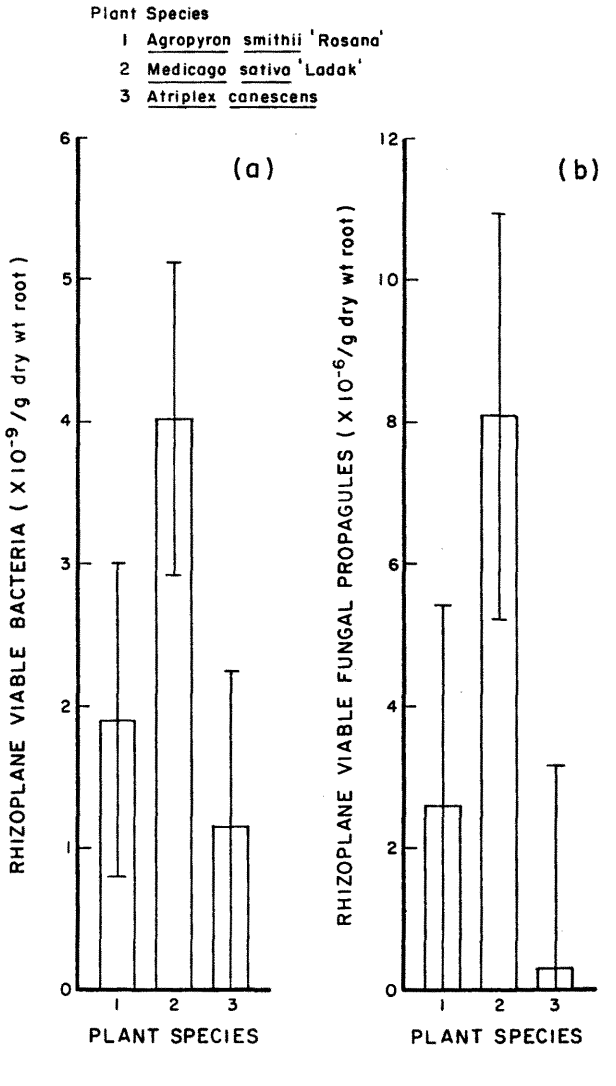

Fig. 14. Plant Species Effects on Rhizoplane Bacterial and Fungal Responses, Retorted Shale Rhizosphere Studies--1983. (LSD range ($p \leq 0.05$) is given.)

DISCUSSION

The field and laboratory studies carried out in 1982 and 1983 have been directed towards better understanding the mechanisms of development of plant-soil systems after disturbance, especially in terms of the microbial contributions to development of plants on energy waste materials.

This research has involved both field and laboratory investigations, and these have provided complementary information to allow a better understanding of the microbial role in development of plant-soil systems after disturbance, and especially in terms of the microbial contributions in development of plant communities on energy exploited areas.

The revegetation technique plot has shown the long-term effect of irrigation on belowground processes. Essentially all of the variables measured showed responses to initial irrigation. These trends have continued and provide strong evidence for the beneficial value of such initial increased water availability. The distinct effect of the introduced species mixture on increased dehydrogenase suggests that these plants may be capable of increasing carbon accretion in the belowground system more efficiently than native plants. With the increases in other enzyme activities in response to irrigation, the ability of these plant types to quickly respond in the presence of irrigation has been emphasized. If irrigation might be available, even if only initially in a reclamation program, a different group of plants may be more suitable for establishment of desired plant communities.

The retorted shale successional plot continues to show responses related to the plant and capillary barrier treatments. This involves a

continuing increase in the carbon processing potential on the 60- and 90-cm soil panels, which was particularly emphasized for the zymogenous dehydrogenase activity. Even with added glucose, the dehydrogenase activity of the panels directly in contact with the shale has reached the values of the controls. For phosphatase and nitrogen fixation potential, however, the 30-cm panel still shows depressed activities.

The effects of fertilization are still evident on this study plot. With added nitrogen, increased ammonium ion and nitrite oxidation potentials were still observed and decreases in fungal hyphal lengths were evident. This suggests that with fertilization the development of the microbial community is being retarded, an observation made by Fresquez and Lindemann (1981). In the present study, the decreases in fungal development in relation to the added fertilizer could be the result of a series of possible interactions. More nitrogen could have influenced plant root exudation patterns or could have been an indirect effect of shifted carbon-nitrogen ratios which influenced the fungal-bacterial balance in decomposition. Fertilizer availability could also have led to the functioning of a smaller, yet more active, fungal population with a higher turnover rate. These can only be suggestions with our present level of understanding of fertilizer effects on plant-microbe interactions. Further research would be required to better explain these interesting results, which could lead to an improved understanding of management effects on secondary succession processes.

An especially clear fertilizer effect was shown for the inorganic phosphorus where essentially a direct relationship between phosphorus added and extractable phosphorus was evident. These results again emphasize the long-term effects of initial fertilization in this type of arid ecosystem.

The stored soil plot showed trends which were evident during the last 1981 sampling, in that the presence of the plant community had major effects on the composition of the microbial community and on several of the enzymatic measurements. The increased phosphatase activity with plant presence suggests that both the plant and the microbial community can contribute to this activity. The microbial responses to plant presence suggest that without a continuing source of easily utilizable organic matter the actinomycetes will tend to become relatively more dominant in soils, in terms of shifts of the broader microbial groups of bacteria, actinomycetes, and filamentous fungi.

The retorted shale-rhizosphere response studies have provided some of the first information on the effects of retorted shale on microbial development in the plant root zone. It is evident that plant root zone will allow more distinct development of microbial communities in the shale material. This may be due to the lower populations of microorganisms in the shale and the lesser competition for exudates outside of the plant root zone. The ability of alfalfa to release more exudates is also suggested, as the most distinct responses were observed with this plant type.

The soil development studies suggest that the retorting process can have major effects on the potential success of nutrient amendment to stimulate microbial process development. Cellulose appears to be a poor nutrient source, which may result from a decreased decomposability under these more alkaline conditions and due to the insoluble nature of this substrate. The use of glucose alone, which led to stimulation, while nitrogen additions alone did not result in a similar response, indicates that carbon is more limiting than nitrogen in these materials. Based on the success which has been shown by these amendment experiments, additional field and laboratory studies, possibly including selected plant types, should be planned in the future.

ACKNOWLEDGEMENTS

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IMPORTANCE OF MYCORRHIZAL FUNGI IN REVEGETATING DISTURBED SOILS AND RETORTED SHALE

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INTRODUCTION

From previous studies we have shown that most of the dominant plants in stable ecosystems in the Piceance Basin of Colorado and in the surrounding regions of the semiarid West are colonized by vesicular-arbuscular mycorrhizal (VAM) fungi (Reeves et al. 1979). The function of these fungi is to effectively extend the root system of a plant and thus enhance nutrient and water uptake (Mosse et al. 1981).

Following severe disturbance of semiarid soils, the plants that initially invade are mainly nonmycorrhizal species characterized as annual ruderals (Grime 1979). Since most of these annuals do not serve as hosts for VAM fungi, conditions exist for the gradual elimination of VAM fungi from the soil. With the loss of VAM fungi those species that require mycorrhizal fungi for growth and development would not be able to survive and compete with either nonmycorrhizal species or facultatively mycorrhizal species until suitable populations of VAM fungi are present in the soils. Other conditions that may lead to the absence of VAM fungi include long-term storage of soil, deep mining of soil, or "sterilization" of soil as in oil shale processing. Thus a logical sequence of plant types that occur during succession would be that given in Fig. 1. In Fig. 1 the initial invaders are "ruderals" (non-mycotrophic species). These are followed by "competitors" (facultatively mycotrophic species) that may live without mycorrhizal fungi but have the capacity to host these fungi in their root systems. As the population of VAM fungi increases on the "competitors," conditions exist for the "stress-tolerators" (obligately mycotrophic species) to replace the "competitors." In this scheme the stable ecosystem of "climax" community would be dominated by the "stress-tolerators" but would include some "competitors" as well. This successional scheme has been suggested to occur in the tropics (Janos 1980), and there is evidence for its occurrence in semiarid conditions (Reeves et al. 1979).

To begin to understand the succession of plants that depend on these fungi for survival and to make recommendations for consideration by reclamation specialists to enhance revegetation programs, it is essential to obtain information on the role of these fungi in both undisturbed and disturbed ecosystems. The main goal of this subproject was to determine the population dynamics and function of these fungi in disturbed, stored, and processed (e.g., oil shales) soils.

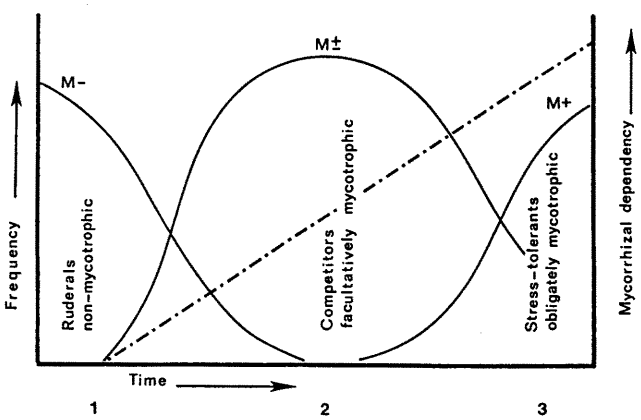

Fig. 1. A hypothetical sequence for succession based on mycorrhizal relationships of plants. Early successional stages, Position 1, are characterized by nonmycorrhizal plants (M-); intermediate successional stages, Position 2, are characterized by facultatively mycorrhizal plants (M±); and late successional stages, Postion 3, are characterized by obligately mycorrhizal plants (M+). As succession proceeds, mycorrhizal dependency increases.

The specific research objectives for the past year were as follows:

1. Monitor the Topsoil Storage Pile at the Intensive Study Site (ISS) for changes in Mycorrhiza Inoculum Potential (MIP) as a function of time, depth of soil, and planting.

2. Monitor Long-Term Fertility plots at the ISS for the effects of added nitrogen fertilizer on the MIP of the soil.

3. Determine the levels of amendments for processed shales necessary to enhance increased mycorrhiza development.

4. Determine the relative ability of nonmycorrhizal species (Atriplex canescens, Ceratoides lanata, and Salsola iberica) to maintain populations of mycorrhizal fungi in disturbed soil.

5. Monitor the Retorted Shale Successional plots at the ISS for changes in MIP as a function of depth of topsoil, fertilizer treatment, and weathering of buried shale.

6. Determine the effects of VAM fungi on growth of native juniper and pinyon pine.

7. Determine the ability of native sweetvetch (Hedysarum boreale) accessions to support mycorrhiza formation.

TOPSOIL STORAGE EXPERIMENT

Introduction

This study was initiated in 1978 in order to obtain information on the changes in microbial processes associated with simulated topsoil storage similar to that used by industry. The stockpile was constructed from the upper 30-50 cm of topsoil removed from the Intensive Study Site. The dimensions of the pile are 3 m high, 5 m wide at the top, and 23.5 m long, with the sides and ends at the angle of repose. In 1979 one-half of the storage pile (north portion) was planted with a mixture of native grasses, forbs, and shrubs; the other half (south portion) was not planted and was manually weeded.

During July 1978 and June 1979 the pile was sampled with a 7.5-cm diameter soil corer to a depth of 150 cm, and in July 1980, August 1981, and July 1982 the pile was sampled to a depth of 270 cm. Four sample bores were made in both 1978 and 1979; ten sample bores (five from the nonplanted half and five from the planted half of the pile) were made in 1980, 1981, and 1982. For each bore, the upper 30 cm was divided into two subsamples (0-15 cm and 15-30 cm). Further subsamples of the core were made at 30-60, 60-90, 90-120, and 120-150 cm during 1978-1982. In 1980-1982 additional samples were made at 150-180, 180-210, 210-240, and 240-270 cm. Soil from each subsample was sieved through a 1-cm sieve and analyzed according to the bioassay developed by Moorman and Reeves (1979). All bioassays were done in a growth chamber (d/n 14/10 hr, temp 28/21°C, light approx 350 $\mu Em^{-2}s^{-1}$) using pregerminated DeKalb XL 3421 corn; bioassays were run for 21 days for each of the soil samples. The Mycorrhiza Inoculum Potential (MIP) of each sample represents a measure of the number of viable propagules remaining in the soil and is measured as the number of colonized 1-cm corn root segments divided by the total number of root segments examined. For each sample, three replicate bioassays were run and 100 1-cm root segments were examined.

Comparable data for 1978, 1979, 1980, 1981, and 1982 were obtained only from the nonplanted half of the pile. The effects of seeding on populations of mycorrhizal fungi were obtained by comparing data from the seeded half of the pile with data from the nonplanted, weeded half of the pile.

Results and Discussion

The specific objective of this research was to determine if, during long-term storage of topsoil, there are significant reductions in the numbers of viable propagules of mycorrhizal fungi and if increasing depths of topsoil increase the longevity of VAM propagules. Results of the change in MIP values over time and at different depths of the pile are given in Table 1.

A one-way ANOVA of MIP values over the five years (1978-1982) shows a highly significant reduction of MIP over time of storage ($p < 0.001$). In Fig. 2, regression statistics for this data give an $R^2 = 0.868$ for an exponential decay equation ($y = ae^{-kt}$, where y = MIP of the soil, a = initial MIP at the time of storage, k = 0.049, and t = number of months storage). This decay equation best fits what is expected to happen; that is, the death of the VAM propagules is rapid at first, and a residual number of propagules are more resistant and thus survive for longer periods of time. Figure 2 illustrates the death curve of the VAM propagules in the top 150 cm of the storage pile.

Table 1. Mean MIP values for different depths of nonplanted, stored topsoil.

Depth (cm)	Jul 1978	Jun 1979	Jul 1980	Aug 1981	Jul 1982	Mean
0- 15	18.8	11.8	6.4	2.6	2.2	8.4
15- 30	25.0	15.8	6.6	2.2	1.7	10.3
30- 60	21.5	14.3	8.7	4.6	1.4	10.1
60- 90	18.8	14.0	6.4	6.2	3.2	9.7
90-120	17.5	15.5	6.5	7.8	4.0	10.3
120-150	25.0	24.3	5.2	6.0	1.6	12.4
Mean	21.1	15.9	6.6	4.9	2.4	

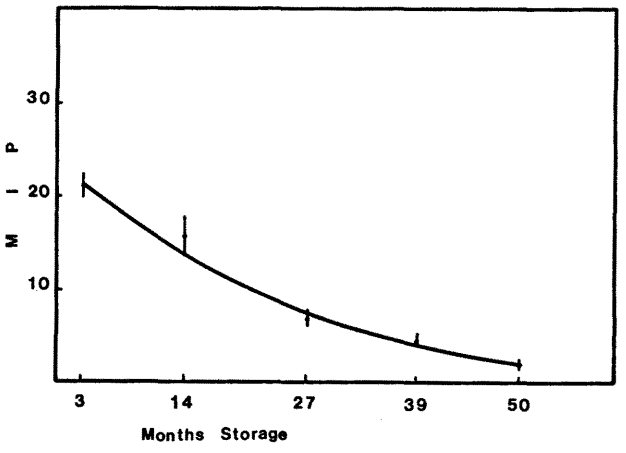

Fig. 2. A plot of the decrease in Mycorrhiza Inoculum potential (MIP) of the upper 150 cm of nonplanted topsoil stored for 50 months. Standard error of the mean is given for each sampling.

In the upper 150 cm of the pile, no significant depth effect is obvious from the data.

In Table 2 the 1980, 1981, and 1982 MIP values of the upper 90 cm of soil (effective root zone) on the **planted** half of the pile are compared to the MIP values of the **nonplanted** half of the pile; a significant ($p < 0.01$) difference between halves was found.

There is a significant ($p < 0.01$) decrease in MIP values between 1980 and 1982 on the nonplanted half of the pile and a significant ($p < 0.01$) increase in MIP values between 1980 and 1982 on the planted half of the pile. On the nonplanted half there is an apparent increase in MIP values with depth, but this increase is not significant ($p = 0.64$). However, the decrease in MIP values with depth on the planted half of the pile is highly significant ($p < 0.01$). This decrease can be ascribed to fewer roots at the deeper depths and is consistent with our previous findings for the undisturbed sagebrush community (Schwab and Reeves 1981).

In 1980, 1981, and 1982 samples ($n = 10$ for each depth) from deeper depths of the storage pile were taken. MIP data are given in Table 3. There is a significant ($p < 0.01$) decrease in MIP values between 1980 and 1982 and a significant ($p < 0.01$) increase in MIP values with increasing depths for three years. The decrease between 1980 and 1982 also is reflected in the upper portion (0-150 cm) of the nonplanted half of the pile (Table 2) although the decrease in the lower portion (150-270 cm) of the pile is less than in the upper portion. The differences between the upper and lower portion of the pile may reflect the methods used in the construction of the pile. The base of the pile was constructed from the upper layers of topsoil, with higher MIP values, and the lower layers of topsoil, with lower MIP values, were used to form the top of the pile.

Table 2. Mean MIP values for the upper 90 cm (root zone) of soil from planted vs. nonplanted halves of the Topsoil Storage Pile (data for 1980-1982).

Depth (cm)	Nonplanted				Planted			
	1980	1981	1982	Mean	1980	1981	1982	Mean
0-15	6.4	2.6	2.2	3.7	25.2	41.3	43.8	36.8
15-30	6.6	2.2	1.7	3.5	11.2	39.4	37.7	32.0
30-60	8.7	4.6	1.4	4.9	16.4	35.2	32.0	30.7
60-90	6.4	6.2	3.2	5.2	12.0	15.0	10.8	12.6
Mean	7.0	3.9	2.1		16.2	32.3	31.1	

Table 3. Mean MIP values for the lower (150-270 cm) depths of the Topsoil Storage Pile (data for 1980-1982).

Depth (cm)	1980	1981	1982	Mean
150-180	8.3	8.3	6.1	7.6
180-210	9.9	9.5	3.0	7.5
210-240	12.0	13.7	8.4	11.5
240-270	13.3	16.0	9.0	9.8
Mean	10.9	11.9	6.6	

Summary and Conclusions

Data for the past four years clearly indicate significant and predictable reductions in the numbers of viable VAM propagules in stored topsoil when the soil is not planted. An equation for the predicted loss of VAM fungi is given.

When topsoil is planted with species able to host mycorrhizal fungi, the number of viable propagules of VAM fungi is initially increased, at least in the rooting zone (upper 90 cm) of the plants, and then stabilizes. The effective root zone appears to be limited to the upper 90 cm of stored topsoil. Thus the numbers of VAM fungi will not increase in deeper portions of the pile. Data from the deeper portions (>90 cm) of the plant portion of the topsoil pile indicate a reduction of VAM fungi that parallels that found on the nonplanted half of the pile.

The apparent initial preservation of VAM fungi (data for 1980-1981) in the deeper portions of the Topsoil Storage Pile, when compared to the upper portions of the pile, does not continue for longer than 39 months. Significant reductions in MIP values in this portion of the pile occurred between 1981 and 1982.

For long-term preservation of VAM fungi on stored topsoil, it will be necessary to plant the topsoil with deep-rooted species that are able to host mycorrhizal fungi. Nonplanted topsoil cannot be stored for periods longer than 14 months without

significant reductions in the numbers of viable mycorrhizal propagules. To insure that a viable population of VAM fungi is present after prolonged storage, the upper layers (upper 90 cm) of planted topsoil should be used as an inoculum. This soil could be mixed with lower layers of stored topsoil that will be applied to reclaimed areas to enhance populations of mycorrhizal fungi.

LONG-TERM FERTILITY PLOTS

Introduction

These plots were established in 1977 to determine the long-term fertility requirements for the establishment and growth of plants on soil over processed shale. Disturbed topsoil (60 cm) was placed over Paraho processed oil shale (60 cm), and a uniform application of 130 kg P/ha was broadcast over the plots. Subplots received various nitrogen applications ranging from 0 to 448 kg/ha/yr or up to 1792 kg/ha initial application with both receiving the same amount of N after four years. Various levels of sewage sludge also were used as an initial application of fertilizer. Each subplot was replicated three times and planted with a mixture of native species. Details of these plots are found in the 1981 progress report for this project.

The subplots selected for sampling were those receiving uniform P applications (130 kg/ha) and differing inorganic N applications (Plots 1-8) and three control subplots (Plot 20) with no additional N (Table 4). Sampling (3 cores/plot each 15-cm deep, 7.5-cm diameter) was done in October 1980, March 1981, June 1982, and June 1983. Soil was returned to the laboratory, and a 21-day bioassay was run in growth chambers using the methods previously described.

Table 4. Mean MIP values of selected Long-Term Fertility Plots (disturbed topsoil over processed shale) receiving various amounts of nitrogen. All plots received a uniform phosphorus application (130 kg/ha) in 1977.

Plot	Nitrogen Treatment	MIP Value				
		Oct 1980	Mar 1981	Jun 1982	Jun 1982	Mean
1	56 kg/ha/yr†	73.0	39.0	72.3	68.7	63.3
2	112 kg/ha/yr	54.0	40.7	37.0	66.3	49.5
3	224 kg/ha/yr	28.7	11.7	55.7	45.0	35.3
4	448 kg/ha/yr	26.3	29.3	39.7	21.7	29.3
5	224 kg/ha initial	65.0	35.7	76.7	69.7	61.8
6	448 kg/ha initial	74.0	46.7	70.3	84.3	68.8
7	896 kg/ha initial	55.7	37.7	60.0	63.3	54.2
8	1792 kg/ha initial	64.0	41.0	55.3	79.3	59.9
20	0 kg/ha	74.3	62.7	88.0	81.7	76.7

†Plots 1-4 received fertilization in these quantities each year for four years (1977-1981).

Results and Discussion

The specific objective of this subproject was to determine if there is evidence of differential effects on MIP values when moderate to high levels of N fertilizer are applied to disturbed topsoil over shale.

Recent reviews (Hayman 1982, Safir and Duniway 1982) of the effects of soil fertility on VAM fungi emphasize that N fertilizer may have a negative effect on mycorrhiza formation. However, a positive effect of added N is reported for certain soils (Kruckelmann 1975).

Data for Plots 1-8 and Plot 20 are given in Table 4. For the years 1980-1983, the general trend was that when N was added to topsoil over shale in yearly increments (Plots 1-4) there was a significant ($p < 0.01$) decrease over time in the MIP values (Fig. 3). This supports the general findings of previous researchers (Hayman 1982). However, when N was added initially (Plots 5-8), even at the highest level (1792 kg/ha), there was no significant ($p = 0.01$) reduction in MIP on Plot 7 (896 kg N/ha) and Plot 8 (1792 kg N/ha). It is obvious in Fig. 3 that, over time, the incremental additions of N differ significantly from an initial heavy application of N.

It would appear that the heavy, initial application of N (Plots 5-8) has an effect on MIP, but the initial effect of reducing MIP values of the soil rapidly equilibrates. Perhaps the heavy initial application of N was rapidly volatilized so that it was not available to the developing plant cover and thus did not affect the MIP of the soil. In contrast, the continued application of N at the higher levels (112, 224, and 448 kg/ha/64) appears to be cumulative and leads to a reduction of MIP in these soils. An exponential decay equation, with an $R^2 = 0.894$, that describes this cumulative effect has been calculated. This equation is $y = ae^{}$, where y = MIP of the soil, a = 68.3,

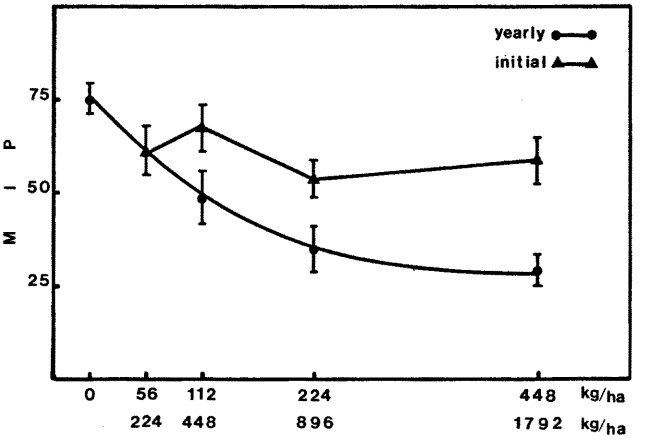

Fig. 3. Changes in mean Mycorrhiza Inoculum Potential (MIP) on Long-Term Fertility Plots as a function of added nitrogen fertilizer. Standard error of the mean is given for each nitrogen treatment.

b = 0.002, and c = yearly application N in kg/ha. The biological significance of this equation remains elusive. No doubt many of the soil microorganisms are greatly affected by the annual additions of N. The interaction of added N with soil microorganisms should be carefully studied.

These results suggest that the manner in which N is added to the soil and the amount of N added to the soil can elicit quite different response in MIP values. These results may help clarify the paradoxical data from previous researchers (Hayman 1982, and Kruckelmann 1975).

Summary and Conclusions

The application of moderate (56 kg/ha/yr) yearly additions of N or heavy (up to 448 kg/ha) initial applications of N to disturbed topsoil over processed shale does not significantly affect the MIP values of the soil after six years. Nitrogen in excess of 56 kg/ha/yr or in excess of 448 kg/ha initial application significantly reduce the MIP values of disturbed topsoil over processed shale. However, even the highest applications of N (Plots 4 and 8) followed by replanting do not reduce MIP values to critically low levels. It appears that a single 224 kg/ha initial application is equivalent to an annual application of 56 kg/ha/yr in terms of effect on MIP of the soil. It will be necessary to determine the minimum level of added N needed to insure successful species establishment for the maximum cost/benefit ratio.

EFFECTS OF RETORTED SHALE ON MYCORRHIZA INOCULUM POTENTIAL

Introduction

Results from many field trials have shown that retorted oil shale is not a desirable medium for establishing diverse vegetation unless the shale is leached or treated. Our results have demonstrated that retorted oil shale alone does not readily support mycorrhiza formation in most plants native to the semiarid conditions of Colorado. A standard revegetation technique is to apply topsoil over retorted shale and establish a vegetation cover on the topsoil. However, our results have demonstrated that once the roots of plants reach the shale layer beneath the topsoil, there is little invasion of the roots into the shale layer and there is effectively no mycorrhiza formation in the shale layer.

The objective of this series of experiments was to determine the quantity of processed shale that can be mixed with topsoil and still support mycorrhiza formation in plants. The purpose of these experiments was to determine what level of processed shale significantly decreases VAM formation in experimental plants.

Our previous results (Schwab and Reeves 1980) had shown that recently processed Paraho shale reduces mycorrhiza formation when 50% or more shale is mixed with topsoil. However, these experiments did not include sufficient replicates to conclusively demonstrate the effect of processed shale on mycorrhiza formation.

In the current experiments weathered, processed oil shale was collected from the Intensive Study Site in the spring of 1982. This shale was collected from the upper 15 cm of the Shale-to-Surface Plots of the Retorted Shale Successional Study. The shale had a pH of 8.97 (slurry paste). It has been exposed to leaching and atmospheric CO_2 for five years in the field.

In order to compensate for the effects of shale on ameleoration of the clay-loam topsoil used, a parallel series of replicates using sterile sand was devised. Processed oil shale and sterile sand were added to a homogeneous mixture of topsoil. These mixtures included the addition of 10% sand or 10% shale, 25% sand or 25% shale, 50% sand or 50% shale, and 75% sand or 75% shale. Controls were 100% sand, 100% shale, and 100% (undiluted) topsoil.

A bioassay, as previously described, was run on the shale, sand, topsoil, and topsoil + sand in order to determine the effects of shale on mycorrhiza formation.

Results and Discussion

Results from these experiments again demonstrate that processed oil shale does not permit mycorrhiza formation (100% shale, Table 5). The processing of shale renders this material effectively sterile in terms of VAM propagules; this material does not permit mycorrhiza formation after five years (1977-1982) weathering in the field. However, when this processed oil shale is mixed with topsoil containing viable propagules of VAM fungi, mycorrhiza formation occurs. In fact, up to 50% weathered shale may be mixed with topsoil before a significant reduction in mycorrhiza formation occurs (Table 5).

There is a significant ($p < 0.01$) reduction of mycorrhiza formation when topsoil is diluted with either sterile sand or processed oil shale to 75%. The 10%, 25%, and 50% added sand or shale are not significantly ($p < 0.01$) different from one another at comparable levels. When either sand or shale is added to topsoil at the 10% level, there is a significant ($p < 0.01$) increase in the ability of the medium to support mycorrhiza formation. This increase probably is due to a reduction in the relative clay content of the soil. With the addition of 25% sand or shale there is no significant increase in MIP values with sand, but an increase in MIP values with shale. The addition of 50% sand or shale is not significantly ($p < 0.01$) different from the topsoil control. When 75% sand or shale is added to topsoil, there is a significant ($p < 0.01$) decrease in MIP values when compared to the topsoil control or any of the other dilutions (Table 5, Fig. 4).

Table 5. Effects of weathered, processed oil shale and sterile sand on mycorrhiza formation.

Treatment		Mean MIP Value	Standard Error
Sand (sterile)		0.0	0.0
Shale (weathered)	(pH = 8.97)	0.0	0.0
Topsoil	(pH = 8.87)	79.8	1.4
Topsoil + 10% sand		87.7	1.0
Topsoil + 10% shale		89.0	3.6
Topsoil + 25% sand		80.7	3.4
Topsoil + 25% shale		88.4	1.0
Topsoil + 50% sand		79.2	5.4
Topsoil + 50% shale		84.0	2.4
Topsoil + 75% sand		66.3	2.2
Topsoil + 75% shale		50.1	3.0

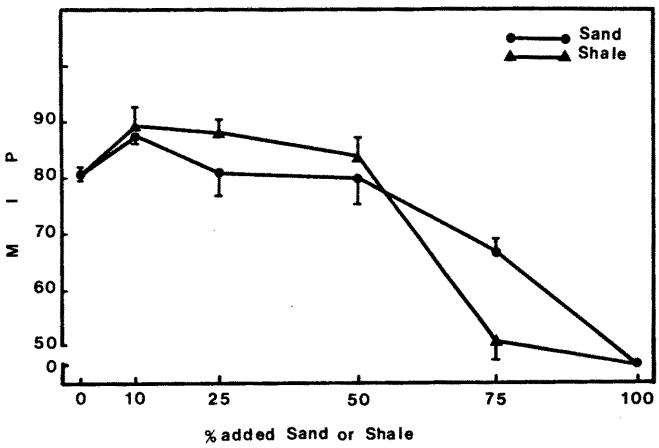

Fig. 4. Changes in mean Mycorrhiza Inoculum Potential (MIP) of topsoil as a function of added sterile sand or processed oil shale. Standard error of the mean is given for each addition of sand or shale.

Summary and Conclusions

There is a significant reduction in the ability of topsoil to support mycorrhiza formation when quantities in excess of 50% processed shale are mixed with topsoil. The reduction in MIP values cannot be ascribed solely to the dilution effect of the shale since comparable quantities of sterile sand do not reduce MIP values as much. Since processed shale clearly inhibits mycorrhiza formation, several factors should be considered as potential reasons for this reduction. The weathered shale had a pH of 8.97 which is not excessive when compared to topsoil with a pH of 8.87. Thus the significant decrease at 75% shale is probably due to toxic qualities in the retorted shale. These qualities may directly affect root formation and thus mycorrhiza formation, or the qualities may affect germination of mycorrhizal propagules.

The lack of VAM formation in 100% shale in this experiment corroborates our findings of no mycorrhiza formation in soil over shale (see Retorted Shale Successional Plots of this report). If mycorrhiza formation is to be achieved, no more than 50% processed shale may be mixed with topsoil containing viable VAM propagules.

DETERMINE THE ABILITY OF NONMYCORRHIZAL SPECIES TO MAINTAIN VAM FUNGI

The objectives of this study were not accomplished during this time period. We hope to begin this study in the spring of 1984.

RETORTED SHALE SUCCESSIONAL PLOTS

Introduction

This study was initiated in 1977 to test the effect of surface disposal plans for processed shale on plant growth and succession and on microbiological processes in soil as well as in the retorted shale. Six plots, representing simulated profiles of soil over processed shale, were constructed. Vertical profiles of these plots (Fig. 5) are characterized as follows:

1. Retorted shale (60 cm) to surface
2. 30 cm topsoil over retorted shale (60 cm)
3. 90 cm topsoil over retorted shale (60 cm)
4. Control plot (no shale, only soil)
5. 60 cm topsoil over retorted shale (60 cm)
6. 60 cm topsoil over rock capillary barrier over retorted shale (60 cm)

To determine the effects of topsoil over shale on MIP values of both the topsoil and the underlying shale, three subplots, B1, B2, and B3 (three replicates of each), were selected. These subplots had been previously planted with a native grass-forb-shrub species mixture and fertilized at 112 kg N + 56 kg P/ha (B1), or 56 kg N + 28 kg P/ha (B2), or 0 kg N + 0 kg P/ha (B3). Each soil/shale treatment was sampled to a depth of 30 cm into the shale below the soil, with the exception of Plot 6 which was sampled to the rock capillary barrier. (Details of the initial treatments on these plots are found in Redente et al. in the 1982 progress report.)

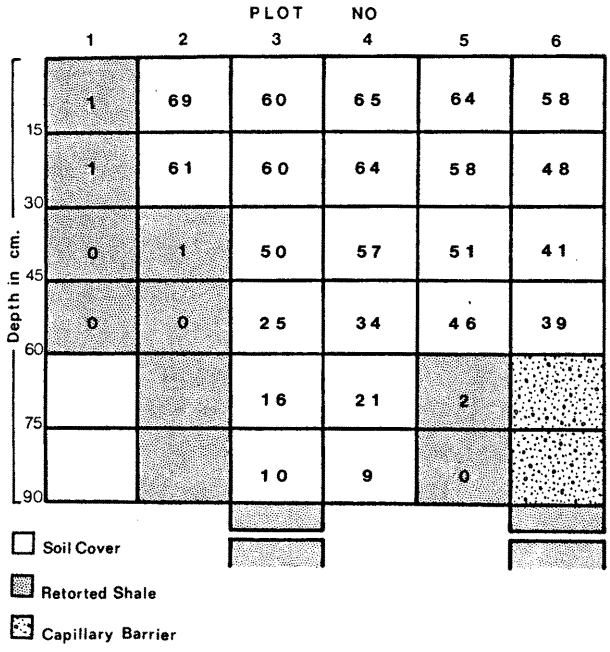

Fig. 5. Vertical profiles of Retorted Shale Successional Plots 1-6. Number in each rectangle is the mean Mycorrhiza Inoculum Potential (MIP) of that soil or shale at the depth indicated on the left axis. Data is based on mean values for 1980, 1981, and 1982.

On June 11, 1980, June 3-4, 1981, and June 12-14, 1982 the B1, B2, and B3 subplots were sampled using a 7.5-cm diameter soil corer. Soil and shale samples were each divided into 15-cm length samples. In the laboratory each sample was sieved through a 1-cm sieve and analyzed for MIP values using a modification of the corn bioassay (Moorman and Reeves 1979). Rather than using 9-cm square pots, tubular Conetainers™ (used in forest nursery practices), 3.5x21 cm, were planted with pregerminated DeKalb XL 321 corn. The bioassay was run for 21 days in a growth chamber (d/n 14/10 hr, temp 28/21°C, light approx 350 $\mu Em^{-2}s-1$).

Results and Discussion

Analysis of the 1980-1982 data from the soil of subplots B1, B2, and B3, comparing equivalent depth samples, revealed no significant differences in MIP values due to **fertilizer effects**, i.e., subplots B1-B3 were similar in their MIP values in the 0-45 cm of soil. These data are consistent with our findings on the Long-Term Fertility Plots where significant effects of N on MIP values were not obvious until 896 kg N/ha was applied to topsoil. Significant ($p < 0.01$) differences were found when soil was compared to retorted shale at equivalent depths--the retorted shale had MIP values near 0 (Fig. 5).

For the three years the effect of soil depth on MIP values is variable. At 0-15 cm, for comparable soils (Plots 2-6), there is no significant ($p = 0.08$) difference in MIP values. At 15-30 cm, for comparable soils (Plots 2-6), Plot 6 (capillary barrier treatment) had significantly lower MIP values than the other plots. The reason for these lower values is unclear, but at the time of sampling the soil from Plot 6 appeared to contain much more water than the comparable soils from Plots 2-5. At 30-45 cm, for comparable soils (Plots 3-6), there is no significant ($p = 0.08$) difference in MIP values. At 45-60 cm, for comparable soils (Plots 3-6), there is no significant ($p = 0.11$) difference in MIP values. At 60-75 cm, for comparable soils (Plots 3 and 4), there is no significant ($p = 0.26$) difference in MIP values. At 75-90 cm, for comparable soils (Plots 3 and 4), there is no significant ($p = 0.82$) difference in MIP values.

When comparisons are made among the deeper soils, a series of interesting results occur. There is a significant ($p < 0.01$) decrease in MIP values with depth on Plots 3 and 4. These data corroborate our earlier findings for undisturbed sagebrush communities (Schwab and Reeves 1981). When comparable depths in Plots 3 and 4 are compared to Plots 5 and 6, at 45-60 cm Plots 3 and 4 have significantly ($p = 0.02$) lower MIP values than Plots 5 and 6. The roots penetrate deeper in Plots 3 and 4, but appear to be restricted to the soil zone in Plots 5 and 6. The restriction of the roots to the upper 60 cm in Plots 5 and 6 leads to higher MIP values at this depth. The lack of penetration of the roots into the shale layer at 30 cm on Plot 2, 90 cm on Plot 3, and 60 cm on Plot 5, and the very low MIP values of the shale beneath soil and shale to surface (Plot 1) corroborates our findings that 100% shale does not permit mycorrhiza formation (see Effects of Process Shale on MIP in this report).

Summary and Conclusions

Based on our data for 1980-1982, there appears to be no adverse effect, in terms of MIP values, of soil over processed oil shale or fertilizer treatments at the level used in this series of experiments. However, it is clear that mycorrhiza formation is restricted to the soil and does not occur in the shale beneath the soil. Thus the depth of soil over shale determines the depth at which mycorrhizae will form. When 90 cm of soil is placed over shale, MIP values comparable to "natural" (control Plot 4) conditions prevail. When shallower depths of topsoil are placed over shale, no mycorrhiza formation occurs in the shale layer. Thus the shallower depths are not comparable to the control conditions.

For more effective penetration of the roots and for mycorrhiza formation at the deeper depths, it may be advisable to mix the shale with soil to induce deeper rooting.

MYCORRHIZAL STUDIES OF PINES AND JUNIPERS

Introduction

One of the major vegetation associations of the Piceance Basin is the Pinyon-Juniper Woodland. These species occupy approximately 35% of the basin (Terwilliger et al. 1974). In a series of related studies we have begun to examine the mycorrhizal relationships in pinyon pine (Pinus edulus) and Utah Juniper (Juniperus osteosperma). Both species characterize "climax" communities and thus were expected to be mycorrhizal (see INTRODUCTION to this progress report).

Previous research (see 1982 progress report) has shown that both species were mycorrhizal. The pines are predominantly ectomycorrhizal, and the junipers are predominately endomycorrhizal. Our previous research on pines, using selected ectomycorrhizal fungi (Pisolithus tinctorius, isolate PT133, and Suillus granulatus, isolate SG75-20), demonstrated that these fungal isolates did not stimulate growth in the pines. We suggested that these isolates were not adapted to this species and thus were nonfunctional for these pines.

During the last year we have attempted to isolate a series of fungi that are associated with pinyon pine. The most common fungus associated with the roots of pinyon is a Rhizopogon species (as yet undetermined). We believe that we have this species in culture, and a series of experiments using this fungus are planned. This spring we will attempt to isolate and culture additional strains of the fungi growing in association with the pines. Results to date have been very limited because the mycorrhizal fungi appear to be mainly subterranean species and are exceedingly difficult to find.

The common VAM association of junipers involves an association with the mycorrhizal fungus Glomus fasciculatum. We have this fungus in pot cultures, and we have completed a series of experiments that demonstrate that junipers exhibit a positive growth response when inoculated with this fungus.

In these experiments, topsoil from the basin was collected,, it was steam sterilized, and half the pots were inoculated with soil from the pot culture of G. fasiculatum. All experiments were conducted in a growth chamber to produce uniform growth conditions and reduce possible contamination from other mycorrhizal fungi. Data included number of leaves, height of plants, wet and dry weight of plants, and percent infection of roots after seven months of growth.

Results and Discussion

Results of these experiments on juniper are given in Table 6. After only one month of growth, the plants inoculated with the VAM fungus showed more rapid growth and this growth continued to exceed the noninoculated plants. The increase in the number of leaves in the inoculated plants was obvious after three months of growth. Wet and dry weight determinations were made at the end of the experiment. Both the wet and dry weight of the colonized juniper plants were significantly ($p < 0.01$) greater than the noncolonized plants. Analysis of the roots after seven months of growth showed that the noninoculated plants were not infected with VAM fungi (% colonization = 0), whereas the inoculated plants had a mean colonization of 61.9%.

Table 6. Mean growth responses of Utah juniper inoculated (M+) and noninoculated (M-) with the VAM fungus Glomus fasciculatum.

Growth Period (months)	Height		No. of Leaves		Wet Weight		Dry Weight		Infection	
	M+	M-	M+	M-	M+	M-	M+	M-	M+	M-
1	2.4	1.9	14	12						
2	2.8	2.3	26	23						
3	3.5	2.8	41	37						
4	4.0	3.0	53	45						
5	5.1	3.1	70	49						
6	6.4	3.3	87	52						
7	8.2	3.5	111	54	0.49	0.09	0.19	0.07	61.9	0.0

Clearly juniper responds favorably to VAM infection in soils with low P levels as found in the Piceance Basin. These results indicate that if junipers are transplanted in soils low in numbers of viable propagules of mycorrhizal fungi, it will be beneficial to preinoculate the junipers with VAM fungi to increase their growth rate.

SWEETVETCH AND MYCORRHIZA FORMATION

Progress to Date

Legumes are potentially important species in the reestablishment of plant communities because many support a symbiotic bacterium, Rhizobium, that fixes nitrogen. Data from several laboratories indicate that the rate of nitrogen fixation and the rate of growth in certain legumes are enhanced when the legumes are colonized with VAM fungi (Gerdemann 1975). We have demonstrated an increased growth response in sweetvetch (Hedysarum boreale) when it is inoculated with the VAM fungus Glomus fasiculatum (Redente and Reeves 1981). The purpose of these experiments was to determine if several accessions of sweetvetch from Colorado demonstrate different growth responses when inoculated with a native strain of G. fasciculatum and Rhizobium. The experiments were begun in the late summer of 1983.

The experimental procedure was to grow sweetvetch with and without the VAM fungus, with and without the bacterium, and with both the fungus and the bacterium in sterilized topsoil collected from the Piceance Basin. Two technical difficulties have arisen. In all our experiments the sweetvetch plants were colonized by Rhizobium, thus there were no controls available for growth

comparisons. The second difficulty was that the VAM inoculum used had been parasitized with another fungus and was not functional. Attempts to control the Rhizobium contamination with streptomycin were unsuccessful because the streptomycin inhibited root formation. We have been advised that contamination of soil with Rhizobium is a common occurrence in many experiments and that inoculated and noninoculated plants should be grown in separate growth chambers to avoid contamination. These experiments will be repeated using separate growth chambers, new VAM inoculum, and improved sterile technique.

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RECARBONATION OF PROCESSED SHALES

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INTRODUCTION

During the processing of oil shale, high temperature destroys carbonate minerals and drives off carbon dioxide. This decarbonation process often causes the pH of processed shales to approach 12.0, resulting in a reduced availability of plant nutrients and an increased release of potentially toxic elements. Because of these effects, direct revegetation of oil shale wastes is often very difficult.

Several studies have examined the factors causing the high pH in retorted shale and the reason for a reduction in pH as recarbonation processes occur. However, many of the details of these processes are not clear. This research was undertaken to more closely study decarbonation and recarbonation processes in spent shales. The specific objectives of this research were (1) to evaluate the reactions of carbonate minerals during the processing of oil shales, (2) to examine precipitation of carbonate minerals from dissolution of silicate minerals when CO_2 is bubbled through spent shale to lower its pH, and (3) to examine chemical equilibrium relationships involved in the solubility of different calcium and magnesium minerals.

MATERIALS AND METHODS

Three spent shales TOSCO (leached), Paraho, and Lurgi were used in this study. Samples of 15 g of spent shale were shaken with 30 ml distilled H_2O for 24 hours on a mechanical shaker, pH measurements were taken, and the suspensions were filtered. The filtrate was divided into two samples. One was acidified with two or three drops of concentrated HCl and the other was left untreated. The acidified sample was used for analysis of Ca, Mg, Na, K, Si by atomic absorption, SO_4 by titrimetric method using nitrochromeazo as an indicator, and P by the ascorbic acid molybdo-tartrate method. The treated samples were analyzed for EC, Cl, carbonates, and bicarbonates. Electrical conductivity was measured using a conductivity bridge (Model PM-70C B). Chlorides were analyzed with a specific ion electrode while carbonates and bicarbonates were determined by titration with standard acid. The $CaCO_3$ equivalent of the shales was determined by reacting 0.1 g of spent shale with 10 ml of 1 N HCl for one-half hour using pressure calcimeter.

To measure the equilibrium partial pressure of CO_2 in spent shales, 10 g of spent shale were shaken with 20 ml of distilled H_2O for 24 hours on a mechanical shaker. Each flask was closed with a stopper in which a serum cap was mounted. Ten milliliters of the gas phase was carefully taken from the shaking flasks using a syringe. The gas sample was slowly bubbled into 10 ml of standard NaOH containing three drops of phenolphthalein. The flasks were covered immediately with parafilm to avoid exchange of CO_2 with the air. After adding three drops of methyl orange (1%), the solutions were rapidly titrated with standard HCl to a gold color end point. To determine the alkalinity of the blank, three drops of phenolphthalein and three drops methyl orange were added to 10 ml of NaOH and titrated with standardized HCl to a gold color end point. The partial pressure of CO_2 was calculated from the formula:

$$CO_2(g)\ \text{atm.} = \frac{(\text{ml of acid for blank} - \text{ml of acid for sample}) \times N \text{ of acid} \times 22.4}{2 \times \text{ml of gas sample}}$$

To examine the mineralogical composition of Lurgi spent shale, a 50-g sample was washed with distilled H_2O several times and centrifuged at 2500 rpm for 10 minutes to separate shale from solution. The solids were then dried at 50°C for 1 hour and x-rayed.

For the recarbonation studies Lurgi processed shale was selected because of its high pH (11.3). A 1-liter Plexiglas cylinder similar to that of Schwab and Lindsay (1983) was used. A combination pH electrode was used to measure pH. The gas inlet was connnected to Flask A (Fig. 1) to admit CO_2. Gas outlet tube was connected to an ascarite tube to absorb excess CO_2. A 50-g sample of spent Lurgi shale was suspended in 50 ml H_2O, using a magnetic stirer. The CO_2 produced from adding 1 N HCl to $CaCO_3$ (calcite) in Flask A was slowly bubbled through the spent shale suspension. The amount of CO_2 absorbed by the Lurgi shale and the decrease in pH were recorded periodically.

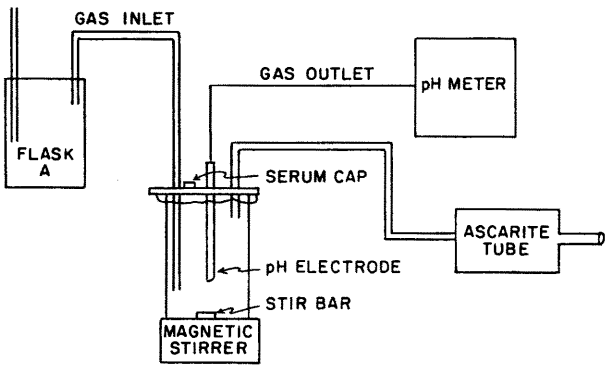

Fig. 1. Experimental setup for the recarbonation studies.

When the pH was lowered and stabilized near 7.9, approximately 50 ml of shale suspension was taken from Plexiglas cylinder with a syringe and centrifuged immediately. The supernatant was divided into two samples. One sample was acidified with two or three drops of concentrated HCl and used for analysis of Ca, Mg, Na, K, P, Si, and SO_4. The unacidified sample was used to analyze for EC, Cl^-, CO_3^{2-}, and HCO_3^-. The shale sample was dried at 50°C for 1 hour and x-rayed for mineralogical composition. A 10-ml sample of the gas phase from the Plexiglas cylinder was taken through the serum cap and analyzed to obtain the equilibrium partial pressure of CO_2. The activities of Ca^{2+}, Mg^{2+}, SO_4^{2-}, and $H_4SiO_4^o$ in solution were calculated after correcting for ion pairs as described by Lindsay (1979). The species considered for total Ca were Ca^{2+}, $CaCl^+$, $CaCO_3^o$, $CaSO_4^o$, and $CaHCO_3^+$; for total Mg they were Mg^{2+}, $MgCl^+$, $MgSO_4^o$, $MgHCO_3^+$, $MgCO_3^o$, and $MgOH^+$; for total SO_4 they were SO_4^{2-}, $CaSO_4^o$, $MgSO_4^o$; and for total silica they were $H_4SiO_4^o$, $H_3SiO_4^-$, $H_2SiO_4^{3-}$, $HSiO_4^{3-}$, and SiO_4^{4-}. Equilibrium constants for these species were taken from Lindsay (1979). The ionic strength (μ) was calculated from EC using the equation:

$$\mu = 0.013 \times EC$$

taken from Griffin and Jurinak (1973). Activity coefficients for ionic species were calculated using Davies equation. Calcite was precipitated by adding CO_2 to calcium chloride solution and x-rayed to compare the peaks with those obtained for recarbonated Lurgi shale.

RESULTS AND DISCUSSION

Analytical data for spent shales are given in Table 1, and the activities of Ca^{2+} and Mg^{2+} are plotted in Figs. 2 and 3. In these figures dashed lines represent metastable solid phases and solid lines represent stable solid phases under the specified conditions. The experimental points are plotted as closed and open symbols. The results suggested that for Paraho shale at pH 8.5, Ca^{2+} and Mg^{2+} activities in solution were controlled by the solid phases calcite ($CaCO_3$) and magnesite ($MgCO_3$) at measured CO_2 pressure ($10^{-3.65}$ atm.).

For TOSCO shale at pH 8.2, Ca^{2+} and Mg^{2+} activities in solution were controlled by the solid phases calcite and serpentine when CO_2 was $10^{-3.4}$ atm. and $H_4SiO_4^o$ activity was $10^{-4.37}$ M. For Lurgi shale at pH 11.3, the Ca^{2+} and Mg^{2+} activities in solution were controlled by metastable minerals such as pseudowollastonite ($CaSiO_3$) and clinoenstatite ($MgSiO_3$) in equilibrium with $H_4SiO_4^o$ measured at $10^{-5.25}$ M.

One possible explanation for the formation of metastable minerals at high pH in spent Lurgi shale is that during the retorting, high temperatures (705°C) were sufficient to decompose carbonate minerals and form silicate minerals according to the reaction:

$$CaMg(CO_3)_2 \text{ (dolomite)} + 2SiO_2 \xrightarrow{\text{heating}} MgSiO_3 + CaSiO_3 + 2CO_2(g)\uparrow \quad (1)$$

The findings reported in this study agree in part with the results of Matzick et al. (1966). After retorting at temperatures sufficient to decompose carbonate minerals, a sample of spent shale was analyzed for free CaO. None was found, however, even when 47% of the carbonates were decomposed (Matzick et al. 1966). Based on this information the authors suggested that monocalcium or dicalcium silicate minerals were formed, but they did not show which silicate minerals may have precipitated.

Table 1. Analyses of spent oil shale extracts (1:2 shale/water ratio).

Spent Shale	pH	Ca	Mg	Na	K	Si	HCO_3	CO_3	Cl	SO_4	PO_4	μ	$CO_2(g)$ - log atm.†	% $CaCO_3$ Equiv.	Approx. Retorting Temp. (°C)
	(ppm)														
TOSCO-L	8.20	37	35.00	200	10	1.20	122.00	---	7	450	<0.1	0.016	3.48	58.50	370
Paraho	8.50	15	125.00	27	39	2.30	206.00	15	8	310	<0.1	0.013	3.65	49.50	480
Lurgi	11.30	750	0.30	140	200	6.25	48.31	161	43	1970	<0.1	0.050	<5.72	26.00	700

†Measured in triplicate.

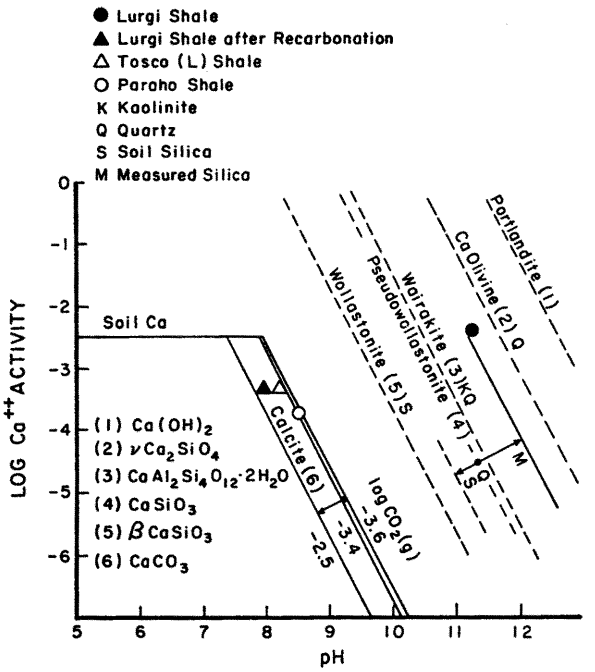

Fig. 2. Solubility of calcium minerals.

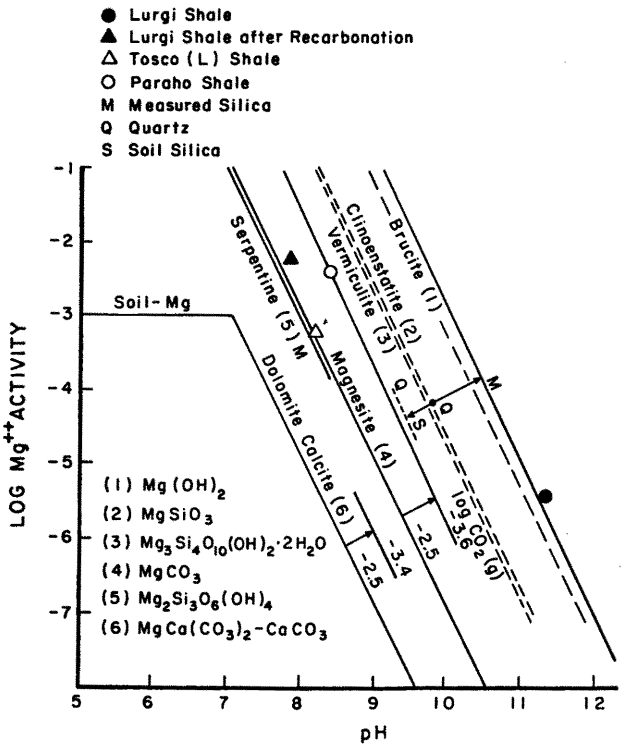

Fig. 3. Solubility of magnesium minerals.

The x-ray analysis of Lurgi spent shale, in this study, indicated the presence of pseudowollastonite mineral. Details are given in Table 2. The data in Table 1 indicates that $CaCO_3$ equivalent and CO_2 pressure decreased with the increase of temperature. Also as retorting temperature was increased, more carbonates were destroyed and the pH of spent shales went up.

Details on the amount of CO_2 absorbed by Lurgi spent shale and the changes in pH during recarbonization are shown in Table 3 and plotted in Fig. 4. The CO_2 absorbed in the initial stage of the experiment by the Lurgi shale was high and decreased with time as the system became saturated with respect to CO_2.

The analytical data on recarbonated Lurgi spent shale are given in Table 4. The Ca^{2+} and Mg^{2+} activities in solution are plotted in Figs. 2 and 3. The results indicate that when Lurgi shale was recarbonated at a CO_2 partial pressure of $10^{-2.54}$ atm., the Ca^{2+} and Mg^{2+} activities in solution were controlled by solid phase calcite ($CaCO_3$) and magnesite ($MgCO_3$).

Table 2. X-ray differentiation analysis of spent and recarbonated oil shales and calcite.

	Spent Lurgi Shale				Recarbonated Lurgi Shale	
	Experimental Peaks CuK α 2θ		Book Values CuK α 2θ		Experimental Peaks CuK α 2θ	
Mineral	d(A°)	RI	d(A°)	RI	d(A°)	RI
Pseudowollastonite	3.210	80	3.200	100	3.200	20
	2.406	60	2.460	60	2.800	5
	3.413	20	3.410	40	3.416	5
	1.827	20	1.828	10	1.827	5
Calcite	3.040	30	3.040	100	3.040	80
	2.290	10	2.289	18	2.286	40
	2.090	10	2.090	18	2.090	20
	1.913	<10	1.912	17	1.913	10
	1.873	<10	1.873	17	1.873	10
Calcite precipitate	3.040	100	3.040	100	--	--
	2.286	18	2.290	18	--	--
	2.090	18	2.090	18	--	--
	1.910	17	1.912	17	--	--
	1.873	17	1.873	17	---	---

Table 3. Quantity of carbon dioxide absorbed by the Lurgi spent shale with the accompanying changes in pH.

1 N HCl Added (ml)	CO_2 Released (mmol/L)	CO_2 Absorbed by the Ascarite (mmol/L)	CO_2 Absorbed by the Lurgi Spent Shale (mmol/L)	pH
0	0.0	0.00	0.00	11.68
20	10.0	0.13	9.88	9.90
40	20.0	0.34	19.66	8.97
60	30.0	1.20	28.86	8.50
80	40.0	3.54	36.45	8.33
100	50.0	9.90	40.10	8.01
120	60.0	17.16	42.84	8.00
130	65.0	22.00	43.00	7.80
133	66.5	23.58	43.02	7.90

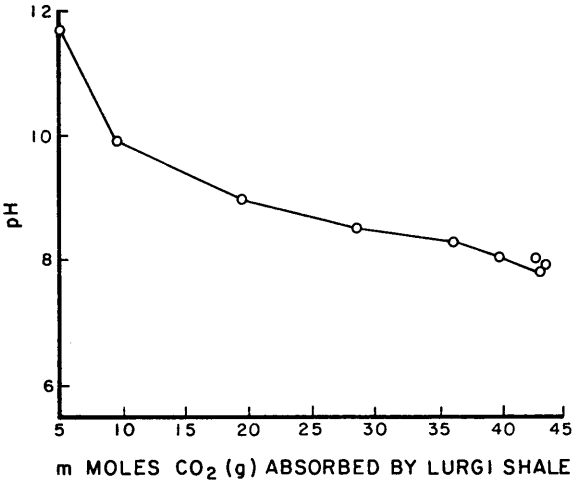

Fig. 4. Quantity of carbon dioxide absorbed by the Lurgi spent shale with the accompanying changes in pH.

The decrease in pH, resulting from the bubbling of CO_2 through Lurgi spent shale is attributed to the dissolution of silicate minerals and the precipitation of carbonate minerals. The corresponding reactions are given below.

$$Ca^{2+} + CO_2(g) + H_2O \rightleftharpoons CaCO_3 \text{ (calcite)} + 2H^+ \quad (2)$$

$$Mg^{2+} + CO_2(g) + H_2O \rightleftharpoons MgCO_3 \text{ (magnesite)} + 2H^+ \quad (3)$$

The Ca^{2+} and Mg^{2+} released from dissolution of silicate minerals combine with the bubbled CO_2 and precipitate as calcite and magnesite.

The x-ray analysis of recarbonated shale indicated the presence of calcite solid phase with peaks from 29.00 to 29.52° (CuK α 2θ). Details are given in Table 2 and are shown in Fig. 5. The most intense peak for pseudowollastonite, in the recarbonated shale, decreased approximately by 60-fold and the relative intensity for the major calcite peak was enhanced by 50-fold. However, no x-ray analyses showed peaks for clinoenstatite ($MgSiO_3$) and magnesite ($MgCO_3$). This may be due to the presence of only small amounts of these minerals which yield broad peaks of low intensity and which sometimes overlap high intensity peaks from calcite and quartz. The x-ray pattern of freshly precipitated calcite is also shown in Fig. 5. These results further indicate the presence of calcite solid phase in recarbonated spent shale.

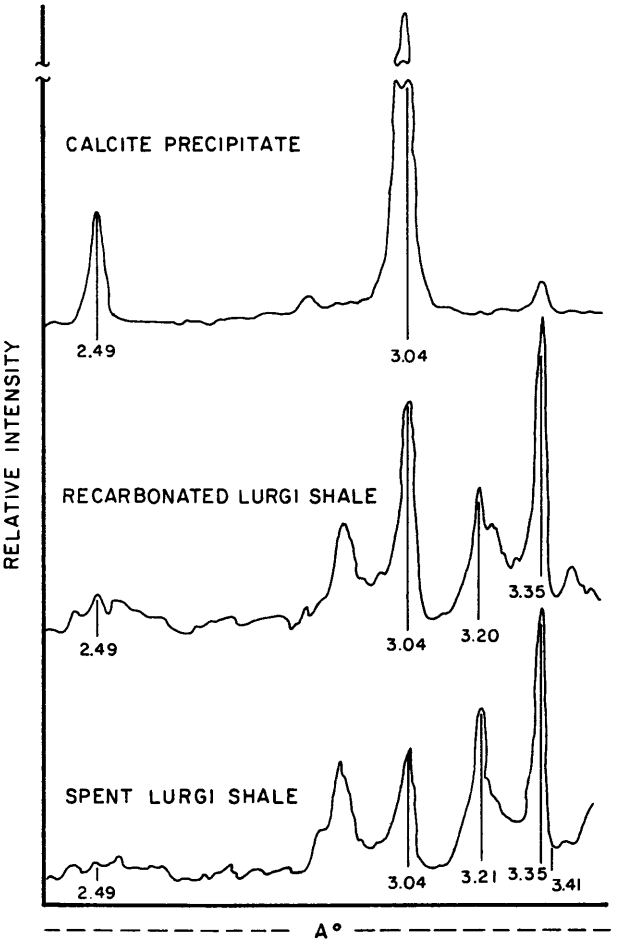

Fig. 5. X-ray diffraction peaks of Lurgi spent shale, recarbonated Lurgi shale, and calcite precipitate.

CONCLUSIONS

Recarbonation studies of spent oil shales show that during the processing of oil shale, high temperatures destroy carbonate minerals and

Table 4. Analytical data for recarbonated Lurgi shale extract.

pH	Ca	Mg	Na	K	Si	SO_3	Cl	HCO_3	CO_3	PO_4	μ	$CO_2(g)$ - log atm.†	pIAP	
					(ppm)								Calcite ($CaCO_3$)	Magnesite ($MgCO_3$)
7.9	87	720	224	210	26	2600	63	430	---	<0.1	0.062	2.54	9.96	11.12

†Measured in triplicate.

form silicate minerals like pseudowollastonite and clinoenstatite. Recarbonation of high pH Lurgi shale by bubbling CO_2, decreased the pH and precipitated calcite and magnesite minerals. Further investigation is needed to develop methods to lower pH of spent shales under field conditions

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RESPONSE OF SHRUB ECOTYPES TO MINING WASTE MATERIAL IN SOIL PROFILES AND COMPETITIVE INTERACTIONS OF WOODY SPECIES UNDER EXPERIMENTAL AND NATURAL CONDITIONS

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OBJECTIVES

1. Evaluate the responses of shrub ecotypes to the presence of mining waste materials in the soil profile.
2. Evaluate above- and belowground competition of shrub ecotypes in experimental situations.
3. Evaluate competition between woody species in field situations.
4. Evaluate the natural variation within species (especially shrubs) native to the Piceance Basin, Colorado, and make recommendations regarding source materials which can be expected to give long-term, natural stability to successional plant development on disturbed lands.

RESULTS AND DISCUSSION

The research reported herein is divided into four sections. The first two concern new studies initiated during the 1983 field season. The third section contains results of field studies on shrub and tree competition. Lastly, results of studies on ecotypic variation in eight native species are summarized.

Shrub-Retorted Shale Studies

Methods and Materials

A study was initiated to determine if plant materials from different habitats and geographic areas were differentially adapted to growing in the presence of mining waste material (retorted shale) in the soil profile. Two genetically variable species known to grow well in the Piceance Basin were selected: snowberry (Symphoricarpos oreophilus) and winterfat (Ceratoides lanata). Two snowberry sources were native to Utah and one source was derived from Grand Mesa, Colorado. The Utah plants were supplied in tube packs; the others were grown during 1982 and held outside over winter. One winterfat source came from New Mexico, and two were collected in the Piceance Basin, Colorado, during the summer of 1982 and maintained outside in pots in Fort Collins, Colorado.

Seedlings from these sources were planted in five topsoil-retorted shale treatments of the Retorted Shale Successional Study. Eighteen relatively bare locations (i.e., no large plants within 25 cm) were selected in the native seed mixture-no fertilizer treatment. Six representatives of each of three snowberry sources were randomly assigned to the locations. Winterfat representatives were similarly located in a separate replicate of the same seed mixture-fertilizer treatment.

The plants were watered at the time of planting (1 June 1983) and again on 13 July. Several plants from one Utah source appeared dead and were replaced 13 July. Plants were inspected for vigor and survival on 10 August and 8 September 1983. Since the sources within each species were of different ages, plant height was measured to use as a co-variate to correct future measurements of plant response to the experimental conditions.

Results and Discussion

Although the plants have not had enough time to respond to the presence of retorted shale, some of the results may relate to the suitability of different plant sources for the climatic conditions of the Piceance Basin. Snowberry plants from Grand Mesa, Colorado, suffered substantially more mortality within these plots than plants from the two Utah sources (58% mortality versus 13% and

20% by 8 September 1983). The Grand Mesa site has a rather mesic environment while the two Utah sites have a xeric environment more similar to that of the Piceance Basin. Winterfat suffered uniformly low mortality (~5%) for all sources.

Shrub Competition--Garden Studies

Methods and Materials

A study of the competitive abilities of three sources of snowberry was initiated at the Intensive Study Site. Plant materials from the three sources described above were transplanted (2 June 1983) into four experimental situations in the ecotype garden. The transplants were placed at various distances from large (2 m diameter) snowberry plants already growing in the garden. One set was planted under the canopies of the garden plants and will presumably encounter above- and belowground competition. Another set was planted beyond the canopy but still within the root zone of the garden plants, where only belowground competition is expected. A third set was planted in the root zone, but the existing garden plant was root-trenched. All plants in these three sets were placed on the north side of the garden plants. The last set of transplants, a control, was placed away from the influence of any other shrubs. Plants were located randomly within each treatment, watered when planted, and watered again on 13 July 1983. Survival, vigor, and plant height were measured on 10 August and 8 September 1983.

Results and Discussion

No differences in plant size across treatments or among the three sources were evident after one growing season. However, as in the shrub-retorted shale study described above, differences in mortality among the three population sources existed. The Grand Mesa source again had the highest mortality (25% versus 4% and 8% for the two Utah sources).

Shrub and Tree Competition--Field Studies

Methods and Materials

This study was designed to measure the intensity of competition between selected species of trees and shrubs and to relate the intensity of competition to the abiotic environment. The hypothesis to be tested was one proposed by several plant ecologists (Terborgh 1971, Grime 1979) that the intensity of competition is negatively correlated with the degree of abiotic stress.

The intensity of competition between plants was measured using methods described by Pielou (1961, 1962), Yeaton and Cody (1976), Gutierrez and Fuentes (1979), and Fuentes and Gutierrez (1981). A regression is calculated between the distance separating two neighboring plants and the sum of their sizes. In this study, the size measures used were canopy volume and vertically-projected canopy area. These were calculated from measurements of two perpendicular canopy diameters and height for each plant. Preliminary analysis showed that canopy area yielded more numerous significant regressions than did canopy volume; therefore, area was used in all subsequent analyses.

Regression analysis yields three quantities that describe the relationship between the variables. These are: the slope of the line which passes as closely as possible through all the data points, the point at which this line crosses the y-axis (the y-intercept), and the degree of scatter of the data points about this line (measured by the correlation coefficient r). Any of these may be used as a measure of the intensity of competition. If two regressions differ in slope, the steeper slope indicates more intense competition because it means that at a given separation neighboring plants are smaller (Fig. 1a, Lines a-a', a-a"), and conversely because plants of a given size are farther apart (Fig. 1a, Lines b-b', b-b"). If two regressions have the same slope but different intercepts, the higher intercept indicates more intense competition for the same reasons (Fig. 1b). If two regressions differ in their values of the correlation coefficient, the higher correlation indicates more intense competition because it means that the distances between the plants are more strictly controlled by their sizes (Fig. 1c). All three of these proposed measures of the intensity of competition were used in this study.

Six stands occupied by mixed, mesic shrub vegetation were chosen for study. They lay along an elevational gradient from 2591 m to 2298 m, which closely approximates the elevational range of this vegetation in the Piceance Basin. Chosen for study were three dominant shrub species which occur with sufficient abundance for adequate sampling over this range: big sagebrush (Artemisia tridentata), serviceberry (Amelanchier utahensis), and snowberry.

Pairs of shrubs were chosen for study if both members of the pair were taller than 20 cm and no other shrub occurred between them. Because serviceberry and snowberry typically have many stems, it was difficult to distinguish a large individual from a clump of smaller ones. Such uncertainty can introduce bias into the sample and render analyses invalid (Ebert and McMaster 1981). Therefore, only interspecific pairs were used, giving three species-combinations: big sagebrush-serviceberry, snowberry-big sagebrush, and snowberry-serviceberry.

In four of the six shrub-dominated stands, soil samples were taken and analyzed for pH, conductivity, organic matter, and plant nutrient levels. The soils were remarkably uniform and therefore unlikely to be a cause of differences in competitive intensity, so no further soil analyses were pursued. Soil depth was measured in all six stands.

Elevation of each stand was determined from topographic maps, and slope and aspect were measured in the field. From these data several

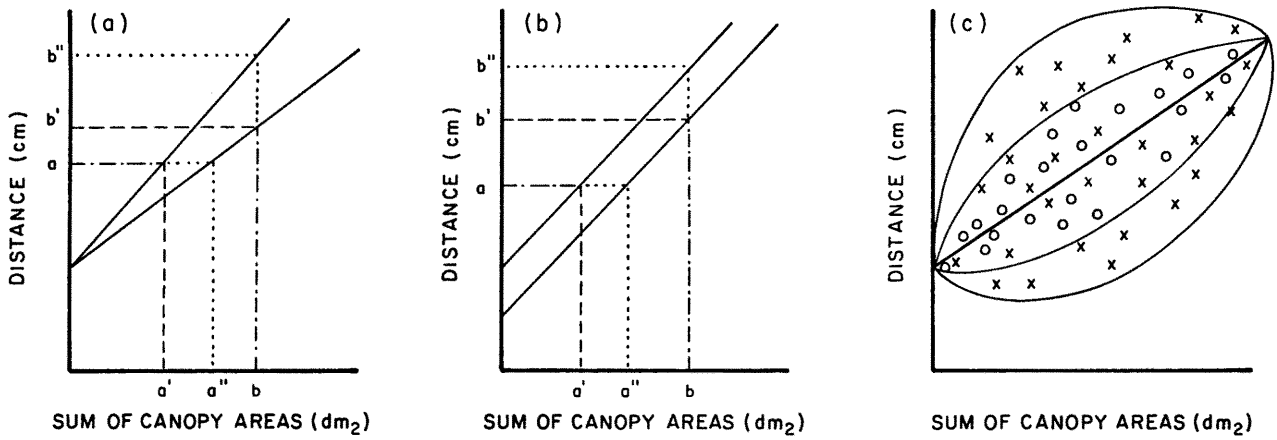

Fig. 1. The measures of intensity of competition. **(a)** A steeper slope implies more intense competition because for a given separation, members of a pair are smaller (Lines a-a', a-a") and because for a given size members of a pair are farther apart (Lines b-b', b-b"). **(b)** A higher intercept implies more intense competition for the same reasons as in "(a)". **(c)** A higher value of the correlation coefficient implies more intense competition because the data points (o's) are less widely scattered about the regression line. More widely scattered points (x's) imply that the spacing of the plants is less tightly controlled by the sizes of their neighbors, i.e., competition is less intense.

moisture-relation parameters were calculated, using equations derived by Wymore (1974) for the Piceance Basin. Parameters calculated included potential evapotranspiration, effective precipitation, and moisture deficit. All were calculated for the year and for a hypothetical April-to-October growing season.

Six more stands were chosen for the study of competition between pinyon (Pinus edulis) and juniper (Juniperus osteosperma). Four of these were pinyon-juniper woodlands, dominated by the large mature pinyon and juniper trees and having nearly closed canopies and little or no shrub understory. Two other stands were dominated by big sagebrush with scattered, small emergent pinyon and juniper trees. These six stands lay along an elevational gradient from 2164 m to 1802 m, which closely approximates the elevational range of this vegetation in the Piceance Basin.

These stands were analyzed by the techniques described above for shrub-dominated stands, with three differences. Since individual pinyons and junipers are easy to identify, intraspecific as well as interspecific pairs were analyzed, again yielding three species combinations: pinyon-pinyon, pinyon-juniper, and juniper-juniper. Canopy area for the trees was calculated from one canopy diameter, and the minimum height of tree for inclusion in the sample was 1 m. Environmental measures included elevation, slope, and aspect.

Regressions were calculated between the distance separating neighboring plants, as the dependent variable, and the sum of their two sizes, as the independent variable. The regressions were compared across stands within a species-combination by a multivariate F-test. That is, the regression for the big sagebrush-serviceberry species combination (e.g.) in each shrub stand was compared to the regressions for the same species-combination in the other five stands, and similarly for the other species combinations.

Results and Discussion

The analysis of results for the shrub stands is complete. For each species-combination, some stands had significant regressions ($p < 0.05$) while others did not (Fig. 2). Only those stands with significant regressions for a given species-combination were used in further analysis of the species-combination. For the stands with significant regressions for any given species-combination, the F-test showed that there was a significant difference among the regression lines, either in slopes or intercepts.

To determine whether these significant differences were due to differences in the slopes or the intercepts of the regression lines, an analysis of covariance was performed for those stands with significant regressions. In every case but one, this analysis showed that the slopes of the regression lines were not significantly different. Therefore, the significant value of F was presumably due to one or more differences among the intercepts. The exceptional case was the snowberry-serviceberry combination, which yielded significant regressions in only two of the six stands. These two regressions differed significantly in their slopes, but too much importance should not be attached to this result. Since a large number of tests were performed (at the 5% level), a spurious significant result can be expected to occur by chance.

The slopes, y-intercepts, and correlation coefficients of all regressions (both significant

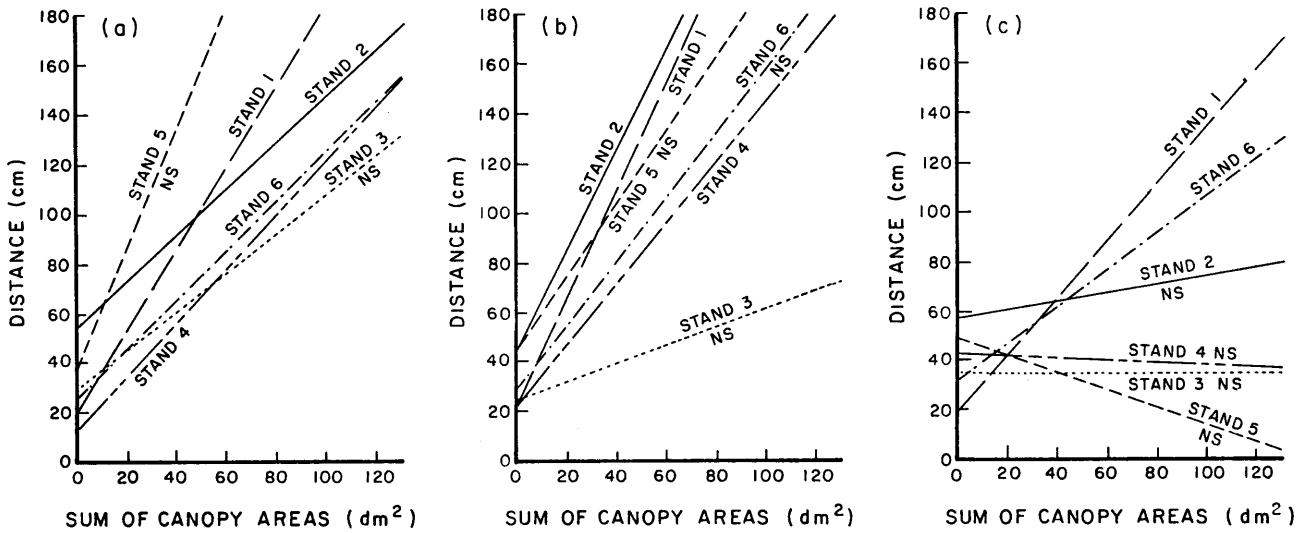

Fig. 2. Size-distance regressions in the six shrub stands. **(a)** Big sagebush-serviceberry combination. **(b)** Big sagebrush-snowberry combination. **(c)** Snowberry-serviceberry combination. Regression lines marked "NS" have slopes not significantly different from 0 at the 5% level.

and nonsignificant) were compared with each of the moisture-relations parameters for each stand (Fig. 3). No significant linear correlation between intensity of competition and any environmental parameter was found. Neither was percentage cover of any shrub species correlated with any environmental parameter. The data offer no support for the hypothesis that intensity of competition between shrubs in these habitats is correlated with the abiotic environment; planting densities for shrubs on the landscapes may thus be selected without considerations of shrub competition as related to different environments.

The analysis of results for trees is similar. No significant regressions were found in the higher-elevation big sagebrush-dominated stand. In the lower stand dominated by big sagebrush, only the juniper-juniper species combination regression was significant ($p < 0.05$). In the lowest-elevation woodland pinyons were too rare to sample, but the juniper-juniper regression was significant.

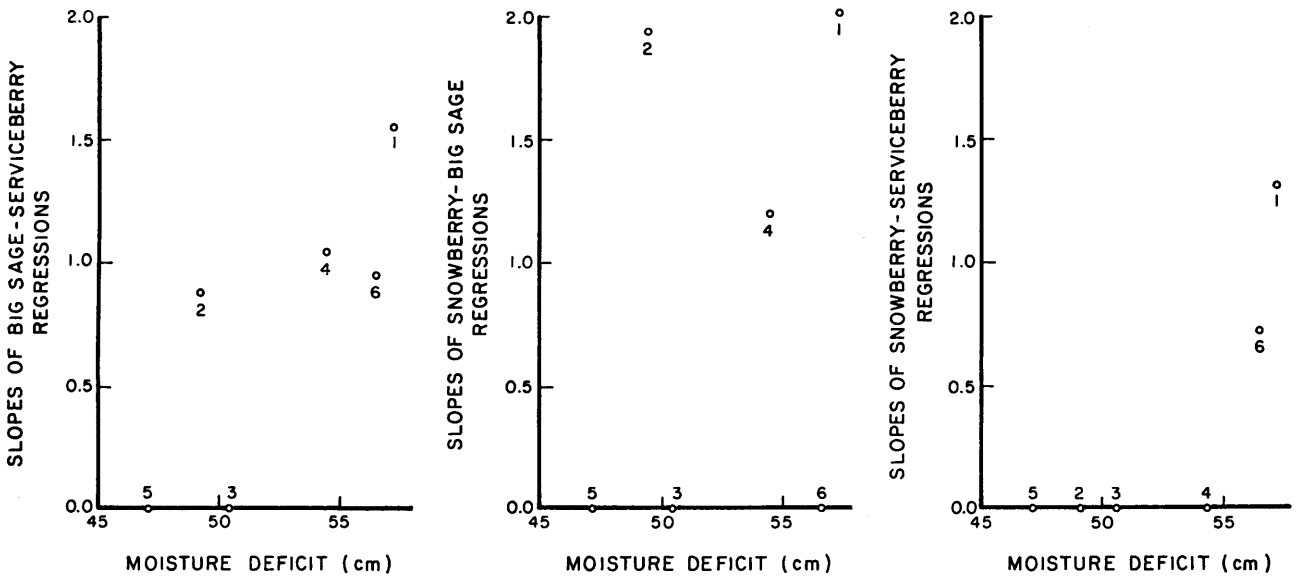

Fig. 3. Comparisons of slopes of regression lines with moisture deficit for the growing season in the six shrub stands. Numbers in the bodies of the graphs are stand numbers. **(a)** Big sagebrush-serviceberry combination. **(b)** Big sagebrush-snowberry combination. **(c)** Snowberry-serviceberry combination.

Analysis of data from the tree stands will be completed by the end of the grant period.

Shrub Ecotypes--Common Garden Studies

Results and Discussion

Results for common garden studies of genetic variation within five shrub, two grass, and one forb species are reviewed herein. Details on sampling, garden measurements, and analysis are found in previous reports (Slauson and Ward 1982, Slauson 1983).

In general, three patterns of genetic (ecotypic) variation were displayed in the garden. First, bitterbrush (Purshia tridentata), mountain mahogany (Cercocarpus montanus), scarlet globemallow (Sphaeralcea coccinea), and junegrass (Koeleria cristata) reveal no or minimal interpopulation differences. Typically, in these species only one or two of the 15-20 garden responses measured in three growing seasons proved statistically different.

In bitterbrush, plant height and leaf size were not significantly different. Phenological advance, scored six times in 1980 and again in 1981, was significantly different for only one date in 1981. Stem length was different among populations for 29 July 1980, the only time measured. Plants with the longest (27.8±1.8 cm) and shortest (23.2±10.8 cm) stems came from pinyon-juniper stands about 2 km apart, while the two populations with intermediate stem length, which are not significantly different from either extreme (Tukey-HSD), came from a more distant, lower elevation pinyon-juniper stand and a higher elevation, upland big sagebrush stand. Correspondence was not evident between stem length differences and differences among the native sites.

Results showing differences among bitterbrush populations suggest that there were some genetic differences among Piceance Basin populations, but that no adaptive differences among Piceance Basin populations were expressed in the common garden. Ecogenetic differences across the Great Basin have been suggested (Blaisdell and Mueggler 1956), but more study would be required before ecogenetic variation within this smaller landscape could be shown.

Plant height measured several times in 1980 and twice in 1981 was not significantly different among three Piceance Basin and two Front Range populations of mountain mahogany. Leaf size and phenological advance also were not different. But, percent leaf loss on 29 October 1980, a measure of dormancy, was significantly different. Contingency table analysis of five populations versus percent leaf loss in four percent classes (e.g., 1-25%) gave a significant chi-square.

Plants representing two Front Range locations and an upland big sagebrush site in the Piceance Basin lost less than 25% of their leaves by 29 October 1980. More (75-100%) were lost by the two other Piceance Basin populations: one from a pinyon-juniper stand of lower elevation than the big sagebrush stand and the other from a high elevation mixed shrub site. Early dormancy may be an ecotypic adaptation of populations from areas with short growing seasons, but our results for mountain mahogany are not consistent with this response.

Scarlet globemallow and junegrass similarly had few significant interpopulation differences, and those that were significant showed no correspondence with features of the native environment. Since, for these four species, a large number of measurements wre tested, a few significant differences can be expected by chance alone. This and the lack of correspondence between garden responses and the environments of the native sites suggest that ecotypic adaptation with respect to the characters measured has not taken place. Accordingly, no specific recommendations concerning the source material of these species for use in revegetation is made.

Snowberry and Indian ricegrass (Oryzopsis hymenoides), however, have significant interpopulation differences for many characteristics measured in the garden (e.g., plant and leaf size, the timing and rate of vegetative growth, and the timing of flowering and fruiting). But still, within each species no consistent correspondence of garden response with the condition of each population's native environment was found. Accordingly no conclusions regarding ecotypic adaptation in these species can be made, but it is concluded that these species are genetically diverse. No special recommendations for these species is made, but since populations vary genetically, different sources may respond to revegetation differently.

Serviceberry and winterfat display the third pattern of response in the common garden. Both species expressed genetic differences many of which are interpreted to be ecotypic adaptations.

Winterfat populations differ in the timing of flowering and fruiting, the onset of dormancy, and the amount of vegetative growth. Plants with the most rapid phenological advance and the earliest dormancy came from a high elevation site in the Piceance Basin that has a short growing season (<60 days). Plants with the slowest phenology and latest dormancy came from southern Colorado with a long growing season (>100 days). Plants with intermediate phenological rates and dormancy came from sites in the Piceance Basin with intermediate growing season lengths (61-100 days). Spearman's rank correlation between the garden measurements and growing season are significant at the 1% level.

Perhaps the most biologically significant result is the 100% mortality in the garden of winterfat from the long-season site while the other populations had few or no mortalities. Presumably the long-season plants cannot survive in the shorter season provided by the common garden. Plant sources from areas with relatively long growing seasons are not recommended for revegetation use in the Piceance Basin. Another conclusion

suggested by Slauson and Ward (1982) is that high-elevation (short-season) sources of winterfat material be avoided in revegetation of lower-elevation areas; these plants had the least amount of vegetative growth, thus putting them at a competitive disadvantage in lower elevations.

Serviceberry also shows adaptive ecotypic differentiation. The main conclusions of Slauson (1983) are reiterated here. Three ecotypes within the Piceance Basin are distinguished: (1) a mesic shrub type adapted to high elevation mixed, mesic shrub communities; (2) a xeric type adapted to drier mixed, shrub vegetation; and (3) a type adapted to more mesic forest vegetation. Since the first type occupies sites where serviceberry as a species has its maximum ecological development within the Piceance Basin, it is called the central ecotype. The others are called peripheral types since they occupy environments ranging away from the species' optimum: one occupies drier, open sites and the other occupies more moist sites with a closed canopy.

One way to understand these results is to think of the central ecotype as a benchmark and consider how the others differ. Plants of the central type are the tallest in the garden, have an intermediate leaf size, and the most rapid vegetative growth. Plants of the xeric ecotype are shorter, have smaller leaves, and less shoot growth than the mesic shrub ecotype. The characteristics of the xeric, peripheral type make sense as adaptations for water and heat stressed plants. Grime (1979), for example, has data from a large number of plant species showing that species from stress producing environments are smaller, have smaller leaves, and have slower growth rates. These results suggest that genetic varieties within a species can also show these differences.

The other peripheral ecotype, which grows in the more mesic Douglas-fir and aspen forests, might also be thought to grow under stressful conditions. But here stress comes from the low light and nutrient levels that develop under the sometimes very dense canopies of the overstory. These plants too are smaller than the mesic shrub ecotype, have depressed shoot growth, and larger leaves. Small stature and slow growth again indicate adaptation to stressful growing conditions and large leaves as an adaptation of shade plants is well known.

Besides populations native to the Piceance Basin, five serviceberry populations collected from other areas of Colorado and southern Wyoming were measured in the common garden. These populations are most similar in their garden responses to the mesic forest ecotype. Serviceberry thus exhibits adaptive differences within and outside the Piceance Basin.

Recommendations for revegetation using serviceberry follow from these results. First the nature of the site to be reclaimed should dictate which source materials are to be used. For example, in revegetation of xeric, mixed shrub communities the small-leaved, slower growing ecotype, native to drier situations, should be used. Similarly, more mesic sites to be revegetated should be matched with source materials deriving from more mesic situations. One precaution regarding serviceberry source materials derives from field observations of fruit production in different populations. Fruit is set more regularly from season to season and in greater amounts in the moist forest ecotype, less regularly and profusely in the mesic shrub type, and least regularly and abundantly in the xeric shrub type. This means that source material collections may be biased toward those with the more available seed supply and may not represent the most appropriate type for revegetation of mixed, mesic, and xeric shrub communities.

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RESPONSES OF GRASS SPECIES TO COMPETITION AS AFFECTED BY SOIL DEPTH AND FERTILIZER

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INTRODUCTION

Early studies of competition between and among grass species were originally conducted in the field, and effects were evaluated on the basis of herbage and root biomass differences (Clements 1905, Weaver 1919, Clements et al. 1929). More recent technological advancements have allowed the use of controlled growing conditions and improved statistical techniques to determine the source(s) and significance of competition.

Little attention in research has been placed upon competitive evaluations for native plant species. Most studies have concentrated on annual and pasture species. These studies have been conducted primarily by agronomists and geneticists (Freeman and Perkins 1971, Hardwick and Wood 1972, Breese and Hill 1973, Harris and Lanzenby 1974). However, Bonham (1983), Davis and Bonham (1979), Reece (1978), Davis (1978), and Reece and Bonham (1977) all reported on competitive relationships evaluated for some native species on rangelands of eastern Colorado.

Competition data for annual species may be graphically evaluated by plotting the ratio of the seed yields of two species on a logarithmic scale against time (de Wit and van den Bergh 1965). The trend in the relative reproductive rates and the resulting changes in vegetation structure are reflected on such graphs. However, this approach is not adequate for perennial species because of perennial regrowth of the plant. Consequently, each year the plant biomass may be produced under different environmental conditions and growth may occur at irregular intervals throughout the growing season. de Wit and van den Bergh (1965) developed a relative yield index which used a mean monoculture (pure stand) response for each species as a base to compare competition effects found in perennial herbaceous species.

The relative yield of above- and belowground biomass is a numerical index which contrasts inter- and intraspecific competition by expressing the mixed-stand response as a percent of the pure-stand response. This index can be interpreted as the mean pure-stand response which is an integrated mean species response to the microenvironmental variability within a given site (Reece and Bonham 1977).

Another coefficient used to evaluate competitive responses is a crowding coefficient (Torssell 1973). This coefficient is dimensionless and characterizes competitive interference, irrespective of variation in monoculture yields. A simple calculation for crowding coefficient was developed by Bakhuis and Kleter (1965). Their crowding coefficient, modified from de Wit (1960, 1961), is the weighted ratio of a species mixed-stand response to the difference between its pure and mixed-stand response. Relative frequencies were used to weight the ratio (van den Bergh and Elberse 1962).

Total gross energy in the biomass of species in mixed-stands can, like relative biomass, be a measure of competition. Methods used to determine gross energy content of plants have been based on plant biomass harvest data (Pearson 1965, Kucera et al. 1967, Botkin and Malone, McLendon 1973). Plant material is usually separated by species and plant parts, oven-dried, and gross energy determined with a calorimeter.

METHODOLOGY

The Retorted Shale Successional Study at the Intensive Study Site was used for the competition study. Treatments had been applied in 1977. Two depths of topsoil, 30 and 90 cm over retorted shale, and one fertilizer application of N at 112 kg/ha plus 56 kg/ha of P were treatments used in the current study. No fertilizer was used on the soil depths as a control to determine fertilizer effects. A seed mixture of native species was evaluated in this study of grass competition. The species studied were Rosana western wheatgrass (Agropyron smithii), Sodar streambank wheatgrass (Agropyron riparium), big bluegrass (Poa ampla), and beardless bluebunch wheatgrass (Agropyron inerme). These species were selected to compare

differences in responses to competition by bunchgrasses vs. single-stemmed, rhizomatous species.

Sampling was conducted at three stages of plant development: (1) early growth (one to three leaves), (2) inflorescence, and (3) senescence. Data were collected for all combinations of species pairs (Table 1). An individual of a species and its nearest neighbor were selected in sets for all combinations of species studied. Each set provided a pair of a monoculture (a pair of similar species) or biculture (a pair of dissimilar species) observations to evaluate the effects of competition (Table 1).

Plant basal area and phenology of each individual plant in each set were recorded prior to the collection of plant biomass. Each individual plant was partitioned into three compartments: herbage, crown, and roots. Herbage for each individual plant was clipped while crown and root biomass was collected with a soil core sampling implement. The core sample was taken through the center of the crown of each study species. The probe used in this study was 2 cm in diameter and 25 cm in length. Soil samples were washed to remove crown and root materials which were hand separated, and weighed. Root weights were converted to grams per unit weight of soil in the core. All plant material was oven-dried at 60°C for a period of 48 hours.

Gross energy content of two bunchgrass species, Poa ampla and Agropyron inerme, was determined for roots, crowns, and herbage biomass. These two species were the only ones which provided enough biomass in a sample to determine gross energy content in all compartments. The other two species were single-stemmed and did not produce sufficient biomass by plant compartment to provide adequate estimates of gross energy values. Plant materials collected during inflorescence (July 15, 1983) and senescence (August 31, 1983) were used to determine the gross energy content. An analysis of variance was used to determine significant differences in energy partitioning between seasons, between species, and the effects of intra- and interspecific competition. Plants for gross energy determinations were obtained only from plots with 30 cm of topsoil over retorted shale without initial fertilizer application. All samples were oven-dried at 60°C for a period of 48 hours. Samples then were ground in a Wiley mill to pass through a 20 mm screen. Gross energy values were determined for each sample by the use of an oxygen bomb calorimeter as described by the AOAC (1975). These values were expressed as kilocalories per gram of plant material.

Table 1. Intraspecific and interspecific competing combinations of species.

Competing Species Pairs
Agropyron smithii (Agsm) - Agropyron smithii (Agsm)
Agropyron smithii (Agsm) - Agropyron riparium (Agri)
Agropyron smithii (Agsm) - Poa ampla (Poam)
Agropyron smithii (Agsm) - Agropyron inerme (Agin)
Agropyron riparium (Agri) - Agropyron riparium (Agri)
Agropyron riparium (Agri) - Poa ampla (Poam)
Agropyron riparium (Agri) - Agropyron inerme (Agin)
Agropyron inerme (Agin) - Agropyron inerme (Agin)
Poa ampla (Poam) - Poa ampla (Poam)
Poa ampla (Poam) - Agropyron inerme (Agin)

Data Analysis

Biomass of individual plants was used to calculate the effects of competition as observed for each pair of species. Data for each plant was averaged according to herbage biomass/basal area ($g\ cm^{-2}$), and root biomass/basal area ($g\ cm^{-2}$). Since crown biomass was very small for most samples, this data was not analyzed. Analysis of variance was calculated to determine effects of soil depth, fertilizer, and phenological stage on the amount of biomass found in each plant compartment of each species. Analysis of variance was also used to determine seasonal differences in energy content for the two species used in this part of the study.

A crowding coefficient (k) also was used to evaluate the effects of competition between each pair of individual plants. Effects were evaluated for soil depth, fertilizer, and phenological stage. The equation used was

$$k = \frac{P}{Q - P}$$

where P was the average biomass found in a given species plant compartment when individuals of two different species occurred together and Q was the biomass value in that same compartment for the same species with itself. The values for k were interpreted as an indication that interspecific (between species) competition responses occurred when the value for k was less than 1.0 (Fig. 1). On the other hand, a k value greater than 1.0 was an indication that intraspecific (between individuals of the same species) competition response occurred. Biomass for each plant compartment was used to determine k values of all species pairs. These k values were not compared across plant compartments. For example, a k value for root biomass of a competitive pair may have indicated interspecific competitive responses while the k value for herbage biomass may have suggested intraspecific responses. Responses to competition may have shifted from one compartment to another over time, soil depth, or fertilizer treatment. This shift was recognized by a change in k from a value <1.0 to a value >1.0 or vice versa. The k value also changed when Species A was compared to Species B as opposed to Species B compared to Species A, because the value of Q changed.

RESULTS AND DISCUSSION

All values for plant compartment biomass (g/cm are reported on an oven-dry basis

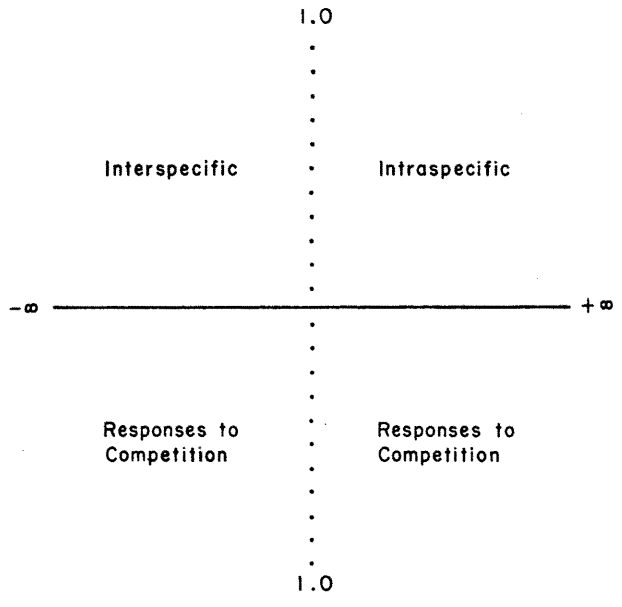

Fig. 1. Graphical interpretation for the crowding coefficient, k. See text for equation.

(Appendix, Tables A1-A12). These data were used to calculate a k value for each species pair for each treatment. These k values were averaged and presented in Table 2. The use of Fig. 1 will facilitate the interpretation of k values found in Table 2. If biomass levels were found to be nonsignificant by analysis of variance according to soil depth, fertilizer, or phenological stage, no k value was calculated for that combination of species within a treatment or phenological stage.

Agropyron smithii

Root biomass production of western wheatgrass was suppressed by interspecific competition when the species occurred with streambank wheatgrass (Table 2). Neither fertilizer addition nor increased soil depth affected this response which occurred during the inflorescence stage of both species ($k < 1.0$). All other measures of responses to competition between these two species were not significant.

Herbage biomass of western wheatgrass during inflorescence and senescence stages was suppressed when this species occurred in the presence of big bluegrass ($k < 1.0$). Neither fertilizer nor soil depth effects changed this competitive response of western wheatgrass to its association with big bluegrass. However, amount of root biomass of western wheatgrass was affected somewhat less than aboveground biomass by its occurrence with big bluegrass during senescence and on 30 cm of soil with no fertilizer added ($k = 1.20$).

Western wheatgrass herbage and root biomass both were variously affected by soil depth, fertilizer, and phenological stage when grown in association with beardless bluebunch wheatgrass. Values of the crowding coefficient ranged from $k = 5.21$ to $k = 54.06$, which indicated that effects on biomass of western wheatgrass in association with beardless bluebunch wheatgrass were both inter- and intraspecific depending upon depth of soil, fertilizer treatment, and compartmental biomass analyzed. In particular, both herbage and root biomass of western wheatgrass was suppressed by its association with beardless bluebunch wheatgrass during the early stage of growth (three-leaf stage) for both soil depths and for both fertilizer treatments (Table 2). However, the addition of N and P fertilizer caused the competition effect, as expressed by herbage biomass, to change to that of intraspecific during the senescence stage for both soil depths ($k > 1.0$). Fertilizer added on 30 cm of soil also caused the competition effect to change in root biomass from an inter- to an intraspecific effect during inflorescence. This was in contrast to the effect of fertilizer on root biomass produced in 90 cm of soil during senescence. Western wheatgrass has been found to respond to nitrogen fertilizer application on native rangelands, but no ecological strategies have been discussed (Houston and Hyder 1975).

Agropyron riparium

Herbage biomass of streambank wheatgrass was reduced when the species was grown in association with western wheatgrass on 30 cm of soil. This interspecific competition effect occurred during the inflorescence stage only, and fertilization did not change the competition effect ($k = 0.06$ and -1.10, respectively, for fertilizer and no fertilizer) (Table 2).

A large k value (38,197.6) occurred for herbage biomass during inflorescence on 90 cm of unfertilized soil. This value was indicative of the level of intraspecific competition that occurred between two adjacent streambank wheatgrass plants on the deeper, unfertilized soil. Recall that the equation for k involves a difference between two streambank wheatgrass individuals collectively, compared to an individual streambank wheatgrass and its association with western wheatgrass. The latter response (P) in herbage biomass was compared to the difference (Q - P) which resulted in a large value of k. Therefore, k values were used only as relative measures of competitive effects.

Herbage biomass was reduced during the inflorescence stage of streambank wheatgrass when it was grown with big bluegrass on 30 cm of soil. Fertilizer did not affect this reduction of herbage biomass. Herbage amount of streambank wheatgrass was also reduced on 90 cm of unfertilized soil, but fertilizer enabled streambank wheatgrass to compete more successfully with big bluegrass on 90 cm of soil ($k = 1.20$).

Effects of competition measured for the association of streambank wheatgrass with beardless bluebunch wheatgrass were interspecific except on 30 cm of fertilized soil during early growth. That

Table 2. Crowding coefficients (k values) for herbage and root biomass of the competing pairs.

Species	Competing Species	Soil Depth	Fertilizer Level	Herbage Biomass Sampling Period 1	Herbage Biomass Sampling Period 2	Herbage Biomass Sampling Period 3	Root Biomass Sampling Period 1	Root Biomass Sampling Period 2	Root Biomass Sampling Period 3
Agsm	Agri	30 cm	Fert.	*	*	*	*	-1.32	*
			No Fert.	*	*	*	*	-0.40	*
		90 cm	Fert.	*	*	*	*	0.54	*
			No Fert.	*	*	*	*	-1.90	*
	Poam	30 cm	Fert.	*	-1.30	0.50	*	-1.71	0.07
			No Fert.	*	-0.01	0.98	*	-1.70	1.20
		90 cm	Fert.	*	0.30	-1.23	*	0.20	-1.22
			No Fert.	*	0.61	-1.50	*	0.13	-0.40
	Agin	30 cm	Fert.	-1.60	-0.64	2.47	-1.20	-0.60	12.60
			No Fert.	-5.20	0.77	0.13	-0.50	2.13	0.40
		90 cm	Fert.	-0.30	0.44	2.05	-0.30	0.09	-0.93
			No Fert.	-1.23	2.60	-5.21	-1.20	54.06	4.73
Agri	Agsm	30 cm	Fert.	*	0.06	*	*	*	*
			No Fert.	*	-1.10	*	*	*	*
		90 cm	Fert.	*	2.45	*	*	*	*
			No Fert.	*	38197.60	*	*	*	*
	Poam	30 cm	Fert.	*	-1.42	*	*	*	*
			No Fert.	*	-1.39	*	*	*	*
		90 cm	Fert.	*	1.20	*	*	*	*
			No Fert.	*	-1.50	*	*	*	*
	Agin	30 cm	Fert.	1.72	-0.52	*	*	-0.30	*
			No Fert.	-2.60	-1.14	*	*	-1.44	*
		90 cm	Fert.	-1.60	-1.97	*	*	-0.44	*
			No Fert.	-0.03	-0.70	*	*	-0.50	*
Poam	Agsm	30 cm	Fert.	*	-0.06	7.64	*	*	*
			No Fert.	*	0.50	-2.01	*	*	*
		90 cm	Fert.	*	0.30	14.81	*	*	*
			No Fert.	*	-2.41	-0.03	*	*	*
	Agri	30 cm	Fert.	*	-0.41	*	-3.70	-0.45	*
			No Fert.	*	0.60	*	-5.60	0.49	*
		90 cm	Fert.	*	1.20	*	-1.97	-7.80	*
			No Fert.	*	-1.12	*	-0.70	-1.10	*
	Agin	30 cm	Fert.	*	*	0.60	*	*	*
			No Fert.	*	*	-8.10	*	*	*
		90 cm	Fert.	*	*	18.82	*	*	*
			No Fert.	*	*	-8.20	*	*	*
Agin	Agsm	30 cm	Fert.	*	*	*	*	*	*
			No Fert.	*	*	*	*	*	*
		90 cm	Fert.	*	*	*	*	*	*
			No Fert.	*	*	*	*	*	*
	Agri	30 cm	Fert.	*	*	*	*	16.11	0.17
			No Fert.	*	*	*	*	-4.70	0.95
		90 cm	Fert.	*	*	*	*	-0.95	0.04
			No Fert.	*	*	*	*	3.60	-0.40
	Poam	30 cm	Fert.	*	-0.80	0.64	*	-1.50	*
			No Fert.	*	-9.20	0.51	*	0.64	*
		90 cm	Fert.	*	-6.41	-4.90	*	1.43	*
			No Fert.	*	1.62	0.40	*	7.16	*

*Differences were not significant.

is, herbage and root biomass of streambank wheatgrass was reduced for all treatments and seasonal periods. Fertilizer added to the shallow soil caused streambank wheatgrass to successfully compete with beardless bluebunch wheatgrass during the early stage of growth (k = 1.72). Houston and Hyder (1975) found that the frequency of the species was not affected by nitrogen fertilizer applications.

Poa ampla

Herbage biomass of big bluegrass was reduced by its occurrence with western wheatgrass during the inflorescence stage of growth and on both soil depths, fertilized and unfertilized (Table 2). During the senescence stage, fertilizer on both soil depths enabled the species to compete more successfully with western wheatgrass by changing competition effects from those of inter- to intraspecific (from k = 2.01 and -0.03 to k = 7.64 and 14.82 for 30 and 90 cm of soil, respectively).

Big bluegrass herbage biomass amount indicated that fertilization on 90 cm of soil changed changed the competition effects from inter- to intraspecific when individuals of the species occurred adjacent to streambank wheatgrass plants during early growth stages. All other biomass, herbage and root, of big bluegrass was reduced when streambank wheatgrass was the competitor species.

Fertilizer, N and P combined on 90 cm of soil, caused competition effects between big bluegrass and beardless bluebunch wheatgrass to be of the intraspecific kind. This was indicated by herbage biomass during the senescence growth stage. Otherwise, the effects of competition between these two species were observed to be interspecific on both soil depths.

In Colorado, number of tillers, shoots, and total foliage weight of big bluegrass were increased by nitrogen fertilization (Haferkamp and Currie 1973). A significant interaction between nitrogen and phosphorus was observed for root system weights.

Agropyron inerme

Beardless bluebunch wheatgrass root biomass showed that fertilizer on 30 cm of soil caused the species to have an intraspecific response in the presence of streambank wheatgrass during the inflorescence stage of growth (Table 2, k = 16.11). This response in root biomass was in contrast to the response observed when fertilizer was added to 90 cm of soil; the response was interspecific while no fertilizer on the deeper soil caused an intraspecific response to occur (k = 0.95 and 3.60, respectively). During senescence, all competition responses were interspecific.

When beardless bluebunch wheatgrass occurred with big bluegrass, amount of herbage biomass of the former species indicated that competition was interspecific with the exception of no fertilizer on 90 cm of soil (Table 2). The magnitude of this competitive relationship was less on the fertilized, shallow soil (30 cm) during the early growth stage (k = -0.80) compared to the unfertilized soil (k = 9.20).

Root biomass amount for beardless bluebunch wheatgrass indicated that competition effects on this species grown on 30 cm of soil in the presence of big bluegrass were interspecific. Competition effects were intraspecific when these species occurred together on 90 cm of soil. The addition of fertilizer did not affect these competition responses as measured from root biomass.

Mueggler (1972) noted that a partial reduction of competition from surrounding vegetation doubled total herbage production the following year in beardless bluebunch wheatgrass. Elimination of competition resulted in a six-fold increase in herbage production, and Mueggler concluded that production was greatly suppressed by competition from surrounding vegetation. Bayoumi and Smith (1976) concluded that beardless bluebunch wheatgrass responded favorably to nitrogen applications. No response was observed from applying phosphorus, and phosphorus plus nitrogen were not different from nitrogen alone. A 10-year response of the species to a single nitrogen application was nearly doubled when 504 kg N/ha was applied (Mason and Miltimore 1972).

Gross Energy

As stated previously, gross energy content of two bunch grass species, big bluegrass and beardless bluebunch wheatgrass, was determined for roots, crown, and herbage. In order to obtain sufficient plant material for analysis, plants obtained during inflorescence (July 15, 1983) and senescence (August 31, 1983) were used.

Gross energy values (kcal/g) are reported in Table 3). These values were multiplied by the amount of biomass in each plant compartment to express total gross energy as kcal per individual (Hickman and Pitelka 1975). Values for gross energy per plant compartment are shown in Table 4.

Statistically significant ($p < 0.10$) changes were observed for total gross energy in all plant parts of both species, except for roots of big bluegrass as the season advanced. Increases were observed on all plant parts except a 37% decrease which occurred in total gross energy of herbage for beardless bluebunch wheatgrass from inflorescence to senescence. Gross energy values (kcal/g) were significantly lower ($p < 0.10$) in August compared with July for roots and herbage of both species (Table 3).

Thus, the concentration of energy (kcal/g) may decrease with advanced growth stages of the plants, but total energy per plant may increase or decrease depending upon the total biomass produced at the end of the growing season.

Table 3. Mean gross energy values reported as kcal/g.

Species	Root	Crown	Herbage
Poa ampla			
July 15, 1983	3201	3880	4150
August 31, 1983	2680	3671	4090
Agropyron inerme (spicatum)			
July 15, 1983	3343	4107	4154
August 31, 1983	2773	4157	4098

Table 4. Mean total gross energy values reported as kcal/individual.

Species	Root	Crown	Herbage
Poa ampla			
July 15, 1983	277	913	10900
August 31, 1983	337	3896	22451
Agropyron inerme (spicatum)			
July 15, 1983	248	955	24354
August 31, 1983	375	2030	15212

When gross energy values (kcal/g) for roots, crown, and herbage in Table 3 are multiplied by the biomass of these plant compartments and summed for beardless bluebunch wheatgrass for inflorescence stage (Table 3) and for senescence (Table 4), crowding coefficients (k) can be determined based upon total gross energy in the plant. The k value for July 15 for beardless bluebunch wheatgrass and big bluegrass was -1.85 which indicated interspecific competition. However, low yield of total gross energy in the total biomass of beardless bluebunch wheatgrass during senescence showed marked competition with big bluegrass.

CONCLUSIONS

Four perennial grass species were tested for their responses to inter- and intraspecific competition when grown in adjacent combinations with one another (as a pair). Responses of these individual plants of different species were measured in amounts of herbage and root biomass as affected by fertilizer applied on 30 and 90 cm of soil which had been placed over retorted shale in 1977 prior to sampling in 1983.

The crowding coefficient, k, was useful in determining whether effects of competition were inter- or intraspecific during plant growth stages of early (three-leaf), inflorescence, and senescence. A change in the k value from >1.0 to <1.0 suggested that responses of a competitive relationship between two species changed from an intraspecific effect to an interspecific effect. The reverse may also happen. The effects of fertilizer and soil dpeth in various combinations were evaluated over all species combinations and growth stages of these species.

Western wheatgrass was found to compete most successfully with beardless bluebunch wheatgrass during the inflorescence stage of growth when no fertilizer was added to 90 cm of soil. Addition of fertilizer to either soil depth suppressed the amount of root biomass of western wheatgrass in the presence of beardless bluebunch wheatgrass until senescence of the species. At that time shallow soil which was fertilized gave western wheatgrass a competitive advantage over beardless bluebunch wheatgrass.

Biomass of streambank wheatgrass in both herbage and root compartments reflected the greatest competitive effects when the species was grown with beardless bluebunch wheatgrass. Fertilizer added on the shallow soil depth (30 cm) enabled the former species to compete successfully with the latter species during early growth stages. Otherwise, beardless bluebunch wheatgrass suppressed both herbage and root biomass of streambank wheatgrass on fertilized and unfertilized soils at 30- and 90-cm depths. Season or phenological stage made no difference in these responses.

Biomass of roots and herbage of big bluegrass were suppressed the most when the species was in competition with streambank wheatgrass. Depth of soil and phenological stage did not affect this competition response. However, fertilizer added to 90 cm of soil did increase herbage biomass of big bluegrass during the early growth stage and when the species was in competition with streambank wheatgrass.

Beardless bluebunch wheatgrass had the most significant number of competiton responses when it was grown with big bluegrass. Herbage biomass of the former species was decreased by the competitive relationship during inflorescence and senescence. When growing on 90 cm of soil, beardless bluebunch wheatgrass was intraspecifically affected by competition as displayed by root biomass but interspecifically competitive with big bluegrass at the 30-cm soil depth during inflorescence. The addition of fertilizer to 90 cm of soil apparently increased the competitive advantage of big bluegrass with beardless bluebunch wheatgrass as shown by the increased biomass of big bluegrass.

The caloric content (kcal/g) of herbage decreased with advanced stages of growth for both roots and crowns. However, total gross energy in total roots and herbage increased except for herbage of beardless bluebunch wheatgrass. The total energy in the crowns of both species was substantially greater during senescence compared to inflorescence. This would be expected since carbohydrate storage in the crowns, instead of herbage, should be taking place between inflorescence and senescence. More translocation would be expected had plants been left to cure during the fall. Soluble carbohydrates would have drained

almost completely from the herbage into the crowns and roots. Under the conditions at the Piceance Basin site, beardless bluebunch wheatgrass appears to have a shorter growing season than big bluegrass.

Significant differences in competition, as shown in energy compartmentalization between wheatgrass and big bluegrass, were found in both crowns and herbage. Total energy in the total root biomass was not materially different at the last sampling date during senescence, but if plants had been allowed to complete senescence, the roots, no doubt, would have responded to increased stored carbohydrate reserves.

When gross energy values for total plant biomass were used to determine crowding coefficients, it was found that beardless bluebunch wheatgrass and big bluegrass were interspecifically competitive as indicated by the marked energy reduction in wheatgrass during early senescence.

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APPENDIX

Table A1. Mean values for herbage, crown, and root biomass for each species at the three-leaf stage (May 25, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	1.89	0.76	1.83	2.05
Crown	0.27	0.08	0.14	0.39
Root	0.07	0.06	0.02	0.08
Poa ampla				
Herbage	0.95	3.44	1.39	2.47
Crown	0.12	0.29	0.11	0.34
Root	0.02	0.04	0.03	0.09
Agropyron smithii				
Herbage	4.77	5.31	3.71	4.77
Crown	4.77	3.71	1.26	4.77
Root	0.49	0.13	0.18	0.18
Agropyron riparium				
Herbage	4.77	1.70	4.77	2.57
Crown	4.77	1.70	4.77	2.47
Root	1.10	0.15	0.21	0.44

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A2. Mean values for herbage, crown, and root biomass for each species at the three-leaf stage (May 25, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	1.77	1.42	1.55	2.41
Crown	0.23	0.24	0.11	0.18
Root	0.13	0.13	0.11	0.05
Poa ampla				
Herbage	2.12	0.65	1.08	1.96
Crown	0.14	0.08	0.16	0.17
Root	0.09	0.02	0.09	0.09
Agropyron smithii				
Herbage	9.55	6.37	3.58	7.96
Crown	6.37	6.37	2.06	4.77
Root	1.91	2.55	0.36	1.19
Agropyron riparium				
Herbage	2.79	6.90	3.98	4.51
Crown	1.19	3.71	3.98	4.51
Root	1.40	0.43	1.07	0.88

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A3. Mean values for herbage, crown, and root biomass for each species at the three-leaf stage (May 25, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale and without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	1.68	1.70	5.48	1.57
Crown	0.09	0.05	0.28	0.08
Root	0.03	0.01	0.09	0.01
Poa ampla				
Herbage	7.87	1.66	14.39	0.96
Crown	0.29	0.09	0.57	0.06
Root	0.01	0.01	0.01	0.01
Agropyron smithii				
Herbage	15.92	6.37	2.34	9.55
Crown	15.92	6.37	1.07	6.37
Root	2.23	0.57	0.20	1.85
Agropyron riparium				
Herbage	1.47	1.59	1.43	1.64
Crown	0.19	0.17	0.09	0.18
Root	0.06	0.04	0.02	0.02

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A4. Mean values for herbage, crown, and root biomass for each species at the three-leaf stage (May 25, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	5.40	2.08	18.19	1.73
Crown	0.35	0.06	0.93	0.06
Root	0.08	0.02	0.02	0.01
Poa ampla				
Herbage	1.74	2.90	242.36	1.54
Crown	0.17	0.23	25.49	0.13
Root	0.02	0.03	1.28	0.01
Agropyron smithii				
Herbage	3.38	19.10	1.15	26.07
Crown	3.25	15.92	0.38	12.93
Root	0.17	2.32	0.04	2.08
Agropyron riparium				
Herbage	2.39	5.73	1.50	2.40
Crown	0.50	0.25	0.06	0.64
Root	0.02	0.10	0.02	0.11

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A5. Mean values for herbage, crown, and root biomass for each species at inflorescence (July 15, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and and without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	9.19	6.14	4.80	7.29
Crown	0.34	0.39	0.31	0.53
Root	0.15	0.05	0.04	0.28
Poa ampla				
Herbage	5.52	10.87	2.76	2.02
Crown	0.60	0.86	0.53	0.81
Root	0.19	0.36	0.24	0.03
Agropyron smithii				
Herbage	62.07	305.58	350.41	152.79
Crown	13.53	25.46	10.88	25.46
Root	3.75	33.36	14.90	9.29
Agropyron riparium				
Herbage	381.97	165.52	572.96	36.08
Crown	185.33	25.46	63.66	14.06
Root	16.71	10.19	32.21	7.27

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A6. Mean values for herbage, crown, and root biomass for each species at inflorescence (July 15, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	8.57	8.21	16.37	10.95
Crown	0.25	0.52	0.93	1.02
Root	0.07	0.31	0.20	0.16
Poa ampla				
Herbage	10.52	10.34	54.38	39.22
Crown	0.71	0.73	6.63	6.57
Root	0.69	0.24	3.00	5.30
Agropyron smithii				
Herbage	77.31	190.99	57.30	190.99
Crown	12.80	25.46	11.94	25.46
Root	6.29	8.40	4.58	19.86
Agropyron riparium				
Herbage	420.17	292.84	2.18	79.58
Crown	25.46	25.46	0.19	15.12
Root	14.77	17.44	0.11	15.13

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A7. Mean values for herbage, crown, and root biomass for each species at inflorescence (July 15, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale and without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	7.31	21.94	10.72	28.96
Crown	0.49	0.54	0.35	1.64
Root	0.07	0.15	0.26	0.64
Poa ampla				
Herbage	9.55	3.99	36.45	68.83
Crown	0.61	0.17	1.93	5.57
Root	0.07	0.03	0.26	0.34
Agropyron smithii				
Herbage	165.52	85.94	229.18	127.32
Crown	25.47	15.92	31.83	25.46
Root	17.06	5.35	41.89	24.83
Agropyron riparium				
Herbage	113.00	89.13	63.66	89.13
Crown	14.32	25.46	25.46	25.46
Root	8.86	11.84	19.35	7.07

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A8. Mean values for herbage, crown, and root biomass for each species at inflorescence (July 15, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	12.27	14.30	227.92	8.60
Crown	0.72	0.55	19.36	0.34
Root	0.23	0.14	2.55	0.06
Poa ampla				
Herbage	7.03	9.70	1.88	5.19
Crown	0.33	0.62	0.14	0.30
Root	0.14	0.07	0.02	0.06
Agropyron smithii				
Herbage	44.62	137.93	509.29	292.84
Crown	3.20	13.79	38.20	25.46
Root	1.60	4.60	25.97	9.17
Agropyron riparium				
Herbage	227.59	89.13	140.06	77.99
Crown	14.32	25.46	25.46	14.85
Root	7.13	16.93	17.19	7.26

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A9. Mean values for herbage, crown, and root biomass for each species at senescence (August 31, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	12.79	4.57	4.86	3.51
Crown	1.76	0.44	0.66	0.12
Root	0.41	0.24	0.17	0.13
Poa ampla				
Herbage	6.76	7.44	6.42	18.55
Crown	1.12	1.52	0.78	0.59
Root	0.14	0.21	0.45	0.06
Agropyron smithii				
Herbage	14.80	47.75	145.31	23.71
Crown	2.18	41.38	22.33	4.58
Root	2.25	12.23	8.25	3.48
Agropyron riparium				
Herbage	23.55	4.17	39.63	43.45
Crown	22.28	0.23	15.92	9.55
Root	5.65	0.03	4.75	10.26

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

Table A10. Mean values for herbage, crown, and root biomass for each species at senescence (August 31, 1983) in combination with itself and other species with 30 cm of topsoil over retorted shale and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	13.74	5.53	6.71	---‡
Crown	1.54	0.25	2.47	---
Root	0.22	0.10	0.52	---
Poa ampla				
Herbage	8.36	6.38	5.59	22.47
Crown	1.72	1.42	0.77	2.28
Root	0.12	0.22	0.12	3.32
Agropyron smithii				
Herbage	21.01	7.43	255.52	---
Crown	12.73	1.17	15.74	---
Root	7.60	0.49	8.21	---
Agropyron riparium				
Herbage	---	81.70	---	27.61
Crown	---	19.10	---	3.26
Root	---	13.64	---	13.15

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

‡Combinations were not available for sampling of Agropyron riparium with Agropyron inerme and Agropyron smithii.

Table A11. Mean values for herbage, crown, and root biomass for each species at senescence (August 31, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale without fertilization. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	15.55	7.17	10.05	---‡
Crown	2.55	0.78	0.75	---
Root	0.23	0.08	0.24	---
Poa ampla				
Herbage	24.90	14.81	15.05	---
Crown	3.02	1.53	1.54	---
Root	0.88	0.42	0.69	---
Agropyron smithii				
Herbage	39.49	47.11	15.59	---
Crown	2.54	12.52	2.44	---
Root	3.32	4.74	0.69	---
Agropyron riparium				
Herbage	---	---	---	35.64
Crown	---	---	---	4.08
Root	---	---	---	1.38

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.

‡Combinations were not available for sampling of Agropyron riparium with the other species; therefore, it is in combination only with itself.

Table A12. Mean values for herbage, crown, and root biomass for each species at senescence (August 31, 1983) in combination with itself and other species with 90 cm of topsoil over retorted shale and 112 kg/ha N and 56 kg/ha P fertilizer application. Units are g x 10^2 x cm^{-2}.†

	Competitive Association			
	Agropyron inerme	Poa ampla	Agropyron smithii	Agropyron riparium
Agropyron inerme				
Herbage	11.19	18.87	10.15	---
Crown	2.06	2.26	3.04	---
Root	0.29	0.15	0.24	---
Poa ampla				
Herbage	14.82	12.63	11.31	---
Crown	0.93	5.02	2.46	---
Root	0.13	0.47	0.38	---
Agropyron smithii				
Herbage	28.75	241.91	40.37	---
Crown	9.95	41.38	10.19	---
Root	5.31	29.76	4.39	---
Agropyron riparium				
Herbage	---	---	---	29.63
Crown	---	---	---	13.40
Root	---	---	---	2.84

†Biomass was measured to the nearest 0.1 g and often resulted in the same value of biomass/basal area when the amount of biomass was very small.