Evaluating Reclamation Success Using Ecological Principles: A Holistic Approach

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The reclamation of entire ecosystems is one of the greatest challenges that ecologists face. Because of the worldwide demand for mineral resources, ecosystems containing these resources are often severely and progressively disturbed. Only within the past 20 years have laws been passed in the United States requiring that disturbed ecosystems be reclaimed to resemble predisturbance ecosystems. In many cases, we have been learning about the development of these ecosystems at the same time that we have been attempting to evaluate if reclamation success has been achieved. This has resulted in a synergism in which ecological principles are used to reclaim ecosystems and to evaluate reclamation success, while the data gathered are used to develop new principles and to test ecological theory. This chapter attempts to synthesize some of the more important new principles as presented in the previous chapters.

A holistic approach for both achieving and evaluating reclamation success is emphasized throughout this volume. Successful reclamation requires fundamental knowledge of both biotic and abiotic factors and of ecological processes at several different levels and scales. Because our focus is on building ecosystems from the bottom up, it is necessary to start with the properties of the reconstructed soils. Soil physical and chemical characteristics are an extremely important component of ecosystem structure. Severely disturbed soils, e.g., minesoils, are often poorly developed as there has been little time for active soil formation. Differences in reconstructed soils and native soils include higher percentage coarse fragments and lower soil water storage capacity due to higher bulk density and lower saturated hydraulic conductivity (e.g., McFee et al. 1981; Hauser and Chichester 1989). Measurement of soil properties does not give a direct assessment of ecological functioning, but often provides a more accurate indication of potential long-term vegetation productivity (Doll and Wallenhaupt 1985) and of successional trajectories (Biondini et al. 1985) than vegetation characteristics of newly restored sites.

Measures of the activity of the soil microflora and microfauna can serve as important indicators of the level of ecosystem functioning. Decomposition and nutrient cycling are closely linked with the activity of the soil microflora (bacteria and fungi) and the microfauna (protozoa, nematodes, and microarthropods). Because they require carbon and nutrients for growth, fungi and bacteria in soils constitute an important sink and source of essential plant nutrients. Assessment of the soil microbiota to evaluate reclamation success is not a legal requirement, but provides important information about the microbial aspects of nutrient cycling. At the community level, measures of the structure of the microbial assemblages (numbers of species and their relative abundances) are the most valuable (Zak et al., this volume). To evaluate ecosystem functioning, variables that integrate microbial function, primary production, and decomposition such as C_{micro}/C_{org} (Insam and Domsch 1987) and qCO_2 (Insam and Haselwandter 1989) are most appropriate.

Mycorrhizae are mutualistic associations between plants and fungi that can determine the success of reclamation efforts by their presence or absence (Allen and Friese, this volume). Almost all North American terrestrial plants form mycorrhizae except annuals in the Chenopodiaceae, Brassicaceae, and Amaranthaceae families. Certain species, especially trees, require these associations for survival. Many other desirable reclamation species benefit from these associations through increased growth and fitness and, thus, ability to compete with weedy annual species that exhibit little or no response to mycorrhizal associations. Rigorous evaluations of reclamation success must necessarily evaluate the structure and functioning of mycorrhizal associations. Surveys of mycorrhizal activity can be conducted at the same time as vegetation assessments. To determine the presence of mycorrhizae, a survey of percent infected root segments of the dominant plants should be made. To evaluate reproduction, density and species diversity of sporocarps of ectomycorrhizal fungi should be assessed.

A properly functioning nutrient cycle is an essential element of reclamation success that is highly dependent upon both the characteristics of the soils and the activity of soil microbiota. Nutrient deficiency is a common characteristic of many disturbed soils and can result either from a lack of one or more major nutrients or an impediment to the cycling and supply of nutrients (Palmer, this volume). Low nitrogen

availability often limits plant growth on mined lands, especially if the topsoil is not replaced. Palmer suggests that colliery spoil requires a minimum level of mineralizable N (20 to 40 kg/ha) before the site is naturally colonized by many unsown species. For these sites to be self-sustaining and support a level of productivity comparable to natural ecosystems, a much higher "capital" of mineralizable N (700 kg/ha) is needed. Overfertilization initially may result in dominance by highly productive species and lead to declining stands with high C:N ratios. The inclusion of legumes can provide a steady but low level input of mineral nitrogen. Sites with inherently low nutrient levels may be naturally colonized and eventually exhibit a diverse compliment of desirable native species.

The establishment of vegetation is one of the more critical aspects of successful reclamation because of the lasting effects of this process on species composition. An important prerequisite is knowledge of the germination systems of seeds and of the potential of the seedbed to support germination and seedling establishment (Young, this volume). Seeds may exhibit several forms of dormancy that may be overcome through the proper planting techniques or that may require specific physical manipulation of the seeds. For example, species with hard seed coats (legumes) may require scarification of the seed coat to promote germination. Regardless of the pretreatment, the planting methods used must be appropriate for the physiological requirements of the seeds. Young (this volume) suggests that the most common causes of seeding failure are: (1) improper seed placement and coverage; (2) competition; (3) use of nonadapted species; (4) predation of seeds or seedlings; and (5) environmental factors such as drought, wind erosion, or water erosion.

Measurements of reclamation success often emphasize the vegetation component of the reconstructed community (Allen, this volume). The 1977 Surface Mining Control and Reclamation Act provides for the evaluation of community-level structure and function by requiring mining companies to "establish . . . a diverse, effective, and permanent vegetative cover of the same seasonal variety . . . capable of self regeneration and plant succession at least equal in extent of cover to the natural vegetation of the native area . . ." Although it is often difficult to exactly replicate the native community, a functional diversity that includes the dominant life forms and phenologies can often be achieved. Within- and between-habitat diversity should also be considered as natural landscapes are often heterogeneous and exhibit a high degree of patchiness. To maximize both species diversity and productivity, plants should be selected that differ in their temporal and spatial use of resources and, thus, minimize competitive interactions in mixtures. Inclusion of keystone plant species, such as shrubs that provide microsites for later plant establishment, and of uncommon species with important functions, such as nitrogen fixation, will increase species diversity and aid community functioning.

The basic processes of succession are identical to those required for the reclamation of disturbed land (MacMahon 1987; Redente and DePuit 1988). These universal processes include the arrival of propagules at the disturbed site, species establishment, alteration of the abiotic environment by tthe initial colonizers, competition and further changes in the environment, and eventual stabilization. Differences in successional processes among the major biomes (deserts, tundra, grasslands, coniferous forest, deciduous forest, and rain forest) can influence the goals and methods of reclamation used and, consequently, the successional outcomes (Chambers et al., this volume). For example, large differences exist among biomes in the length of time required to obtain climax, and the degree to which reclamation success can be measured varies considerably. In deserts and tundra only a limited number of species are adapted to the harsh climate. Once the critical plant establishment phase has been achieved in these ecosystems, the reclaimed ecosystem will rather quickly resemble the surrounding area (10 to 50 years). In contrast, because of the nature of successional processes and the length of time required for succession in forests, it will almost never be possible to reclaim a forest to resemble a late successional stage within the bonding period.

Animals integrate numerous abiotic and biotic factors and can serve as important indicators of ecosystem development and functioning (Major 1989; Parmenter and MacMahon, this volume). Reestablishing the habitat of a single species or of species groups is often a specific reclamation goal. The assessment of faunal community development on reclaimed lands requires careful selection of both species and measurements (Parmenter and MacMahon, this volume). Assessments of vertebrate populations often suffer from small sample sizes and are difficult to evaluate statistically. Invertebrate populations are often more easily assessed and can provide useful measures of both successional trajectories and reclamation success. The development of plant structural diversity on reclaimed sites significantly influences the recolonization of both vertebrates and invertebrates, and assessments of animal species must be accompanied by habitat evaluations. Parmenter and MacMahon have tracked both vertebrate and invertebrate assemblages in a reclaimed and undistrubed sagebrush-steppe ecosystem in Wyoming. During the early stages of succession on the reclaimed sites the colonizing species and the community structure were similar among treatments. Treatments that included patches of shrubs for the purpose of diversifying the vertical and horizontal vegetation architecture were colonized by higher numbers of species representing a wider array of guilds.

A holistic assessment of the reclamation process necessarily involves a landscape perspective (Tueller, this volume). All landscapes, including reclaimed ones, exhibit a spatial diversity with both horizontal and vertical boundaries. Landscape resources include all aspects of the ecosystems of interest including geology, soils, vegetation, animals, water, and air quality. A thorough understanding of landscape properties can be obtained through the application of synecological principles, remote sensing techniques, geographic information systems (GIS), and multivariate analysis procedures (Tueller, this volume).

Data obtained using these tools can be analyzed in order to understand the polygons of the landscape and their relationships to one another. These data should be collected prior to mining and can be used in the development of the reclamation plan as well as in the assessment of reclamation success. As our knowledge of landscape ecology increases, our ability to restore the natural heterogeneity of ecosystems and the diversity of the fauna and flora will increase.

A landscape-scale perspective is useful in the assessment of the cumulative effects of mining and other land disturbances on ecosystems. On-site cumulative effects resulting from progressive surface or underground mining may alter soil and vegetation composition, slope stability and surface erosion potential (Halverson and Sidle, this volume). Off-site effects may result from multiple mining disturbances within a watershed or from the interaction of mining activities with other land uses such as grazing, residential development, recreation, or timber harvest. Effects may include changes in water chemistry, channel sediments, riparian ecosystems, aquatic habitat, and peak flows. Because all of the components of ecosystems can potentially be affected, an integrated approach that uses our knowledge of physical, chemical, and ecological process is needed to address these issues. This approach can result in reclaimed ecosystems that meet the desired land use goals without adverse affects to the landscape.

Taken together, the chapters in this volume present a broad framework for evaluating reclamation success using ecological considerations. They illustrate that a holistic approach is necessary to insure that reclaimed ecosystems remain stable and productive and that they have beneficial and not detrimental effects on the landscape. Currently, most assessments of reclamation success by mine operators only include the vegetation community. As our knowledge of reclaimed ecosystems continues to expand, it may be desirable to measure other components of ecosystems that convey a high level of functioning. In addition, it will be possible to refine our methods of assessment to more accurately reflect the level of functioning.

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