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ECOLOGICAL RESTORATION

V.J. GERHART, W.J. WAUGH, E.P. GLENN, AND I.L. PEPPER

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Human beings have greatly disturbed most of the world's natural ecosystems. Socioeconomic pressures, land-use patterns and recently, the wide scale removal of natural resources, such as forests, have devastated vast tracts of land across the globe. Often the original species' composition of the area is lost, but the essential biophysical resources may remain intact. The primeval forests of Europe were cleared for farms and settlements thousands of years ago, and although there is little chance that they will return to their former state, they remain productive albeit in a different form. Activities that result in degraded lands that are candidates for restoration include: deforestation; overgrazing; secondary salinization from poor irrigation management; wetland clearing and draining; oil production; mining; and toxic spills. In fragile ecosystems such as the desert and semidesert regions of the world, overuse of land can lead to the irreversible loss of fertile top soil, vegetation, and nutrient cycling, a process called *desertification*. According to the United Nations Atlas of Desertification (Middleton and Thomas, 1997), over half of the world's arid and semi-arid lands have been affected by desertification. In wet regions of the world deforestation and other unsustainable land-use practices have left large tracts of land with unusable, unfertile soils prone to water and wind erosion. In any ecosystem there is a threshold for self-repair, but once that threshold has been crossed, severe degradation occurs. It has become apparent that land, and particularly soil, are finite resources that need to be preserved and restored whenever possible.

Increasingly strict regulations have been promulgated to reduce potentially destructive land use. Today, for example, nearly all mining activities in developed countries require a *closure plan* that describes how the land will be restored to a productive state after mining ceases. The United Nations has an antidesertification program that aims to return millions of hectares of arid lands around the world to productivity. In the United States the Endangered Species Act has mandated that key ecosystems, such as riparian corridors and wetlands that have become degraded, must be restored or recreated to provide habitat for threatened species. In return for permits to build new factories and power plants, developers are now often required to provide *environmental offsets*, in which they restore abandoned farmland, create wetlands, or plant trees on logged-over property. The science of *ecological restoration* has developed, rather recently, to find ways of repairing damage to disturbed ecosystems.

In 1996 The Society for Ecological Restoration defined restoration as ‘‘the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices.’’ Technically, *rehabilitation, revegetation,* and *reclamation* fall under the umbrella of *restoration*, each referring to specific goals within a restoration project. However, these terms have been widely used by different land-management agencies, and their definitions tend to be interchangeable. Rehabilitation means repairing some or most of the damage done to land so that it can serve some productive function. For example, salinized farmland, unable to support native plants, can be planted with salt-tolerant plants (*halophytes*) to prevent erosion and provide wildlife habitat. Revegetation involves planting or seeding an area that has received minor damage. In contrast, reclamation is often used as a synonym for rehabilitation, although it generally refers to restoring biotic function and productivity to the most severely degraded land, such as an Environmental Protection Agency (EPA) Superfund site (see Chapter 18). However, by another definition reclamation means ‘‘ . . . making land available for human use by changing natural conditions’’ (Merriam-Webster, 1993). This is the definition adopted by the U.S. Bureau of Reclamation, which has sponsored programs to convert desert land in the southwestern United States into irrigated farmland. By this definition, the original human inhabitants of Europe could be said to have engaged in a massive reclamation project by converting the forests to farms and towns. In this chapter we are concerned with methods to repair human-caused damage to natural ecosystems, and like many restoration ecologists, we tend to use the aforementioned terms interchangeably.

In the following sections we describe the aims and methodology of restoration ecology. The process usually starts with a *site characterization*. This includes a *conceptual plan* and a *site assessment*. These two components are often combined to provide a complete picture of a project site. The conceptual plan summarizes the restoration potential of a particular site, whereas the site assessment details current conditions. Essentially the questions asked at this point include: What was the land like before human intervention? What is it like now? What changes in topography, soil properties, surface and subsurface hydrology, and vegetative cover have taken place? The information garnered during this stage enhances the development of realistic restoration objectives. Can the land be reasonably restored to its original state, or has it been so altered that it must be converted into a different type of habitat? Once the objectives are set, a *site design* and *implementation* follows, which includes a schedule and detailed protocols for repairing the land. Abiotic components such as soils must be replaced, stabilized, or amended so they can once again support plants, and biodiversity must be restored to the site. Restoration even under favorable circumstances can take many years. The final stage of the process is *monitoring and evaluation*. Did it work? What more must be done? There must be feedback loops built in to the plan so necessary changes can be made along the way. The costs associated with restoration can reach millions of dollars for the most severely disturbed sites, but if the plan is not cost effective, it is not likely to be implemented despite its benefits to the environment.

In reading this chapter, keep in mind that restoration ecology is a new science. There is no cookbook method for restoring a damaged ecosystem, and each restoration site has its own unique characteristics and problems. As the field of restoration ecology moves out of its infancy, practitioners commonly define specific output goals, which in turn provide the blueprint for input and management decisions. Clearly the best restoration project is the one that is not required because safeguards minimizing land degradation were built into the original land-use plan.

SITE CHARACTERIZATION

In an ideal world the restoration objectives for a site will be chosen in advance, even before the site is disturbed. For example, a new electric power plant might have a useful life of 50 years. A closure plan will be submitted along with the application for a construction permit for review by local, state, and federal agencies and other interested parties (*stakeholders*). Thus when the plant is closed, the original site conditions will have been documented, and a procedure for mitigating any damage to the land will already be in place. In reality most current restoration work is done after the fact. Land that decades ago was converted to some use, such as mining or farming, then abandoned, may only recently have become a candidate for restoration through stricter environmental laws. Often state or federal agencies assume responsibility for restoration, even if the land was damaged by private owners. Restoration of these sites starts with a conceptual plan and site assessment that can proceed like a detective story. Figure 19.1 shows the main points to be considered during each step of the process, from conception to final evaluation. As you read through the following sections, refer to the case study on a former uranium mill site on the Navajo Reservation in Monument Valley, Ariz., which details the formal procedure followed by the U.S. Department of Energy as they began the restoration process.

CONCEPTUAL PLAN AND SITE ASSESSMENT

A conceptual plan often begins with a detailed history of the site where information is collected to determine the anthropogenic changes that have lead to the current state of degradation. This information is cross referenced against historical and current topographical, geological, and vegetation maps to determine what changes have occurred spatially and temporally. Information on the physiochemical soil properties and the water quality of the site, before disturbance, can show the restoration potential of the area, and perturbations or stressors that enable the degradation process are identified. Before deciding to proceed with a project, social and cultural values of the neighboring residents need to be assessed to ensure that the proposed restoration objectives are compatible with the local socioeconomic needs of the public.

Once a complete history of the site has been compiled, and it has been determined that the restoration project is feasible, a thorough site assessment of abiotic and biotic conditions takes place. This step is probably one of the most important in any restoration project, since it not only provides baseline measurements on such parameters as hydrologic features, soil conditions, and biological information, but it also serves as the benchmark on which to evaluate the project through time. This step involves placing the site in the context of the regional landscape with respect to habitat fragmentation, disconnected surface and subsurface hydrological flows, water quality issues, physical and chemical properties of the soil, and finally plant and sometimes animal inventories. Depending on the nature of degradation, additional data may be collected on the presence or absence of toxic chemicals, such as organophosphates, heavy metals, and radioactive waste, as discussed in Chapter 16. In assessing a site it is important to determine which basic ecological functions are damaged or fragmented because this often sets the restoration priorities, and ultimately the success of the project.

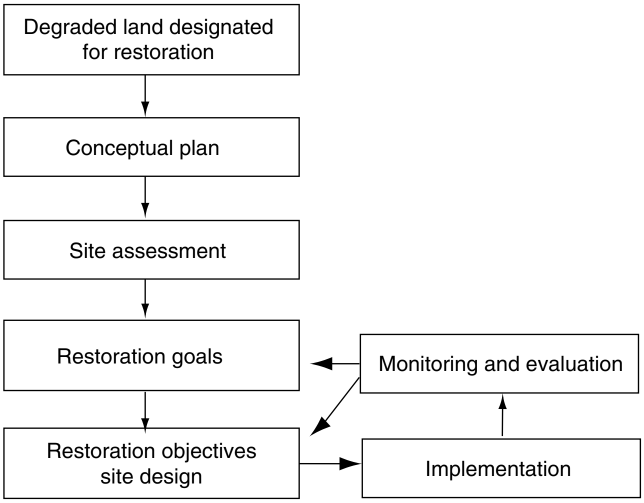

FIGURE 19.1 Flow chart of the restoration process. Built-in feedback loops are needed to allow for project modification.

It is worth noting that the soil conditions and water quality in a given area generally dictate the type of vegetation cover and thus the biodiversity of biotic components, so extra care should be taken in analyzing and describing these two elements both horizontally and vertically across the landscape. Figures 19.2 to 19.4 show the soil moisture and soil salinity gradients, plus the depth to the impeding layer at a restoration site in western Maricopa County, Ariz. This 11,000-acre site was a cotton farm until it was abandoned in the late 1980s due to salinity problems and decreases in the price of cotton. The climatic conditions of this site are harsh, with annual precipitation ranging from 150 to 200 mm per year and summer temperatures rising to 44°C. During preliminary surveys taken in the fall of 2000, it was found that although some areas had extensive stands of mesquite trees, and other areas were covered with saltbush, most of the ground was bare and subject to wind erosion. A detailed soil sampling across the site to a depth of 5.4 meters (18 feet) showed that the difference in vegetation types were related to the soil moisture and soil salinity found in the root zone, which were, in turn, related to discontinuities in the soil profile. Sandy loam is the predominant soil type within the plow layer, but it is underlain by clay lenses, caliche (cemented calcium carbonate), and sandy gravel. In the mesquite bosques a low-permeability clay lense was found at 3 meters and this held the soil moisture at approximately 13%, which was sufficient to allow the mesquite trees to thrive. In contrast, the bare ground contained approximately 3% moisture, whereas saltbush was located in areas with 7% moisture and high salinity levels. Obviously, any restoration plan for this site has to address the issue of retaining water within the upper part of the soil

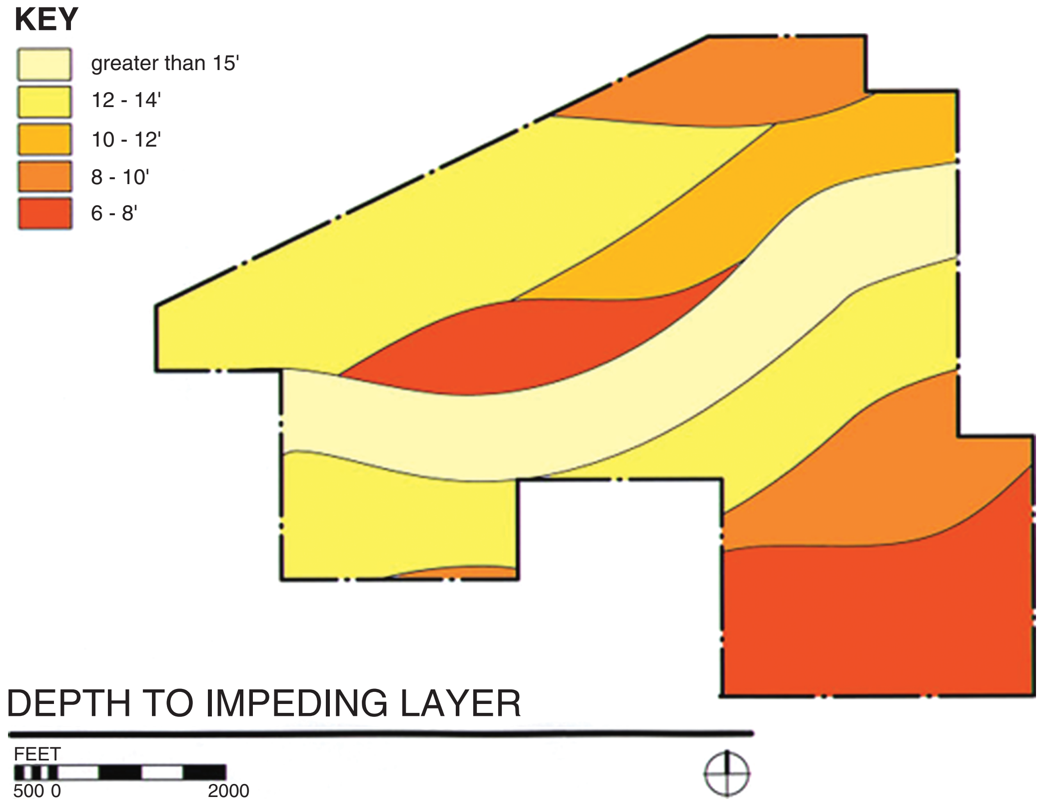

FIGURE 19.2 The depth to the impeding layer in the soil profile at a restoration site in Maricopa County, Ariz.

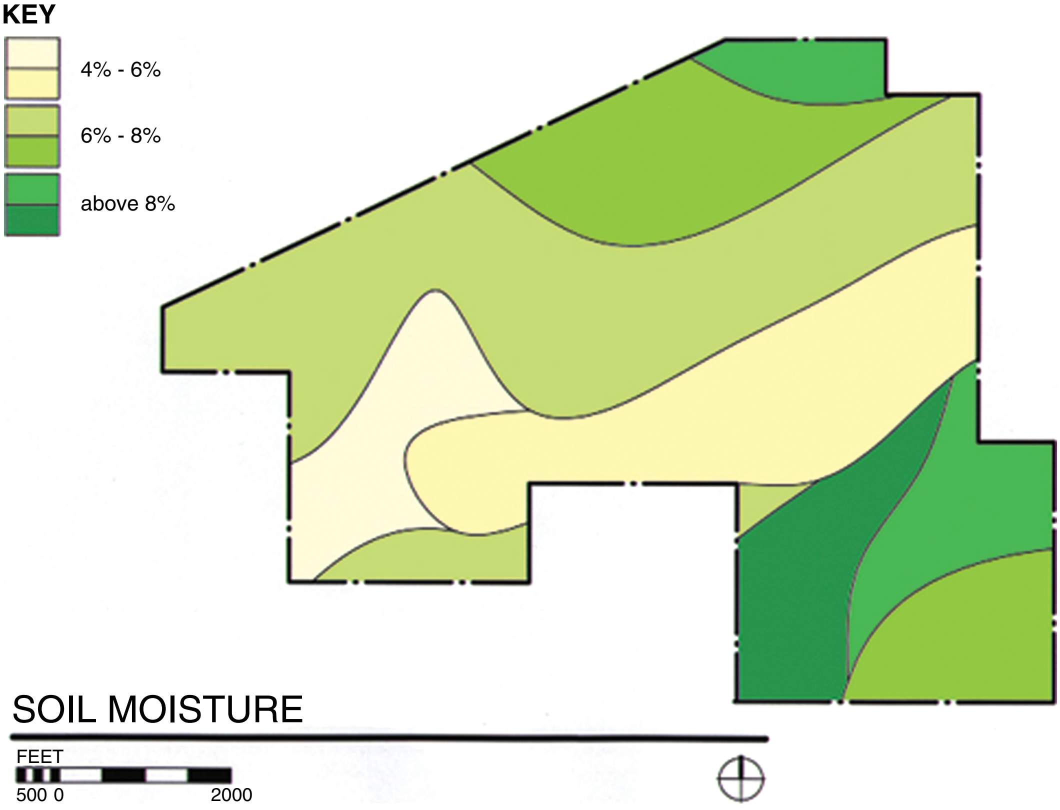

FIGURE 19.3 Soil moisture gradients at a restoration site in Maricopa County, Ariz.

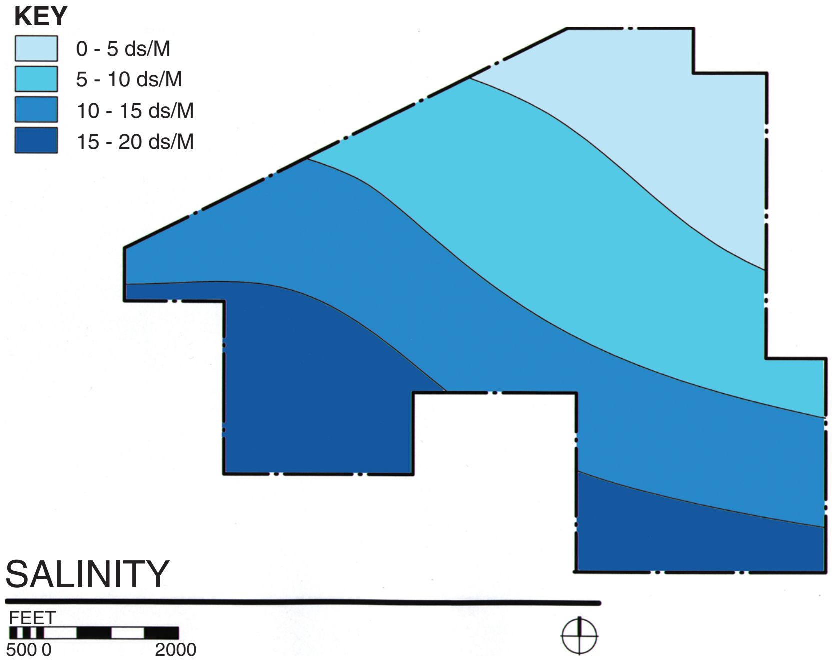

FIGURE 19.4 Soil salinity gradient at a restoration site in Maricopa County, Ariz.

profile and, where possible, leaching salts below the root zone.

Plant Surveys

The occurrence and relative abundance of certain plant species and their physiological and ecological tolerances provide information about environmental conditions that are of importance for understanding the nature of a site, and potential human health and ecological risks, plus the feasibility of different restoration alternatives. Typically, plant ecology investigations include four types of studies: (1) *plant species survey*; (2) estimates of the *percent cover* and age structure of dominant, perennial plant species; (3) evaluation of the composition, relative abundance, and distribution of *plant associations*; and (4) *vegetation mapping*.

The plant species survey is conducted by traversing a site, usually on foot, and noting each species present. Sometimes the survey is confined to perennial species only, and unknown species are collected for later identification at an herbarium. In formal surveys *voucher specimens* of each plant species are collected, pressed, and mounted on cardboard herbarium sheets to be deposited in a university or other recognized herbarium. Sufficient information is included on the label accompanying the specimen so that others can relocate the collection site, if necessary.

The percent-cover study attempts to quantify the percent of the site that is covered by bare soil or individual plant species. Generally, a *line intercept* method is used, employing a *baseline and transect* sampling scheme (Bonham, 1989). First, the plant community to be described is delineated on a map, and then 30-meter transect lines are chosen where actual plant counts will take place. In the field a 30-meter tape is stretched out, and the total distance intercepted by each plant species is recorded and used to calculate the percent cover of each species. For example, a transect might consist of 12% fourwing saltbush, 10% black greasewood, and 78% bare soil. The results from all transects were averaged to give an estimate of percent cover over the whole site. Each individual plant encountered along the transects can be further measured to determine height, width, leaf area, and age (if it forms annual rings), allowing a vegetation history of the site to be developed.

The plant association and vegetation mapping studies are used to delineate land management units with respect to ecological condition and potential for enhancement by revegetation. An association is a unit of classification that defines a particular plant community, and generally has a consistent floristic composition, a uniform appearance, and a distribution that reflects a certain mix of environmental factors that can be shown to be different from other associations. The association is a synthesis of local examples of vegetation called *stands*. There are several methods for delineating and mapping plant associations. One of the simplest to use is the *relevé* method (Barbour *et al.*, 1987), where stands are characterized, then grouped into associations using simple *ordination* and *gradient analysis* techniques.

SITE RESTORATION

Setting realistic goals for a restoration project is probably one of the most difficult parts of the process. The tendency is to aim at recreating an ideal habitat or ecosystem, one that mirrors adjacent undisturbed areas in biodiversity, ecological function, and services. The inability to achieve this level of restoration leaves many projects labeled as failures, when in fact, there are many incremental successes. We as human beings can design a restoration project and put it on a desired trajectory, but ecological processes are not static; rather they are in a constant state of change and readjustment in response to human and natural perturbations. Current trends in the field of restoration ecology suggest that the "dynamic nature of ecosystems be recognized, and accept that there is a range of potential short- and long-term outcomes of restoration projects" (Hobbs and Harris, 2001) and the focus should be on "desired characteristics of the (eco)-system *in the future*, rather than in relation to what these were in the past (Pfadenhauer & Grootjans, 1999). Realistic goals, then, should specify ecological changes or outputs at a project site within the realm of its intrinsic dynamic nature. The better these goals are defined with respect to habitat creation, biodiversity, and socioeconomic needs, the greater the need to define inputs and intervening processes (Box, 1996), and the higher the success rate of the project. Restoration goals will always follow the key concepts of ecological systems: sustainability, resistance to erosion and invasion of alien species, productivity, nutrient retention, and a degree of biodiversity sufficient to support multilevel biotic interactions (microbes, plants, and animals). Often, specific ecosystem requirements are built into the restoration goals. For example, constructed wetlands are designed as replacement habitat for specific, sensitive bird species in areas where natural wetlands have been drained.

The methods chosen for the restoration of a particular site will be determined by the nature of the site, the level of existing degradation, and the desired outcome over time. The underlying causes of the degradation must be identified as either biotic, abiotic, or a combination of both. The restoration ecologist may ask, for example, whether the degradation of land was caused by simple overgrazing, or if the physiochemical soil and hydrological processes were changed to the point where biodiversity has been compromised. In highly polluted sites it may be necessary to remove contaminants from the soil and/or water before beginning restoration work. For example, mining activities may have contaminated the soil to the extent that it is toxic to humans, animals, and plants, in which case it must be removed and replaced by clean soil at the beginning of the restoration process. Thus for some sites, soil and groundwater remediation activities (Chapter 18) may be a component of an ecosystem restoration project. Yet, in other cases, minimal work such as managing grazing will be all that is necessary to make the site suitable for plant establishment and growth. The degree of intervention required in restoring a site ranges from "natural" restoration through passive to active restoration. The information gathered for the conceptual plan and from the site assessment should paint a fairly clear picture of the path a restoration project will follow, and will shape the achievable goals through carefully constructed project objectives, design, and implementation strategies.

Restoration Objectives

A project's implementation plan spells out the activities that are required to achieve the restoration goals, and thus is an integral part of the overall project design. Up to this point in the process, the main participants involved in developing restoration goals for a site will be scientists, politicians, federal and state employees, and possibly, local residents. However, once there has been a consensus on the restoration goals, and the planning stage moves to setting the objectives, a myriad of other players can become involved, depending on the complexity of the work. As we will see in the Monument Valley case study, *Phase 1* involved removing radioactive topsoil, then transporting, and capping it in a different and presumably safer location. The list of objectives to carry out this one goal was obviously very complex and explicit. Overall, objectives have to be measurable, and performance standards established that represent milestones of accomplishments for each portion of the project. It has already been noted that ecosystems are a dynamic entity and each small, natural, or anthropogenic change to a given site can cause unintended reactions. By documenting and measuring each objective in an unbiased way, it will not only be easier to pinpoint problems and make adjustments, but it will also be easier to explain minor setbacks to concerned stakeholders.

It is advantageous to integrate into a restoration project scientific studies that will quantitatively measure abiotic and biotic factors spatially and temporally. It is at this stage of the project that research experiments need to be carefully designed so they can become an integral part of the implementation process. A large body of literature addresses the experimental design and analysis of data for ecological and agronomic studies; however, the complexity of interactions, and the logistical challenges found in ecosystem restoration are often viewed as insurmountable, and data is simply not collected (Michner, 1997). New methods of handling and analyzing data allow more complex ecological interactions to be interpreted, which will benefit the field of restoration ecology immensely.

PROJECT IMPLEMENTATION

Just as an architect draws plans for a house and presents construction documents to a builder, so must a restoration ecologist draw a project plan, and compile a set of documents that identify all the actions and treatments needed to satisfy each project objective. These can include, but are not limited to, equipment, personnel, supplies, seeds, and plants. In some cases the reintroduction of animals may be a stated objective. The need for specific, sequential work orders is of paramount importance at this stage, since retrofitting a particular task will generally be more costly, and will delay the implementation of other parts of the project. General maintenance should also be scheduled into the overall plan.

Most of the installation in a restoration project will be completed in the first few years, but other objectives may not be met for some time. In constructing a wetland the reintroduction of aquatic life may have to wait until the site matures and optimal conditions regarding water quality and primary production will ensure the survival of the reintroduced species. As work proceeds, performance standards should be evaluated and recorded for each part of a restoration objective. This continuous monitoring will allow for adjustments if unforeseen problems arise. The flexibility to modify the plan as needed during the implementation phase is crucial to ecological restoration projects. Unlike a traditional engineered plan for, say, a new bridge where a predictable outcome is guaranteed, restoration projects are less predictable.

SITE MONITORING

"Success criteria need to relate clearly back to specific restoration goals" (Hobbs and Harris, 2001) and restoration objectives. Up until a few years ago, most projects were monitored in the field using typical agronomic and plant ecology techniques and in controlled greenhouse experiments that measured soil, microbial, and plant interactions. Although these methods are considered vital in describing the status of plant establishment, water quality, changes in soil chemistry, and microbial populations, the current trend is to try to integrate this information into a broader ecological picture. With increased computing power and sophisticated data collection techniques, real-time data can more easily be obtained without additional personnel, thus giving restoration ecologists larger data sets with which to work.

SHORT- AND LONG-TERM MONITORING

Most restoration projects rely on short-term monitoring to assess the success of a project. Sponsors want to see the results of their investments, and the public expects immediate results. The reality of the situation is that ecological processes can take from decades to centuries to achieve a level of maturity; a time span that is not economically compatible with monitoring programs. Instead, shorter-term monitoring programs collect data, which are then extrapolated to predict generalized ecological patterns of change against a referenced ecosystem.

Restoration monitoring investigations must be sufficiently quantitative so that differences before and after restoration can be detected, and comparisons made between disturbed and referenced sites. In general, sampling methods must be sufficiently robust to detect differences of 10% to 15% with 95% certainty. Data should be collected on each specific project objective, which, for example, could include the efficacy of soil surface preparation, the addition of soil amendments, variable seeding rates, and survival of transplants under dry land or irrigated conditions. The analysis of this type of data from short-term monitoring is crucial in the evaluation process.

RESTORATION EVALUATION

At the beginning of this chapter we introduced ecological restoration as the process of assisting the recovery and management of ecological integrity, which includes: a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices. With these parameters in mind, the evaluation of a restoration project should be sufficiently thorough to address the issues of ecological function, biodiversity, and sustainability over time. Commonly, projects are evaluated on a limited set of criteria, which are then compared to a reference ecosystem. This implicitly creates a success/failure scenario without taking into account ecosystem dynamics. Evaluations therefore should not only include quantitative data on specific project performance standards, but they should also incorporate how the project has fit into the greater regional, historic, and social landscape (Case Study 19. 1).

CASE STUDY 19.1 *Monument Valley, Arizona (Glenn et al., 2001)*

This case study involves a former uranium mill site on the Navajo Indian Reservation in Monument Valley, Ariz., that the U.S. Department of Energy had placed in its Uranium Mill Tailing Remedial Action (UMTRA) program. Each step in this restoration process follows a formal procedure that has been well documented. Starting in the 1950s, the Atomic Energy Commission encouraged the mining of uranium ore in the southwestern United States to provide fuel for the nuclear power industry and material for weapons. The milling process produced large masses of crude ore and tailings that covered many acres. These waste areas were surrounded by unlined evaporation and leaching ponds, from which ''yellow cake,'' a crude form of uranium, was extracted. In the 1970s the price of yellow cake collapsed, and most of the mills went bankrupt and were subsequently abandoned. The owners made no effort to clean up the sites. In the 1980s, the Department of Energy was given the responsibility for restoring these sites. The primary problem associated with these sites is the piles of crushed ore and tailings, each pile covering several acres, which are mildly radioactive. In addition, toxic chemicals (heavy metals, nitrates, ammonia, and sulfates) have leached into the soil, and ultimately, the groundwater at many of these sites.

The first task in the restoration process was to determine the history of the Monument Valley site. A search was made of company records, former workers were interviewed, and archives of aerial photographs were assembled. An overview of how the mill operated was developed, and areas of concern for remediation and restoration were pinpointed. A map of the site was made, showing where the different processes in the milling operation took place. The second task was to determine the current extent and state of contamination. Intensive soil sampling for radioactivity, heavy metals, and other potentially toxic chemicals was undertaken. Bore holes were drilled into the water table to determine if the underlying aquifer was contaminated, and vegetation cover across the site was assessed. Maps were produced that detailed the extent of the contamination not only on the site, but also on adjacent land.

Once the site had been characterized, and the extent of contamination problems determined, a baseline risk assessment report was released that evaluated the potential for human and environmental damage if the site was not repaired. The Monument Valley site was given a high priority for remediation, and further studies were conducted to develop a set of restoration goals and objectives. Federal, state, and private stakeholders reviewed these goals in a series of public meetings. Those attending the meetings included representatives from the Department of Energy, the EPA, the Navajo Nation UMTRA, the Navajo Nation EPA, and the local community. Local residents were vocal in opposing plans that would negatively impact their traditional uses of the land. Stakeholder participation during this planning phase was critical to the ultimate acceptance of the plan by the community. The restoration plan for this UMTRA program is shown in Table 19.1.

Phase I of the restoration plan generated little controversy. It was quickly decided that the ore and tailings had to be removed from the site, and that the soil around the site had to be removed down to the level at which there was no more radioactivity. Subsequently, a fence was placed around the property to prevent grazing animals from entering. A graded road to the site was constructed across 20 miles of desert, and a fleet of trucks was commissioned to haul away the contaminated material. Local citizens were trained as truckers and equipment operators for the project. The contaminated material was taken to the nearby town of Mexican Hat, where it was spread over an impermeable bedrock surface and covered with three layers of material to prevent radon gas and radioactivity from escaping. The first layer was compacted clay (from a local site); the second layer was bedding sand; and the third layer was made up of large rocks. The rock layer was thick enough that plants could not easily establish themselves on the surface of the containment cell. The design of the containment cell was such that it is expected to prevent contaminants from leaking for at least 1000 years.

Phase II, still under development, involves first, repairing the damage to the land from Phase I, and second, dealing with a plume of contaminated water that is migrating underground away from the site. In removing surface contamination, over 100 acres of the site was denuded of native vegetation. It was necessary to replace this vegetation. The main chemical of concern in the contaminated groundwater plume is nitrate, originating as nitric acid that was used to leach uranium from the ore. Nitrate levels in the groundwater greatly exceed EPA standards for drinking water (44 mg L^{-1}), and this nitrate must somehow be removed. How to deal with the two problems was analyzed through a process called *value engineering*. All possible alternatives for restoring vegetation and cleaning up contaminated water were listed after preliminary analysis by the study team. The list was shortened to those that appeared to be both likely to succeed and were cost effective.

Options for restoring vegetation ranged from relatively low-cost measures, such as application of mulch and seed to the land in a liquid spray (*hydroseeding*), to higher cost measures, such as transplanting to the site native shrubs that were originally grown in a greenhouse, and providing irrigation for several years while they established a root system. In desert ecosystems such as Monument Valley, revegetation success generally increases in direct proportion to the amount of irrigation provided. In general, direct seeding cannot be relied on in areas receiving less than 250 mm of rainfall per year. (The Monument Valley site receives less than 200 mm per year.) Options for remediating the groundwater were even more expensive. Conventional treatment methods required that the water be pumped to the surface and passed through a water treatment plant, using either *deionization*, *evaporation*, or *distillation* to separate nitrates from the water. This process is known as ‘‘pump and treat’’ (see the ‘‘Pump and Treat’’ section in Chapter 18).

Further analysis, however, showed that the revegetation component and the plume remediation component could be integrated into a single solution. By using the plume water as a source of irrigation water for native plants and forages crop that could be planted over the bare areas of the site, the nitrate in the plume water would serve as a fertilizer for the plants to be consumed by the grazing livestock. Using plants to solve environmental problems is called *phytoremediation* (see the ‘‘Phytoremediation’’ section in Chapter 18), and this became the preferred alternative at the Monument Valley UMTRA site because it provided a combined solution to two problems, and did not require construction and operation of an expensive water treatment plant. As of this writing, the phytoremediation option is undergoing review by stakeholders, and a demonstration phytoremediation plot has been established on site.

The planning process undertaken at the Monument Valley UMTRA site illustrates the numerous checks and balances built into a restoration plan. Many different disciplines are involved, and everyone with a possible stake in the outcome of restoration is brought into the process. In most cases a restoration strategy is not adopted until it achieves *consensus* among stakeholders as the best possible choice. Many years of study and planning may precede actual restoration. This is acceptable, as long as there is no imminent hazard, because land restoration is expensive and careful planning may help prevent costly mistakes.

APPROACHES TO ECOSYSTEM RESTORATION

The following sections provide some strategies toward the implementation of restoration goals and objectives; however, it must be remembered that each site will provide a unique set of characteristics and ecological challenges. As you read this section, refer to the case studies for Monument Valley and the Mission Copper Mine.

Natural Restoration

Natural restoration is essentially the process of allowing the ecosystem to heal itself without active management or human interference. Essentially this is the same concept as ‘‘intrinsic bioremediation’’ (see Chapter 18). Depending on site-specific characteristics, natural restoration may not be a viable alternative. Natural ecosystems develop over long periods through the process of *ecological succession*. Think of a lava flow, such as those that still occur on the island of Hawaii on the slopes of Kilavea, burning through portions of the native rain forest. The lava cools quickly but lays barren for many years, too hostile an environment to support life. Eventually rain and wind erosion create tiny fissures in the lava where life can establish a foothold. Microorganisms, usually bacteria, are often the first forms of life to become established, followed by lichens. In fact, very few sites are microbiologically sterile. Microorganisms are a prerequisite for plant growth. Lichens and cyanobacteria are the next colonists to establish themselves on the flow. Continual breakdown of the parent lava by acids secreted by the lichens produces a thin layer of soil in which the first higher plants can root; first small ferns, followed by grasses and shrubs as the fissures widen due to the action of the plant roots. Cyanobacteria fix nitrogen, which supports the plant life. Each stage of succession conditions the lava substrate to favor the next stage, and finally

TABLE 19.1
Restoration Plan for the UMTRA Program

Phase	Description
1a)	Removal of contaminated material
b)	Containment of contaminated material
2a)	Restoration of damaged land
b)	Remediation of contaminated water

the rain forest is restored. This process may take many hundreds or even thousands of years.

The process of succession is slower and less predictable in harsh environments than it is in tropical rain forests. Unfortunately, many of our damaged lands are in severe environments, such as arctic tundra or deserts. These environments pose a special challenge for restoration ecologists. Left alone, these lands often deteriorate further, through wind and water erosion, rather than gradually improving. These lands are most in need of human intervention to make them productive. The challenge for restoration ecologists is to finds ways to encourage the process of succession so it is predictable and takes place in a reasonable time span.

Passive Ecological Restoration

Passive ecological restoration projects primarily apply to land whose ecosystem is still functionally intact, but which has lost vegetative cover and biodiversity from such activities as overgrazing or habitat fragmentation. The implicit goals of these projects are to reduce or eliminate the causes of degradation, while encouraging the growth of indigenous plants to increase the productivity of the area in a sustainable way. In general, minimal soil preparation is needed, soil amendments and irrigation are not required, and seeds are simply broadcast in a designated area. Restoration under these conditions is usually coupled with land conservation objectives.

In many cases, however, improving soil surface conditions and increasing infiltration rates are necessary to ‘‘jump start’’ the restoration process. Table 19.2 outlines some common methods of soil preparation that improve surface conditions and increase infiltration rates. An added benefit of improving soil surface conditions is that the roughness on the surface provides ‘‘safe sites’’ for seeds and captures airborne and waterborne organic material. The focus here is to optimize existing conditions for successful germination and plant growth at minimal cost.

In semiarid and arid areas of the world where water is the limiting factor to successful restoration, the success of dry seeding methods generally declines as aridity increases. Some consider irrigation essential in areas that receive less than 250 mm of annual precipitation, but the need for irrigation, the amount, and application mode have been debated. However, numerous low-cost techniques can be used to capture and retain precipitation where it falls. The simplest and cheapest methods involve placing logs, rocks, or mulch on bare ground to capture moisture, nutrients, seeds, and soil from the surrounding area. Contour furrows, pits, and small depressions in surface soils play the same role in capturing essential elements for plant establishment. Figure 19.5 illustrates a furrow in an abandoned saline cotton field where plant establishment has occurred naturally. In the Sonoran, Mojave, and Chihuahuan deserts of the southwestern United States and Mexico, researchers have shown that ‘‘islands of fertility’’ exist under the canopies of shrubs, whereas the intershrub spaces show little biotic activity or nutrient retention (Schlesinger and Pilmanis, 1998). Beneath the canopies of shrubs and trees in these islands of fertility, nutrient levels were elevated, leaf litter had accumulated, and eolian soil had been captured and retained in mounds. Although this process can take decades, it could be surmised that the initial germination of the shrubs or trees occurred in small depressions in the soil surface where sufficient moisture occurred to ensure plant establishment. Over time, conditions beneath and adjacent to the plant canopies changed to allow recruitment of seeds from the local seed bank, thus increasing the base biodiversity of the area. These scattered plant communities are also found to have healthy populations of soil microbes, as well as attracting a variety of insects, reptiles, small mammals, and birds. In arid areas it is these islands of fertility that need to be recreated as part of any restoration project.

TABLE 19.2
Soil Preparation Methods

Soil Preparation	Advantages	Disadvantages	Cost
Ripping to 1 meter	Improves infiltration by breaking up compacted soil.	Soil horizons are often inverted. In some soils toxic compounds or salts could be deposited on the surface.	Moderate
Chiseling to 15 cm	Roughens surface to soil erosion and improves infiltration. Soil horizons undisturbed.	Soil surface is disturbed and provides good sites for seeds of invasive plants.	Low
Disking	Breaks the upper 2–3 cm of soil crust to improve infiltration.	Soil surface is disturbed and provides good seed sites for invasive plants.	Low
Contour furrows	Minimal surface disturbance. Acts as catchment for airborne nutrients, seeds, and organic material.	Surface compaction by machinery.	Low

FIGURE 19.5 A naturally vegetated farm furrow on an abandoned field in Maricopa County, Ariz.

Active Ecological Restoration

Where the abiotic and biotic functions of an ecosystem have fallen apart, the cost of restoration will rise in proportion to the damage incurred. Active ecological restoration projects can be complex, costly endeavors, as illustrated by the aforementioned Monument Valley, Ariz., case study. However, many other sites fall under this category because they require more intervention than simply seeding designated areas. Anthropogenic damage to an area can alter the biogeochemical function of an ecosystem, and in many cases it is necessary to reintegrate the damaged land with the surrounding landscape; particularly with regard to the hydrological cycle. For example, farmers will level an area for new fields, irrigation canals or ditches will be constructed, and farm roads will likely circumscribe the property. In the process of adding new cultivated fields, the surrounding wildland has become fragmented, surface water has most likely been redirected, and topographical features flattened. Once this land is abandoned, it becomes a candidate for restoration. It will be necessary to reconnect this land to the surrounding wildland, restore the physiochemical functions to the soils, and seed or plant the area to maximize plant establishment and growth. These projects thus become active and generally high cost, because they involve other procedures in addition to simple seeding. Table 19.3 shows some of the methods employed for these higher cost restoration projects. The restoration goals and objectives developed for a project will specify the degree of work necessary to achieve the desired goals.

In general, the methods associated with active restoration fall into several categories: (1) landscape integration; (2) soil surface conditioning; (3) soil amendments; (4) water harvesting and irrigation; and (5) seeding and planting techniques. Landscape integration techniques will not be addressed in this chapter, and soil surface conditioning was covered in the "Passive Ecological Restoration" section. A comprehensive soil analysis of the site will determine the type of amendments necessary to

TABLE 19.3
Potential Procedures for Active Ecological Restoration

Parameter	Procedure
Landscape integration	Removal of irrigation canals, roads
	Reconnect natural drainage features
	Construction of berms, swales, and gabions to redirect runoff and control erosion
	Landshaping to naturalize site
Soil	Grading to enhance soil stability, reduce erosion, and enhance water harvesting
	Creation of microcatchments for water harvesting
	Ripping to diminish compaction
	Tilling to incorporate soil amendments
	Mulching to enhance water retention
	Fertilizer additions to encourage plant growth
	Amendments to adjust soil pH
Plant	Mulching to enhance germination of direct seeding
	Transplants to enhance establishment
	Hydroseeding
	Mycorrhizal inoculations
Other	Supplemental irrigation
	Wire cages to protect against wildlife

restore a favorable chemical balance to the soil. In arid and semiarid areas of the world, a build-up of salts, usually sodium, is the major barrier to plant establishment, and reclaiming this soil is generally a lengthy process. Normally this requires the addition of sufficient water to leach the salts below the root-zone. Since water is scarce in these areas, some of the best strategies involve harvesting rain and using salt-tolerant plants to create islands of fertility. Water harvesting techniques include constructing swales and gabions with contoured berms to catch and disperse water over a large area and redirecting rainfall and sheet-flow to small basins called microcatchments. Microcatchments have been used extensively around the world, with early reports dating back to the nineteenth century where olive trees were grown in Tunisia (Pacey and Cullis, 1986). A microcatchment is a small depression in the soil, often delineated with a small berm, into which water flows during a rainstorm. The size of the microcatchment depends on the porosity of the soil and rainfall characteristics (amount, intensity, and distribution). However, for the purposes of ecological restoration, $100\,\text{m}^2$ is adequate for planting several trees and shrubs.

At sites that can provide water, irrigation can dramatically increase germination rates and survival of transplants. In a study at Tuba City, Ariz. (rainfall approximately $200\,\text{mm yr}^{-1}$), transplanting and deep-irrigation of saltbush shrubs over the first growing season resulted in a 90% survival rate and a sixfold increase in plant volume after 3 years. Irrigation methods can include standard commercial practices, such as center-pivot sprinklers, drip irrigation, microirrigation, and siphon tubes from canals. Irrigation is only used for seed germination and plant establishment, since one of the objectives of any restoration project is sustainability over time, and it is doubtful that continuous irrigation can be seen as meeting this criterion.

Plant selection is generally dictated by site conditions, native plants in the area, and availability of seeds or transplants. Popular opinion stresses the use of native plants; however, there are some circumstances where soil conditions are not conducive to their establishment and growth. In these situations plants will be chosen that are most likely to survive. For example, in highly salinized soils, native plants cannot tolerate the high salts in the soil, but a plant such as four-wing saltbush (*Atriplex canescens*) will not only thrive, but have the ability to sequester salts in specialized vacuoles in its leaves, thereby removing salt from the ground. Table 19.4 includes different methods of seeding sites, ranging from broadcasting to physically planting seedlings.

Many other specialized restoration methods have been developed for specific habitat types. Constructed wetlands have become a popular means for polishing municipal sewage effluent and for providing habitat for waterfowl and other birds. Often, however, the constructed wetlands do not serve as well as natural wetlands in supporting diverse plant and animal communities. In the western United States, considerable attention has been paid to restoring riparian zones, by removing the invasive plant, salt cedar, and replacing it with native trees, such as cottonwood and willow. Often these projects do not succeed because the hydrological conditions of the river have been so altered that they no longer favor the native species (Stromberg, 2001).

Ecological Restoration Using Organic Amendment

Highly disturbed sites often result in surface soils being devoid of organic matter. This can occur from a variety of human activities including: strip mining (where the surface top soil is removed), mine tailing storage (crushed and processed mineral ores deposited over existing topsoil), or from soil erosion. In all cases where organic matter is sparse or entirely absent, there are extremely low microbial populations, and it is common for these sites to have extreme pH, low permeabilities, and high soluble metal concentrations. These conditions are not suitable for sustainable plant growth, and they generally require some form of organic amendment to enhance the restoration process. Problems that occur due to low organic materials are shown in Table 19.5, and common sources of organic materials used to enhance ecosystem restoration are illustrated in Table 19.6.

The concept of organic amendments to enhance plant growth has been utilized for centuries as in the use of "night soil" (human feces and urine) to fertilize agricultural land. The use of raw waste material can spread disease (see Chapter 17), but in the United States, the solid material *(biosolids)* left after treatment of municipal sewage is further refined to eliminate potential pathogens before being applied to agricultural land. The long-term implications of such practices have been well documented (Sloan *et al.*, 1997; Artiola and Pepper, 1992). Biosolids have also been successfully applied to areas containing mining tailings or smelter waste that contain high or even phytotoxic levels of heavy metals (Li and Chaney, 1998). Biosolids that have undergone lime stabilization are particularly useful for such restoration because the increase in pH reduces the bioavailability of metals to plants. Biosolids and composts have also been used to restore diverse ecosystems, such as mountain slopes in the Washington Cascades or stabilize sand dunes in southeastern Colorado.

TABLE 19.4
Comparison of Seeding Methods

General Method	Specific Method	Characteristics	Efficacy	Benefits	Drawbacks
Seeding	Broadcasting	Native seeds spread over an area using farm machinery or airplane. Seeds may or may not be covered with soil.	Low due to seed loss by predation, wind, and water.	Inexpensive.	Seeding rate two times that of other methods.
	Imprinting	Seeds pressed into furrowed soil depressions.	Plant establishment successful over time, particularly in arid and semiarid regions with no supplemental irrigation.	Relatively inexpensive. Not as damaging to soil as other methods.	Cannot control depth of seeding. Poor in very sandy soils.
	Drilling	Seeds are dropped into holes or furrows and covered with soil.	Successful with supplemental irrigation or adequate rainfall.	Minimal soil disturbance.	Not feasible with severe topographic limitations and rocky terrain.
	Hydroseeding	A mixture of water, seed, mulch, fertilizer and a tackifier sprayed onto soil surface.	Three to ten times more effective than free broadcasting of seed.	Erosion control for slopes. Not as damaging to existing vegetation as other methods.	Very expensive. Only suitable for areas close to existing rights of way.
	Pelleting	Seed is coated with powdered soil, clay, or glue and silica sand. Seed can be broadcast using farm machinery or airplane.	More effective in regions with high precipitation.	Less seed used than in broadcasting. Seed can be stored for a long time in dormancy.	Expensive and time-consuming process.
Planting	General evaluation	Trees and shrubs planted individually.	Effective for introducing late successional species of trees and shrubs.	Does not disturb existing vegetation.	More expensive than seeding. Inputs of labor and materials higher. Generally requires supplemental irrigation in dryland areas.

TABLE 19.5
Problems Related to Low Organic Matter Surface Materials

Parameter	Problem
Poor aggregation of primary particles	Compaction Low infiltration rates Low water holding capacity Limited aeration
Low nutrient status	Infertile soils Low microbial populations
Extreme pH	Affects chemical and biological properties
High metal concentrations	Toxicity

TABLE 19.6
Sources of Organic Materials for Ecosystem Restoration

Human and Animal Wastes	Industrial Wastes
Animal manures	Paper mill sludges
Biosolids	Sawdust
Composted wastes	Wood chips

In all cases of organic amendment added to poor soil, the critical parameter appears to be the magnitude of organic material applied. This is particularly important in desert ecosystems where high temperatures result in rapid decomposition and mineralization of organic compounds and materials. If insufficient organic matter is added to a disturbed site, the beneficial effect is not maintained for a sufficiently long time to allow stable revegetation to occur. The case study detailing the revegetation of mine tailings at the Mission Mine in Arizona illustrates the successful use of biosolids for site restoration (Case Study 19.2).

CASE STUDY 19.2 *Mission Copper Mine, Arizona* Reclamation and Revegetation of Mine Tailings Using Biosolid Amendment

In the United States, mining is a large industry that provides valuable raw material and creates economic benefit for local communities. However, the potential environmental damage incurred from this industry ranges from unsightly mine tailings to the leaching of toxic elements into nearby waterways and aquifers. In addition, wind-blown tailings can result in air pollution. Removal of the original vegetation, soil, and bedrock exposes the valuable mineral veins. The mineral ore is then processed to remove copper. Finally, the crushed rock is redeposited on land as a thick slurry. Typically, tailings piles are 30- to 40-m thick.

The physiochemical characteristics of mine tailings are totally unlike the displaced top soil that once supported vegetation in any given area. By removing and crushing bedrock from the mines and placing it on the surface, minerals will oxidize when exposed to the atmosphere. For example, pyrite (FeS_2) common around coal mines oxidizes to sulfuric acid (H_2SO_4) and iron oxide ($Fe[OH]_3$). Acid mine drainage (H_2SO_4), the leachate from tailings, can then contaminate surface and groundwaters, in addition to increasing the solubility of toxic metals. Mining tailings are not the ideal medium on which to grow plants. The crushed rock consists of large and small fragments with large void spaces in between. There is no organic material present, the cation exchange capacity (CEC) is very low, the water holding capacity of the material is poor to nonexistent, and there are few macronutrients (N.P.K.) available for the plants. Soil biota, in the form of bacteria and fungi, are present in low numbers, and finally the pH is usually low, which increases the likelihood that toxic metals are available to be taken up by the plants. The goals of reclaiming mine tailings therefore have to include the application of materials to amend the crushed rock substrate, and provide an adequate environment for plant growth. One potential solution is the use of biosolids.

In 1994 the Arizona Mined Land Reclamation Act was passed, which required reclamation of all mining disturbances on private land to a predetermined postmining use. In 1996 the Arizona Department of Environmental Quality (ADEQ) adopted new rules allowing for the use of biosolids during reclamation. The Arizona Mining Association (AMA) has estimated that there are 33,000 acres of active mine sites that can be reclaimed with the use of biosolids. In southern Arizona, biosolids have been used for almost two decades for land application on agricultural land and the commercial growth of cotton. However, due to large amounts of acreage being sold and retired from agricultural usage, there is currently a shortage of land for the application of biosolids. Therefore the concept that is emerging is that of utilizing one waste, namely biosolids, to reclaim another waste material, namely mine tailings. The issue, of course, is whether or not this can be done in an environmentally sound manner via a process that is economically viable.

Current Arizona regulations limit the amount of biosolids that can be used to reclaim sites. The restrictions are due to concerns over potential nitrogen and heavy metal leaching, both of which could impact underground aquifers and therefore compromise human health and welfare. However, greenhouse tests have shown that large amounts of biosolids are necessary to effectively reclaim mine tailings. Specifically, up to 275 dry tons per hectare may be necessary to promote active vegetation of mine tailings (Bengson, 2000). Thompson and Rogers (1999) conducted greenhouse tests utilizing 67 metric tons per hectare (dry weight basis) of biosolids on three different types of mine tailings, ranging from acidic to neutral. The biosolids are effective in promoting vegetative growth and increasing groundcover. In these studies there was little evidence of significant nitrate below 30 cm, nor was there any evidence of heavy metal increases due to biosolid application. Current ADEQ regulations limit the lifetime loading rate of biosolid applications to mine tailings to 400 dry tons per hectare. However, this amount can be applied as one application. Here we describe a case study illustrating the use of biosolids to restore and stabilize mine tailings.

OVERALL OBJECTIVE: To evaluate the efficacy of dried biosolids as a mine tailing amendment to enhance site stabilization and revegetation.

SPECIFIC OBJECTIVES

1. To evaluate the benefits of land application of dried biosolids to mine tailings, with respect to reclamation and stabilization.
2. To evaluate the hazards of metals and nitrate associated with the application of dried biosolids to mine tailings. Note that pathogens were not monitored because of the use of "exceptional quality" biosolids for the project. Exceptional quality biosolids normally contain very low concentrations of pathogens.

CASE STUDY 19.2 *(Continued)*

Experimental Plan

Study Site. A 2-hectare copper mine tailing plot located near Mission Mine, south of Tucson, was designatedfor this study. Biosolids were applied at a rate of about 220 dry tons per hectare across the site in December 1998, and then seeded with a variety of desert adaptive grass species including: oats, barley, Lehman lovegrass, bufflegrass, and bermuda grass. Supplemental irrigation was not used.

Results

Soil Microbial Response to Biosolids

Pure mine tailings contain virtually no organic matter and very low bacterial populations of approximately 10^3 CFU per gram of tailings, see "The Most Probable Number (MPN) Test" section in Chapter 17 for methods of determination of bacterial populations. A large population of heterotrophic bacteria is essential for plant growth and revegetation, and therefore monitoring soil microbial populations gives an insight into the probability of revegetation success. Biosolids routinely contain very high concentrations of organic matter, including the macroelements carbon and nitrogen, which are essential for promoting microbial growth and metabolism. Following biosolid amendment of the mine tailings, heterotrophic bacterial populations increased at the surface to approximately 10^7 CFU per gram (Table 19.7). Bacteria decreased with increasing depth from the surface, indicating the influence of the biosolid surface amendment on bacterial growth. Table 19.7 also shows that the microbial populations have at this point been stable for 33 months. Overall, the microbial data show the success of biosolid amendment in changing mine tailings into a true soil-like material.

Physical Stabilization: One of the main objectives in reclaiming mine tailings is *erosion control*. This is generally best accomplished through a revegetation program because the root structures of the plants help to hold soil particles in place. In this experiment the application of biosolids and the subsequent broadcast of grass seeds were the primary activities to promote site stabilization. In the desert Southwest, high summer temperatures and limited rainfall are normal; however, despite these extreme conditions, grasses have become established on these tailings. Table 19.8 shows the results of vegetation transect surveys conducted on this site 14 months, 21 months, and 33 months after initial seeding. Note the intrinsic variability in the transect data, and the need for multiple transects to be taken to determine a realistic average. The vegetation cover increased from 18% at the 14-month survey to 78.2% after 33 months. At 14 months the predominant plant species were bermuda grass *(Cynodon dactylon)* and the invasive weed, Russian thistle or tumbleweed *(Salsola iberica)*, but by the 33rd month bufflegrass *(Penni-steum ciliare)* and Lehman lovegrass *(Erangrostis lehmanniana)* had replaced the Russian thistle. Figures 19.6 to 19.8 show the progressive increase of vegetation on this site over time. In this case the use of biosolids for enhanced revegetation and stabilization of mine tailings would be considered a success.

Evaluation of Potential Hazards—Soil Metal Concentrations: At Site 1, soil nitrate (Table 19.9) and total organic carbon (TOC) (Table 19.10) are very high at the surface, but decrease to the levels found in pure mine tailings at lower depths. The fact that nitrate and TOC concentrations are correlated is important because it creates substrate and terminal electron acceptor concentrations suitable for denitrification. Data presented in Table 19.9 show the nitrate concentrations from June 2000 to July 2001. Nitrate concentrations increased during the monsoon rainy season of 2000, most likely due to enhanced ammonification and subsequent nitrification. However, within the soil profile, nitrate concentrations decreased with depth. By the winter and spring of 2001, the nitrate concentrations at all soil depths had decreased. There was no evidence of the leaching of nitrate because concentrations at the 90 to 120 cm depth were always minimal. Therefore the most likely explanation for decreased nitrates within the soil profile is the process of denitrification. Soil nitrate concentrations became extremely high at both sites in the summer of 2001, again, most likely due to nitrogen mineralization and seasonal nitrogen cycling. Specifically during the warmer summer months, rainfall events appear to trigger microbial mineralization of nitrogen as nitrate. Double-digit values of nitrate at the 120 to 150 cm depth illustrate that there is the potential for some nitrate leaching during some portions of the year.

The application of biosolids to a project site brings some concern about the introduction of heavy metals to the environment. Data from this study show that metal concentrations are fairly consistent with soil depth (Table 19.11), indicating that the tailings are the major source of metals, not the biosolids. Further evidence of this is shown by the high molybdenum and copper valves typical of mine tailings. At this site there is little evidence of metals leaching through the soil profile. Additional data were collected on the

(*Continued*)

CASE STUDY 19.2 *(Continued)*

concentration of molybdenum, copper, and zinc in three plants on the site: Russian thistle, salt cedar, and bermuda grass. Table 19.12 shows the uptake of metals by these plants were extremely high and soil sampled beneath vegetation revealed a decrease in soil metal concentrations.

Conclusion

This study on the application of biosolids to mining tailing at the Mission Mine in Arizona shows that soil stabilization has been encouraged through revegetation techniques, and that the leaching of nitrate and heavy metals to important water resources has not been observed. This case study gives an indication of the extensive monitoring that is necessary to understand the restoration process, and the necessary duration of the monitoring process. With careful attention paid to subsurface geological and hydrological features at other sites, the application of biosolids can be a feasible restoration strategy.

TABLE 19.7

Plate Counts of Heterotrophic Bacteria at Mission Mine Project Site

	Depth of Sample (cm)				
Sample Date	**0–30**	**30–60**	**60–90**	**90–120**	**120–150**
			CFU g^{-1}		
06/26/00	1.01×10^7	1.72×10^6	3.11×10^5	1.54×10^5	ND
09/11/00	3.16×10^6	4.44×10^5	8.12×10^5	3.54×10^4	ND
01/22/00	2.74×10^7	2.05×10^7	5.56×10^5	2.31×10^5	ND
03/26/00	3.76×10^7	2.25×10^6	1.99×10^4	7.83×10^4	5.48×10^4
06/11/01	7.74×10^6	6.86×10^5	6.72×10^4	1.22×10^5	6.36×10^4
10/29/01	1.30×10^7	8.36×10^5	2.40×10^5	1.41×10^5	1.19×10^5
09/10/01	1.45×10^6	5.83×10^5	4.10×10^4	1.42×10^5	1.40×10^5

ND, Not done.

TABLE 19.8

Vegetation Transects at the Mission Mine Project Site

	Basal Cover (%)	Crown Cover (%)	Total Cover (%)	Rock (%)	Litter (%)	Bare (%)
			02/23/00 (14 months)			
T-1	15	28	43	3	0	54
T-2	14	16	30	3	8	59
T-3	7	1	8	0	1	91
T-4	1	8	9	2	4	85
T-5	0	0	0	0	5	95
Average	**7.4**	**10.6**	**18**	**1.6**	**3.6**	**76.8**
			09/25/00 (21 months)			
T-1	13	39	52	5	6	37
T-2	11	20	31	6	6	57
T-3	6	45	51	2	1	46
T-4	13	48	61	3	2	34
T-5	1	52	53	0	4	43
Average	**8.8**	**40.8**	**49.6**	**3.2**	**3.8**	**43.4**
			09/24/01 (33 months)			
T-1	4	66	70	2	4	24
T-2	6	62	68	0	6	26
T-3	4	73	77	0	4	19
T-4	0	84	84	0	1	15
T-5	0	92	92	0	0	8
Average	**2.8**	**75.4**	**78.2**	**0.4**	**3**	**18.4**

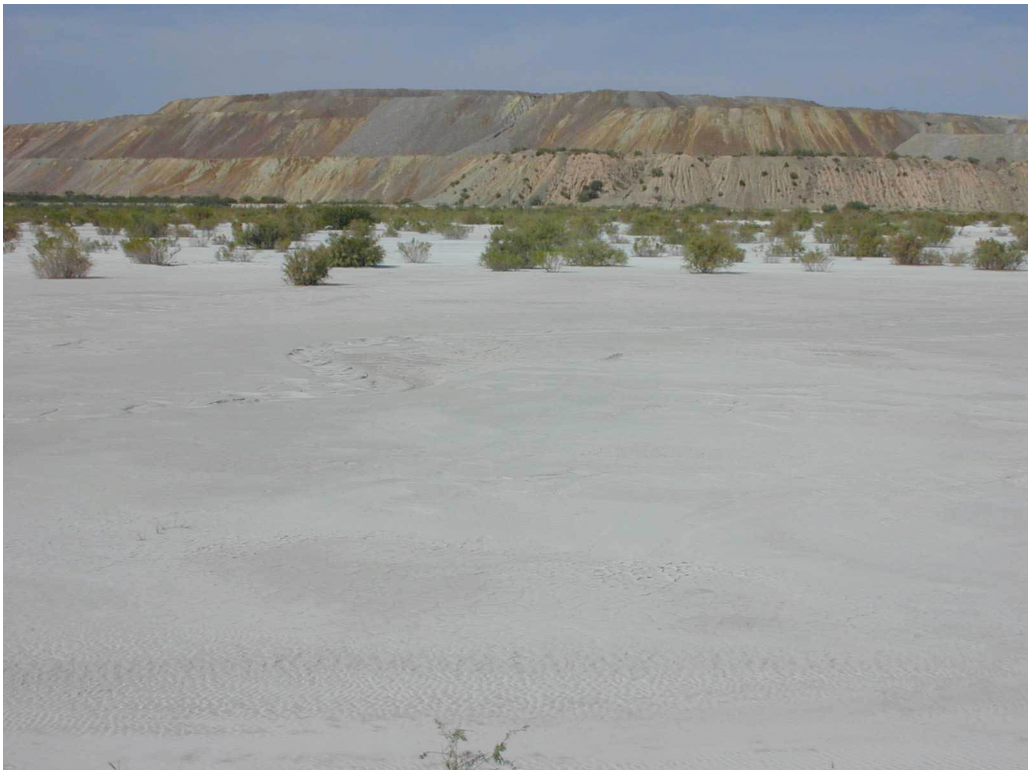

FIGURE 19.6 Mine tailings before biosolid amendment.

FIGURE 19.7 Mine tailings after biosolid application.

FIGURE 19.8 Mine tailings 3 years after biosolid application.

TABLE 19.9

Nitrate Concentrations at the Mission Mine Project Site from June 2000 to July 2001

Sample Date	Depth of Sample (cm) 0–30	30–60	60–90	90–120	120–150
	mg kg^{-1}				
06/26/00	650	250	40	5	ND
07/10/00	1520	120	60	5	ND
07/26/00	1030	200	170	70	ND
02/05/01	480	250	330	150	60
03/26/01	190	40	40	15	5
06/11/01	2350	310	140	260	110
07/13/01	2350	590	220	205	50

ND, Not done.

TABLE 19.10

Total Organic Carbon (TOC)[a] at the Mission Mine from February 2001 to July 2001

Sample Date	Depth of Sample (cm) 0–30	30–60	60–90	90–120	120–150
	%				
02/05/01	1.4	0.2	0.3	0.4	0.3
03/26/01	1.0	0.1	0.2	0.2	0.1
06/11/01	1.6	0.2	0.1	2.0	0.1
07/13/01	1.6	0.4	0.1	0.2	0.2

[a] Mean values.

TABLE 19.11

Total Soil Metal Concentrations at the Mission Mine Project Site

Sample Depth (cm)	Total Metals[a] (mg kg^{-1}) Mo	Pb	As[b]	Cr	Zn	Cu	Ni
0–30[c]	68	23	<50	14	170	414	8.0
30–60	197	19	<50	19	111	1480	8.2
60–90	196	27	<50	15	168	2400	9.0
90–120	180	33	<50	15	130	1320	8.0
0–30	88	19	<34	12	154	247	<33.0

[a] Data are mean of samples collected on 06/26/00, 07/10/00, 07/26/00, and 06/11/01.

[b] Below detection limit.

[c] Biosolid amendment all within 0–30 foot depth.

TABLE 19.12

Total Metal Concentrations in Plant Tissue Samples at the Mission Mine Project Site

	Total Metal (mg kg^{-1} dry weight basis)		
Plant Type	**Mo**	**Zn**	**Cu**
Russian thistle	872	1230	35
Salt cedar	655	94	63
Bermuda grass	100	116	43

Samples taken 02/02/01.

QUESTIONS

1. Differentiate among: (a) rehabilitation; (b) revegetation; and (c) reclamation.
2. Based on your microbial expertise gained from Chapter 17, what soil microorganisms would sequentially be activated after land application of biosolids?
3. Identify the abiotic factors that influence the approach to ecosystem restoration on any particular project.
4. What factors primarily determine whether active or passive ecological restoration should be undertaken?
5. What is the influence of organic amendments on soil physical and chemical properties?

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