NUTRIENT AVAILABILITY AND DEMAND RELATIVE TO SUCCESSIONAL STATUS OF ACID MINE REVEGETATION SPECIES[1]

by

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Abstract. Reclamation regulations require that mined lands be revegetated with a diverse, permanent vegetative cover capable of succession comparable to that of native vegetation. These regulations require revegetation efforts to consider not only the individual species used for revegetation, but how these plants will function as a plant community. This necessitates examining the ability of this plant community to sustain itself and proceed successionally. For a plant community to develop, it must have the necessary resources, which requires that nutrient availability of the reclamation materials be equal to the requirements of the desired plant community. In this paper, nutrient availability of acid mine lands and nutrient demands of revegetation species are discussed. Conflicting views on the differences in nutrient demand by species of early and late seral stages are addressed; these differences can be resolved if the nutrient demands of the plant community are considered, not individual species. Some recommendations are also given for plant community selection and site nutrient availability.

Introduction

Current regulations for reclamation of areas disturbed by mining require "a diverse, effective, and permanent vegetative cover of the same seasonal variety native to the area". They also require that this vegetation be "capable of self-regeneration and plant succession at least equal in extent of cover to the natural vegetation of the area". These regulations suggest that plant diversity, plant community development, and the successional ability of the plant community all be considered as well as the extent of the vegetative cover and community production when revegetating lands disturbed by mining. Only recently has reclamation research focused much effort toward increasing plant diversity with native species or considered plant successional patterns.

Fertilization is one of the most common practices used to aid in the establishment of vegetation on mined lands. In general, fertilization has been found to increase plant survival and production on reclaimed land; however,

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some studies have found that increased nutrient availability caused decreases in plant diversity (Stark and Redente 1985), and can slow the rate of succession (Biondini et al. 1985). The effects of site nutrient status and ameliorative treatments on plants of different successional stages and plant community development are not clear. Doerr and Redente (1983) suggested that environmental factors such as mine material and nutrient availability will determine the nature of the plant community over succeeding years. Ogle and Redente (1988) suggested initial species selection will be the controlling factor over time.

Reclamation efforts will need to consider how ameliorative treatments will not only affect nutrient availability and plant production, but how treatment changes in nutrient availability will affect plant community development. This manuscript will review some assessments of nutrient availability at mine sites, and how differences in nutrient availability could affect establishment of early, mid- and late seral species communities. The focus of the paper will be limited to native or naturalized species and spoils or tailings of acid metaliferous mines, but are also appropriate for revegetation of non-metallic mine lands.

Nutrient Availability of Mine Tailings and Spoils

Metallic mining operations usually generate either spoils (coarse materials dumped from stripping) or tailings (fine grained material usually deposited by sedimentation in ponds or basins). Both of these types of materials will affect plant growth differently, due to physical and chemical characteristics. For example, spoils are usually composed of coarser material, and water retention may be a problem, whereas fine-textured tailings are often anaerobic, creating a poor rooting environment. Differences in site micro-climate can also be expected on both spoils and tailings compared to the surrounding undisturbed lands.

Chemical and nutritional properties are also different between undisturbed lands and spoils or tailings. In general, both nitrogen and phosphorus will be found in extremely low concentrations in metallic mine wastes. Spoils may be somewhat higher in N and P as the original surface soil can be mixed in with this material. Shetron and Carroll (1977) reported 0 kg ha^{-1} of N and 1-8 kg ha^{-1} of P in both iron and copper mine tailings, and 0 kg ha^{-1} of N and 18 kg ha^{-1} of P in spoil dumps. Availability of Ca, Mg and K was variable, but usually higher on the spoils. Tailings from a nickel mine had total Ca, Mg and K of one-half, seven-eighths, and one-fifth, respectively, of typical soils (Rutherford et al. 1982). Clark and Clark (1981) reported an average of 16, 150, 130 and 20 000 µg g^{-1} of extractable N, P, K and Ca, respectively, from heavy metal mining spoils in England. As an example of extractable nutrient and metal availability, Table 1 shows the nutrient and metal concentrations, CEC and pH of copper mine tailings from Washington State (ammonium and nitrate were extracted using 2 M KCl, phosphorus using Bray-1, and metals using DTPA). The tailings analysis indicates obvious deficiencies in N, P and K; Ca and Mg availability is also likely to be limited, as well as other nutrients such as boron. With a rooting substrate such as this, reclamation plants will have to be excellent nutrient scavengers as much of their nutrition may come from atmospheric inputs only.

In addition to concerns about low nutrient availability on mine reclamation lands, pH and high metal levels can also pose problems to plant growth. Not only can metals exceed toxic levels, but they can also interfere with plant uptake of

Table 1. Cation exchange capacity, pH and some extractable nutrients and metals from tailings of the Holden Copper Mine, Washington State.

pH	CEC meq $100g^{-1}$	NH_4	NO_3	PO_4	Ca	Mg	K	Cu	Zn	Fe
					$\mu g\ g^{-1}$					
3.2	2.4	0.03	0.001	0.25	48	35	ND	2.7	0.85	104

essential nutrients. In some cases, heavy metal availability may be the determining factor for survival and growth of vegetation groups (Thompson and Proctor, 1983). Clark and Clark (1981) found a diverse plant assemblage on areas of spoils with lower extractable metals (311 and 65 $\mu g\ g^{-1}$ of Pb and Zn, respectively) and a species-poor community on areas of higher extractable metals (22 000 and 128 $\mu g\ g^{-1}$ of Pb and Zn, respectively). They stated that community diversity was probably related to concentrations of available lead in the spoils.

Numerous types of amendments have been used to bring soil nutrients up to adequate levels for plant growth. Amendments have also been used to ameliorate low pH and high metal levels. Examples of amendments include liming, chemical fertilizers, sewage sludge, wastewater, wood ash, and composts. Most amendments specifically attempt to increase available nitrogen and phosphorus, and raise pH. When revegetation plans are designed to address plant diversity and successional rate, and not just biomass production, then amendments may need to be adjusted to levels specifically favorable to desired plant community.

Fertilization is the most commonly used amendment. It can both enhance or reduce species diversity based on whether the fertilizer is enhancing site potential for an increased number of species or increasing site dominance of a few species by enhancing their fitness. Wilson and Tilman (1991) suggested that at low nutrient levels plant competition is restricted to belowground competition for nutrients and plant densities are insufficient to cause competitive exclusion. As soil fertility and plant density increase, both below- and aboveground competition occurs and can enhance the fitness of competitive species to the exclusion of suppression species (Harper 1977). As an example, Harper described how top-growth competition from *Lolium perenne* resulted in decreased yield of *Phalaris tuberosa* by 32%, root competition decreased yield by 73 % and both reduced yield by 93%. Fertilizing to enhance productivity is often associated with declines in species diversity (Stark and Redente (1985); however, increased nutrient availability can decrease availability and uptake of toxic heavy metals and increase species richness (Clark and Clark 1981). Fertilizer additions must also meet both biomass and nutrient cycling requirements of the desired plant community.

Establishing Plant Communities

The first priority in mine rehabilitation is usually the revegetation of the site to at least indigenous levels of productivity and diversity. Generally, the most limiting factors are the physical and chemical properties of the mine material, particularly the available nutrients (assuming an adequate seed source). Fertilizers are added for nutrients and lime is often added to ameliorate acidity and reduce heavy metal availability. These measures plus irrigation assure initial productivity requirements for plant establishment, which may include introduced species. This initial stage is highly productive but there is little diversity in the vegetative mosaic. Developing a diverse plant community can be difficult where mine materials are extremely homogeneous (which is typical of mine tailings, but can also be true of spoils). Plant diversity is enhanced on mine spoils or tailings by microtopography. Measures to increase site heterogeneity and therefore species diversity can be accomplished by varying site relief (Hatton and West, 1987), altering spoil material composition (Stark and Redente, 1985), adding soils, varying nutrient amendments, and mulching (Schuman and Belden, 1991). Ogle and Redente (1988) reported that grasses did better on fine-textured spoils, while shrubs did better on coarse-textured spoils. They also reported that relief hastened or slowed succession on level and sloping areas, thus increasing diversity across the site. Numerous amendment studies suggest patches of different species composition and production can be created through non-uniform applications (Biondini et al. 1985, Wilson and Tilman 1991, McLendon and Redente 1992). The use of islands of topsoil on mine spoils effectively provides for differences in both soil nutrients and relief. Sindelar and Plantenberg (1978) found that rapid revegetation occurred on a mine site where islands of native vegetation had been left.

Considerable effort is often necessary to establish native plant species on a mine rehabilitation project that is consistent with seral stages and composition of the adjoining landscape. DePuit and Coenenberg (1979) and Redente et al. (1984) have reported that species diversity on revegetated mine sites has declined over time when seeded to native species. This is due to progressively greater dominance of the most vigorous species. Ogle and Redente (1988) caution that species should be selected carefully; aggressive species are likely to form closed communities. They conclude that 1) it is not feasible to rapidly establish stable and diverse plant communities on mined land, and 2) that stable ecosystems will eventually develop as products of succession, but may require 10 to hundreds of years.

Nutrient amendments used in mine revegetation projects usually make it possible for numerous early succession species to achieve substantial biomass accumulations. Some early successional plants commonly used in the United States are listed in Table 2. This table also lists species which are of mid- or later successional stages that have been found or tested on mine sites. Note that some plants, such as *Lespedeza and Alnus spp.*, are nitrogen fixers. Unfortunately, many otherwise suitable N-fixing species are intolerant of the acidic conditions found at many mine sites.

Table 2 also gives the survival rate of some tested species and a listing of special tolerances or growth habits. Though this species list is not complete, it is worth noting that over three-quarters of the species listed which are suitable for some mine revegetation are believed to be mid- to late successional species.

<u>**Site Nutrient Capital and Nutrient Demand during Succession**</u>

In the revegetation of mine spoils and tailings, we are trying to establish functional plant communities. A given plant community is characterized by an on-site nutrient-capital that supports the plant biomass, the litter biomass, and the soil organic matter. As succession proceeds through forb, grass, shrub and tree stages,

Table 2. Species, successional stage, survival rate and special characteristics of selected mine revegetation plants.

Species	Seral Stage Early	Mid	Late	Survival %	Special[1] Characterisctics	Source[2]
Grasses						
Bromus spp.	+			30	VA, rapid growth	1,5
Agropyron spicatum		+	+			5
Poa pratensis		+	+			1,5
Festuca arundinaceae	+	+		60	SA	4
Stipa spp.						1
Andropogon gerardii		+	+		SA	4
Dactylis glomerata		+			SA, limited growth	4,5
Lolium perenne	+			100	A	4
Panicium virgatum		+				4,5
Sitanion hystrix		+				1,5
Forbs						
Lupinus albicaulis	+			60	VA	4
Astragalus spp.		+				4,5
Coronilla varia		+				4
Lespedeza spp.		+		100	A, N-fixer, rapid growth	4
Polygonium cuspidatum	+	+		40	VA, rapid growth	4
Aster spp.		+				1
Penstemon spp.		+				2
Shrubs						
Alnus spp.	+			40	A, N-fixer	4
Berberis spp.		+		48	A	4,5
Ceanothus spp.		+			SA	4,5
Cornus stolonifera		+			SA	4,5
Amorpha fruticosa	+			90	A, N-fixer	5
Robinia fertilis		+		80	VA	4
Rubus occidentalis			+			4
Salix purpurea		+			SA	4,5
Trees						
Pinus ponderosa		+	+	50	A	5
Pinus spp.		+	+	20	SA	4
Larix decidua		+				4
Populus spp.		+	+		SA	4,5

[1]A: Acid tolerant; SA: slightly acid tolerant, pH 6.5-5.5; VA: very acid tolerant, pH <4.5
[2]Sources: 1. Alvarez et al. 1974 2. Wagner et al. 1978 3. Plass 1975 4. Ruffner 1978 5. Thurnberg 1982.

the biomass of the plant community increases dramatically (Peet 1981).

Biomass is a good indicator of nutrient demand (excluding N demand of N-fixing species) (Harper 1977), and the capture of nutrients by perennial plant tissue with increasing longevity is a primary mechanism controlling rate and direction of secondary succession (McLendon and Redente 1992). The total nutrient demand needed to create and maintain plant community structure increases with increasing biomass at each successional stage (Figure 1). Thus, if we are attempting to establish plant communities of later successional stages, the nutrient capital must be present to support the initial development phase of the plant community and the nutrient-cycling processes that insure normal community development and long term sustainability. Total nutrient capital for the fully developed community need not be on the site at the time of establishment, but nutrient capital enrichment through nitrogen fixation or precipitation must occur in amounts to support normal biomass recruitment.

When revegetating nutrient-poor mine spoils or tailings, the selection of species based on reduced nutrient demand has an intuitive appeal. However, there are two opposing hypotheses dealing with changes in the nutrient demand of species during plant succession:

1. "Early successional species prepare the site for later, more nutrient-demanding species" (Cundell 1977, Cargill and Chapin 1987)

2. "Late successional species are more adapted to the site and are less nutrient demanding than early successional species" (Grime, 1979, McLendon and Redente 1992)

These hypotheses are not mutually exclusive if community nutrient demands are considered relative to individual species' nutrient demands. Early successional species have high nutrient demands because of their fast growth and potential to produce large amounts of biomass, but early successional communities have lower nutrient demands as total community biomass is lower, and more plants are annuals. Later successional species may have lower individual nutrient demands, but community nutrient demands can be much greater due to the large amounts of total vegetative biomass present on the site. Although tight nutrient cycles that include translocation of nutrients and rapid litter decomposition may be present, these processes first require the initial capture of soil nutrients.

Soil nutrients will support a specific level of non-N-fixing plant biomass with its required nutrient capital. The disparity between the nutrient capital required by the plant community with the available nutrient capital in the soil limits the probability of establishing and sustaining the desired plant community. Regardless of the nutrient demands of the individual species, if the nutrient capital required for the plant

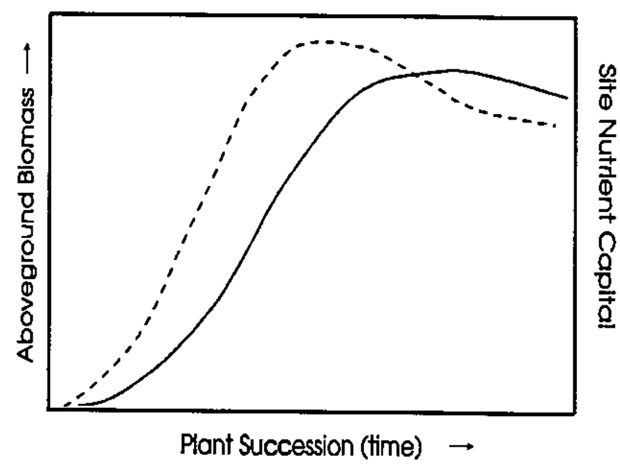

Figure 1. Postulated changes in community aboveground biomass and site nutrient capital (both in vegetation and soil) with plant succession (adapted from Peet, 1981). Dashed line is biomass and solid line is nutrient capital.

community is not present on the site, then the desired plant community cannot be readily established without nutrient inputs to the site. Figure 2 shows this theoretical relationship between plant community nutrient demand and succession, along with disturbance effects.

The effects of nutrient availability on the succession rate of plant communities or success of plants from different seral stages are not clear. Some recent work examining the relationship of nutrient availability to plants of different seral stages has produced conflicting results. Tilman (1986) found that early successional species grew more rapidly at low soil N levels and acquired more nitrogen per plant than late successional species. He demonstrated that early successional species were approximately five times more efficient at extracting N from soils than late successional species. However, later successional species actually removed 40 times the amount of N as early successional species, largely because of the increased soil N available to later successional species. Redente et al. (1992) found that early seral species produced more biomass with lower tissue N concentrations, and late seral species displayed an increasing competitive advantage as N and P availability decreased. In an examination of succession at a semiarid Colorado basin following disturbance, McLendon and Redente (1992) found that early seral dominants had higher N concentrations with higher available soil N, and lower concentrations with lower soil N. However, mid-seral species showed the opposite pattern. The authors suggest that decreases in available soil N, even temporarily, may result in compositional changes associated with succession. Fertilizer applications have been found to increase the dominance of early successional species and slow the rate of succession (Biondini et al. 1985).

Species and Plant Community Selection:

Selection of species for seeding requires the definition of the most probable plant community that can be established given the current tailing or spoil nutrient capital and microclimatic restrictions. If soil nutrient capital has been severely depleted, the prior undisturbed plant community may no longer be possible without amendments. Species for revegetation should be selected on the basis of matching species specialization for a particular ratio of soil and light resources to current and most probable site conditions (Wilson and Tilman 1991). This would involve a two-stage process where species adapted to the current site potential are identified, then species are selected from this group for a particular successional pathway or stage and their ability to tolerate the reclamation material and environment (see Table 2). This is based on the assumption that there are multiple successional pathways defined by differences in site potential and also multiple successional pathways at a single site potential based on degree of disturbance and the species or their propagules on site (Cattelino et al. 1979).

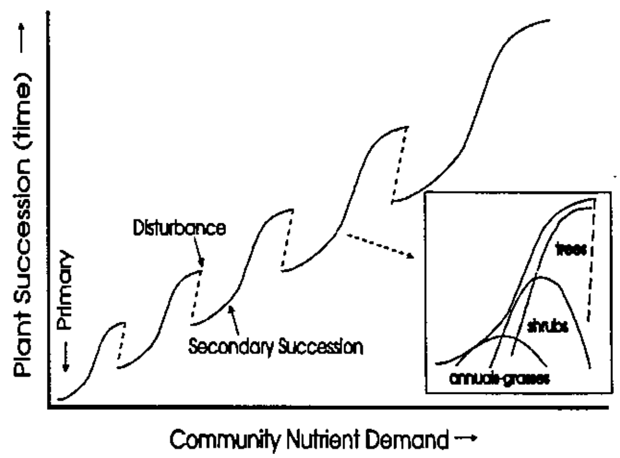

Figure 2. Cyclic changes in community nutrient demand with plant succession and disturbance relative to nutrient demand. Changes in nutrient demand within a cycle are a result of changes in community species (see insert).

In nutrient-depleted sites "stress tolerators" (Fitter and Hay 1987) would dominate the plant community while "competitors" would dominate high nutrient capital sites (Grime 1979). Stress-tolerant species that dominate sites having chronic deficiencies in mineral nutrients are characterized by low productivity and growth, and retain leaves and roots for several years in a tight internal-external nutrient cycle (Grime and Campbell (1991). Shrubs that maintain long-lived, perennial components such as woody stems or persistent leaves are characteristic of droughty sites with low organic matter and nutrient capital (Rundel 1991). It is generally accepted that species adapted to low-nutrient environments have higher and less variable root-to-shoot ratios and slower growth rates. This is usually characteristic of late seral species.

Typically, the nutrient uptake and growth rates of early seral species make them superior competitors and allow them to dominate in early succession. The establishment of short-lived, early successional species is questionable for both nutrient-rich (slows succession rate) and nutrient-poor (immobilizes nutrients) sites. On nutrient-rich sites, annual "ruderal" species (Grime 1979) maintain themselves and delay succession because of rapid growth rates and enhanced ability to extract soil N (Grime and Hunt 1975, McLendon and Redente 1992). In revegetating mine spoils or tailings, the lengthy normal successional pathways may be less desirable than the rapid establishment of later successional plant communities. As an example, the use of *A. spicatum* (a late seral species, Table 2) would be preferable to *S. hystrix* (early successional) if an *A. spicatum* community is the desired end product. If the *A. spicatum* community cannot be sustained at current soil fertility levels, than a N-fixing species (such as lupine or astragalus) could be used as a nurse crop to develop the site for *A. spicatum*. Although early seral species may compete more successfully for soil N than late seral species at either low or high soil nitrogen levels (Tilman 1986, Chambers et al. 1987), the nutrient residence time of the longer-lived, late seral species is eventually detrimental to the shorter-lived species. On nutrient-poor sites, ruderal species are inefficient because plant biomass must start anew each year with limiting soil nutrient capital. Unless decomposition is rapid, nutrients are trapped in litter biomass. The immobilization of soil N by microbial populations reduced N availability and hastened succession on disturbed sagebrush sites (McLendon and Redente 1992). Nutrients tied up in annual litter are not immediately available for later successional species. Although succession may be hastened, the rate of biomass accumulation of later successional species may be reduced by the immobilization of these nutrients.

Limited cycling of nutrients could be a problem at low-nutrient sites where decomposition of litter is limited by low nitrogen or cation levels, or by environmental constraints. On acid soils (pH 3-4), microbial activity and availability of cations (Ca, K, Mg) and micronutrients (Cu, B, Mn) are reduced (Rundell 1991). Biondini et al. (1985) reported total microbial activity, as measured by dehydrogenase activity, increased with perennial grass species dominance, and Cundell (1977) suggested that the rhizosphere of perennial species favored microbial development. The establishment of late seral plant communities also means the establishment of associated soil microbial populations.

Low nutrient status may require the establishment of species that maintain tighter nutrient cycles, characteristic of later successional stages. As nutrient capital may not be sufficient to support the biomass of later stages, sparse or dwarf plant communities could be expected as found in natural communities (Jenny et al. 1969). The challenge is to provide nutrient capital in amounts and timing required to maintain normal development of later seral communities. Chambers et al. (1987) recommended the establishment of late-seral species in alpine mine reclamation to accelerate successional processes and to return species diversity to pre-mining levels. The concept of rapid establishment of late seral species is consistent with the "initial floristics" model of Egler (1954) which suggests that late-seral species are normally on site immediately after disturbance.

The use of early successional species should depend on their ability to enhance rather than deplete nutrient status of the site. Nitrogen-fixing species can significantly increase soil N levels by 17-150 kg $ha^{-1}yr^{-1}$ (Heilman and Ekuan 1982) and provide the nutrient capital required by later successional stages.

Recommendations

Nutrient capital requirements necessary to establish and maintain a desired plant community should be considered when defining the plant community to be established and when planning any fertilizer additions. This requires an initial assessment of available nutrients in the rooting zone of the reclamation material, and an estimate of atmospheric inputs of nutrients. Not only must the plant community be established, but the nutrient cycle that will sustain the plant community over time must be developed. This may require timed inputs of nutrients over extended periods of several years.

The establishment of late seral species appears to be desirable for both nutrient-poor and nutrient-rich sites. On nutrient-rich sites succession would be hastened, and on nutrient-poor sites immobilization of nutrients in litter of early seral species would be minimized. However, the use of N-fixing, early successional species may provide the most rapid means of increasing N levels to support late seral plant community biomass and nutrient cycling requirements. The basis for use of early successional species should be whether they hasten or retard the development of the nutrient capital base required for later successional stages.

Literature Cited

Alvarez, H., J.A. Ludwig and K.T. Harper. 1974. Factors influencing plant colonization of mine dumps at Park City, Utah. Amer. Mid. Nat. 92:1-11. http://dx.doi.org/10.2307/2424198

Biondini, M. E.; C. D. Bonham and E. F. Redente. 1985. Relationships between induced successional patterns and soil biological activity of reclaimed areas. Reclamation and Revegetation Research 3: 323-342.

Cargill, S.M. and F.S. Chapin. 1987. Application of successional theory to tundra restoration: a review. Arctic and Alpine Res. 19(4): 366-372. http://dx.doi.org/10.2307/1551401

Cattelino, P.J., I.R. Nobel, R.O. Slatyer, and S.R. Kessel. 1979. Predicting multiple pathways of plant succession. Environ. Manage. 3:41-50. http://dx.doi.org/10.1007/BF01867067

Chambers, J.C., J.A. MacMahon and R.W. Brown. 1987. Response of an early seral dominant alpine grass and a late seral dominant alpine forb to N and P availability. Reclam. Reveg. Res. 6:219-234.

Clark, R.K. and S.C. Clark. 1981. Floristic diversity in relation to soil characteristics in a lead mining complex in the Pennines, England. New Phytol. 87:799-815. http://dx.doi.org/10.1111/j.1469-8137.1981.tb01715.x

Cundell, A.M. 1977. The role of microorganisms in the revegetation of strip-mined land in the western United States. J. Range Manage. 30:299-309. http://dx.doi.org/10.2307/3897311

DePuit, E.J. and J.G. Coenenberg. 1979. Responses of revegetated coal strip mine spoils to variable fertilization rates, longevity of fertilization program, and season of seeding. Research Rep. 150. Montana Agric. Exp. Station.

Doerr, T.B. and E.F. Redente. 1983. Seeded plant community changes on intensively disturbed soils as affected by cultural practices. Reclam. Reveg. Res. 2:13-24.

Egler, F.E. 1954. Vegetation science concepts. I. Initial floristics composition as a factor in old field vegetation development. Vegetatio 4:412-417. http://dx.doi.org/10.1007/BF00275587

Fitter, A. H. and R. K. M. Hay. 1987. Environmental physiology of plants. Academic Press Limited, London. 415 p.

Grime, J. P. 1979. Plant strategies and vegetation processes. John Wiley and Sons, New York. 222 p.

Grime, J. P. and B. D. Campbell. 1991. Growth rate, habitat productivity and plant strategy as predictors of stress response. In Responses of plants to multiple stresses. Eds. H. Mooney, W.Winner and E. Pell. Academic Press, San Diego. p. 143-147.

Grime, J. P. and R. Hunt. 1975. Relative growth rate: its range and adaptive significance in a local flora. J. Ecology 63:393-422. http://dx.doi.org/10.2307/2258728

Harper, J. L. 1977. Population biology of plants. Academic Press, London. 892 p.

Hatton, T.J. and N.E. West. 1987. Early seral trends in plant community diversity on a recontoured surface mine. Vegetatio 73:21-29. http://dx.doi.org/10.1007/BF00031848

Heilman, P. and Ekuan, G. 1982. Nodulation and nitrogen fixation by red alder and Sitka alder on coal mine spoils. Can. J. of For. Res. 12:992-997. http://dx.doi.org/10.1139/x82-141

Jenny, H., R.J. Arkley and A.M. Schultz. 1969. The pygmy forest podzol ecosystem and its dune associates of the Mendocino coast. Madrono 20:60-74.

McLendon, T. and E.F. Redente. 1992. Effects of nitrogen limitation on species replacement dynamics during early succession on a semiarid sagebrush site. Oecologia 91:312-317. http://dx.doi.org/10.1007/BF00317618

Ogle, P.R. and E.F. Redente. 1988. Plant succession on surface mined lands in the West. Rangelands 10:37-42.

Peet, R. K. 1981. Changes in biomass and production during secondary forest succession. In Forest succession: concepts and application. Eds. D. West, H. Shugart, B. Bothen. Springer-Verlag, New York. p. 324-338.

Plass, W.T. 1975. An evaluation of trees and shrubs for planting surface mine spoils. USDA-FS, Research Paper NE-317. 8 pp. Northeast Forest Experiment Station, Upper Darby, PA.

Redente, E.F., J.E. Friedlander and T. McLendon. 1992. Response of early and late semiarid seral species to nitrogen and phosphorus gradients. Plant and Soil 140:127-135. http://dx.doi.org/10.1007/BF00012814

Redente, E.F., J.M. Stark, M.E. Biondini, and T.A. Oliver. 1984. Vegetation structure and succession as they relate to soil disturbance and retorted oil shale. pp. 1-35. IN: E.F. Redente and C. W. Cook, eds., Ecological Studies of Natural and Established Ecosystems on Energy Related Disturbances in Colorado. Res. Rep. for U.S. Dept. of Energy.

Ruffner, J.D. 1978. Plant performance on surface coal mine spoil in Eastern United States. USDA Soil Conserv. Service, Technical Paper No. 155. 76 p.

Rundel. P. W. 1991. Shrub life-forms. IN Responses of plants to multiple stresses. eds. H. Mooney, W.Winner and E. Pell. Academic Press, San Diego. p. 345-370.

Rutherford, G.K., D. Dimma, G.W. van Loon, and W.G. Breck. 1982. The pedological properties of tailings derived from three mining operations in the Sudbury area, Ontario, Canada. J. Environ. Qual. 11:511-518.
http://dx.doi.org/10.2134/jeq1982.00472425001100030037x

Schuman, G.E. and S.E. Belden. 1991. Decomposition of wood residue amendments in revegetated bentonite mine spoils. Soil Sci. Soc. Am. J. 55:76-80.
http://dx.doi.org/10.2136/sssaj1991.03615995005500010013x

Shetron, S.G. and D.A. Carroll. 1977. Performance of trees and shrubs on metallic mine mill wastes. J. Soil Water Conserv. 32:222-225.

Sindelar, B. W. and P. L. Plantenberg. 1978. Establishment, succession and stability of vegetation on surface mined lands in eastern Montana. Annu. Progres. Rep., Montana Agr. Exp. Sta.

Stark, J.M. and E.F. Redente. 1985. Soil-plant diversity relationships on a disturbed site in northwestern Colorado. Soil Sci. Soc. Am. J. 49:1028-1034.
http://dx.doi.org/10.2136/sssaj1985.03615995004900040048x

Thompson, J. and J. Proctor. 1983. Vegetation and soil factors on a heavy metal mine spoil heap. New Phytol. 94:297-308.
http://dx.doi.org/10.1111/j.1469-8137.1983.tb04502.x

Thurnburg, A.A. 1982. Plant materials for use on surface mined lands in arid and semi-arid regions. USDA Soil Conserv. Service Technical Paper No. 157. 88pp.

Tilman, D. 1986. Nitrogen-limited growth in plants from different successional stages. Ecology. 67(2):555-563.
http://dx.doi.org/10.2307/1938598

Wagner, W.L., W.C. Martin and E.F. Aldon. 1978. Natural succession on strip mined lands in Northwestern New Mexico. Reclamation Rev. 1:63-73.

Wilson, S.D. and D. Tilman. 1991. Components of plant competition along an experimental gradient of nitrogen availability. Ecology. 72:1050-1065.
http://dx.doi.org/10.2307/1940605