Colonization Bottlenecks on Acidic Coal Spoils[1]

by

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Abstract: The hypothesis that the establishment of volunteer aspen on acidic coal spoils is limited by colonization problems was tested by amending bare spoil with surface applications of limestone (5500 kg/ha), fertilizer (750 kg/ha of 5-10-5), and root or stem wood chips (0.5 m^3/ha). The experiment was conducted on lower Allegheny spoils near Emlenton, PA. The amendments were applied in April 1989, one month before seed production by local aspens. The density of aspen seedlings in the experimental plots has been monitored since May 1989. Both limestone and fertilizer significantly increased the initial establishment of aspen during spring 1989. Plots receiving these treatments averaged 97 seedlings/m^2 in June 1989. With the onset of hot dry weather in July, 97% of the established seedlings died. Survival of aspens only occurred in plots that received fertilizer. Between September 1989 and August 1991, the number of seedlings only decreased by 26%. Currently, the highest densities of aspen seedlings, 8.1 seedlings/m^2, are in plots that received fertilizer, limestone and wood chip treatments. The soil chemistry in these plots is returning to pre-experimental levels without outward deleterious effects on the established aspens. The amendment applications used in this experiment to stimulate aspen colonization onto bare spoils could be the basis of a low-cost reforestation strategy for abandoned mined lands in northern Appalachia.

Additional Key Words: *Populus*; Abandoned Mined Lands; Revegetation; Acid Soils; Aspen.

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Introduction

Quaking aspen (*Populus tremuloides*) and bigtooth aspen (*P. grandidentata*) are the dominant woody colonizers of unreclaimed bituminous coal mine spoils in Pennsylvania (Bramble and Ashley. 1955; Hedin 1988). Where volunteer aspens colonized spoils in sufficient numbers, closed-canopy woodlots have developed (Hedin 1988). The moderate environmental conditions created in these woodlots have facilitated the invasion of many species that were unable to colonize the original abandoned spoils. Because of this successional process, the plant communities on many unreclaimed mine spoils are naturally returning to a composition similar to that found on local unmined sites.

Not all unreclaimed surface coal mines in western Pennsylvania, however, are undergoing a reforestation process. Thousands of acres of mine spoils have retained a barren "moonscape" appearance decades after their abandonment. Aspens are commonly the most important species on these poorly vegetated sites, but their density is insufficient to result in site-wide closure of a canopy (Hedin 1988). Growth of the established trees results in islands of woody vegetation surrounded by sparsely vegetated open spoil. Within these islands, amelioration of unfavorable environmental conditions can occur (Bramble and Ashley. 1955). In the open areas, however, biotic invasion is generally limited to lichens (primarily *Cladonia* spp.), mosses (primarily *Polytrichum* spp.) and bunch grasses (*Andropogon virginicus* and *Danthonia spicata*). Because invasion by trees into open areas is uncommon, site-wide reforestation of these mine spoils is often many decades away.

It has been recognized for decades that the reforestation of poorly vegetated mine spoils could be accelerated if methods were developed that facilitated the establishment of trees on these sites. Numerous attempts have been made to revegetate abandoned mine spoils by planting trees (see papers in Hutnik and Davis. 1973). At many sites mined in the 1950's and 1960's in Pennsylvania, the spoils were planted with pines (*Pinus* spp.), spruce (*Picea* spp.), larch (*Larix* spp.) and birch (*Betula* spp.), but the survival of these trees on sites with acidic soils was often very poor. During the construction of Moraine State Park in western Pennsylvania, 135,000 trees were planted on poorly vegetated abandoned mine spoils. Follow-up studies indicated that 78% of the planted seedlings died within 3 years of planting (Medve 1973). The reclamation activities, however, unexpectedly stimulated the colonization and establishment of aspens (Medve 1974). Today, many of the spoils in the park are forested because of the growth of these volunteer aspens, not due to the success of the original tree planting efforts (observation by the author).

A reforestation strategy that has not been attempted for abandoned coal mine spoils is the intentional stimulation of natural colonization processes by native trees. The strategy requires that the environmental features that prevent colonization by native trees be identified and then eliminated for a period long enough to allow successful colonization. Several chemical, physical and biological aspects of unreclaimed coal mine spoils possibly interfere with natural revegetation processes. Poorly vegetated coal mine spoils in the eastern U.S. commonly have extremely low pH (Croxton 1928), low concentrations of available phosphorus (Ciolkosz et al. 1983) and high concentrations of available aluminum (Berg and Vogel 1973). Unshaded mine soils can attain very high surface temperatures and low moisture levels during summer months (Schramm 1966; Bell and Ungar 1982). Mycorrhizal fungi, important symbionts of established trees on mine sites (Marx

1975; Shuffstall and Medve 1979), may be absent on poorly vegetated spoils.

This paper reports the results of an experiment intended to determine whether the colonization of aspen onto barren mine spoils can be stimulated through surface applications of amendments. Aspens were the primary focus of the study because of their importance in forest development on acidic mine spoils in northern Appalachia. Surface amendments were tested because of an interest in developing a low-cost reforestation method. The experimental results indicate that absence of aspens on acidic mine spoils is due to a colonization bottleneck that can be eliminated with applications of limestone, fertilizer and wood chips that are timed to coincide with aspen seed production. The findings may be applicable to mine spoil revegetation efforts wherever aspens are native.

Study Site

The experiment was conducted on strip mine spoils near Emlenton, PA, approximately 70 miles north of Pittsburgh, PA and 20 miles west of Clarion, PA. The site was mined for lower Allegheny coals in the late 1950's and abandoned with little regrading of the spoiled materials and no replacement of the original topsoil. Spruce, pine and larch seedlings were planted on the spoils, but mortality was high. Most of the spoils are currently either barren or sparsely vegetated with a mixture of planted trees and volunteer species. The dominant volunteer trees are quaking and bigtooth aspen. Despite the annual production of seeds by established aspens, little successful colonization of the bare open areas during the last decade is evident. Conditions on the site are typical of thousands of surface mines abandoned in northern Appalachia previous to the enactment of adequate reclamation regulations in the 1970's.

Materials and Methods

An experimental area was established on barren, gently sloping spoils during the spring of 1989. A square grid was established that contained 36 plots, each 2m by 2m. On April 30, 1989, the plots were treated with surface applications of limestone, fertilizer, and wood chips (table 1). The experimental design was a 2 X 2 X 3 factorial replicated three times. The limestone treatment was intended to raise pH. The fertilizer treatment was intended to provide nutrients (N, P, K). Root chips were applied as a potential low-cost mycorrhizal inoculant, while stem chips were applied as non-mycorrhizal chip control. The mycorrhizal aspect of the experiment followed, in modified form, the research protocal of Medve et al. (1977). These researchers prepared a mycorrhizal inoculum by macerating in water mycorrhizal roots that were collected from trees growing on acidic mine spoils. The macerated roots were applied to mine soil underneath hand-planted tree seedlings.

Table 1. Amendment Application Rates

Amendment	Rate
Limestone (86% $CaCO_3$)	550 g/m^2 (5500 kg/ha)
Fertilizer (5-10-5, granular)	75 g/m^2 (750 kg/ha)
Wood Chips	
aspen roots	500 cc/m^2
aspen stems	500 cc/m^2
	(0.5 m^3/ha)

The wood chips used in this experiment were obtained by cutting branches and digging roots from a mature aspen tree growing on the site and chipping them with a standard brush chipper. Care was taken to ensure that no contamination of the stem chips with roots occurred. Between preparation and application, chips were stored for 10 days in black plastic bags at room temperature. During the storage period, the root chips became covered with fungal mycelia. No growth of mycelia was observed on stem chips. Chip treatments should not be considered a mulch, as the application rates were very low.

The number of tree seedlings in each of the plots was determined by two methods. When seedlings were small and numerous, numbers were estimated by counting all seedlings within a rectangular 0.05 m^2 frame that was placed at random locations within each plot. On June 6, 1989, the sampling density was 3 frames/plot. On June 18, July 16 and August 5, 1989 the sampling density was 4 frames/plot. When seedlings were easily visible and less numerous, all seedlings in each plot were counted.

Soil samples were collected from the experimental area and from other locations at the study site. Surface samples were collected by loosening and mixing soil to a depth of 2 cm. Root zone samples were obtained by digging pits under mature aspen trees and immature root sprouts, and collecting soil from the zone that contained dense root growth. The depth under the soil surface of the root zone was typically 10 cm for mature trees and 5 cm for root sprouts.

Soil samples were analyzed by The Pennsylvania State University Merkle Laboratory. Analyses included pH, total available phosphorus (Bray determination), cation exchange capacity (CEC), and exchangeable concentrations of potassium, magnesium and calcium. These parameters were determined using standard methods that are described by Ciolkosz et al. (1983). Concentrations of available aluminum were determined using a DTPA extraction procedure (Baker and Amacher 1981).

The data were analyzed using Statgraphics version 5 computer software (STSC, Inc. Rockville, MD). Seedling counts determined by the frame sampling method were not suitable for parametric analyses because of the absence of seedlings in 40% of the sampling frames. A one-way analysis of variance was calculated by the non-parametric Kruskal-Wallis procedure. Differences between treatment means were evaluated by the Newman-Keuls method using Kruskal-Wallis rank sums (Zar 1974). Differences in seedling densities for the various fertilizer treatments, a subset of the entire data set in which seedlings were present in most counts, were analyzed using parametric one-way analysis of various procedures. Differences between the treatment averages were evaluated by the Newman-Keuls method. Statistical significance was judged for all tests at the 5% confidence level.

Results

Soil Analyses

The average chemical characteristics of barren surface soils at the study site are shown in table 2. Phosphorus (P) and base cation levels (Mg and Ca) were extremely low, making the soils very infertile. The low pH and high aluminum concentrations gave the soils toxic attributes (Berg and Vogel 1973; Foy et al. 1978).

Soils were collected from underneath mature aspens and aspen root sprouts to determine whether the trees' distribution on the site could be explained by current mine soil chemistry. Soil samples collected from the root zones of both mature aspens and immature root sprouts were chemically

Table 2. The chemistry of bare mine soils at the study site.[1]

Parameter	Unit	Mean	Sd	Range
Lab pH		3.9	0.2	3.3-4.3
P (Bray)	kg/ha	11.0	6.2	2.2-23.6
CEC	meq/100g	16.1	0.5	14.2-17.1
K	meq/100g	0.1	0.03	0.07-0.2
Mg	meq/100g	0.4	0.1	0.1-0.7
Ca	meq/100g	1.0	0.4	0.3-2.3
Al	meq/100g	1.5	0.2	1.2-1.7
Base Sat[2]	%	8.7	3.1	3.4-19.3

[1] sample size = 29, except Al, n = 13.
[2] base saturation: (Ca + Mg)/CEC

similar to barren soils (table 3). There was little indication that aspens had preferentially become established in fertile, non-toxic spoil, nor that clonal expansion by root sprouting mechanisms was allowing the exploitation of more favorable soils.

Table 3. Selected chemical characteristics of soils collected from the root zones of mature aspen trees and root sprouts.[1]

Sample Type	pH	P	Al	Base Sat
Bare Soil[2]	3.9	11	1.5	9
Tree Root Zone	4.1	30	na[3]	9
Tree Root Zone	4.0	2	2.1	9
Tree Root Zone	4.2	9	1.8	5
Tree Root Zone	4.0	9	1.6	17
Tree Root Zone	4.2	6	1.9	14
Sprout Root Zone	4.0	24	na	6
Sprout Root Zone	4.3	11	1.9	13
Sprout Root Zone	4.2	15	1.9	11
Sprout Root Zone	5.1	15	0.6	56

[1] See table 2 for units.
[2] Average bare soil values from table 2.
[3] Not available.

The chemical characteristics of soil samples collected from the experimental plots throughout the experiment are shown in table 4. The chemistry of control plots varied little during the experiment. Surface soils in plots that received fertilizer and limestone (F+L) applications in May 1989 had more fertile characteristics than unamended soils throughout the experiment, though the effects have waned recently. At the end of the first growing season (1989), all of the soil samples collected from F+L plots had circumneutural pH (6-8), moderate phosphate levels and none contained high concentrations of aluminum. At the end of the second growing season, two of six plots sampled had pH less than 5 and very low P levels (less than 30 kg/ha). At the end of the third growing season, five of nine plots had pH of 5 or less and very low P levels. Four of these 1991 soil samples had aluminum concentrations that were greater than 0.2 meq/100g; an amount considered excessive by Ciolkosz et al. (1983).

Table 4. The chemistry of soils in the experimental plot.[1]

Treatment Date	n[2]	pH	P	Al	Base Sat
Control					
Apr '89	7	3.7	14	na	7
Sep '89	2	3.6	12	na	8
Aug '91	3	3.9	3	1.6	16
Dec '91	3	4.2	14	1.8	9
Fertilizer plus Limestone					
Sep '89	6	6.6	89	<0.1	86
Jul '90	6	5.0	45	0.2	46
Aug '91	9	5.2	32	0.3	68

[1] See table 2 for units.
[2] sample size

Amendment Experiment

Amendments were applied to the plots on April 30, 1989. Mature aspens in the vicinity of the experimental area produced seed in late May. On May 28, numerous aspen seeds were observed in the experimental area, but no seedlings were evident. On June 6, seed production by aspens had ceased and aspen seedlings were observed in many experimental plots. Between June 6 and August 6, seedling densities were estimated on four occasions using the sampling frame method (table 5). On each sampling day, analysis of variance (Kruskal-Wallis analysis of ranks) indicated a significant treatment effect.

June 1989 was cool and wet in western Pennsylvania, which likely favored aspen germination and establishment. Two counts of aspen seedlings made in this month produced similar estimates of seedling densities for the treatment plots. On both occasions, the control plots contained the lowest densities of seedlings. Densities were also low in plots that received only wood chip amendments. With only one exception (L+S on June 18), plots that received either limestone or fertilizer amendments contained significantly higher seedling densities than the control plots. The highest densities occurred in plots that were amended with root chips and either limestone or fertilizer.

July 1989 was hot and dry in western Pennsylvania. During the month, widespread mortality of the seedlings occurred. Between June 18 and August 5, the total number of aspen seedlings in the experimental area decreased from approximately 11,200 to 380, an overall mortality rate of 97%. Two patterns of seedling mortality were observed during the summer of 1989. In plots that did not receive fertilizer, seedlings grew very little after germination. In July, these tiny seedlings gradually turned red and died, probably from phosphorus deficiency (Salisbury and Ross 1978). In plots that received fertilizer, many seedlings grew tall and spindly during late June. With the onset of dry weather, many of these seedlings wilted and died.

Since August 5, 1989, seedling numbers have been low enough to allow total counts of the seedlings within each plot (table 6). Between August 1989 and August 1991, seedling mortality was only 36%. Approximately 75% of the mortality observed during this two year period occurred in the winter of 1989/90. Inspection of the seedlings at the end of this winter (March 1990) revealed that many root systems were uprooted in a manner consistent with frost heaving (Schramm 1966). During the winter of 1990/91 frost heaving was also evident but little mortality occurred, presumably because the seedlings had more extensive and deeper root systems than during the first winter. The seedlings were browsed heavily by white-tailed deer during both winters and partially defoliated by gypsy moths during the summers of 1990 and 1991. No mortality appeared to be linked to these stresses, instead, many seedlings responded with new growth. By August 1991, most of the seedlings were branching and had grown to a height of 20-50 cm.

Seedling counts increased slightly during the summers of 1990 and 1991 (table 6). These increases were attributable to the sprouting of new stems from living seedlings, and also the resprouting of several seedlings that were considered dead in earlier counts. No colonization by new seedlings was observed in any plots in 1990 or 1991. Aspen trees in the vicinity of the experimental area produced seed in both these years. The weather was cool and wet in the spring of 1990, and appeared suitable for aspen seed germination. The spring of 1991 was, however, very dry and likely unsuitable for aspen germination.

Table 5. Average density of aspen seedling (stems/m^2) for the amendment treatments between May and August 1989.[1]

Treatment	May 28 (rain)	June 6 (rain)	June 18 (rain)	July 16 (dry)	August 5 (dry)
Control	0	2^{a}	10^{a}	2^{a}	0^{a}
Stem (S)	0	26^{b}	10^{a}	0^{a}	0^{a}
Root (R)	0	37^{bc}	39^{b}	2^{a}	0^{a}
Limestone (L)	0	28^{bc}	67^{c}	10^{a}	0^{a}
Fertilizer (F)	0	83^{cd}	72^{c}	15^{a}	2^{a}
L+S	0	46^{cd}	15^{a}	2^{a}	0^{a}
L+R	0	112^{d}	140^{c}	66^{b}	0^{a}
F+S	0	63^{cd}	53^{c}	10^{a}	2^{a}
F+R	0	160^{d}	218^{d}	3^{a}	0^{a}
L+F	0	101^{cd}	85^{c}	31^{a}	5^{b}
L+F+S	0	79^{cd}	121^{c}	54^{c}	30^{d}
L+F+R	0	63^{cd}	102^{c}	31^{a}	20^{c}
All Plots	0	67	78	19	5

[1] Values with the same superscript letter within the same column are not significantly different ($p > 0.05$, Newman-Keuls method using Kruskal-Wallis rank sums).

Table 6. Average density of aspen seedlings (stems/m^2) in plots that received fertilizer amendments[1]. All other treatments had seeding densities less than 0.1

	Aug 5 1989	Sep 9 1989	Jul 20 1990	Aug 23 1990	May 10 1991	Aug 26 1991
Fert (F)	1.7^{a}	1.2^{a}	0.8^{a}	0.7^{a}	0.8^{a}	0.8^{a}
F+Stem (S)	0.8^{a}	0.6^{a}	0.4^{a}	0.4^{a}	0.3^{a}	0.3^{a}
F+Root (R)	1.0^{a}	0.5^{a}	0.5^{a}	0.5^{a}	0.5^{a}	0.6^{a}
F+Lime (L)	3.6^{a}	3.8^{a}	2.8^{a}	2.9_{a}	2.7^{a}	2.5^{a}
F+L+S	13.8^{b}	11.8^{b}	8.5^{b}	9.8^{b}	9.2^{b}	9.3^{b}
F+L+R	10.8^{b}	9.6^{ab}	6.3^{ab}	6.8^{ab}	6.1^{ab}	6.9^{b}
All Fert plots	5.3	4.6	3.2	3.5	3.3	3.4

[1] For all treatments, the sample size is 3 plots. Superscript format is the same as table 5.

The application of fertilizer had a highly significant effect on the survival of aspen seedlings. On August 26, 1991, plots that received fertilizer (n=18) contained a total of 246 seedlings, while plots that did not receive fertilizer (n=18) contained a total of 2 seedlings. These two seedlings colonized limestone plots. No aspens successfully colonized the control plots or plots that received only wood chip treatments. Within the fertilizer treatment, seedling densities were higher in plots that also received limestone, and highest in plots that received fertilizer, limestone and wood chips (table 6). On August 26, 1991, plots that received all three treatments contained an average 8.1 seedlings/m^2, while plots that received fertilizer but no wood chips averaged 1.1 seedlings/m^2. Seedlings density on this date was not significantly affected by the type of wood chip (stem or root).

Discussion

Amendment Experiment

The results of the amendment experiment indicate that the absence of aspen on bare mine spoil in northern Appalachia can be explained by a colonization bottleneck. This bottleneck has chemical and physical components. The low number of seedlings observed in June 1989 in plots that did not receive fertilizer or limestone suggests that chemical features provide an initial barrier to aspen colonization. The most likely chemical constraints are low pH and high concentrations of available aluminum. The germination of most tree seeds is lower at pH values less than 5 than it is in circumneutral conditions (Salisbury and Ross 1978). While no studies of aspen germination at different pH values have been reported, it is likely that the extremely low pH of bare soils at the study site inhibits seed germination. Seeds that do germinate in acidic spoils are exposed to high aluminum concentrations. Aluminum has been shown to markedly decrease seedling vitality by interfering with root growth (Berg and Vogel 1973; Foy 1978).

The application of either limestone or fertilizer caused a significant increase in aspen colonization (table 7). In June 1989, experimental plots that received these amendments averaged five times more aspen seedlings than plots that did not receive them.

Table 7. Number of seedlings in the experimental plots, sorted by limestone and fertilizer treatments.[1]

Treatment	June 18 1989	Sept 9 1989	Aug 23 1990	Aug 26 1991
Lime (L)	2664^b	3^a	2^a	2^a
Fert (F)	4116^b	32^b	19^b	21^b
No L or F	708^a	0^a	0^a	0^a
Both L and F	3696^b	302^c	234^c	225^c

[1] For each treatment class, the number of plots is 9. Superscript format is the same as table 5.

Limestone likely improved germination conditions by raising pH and immobilizing available aluminum as aluminum hydroxide. Fertilizer amendments likely improved germination conditions by raising pH and also immobilizing available aluminum through reactions with phosphate. The absence of a difference between limestone and fertilizer treatments suggests that nutritional factors (N, P, and K) are probably not limiting factors in the germinization stage of aspen colonization.

During summer months, bare mine soils can be subject to high daytime surface soil temperatures (50-60°C) and extremely low moisture levels (Schramm 1966; Bell and Ungar 1982). For seedlings to survive, they must develop root systems that penetrate beyond the zone of hot and moisture-deficient summer soil conditions. This development appears to require nutrient additions. During the summer of 1989, 334 seedlings survived in plots that received fertilizer while only 3 seedlings survived in plots that did not receive fertilizer (table 7). Compared to plots that received only fertilizer, survival of seedlings was enhanced by the application of <u>both</u> fertilizer and limestone. The cause of this interaction is unknown. The calcium provided by limestone applications may increase seedling vitality and root growth. Alternatively, the immobilization of aluminum caused by limestone applications may result in the leaching of phosphate deeper into the soil and thus promote deeper seedling root systems.

Mycorrhizae

Results of the mycorrhizal aspects of the experiment are less definitive than the results of limestone and fertilizer applications because evaluations of the extent of mycorrhizal infection of seedlings were not made in conjunction with measurements of soil chemistry or seedling density counts. Nonetheless, speculative interpretations of these aspects of the project can be made. It is highly likely that the chipped tree roots applied to spoils contained mycorrhizal fungi. Shuffstall and Medve (1979) collected root samples from volunteer aspens growing on acidic coal spoils within 50 km of the study site, and found that 97% were infected with mycorrhizae. The observation of rapid growth of fungal mycelia on the root chips when stored in a humid dark environment supports the assumption that roots contained viable fungal populations.

The ability of chipped mycorrhizal roots to act as an mycorrhizal inoculum when applied to the surface of mine spoils is unproven. Medve et al. (1977) showed that inoculation of the subsoil with macerated mycorrhizal roots resulted in better growth by planted trees and increased colonization by volunteer trees. The researchers did not test surface applications of the mycorrhizal inoculum.

The effects that "wood chip" treatments had on aspen establishment in this experiment are not easily interpreted. During the first month of the experiment, more aspen seedlings colonized "root chip" plots than either "stem chip" plots or "no chip" plots (table 8). The high mortality of seedlings that occurred with the first season's hot and dry weather, however, decreased both "root chip" and "stem chip" plots to similar numbers. Over the last two years of the experiment, seedling numbers were always similar in plots that received either chip treatment.

Table 8. Number of seedlings in the experimental plots, sorted by chip treatments.

Treatment	Jun 18 1989	Sep 9 1989	Aug 23 1990	Aug 26 1991
no chips	2808^{a}	63^{a}	45^{a}	42^{a}
stem chips	2388^{a}	151^{b}	122^{b}	114^{b}
root chips	5988^{b}	123^{b}	88^{b}	89^{b}

[1] For each treatment class, the number of plots is 12. Superscript format is the same as table 5.

The unexpected significance of both chip treatments suggests that either both chip treatments modified the plots in some manner independent of the presence or absence of mycorrhizae, or that stem chips were not a non-mycorrhizal control. Both chip treatments may have ameliorated physical conditions by shading the underlying and surrounding spoil and thus moderated surface temperature and moisture extremes. Additionally, the decomposition of chips may have provided a source of nutrients to the spoil that would alleviate fertility problems. If either of these explanations is correct, then extremely low mulch applications (500 cc/m^2 or one sandwich bag of chips per 2 m^2) can have a highly significant effect on aspen colonization processes.

Alternatively, it is possible that stem chips were not a mycorrhizal control during this experiment. Root chips were covered with mycelia during amendment application. Wind and rain action during the several weeks following chip applications may have dispersed mycelia around the experimental area and caused the fungal infection of the "stem chips". If this scenario is correct, then the inclusion of the mycorrhizal root treatment was important to seedling survival. Further work is in progress to better define mycorrhizal aspects of the experiment.

Applications

Currently, the recommended revegetation strategy used for poorly vegetated coal mines is to modify the mine soils so that desirable agronomic or silvicultural species can be established (McKee and Harper II, 1986). Modification of acidic mine soils typically requires the application of large amounts of limestone and fertilizer. The amendments are incorporated into the mine soil, which is then seeded with grasses and legumes. Sometimes, pine or locust seedlings are planted.

The short-term success of revegetation projects using the standard methods is generally spectacular; complete coverage of grasses and legumes is attained within several months. Often, however, the ameliorating effects of the soil amendments wane within 5-10 years and infertile, acidic soil conditions return. Long-term reacidification of the mine soils is difficult to avoid because of the massive amount of acidic spoil that underlies the shallow zone of amended surface soil. Few of the originally planted species are tolerant of infertile acidic soil conditions. As these species decline, sparsely vegetated conditions commonly return.

The long-term success of standard practices is increased when the mine soils are also amended with an organic substrate such as manure or sewage sludge (Sopper 1990). Organic amendments promote the development of a biologically active soil zone which may buffer against reacidification and also help establishment microbial nutrient cycling processes. Applications of organic matter to mine soils are, however, uncommon because of the added expense involved in their application and incorporation into the mine soils.

An alternative revegetation strategy is to modify the bare spoils so that colonization of preferred volunteer plant species will occur. Spring surface applications of fertilizer, limestone and wood chips can significantly stimulate establishment of aspen seedlings on previously barren, acidic mine spoils. The aspen-colonization method described here is less expensive than the standard revegetation methods because less amendments are used, no incorporation of amendments into the soil is necessary, and seeding of the site is unnecessary (table 9). The simplicity of the aspen-colonization method is potentially attractive to conservation and reclamation groups that do not have access to the mechanized equipment needed for standard revegetation efforts. Lastly, the aspen-colonization method has a positive long-term prognosis. Once aspens are sufficiently established, reacidification of the spoil is unlikely to result in widespread mortality and the return of barren conditions.

Table 9. Comparison of standard revegetation practices for acidic mine spoils and the aspen colonization method.

Revegetation Parameter	Standard Practices[1]	Aspen Method
Fertilizer (kg/ha of N-P-K)	112-224-112	38-72-38
Limestone (kg/ha)	18,000	5,600
Manure (kg/ha dry)	50,000[2]	0
Mycorrhizal inoculant	no	yes
Incorporation of amendments	yes	no
Seeding or planting of spoil	yes	no

[1] Fom McKee and Harper (1985).
[2] When available.

The colonization bottleneck concept has utility beyond the establishment of aspen on barren coal mines in northern Appalachia. Winterhalder (1988) has shown that limestone applications stimulate colonization of birch (*Betula papyrifera*), willow (*Salix* spp.) and aspen (*P. tremuloides* and *P. grandidentata*) onto barren soils around Sudbury, Ontario. Decades of high-sulfur smelter emissions gave surface soils in this region a low pH and high concentrations of copper and nickel. Limestone applications raised the pH, immobilized the metals, and made the remnant soils suitable for plant growth, particularly invasion by local wind-born tree seeds. Aspens are also common volunteers on iron mine spoils in Minnesota (Leisman 1957) and on metal mine spoils in western North America (observation by the author). Iron ore spoils can have pH less than 6 (Leisman 1957) and barren metal mine spoils in Colorado have chemical characteristics that are similar to the coal mine soils described in this paper (unpublished data). Aspen colonization onto poorly vegetated iron ore and metal mine spoils could probably be stimulated by appropriate amendment applications.

The colonization bottleneck concept is probably not limited to aspens. The amendment applications described in this paper were timed to coincide with spring seed production by aspens. The effects that autumn applications of amendments might have on autumn-seeding volunteers such as black birch, red maple, goldenrod, aster, and broomsedge are unknown. It is possible that the abundance of some of these plants on mine spoils is also limited by colonization bottlenecks that could be manipulated with amendments.

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