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SIXTEEN

Active Restoration for the Mojave Desert

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Disturbances to soil and vegetation can create lasting and highly visible legacies on the desert landscape (fig. 16.1). Effects of disturbances, such as the installation of energy pipelines or transmission corridors, military activity, agriculture, mining, and off-road vehicle travel and other recreational pursuits, often remain long after the activity has ceased. Tracks of old roads remain clearly visible and attract curious travelers. Abandoned mines become recreational destinations, visits to which sometimes end with bodily injuries and fatalities. Land managers, faced with land management mandates and public pressure, frequently find that natural recovery processes are too slow (Webb et al., Natural Recovery, *this volume*) or are prevented by repeated disturbance. In such cases, they may choose to take physical action to restore natural processes and native habitat.

Funding availability, political priorities, and scientific knowledge are frequently the most important considerations in deciding how and when to implement active restoration efforts. Maintaining or re-creating the character of congressionally designated wilderness areas, recovering abandoned mining areas, erasing signs of unauthorized vehicle trails, and protecting critical species habitat require that land managers spend scarce federal government funds. Political concerns often manifest as conflicting interests that can delay or even prevent restoration projects.

In addition, while the scientific knowledgebase is increasing, managers still have no comprehensive source of information on the methods, techniques, and results of past restoration projects in the Mojave Desert. There are, however, several well-documented, long-term restoration projects that, when analyzed, can provide invaluable information for planning future efforts. In recent years, land

managers and scientists have been working together to document and monitor the methods and results of restoration projects, and have taken an innovative experimental approach that will facilitate the success of future projects.

However, to ensure that active restoration is cost-effective and meets the goals of land managers, several issues need addressing. The many challenges to successful restoration, including the unique characteristics of the urban-desert interface, the interconnectivity of riparian areas, and the increasing occurrence of wildfires, must be considered. Increasing public awareness needs to become a priority to facilitate political support, funding, and volunteer efforts. Projects need to be implemented on a bioregional scale and utilize an interdisciplinary approach. Managers and scientists with restoration experience must be retained by agencies for long-term maintenance and monitoring of restoration sites as well as to pass knowledge on to others. In addition, practitioners must continue to explore innovative and adaptive techniques for lowering the cost and enhancing the success of restoration efforts.

PROJECT PLANNING AND SITE ANALYSIS

Active restoration can be implemented several ways, depending on the timeframe, the objectives and scale of the project, and the amount of available funding, tools, and access. Projects in the Mojave Desert have diverse goals and objectives. In some cases, work focuses on restoring predisturbance soil conditions. To date, most desert restoration projects have focused on accelerating revegetation, largely of desert shrub and grass species.

The first step to creating a successful project is careful planning and analysis. When choosing between active and natural restoration, the first question to ask is whether the site is likely to recover on its own within the desired timeframe. Using a recovery and restoration timetable, such as the one produced by Lovich (1999), can be useful (appendix 16.1). Once it is determined that active restoration is preferable, many more issues must be taken into account. In addition to financial and political concerns, planners must consider local public values, possible threats to life or property (e.g., wildfire), the presence of endangered and threatened species, the potential affects on resource availability, and air and water quality. Managers must also ensure that subsequent disturbance can be prevented. It is also preferable to locate a paired, undisturbed site to refer to in determining restoration goals; however, these are often difficult to find nearby (Bainbridge 2000).

During the planning phase careful analyses must be used to collect information for the project plan. With any analysis, several factors must be considered. The physical characteristics of the disturbed site and the surrounding area, including soil type, sediment transport, elevation, exposure, slope, climate, and natural and anthropogenic disturbance histories should be carefully documented. Analyses should also include interactions among desert ecosystem processes and

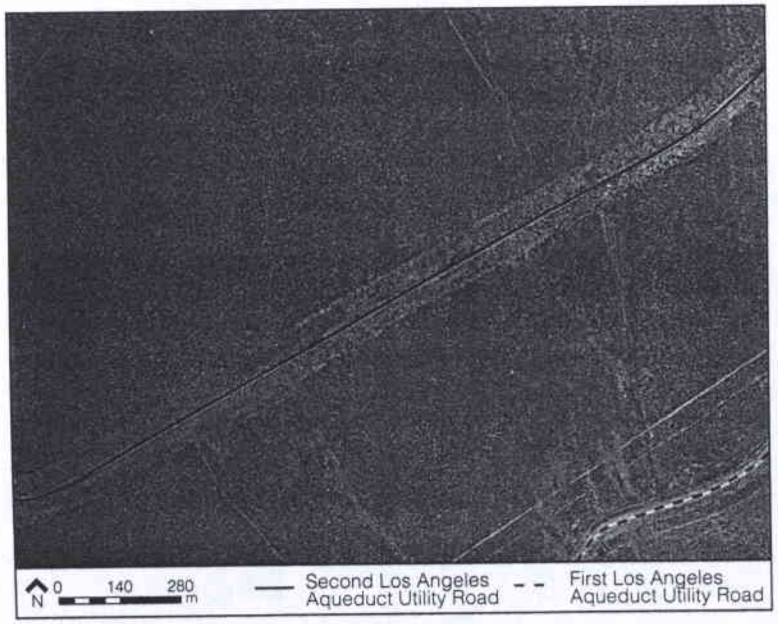

Fig. 16.1. Aerial photograph of the Second Los Angeles Aqueduct Retrospective Restoration Study Site in Kern County, California, August 2001. After forty years, the corridor, which crosses nearly level terrain, remains starkly apparent from 7300 m altitude. The obvious buffer zone around the utility road, indicated by the solid line, demarcates the zone of restored vegetation, and beyond that is undisturbed vegetation. The sinuous road in the lower right of the photograph, indicated by the dash line, is the route of the first Los Angeles aqueduct, constructed between 1908 and 1913.

their effects on urban areas, wildlands, and the urban-wildland interface. With any type of analysis, it is essential to collaborate with land managers and landowners to create an effective restoration plan.

Landscape Analysis

With landscape-based analysis, the area of concern is defined by public priorities and ecosystem interactions, as well as by site conditions. Landscape analysis considers how restoration projects will affect and be affected by the surrounding landscape and view-shed. This type of analysis can clarify how changes in disturbance regimes have resulted in current landscape conditions, and what techniques and options are available for active restoration. Another important consideration is the aesthetic and financial priorities of the local community. These landscape values are human-imposed, and concern the picturesque quality of a

natural landscape, as well as concerns for the value of real estate and the viability of agriculture. These are often major issues where natural desert landscapes lie within walking and driving distance of cities such as Palm Springs (Riverside County) and Ridgecrest (Kern County), where officials have collaborated with the Forest Service and the Bureau of Land Management (BLM) to manage the vistas for these cities.

Watershed Analysis

A second type of analysis is a watershed-based approach in which the area of concern is defined by geomorphology and hydrology. Watershed analyses, which involve biological and physical assessment of a drainage area, are an increasingly common practice in California and provide key guidance documentation for preparing restoration prescriptions (Shilling et al. 2005). The purpose of watershed analysis is to facilitate the coordination of stakeholders and to provide information on the socioeconomic processes within an area, as well as the biological and physical characteristics. Downstream effects and interactions across property lines can make or break restoration efforts. Without the collaborative process of watershed assessment and the resulting shared objectives, even the best-conceived restoration prescriptions can fail.

Cost-Benefit Analysis

A third approach, which should be used in planning every restoration project, is cost-benefit analysis. The lack of resources and public funds means that public land managers are accountable for the cost effectiveness of a restoration project. A cost-benefit analysis of possible prescriptions is a necessary step and facilitates an explicit evaluation of the goals. This type of analysis provides a comparison of estimated costs and benefits side by side on a timeline. Increasingly, labor and travel costs are limiting factors. Training and supervisory costs are also important when working with unskilled (but often enthusiastic) volunteers.

A cost-benefit analysis can be the deciding factor in determining a specific restoration prescription when two or more prescriptions are nearly equal in their environmental benefits. The U.S. Geological Survey (USGS) is currently developing a restoration cost-benefit analysis tool through the Recoverability and Vulnerability of Desert Ecosystems Project (see the Desert Science Database at http://www.dmg.gov/projects.php). This tool will assist managers in evaluating natural versus active recovery, and provide a cost-benefit model for restoration planning.

ACTIVE RESTORATION METHODS

Plants

Salvaging Mature Plants: While desert habitat is invariably lost in the process of urbanization, the land disturbance affords restoration project managers with an

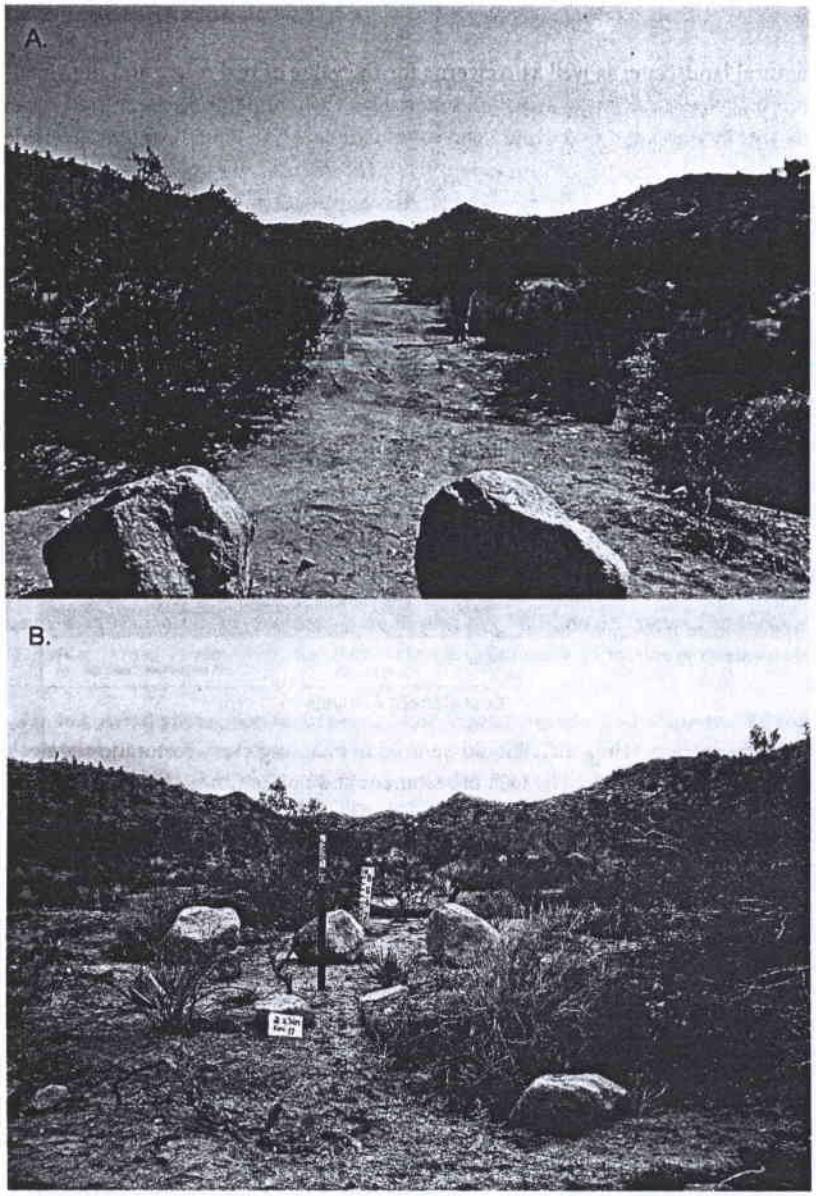

Fig. 16.2. Photographs documenting an abandoned road that was closed at Joshua Tree National Park. *A*, was taken before treatment and shows a devegetated, barren roadway. *B*, was taken immediately after treatment with rock and mulch. The road has been transformed and is well camouflaged from future disturbance (photographs courtesy of the National Park Service).

easily and inexpensively acquired supply of mature vegetation for restoration projects. In road construction, for example, the Nevada Department of Transportation promotes, as a standard practice, the donation of native plant material along with the native topsoil (Nevada Department of Transportation 2005).

Salvaging plant material can significantly reduce revegetation costs and has the added bonus of immediate revegetation on a site. The cost of plant salvage depends on plant size, location, and time of year. Depending upon vertical height and crown size, large *Yucca brevifolia* (Joshua tree) and *Yucca schidigera* (Mojave yucca) can cost as much as $425 per tree to transplant. Large specimens can be temporarily maintained in earthen berms or wooden tree boxes (fig. 16.2), which requires supplemental irrigation. Salvage efforts may be most appropriate in high-use areas that require immediate landscaping, such as visitor centers, campgrounds, road closures, and sites necessary for wildlife habitat.

While most perennial species can be salvaged, some are more cost effective than others. Shallow-rooted species, such as yuccas, cacti, and perennial bunchgrasses are easy to harvest (Schrenk 2002). As part of large-scale road realignment, Joshua Tree National Park (JTNP) in Riverside County, California, salvaged plants extensively between 1999 and 2004. The survival rates were generally high (table 16.1). However, small unprotected plants were subject to increased grazing pressure from rodents and insects—the survival rate for *Pleuraphis rigida* (galleta grass) 18 months after transplanting was only 37% due to herbivory. *Yucca brevifolia* and *Y. schidigera* transplanted during the project had survival rates of 83% and 95%, respectively, after three years (Joshua Tree National Park *unpublished data*). *Yucca brevifolia* produced new roots after four months in wooden boxes. The mortality of the salvaged plants was due to overwatering, soil erosion, and wind. Experimental salvage of *Juniperus californica* (California juniper) revealed that individuals boxed with root-balls intact and wrapped in burlap had 100% survival, while those boxed with bare roots had complete mortality (Cox and Rodgers 2003; Joshua Tree National Park *unpublished data*).

Grass salvage at JTNP has had mixed results—*Pleuraphis, Achnatherum speciosum* (desert needlegrass), and *Achnatherum hymenoides* (ricegrass) salvaged and stored in a nursery had a 50% survival rate when outplanted. Mortality may have resulted from root rot in heavy compacted soils with poor drainage.

Seeding

Since prehistory, people have collected seeds in the Mojave Desert. Managers can take advantage of bountiful seed years; high, well-timed precipitation often results in bumper crops of viable seed from *Larrea tridentata* (creosote bush), *Coleogyne ramosissima* (blackbrush), and other dominant perennial species. One advantage of using seeds is that agencies can amass native seed stocks for producing container plants or for direct application at restoration sites.

Table 16.1 Survivorship by species for Joshua Tree National Park Project No. 173 (Year 3)

Species	Total planted	Percent survival 3 years of post-planting
Acacia greggii	148	75.0%
Atriplex canescens	5	0.0%
Chilopsis linearis	4	100.0%
Coleogyne ramosissima	94	28.7%
Echinocereus engelmannii	7	57.1%
Echinocereus spp.	3	66.0%
Echinocereus triglochidiatus	75	77.3%
Encelia farinosa	33	81.8%
Ephedra californica	4	100.0%
Ephedra nevadensis	60	56.7%
Eriogonum fasciculatum	23	60.9%
Grayia spinosa	98	51.0%
Hymenoclea salsola	5	100.0%
Juniperus californica	1	0.0%
Larrea tridentata	1	0.0%
Lycium andersonii	11	9.1%
Lycium cooperiu	10	10.0%
Opuntia basilaris	23	82.6%
Opuntia echinocarpa	332	48.8%
Opuntia ramosissima	202	63.9%
Opuntia stanlyi	27	70.4%
Prunus fasciculata	34	79.4%
Salazaria mexicana	9	77.8%
Tetradymia spinosa	3	0.0%
Yucca brevifolia	782	54.1%
Yucca schidigera	478	83.5%
Total survival	2,472	61.8%

Direct seeding has had mixed results in desert environments, and natural precipitation is often the deciding factor between success and failure. Even with supplemental water, seeding trials of *Ambrosia dumosa* (white bursage), *Encelia* ssp. (brittlebush), and *Brickellia incana* (wooly brickellbush) at the Fort Irwin National Training Center (NTC) showed no signs of germination (Mason 2001). Projects carried out by the Soil Ecology and Restoration Group (SERG) at San Diego University had similar results, with low germination attributed to seeds lost to wind and herbivory, and unpredictably low levels of precipitation. Field trials using seeds pre-treated by rinsing and soaking in water and thiourea greatly improved germination rates of *Larrea* and *Ambrosia* at the NTC (Ostler et al. 2002). However, many treatments, particularly optimal germination temperatures, are species-specific and thus make successful seeding more difficult and costly.

Tailoring the microenvironment of the planted seeds may also affect germination rates. Anderson and Ostler (2002) experimented with two types of mulches (straw and gravel) and found that the germination densities in the mulches did not differ after a wet year. In the third year, however, straw mulch provided denser shrub survivorship than gravel mulch, and both had significantly higher survivorship than in unmulched treatment sites. In a second set of trails at the NTC in 1999, plastic mulching yielded the highest immediate germination response.

Trials often have poor results because seeding is timed to adhere to funding schedules rather than to coincide with precipitation. The ideal revegetation scenario would be to stockpile native seed and plant propagules during dry years until years of reasonably predictable high precipitation, such as during El Niño events (Bainbridge 2003). On the other hand, some seed does not store well for long periods, and seed storage guides should be consulted prior to undertaking such a program.

Container Planting

Many land managers use container plants for revegetation projects, and several nurseries have been established to provide container plants to agencies such as the National Park Service (NPS), Department of Defense, California State Parks, and the BLM. While container planting can provide immediate, genetically appropriate native vegetation to a disturbed site, these plants often require physical protection and irrigation, which can be problematic in remote sites without access to water.

Large-scale container planting projects have occurred mostly on military and NPS lands. The NTC has used thousands of container plants over the past ten years with mixed results (Soil Ecology and Restoration Group 2005). At JTNP, container plant projects include revegetation of abandoned mine lands, borrow pits, road edges, and closed roads. Over 1,500 tall pots of 23 species were planted between 1988 and 1992 as part of the Cottonwood Road Federal Highways project. Assessment of 1,000 of the plants in 1995 showed a survival rate for each species ranging from 70%–100% (Joshua Tree National Park *unpublished data*). Survival rates appear to be the result of supplemental watering during drought years (1988–1990) and high precipitation during and following outplanting years (1991 = 205 mm, 1992 = 346 mm, 1993 = 309 mm). In Pinto Basin at JTNP, *Larrea* survival rates were 80% one year postplanting ($n = 133$); rainfall between planting and monitoring was 81 mm. Many nurseries maintain unpublished files on propagation of desert species from transplantings, cuttings, and seedings (Joshua Tree National Park *unpublished data*).

Use of nursery stock is not always appropriate at backcountry sites. Closed roads and hill climbs in the Rock House area of JTNP were revegetated in October 1999 and February 2001, and of the 261 shrubs planted, only 25 were alive in May 2003. The rough roads to this isolated site created chronic vehicle problems, and supplemental watering was only possible 1–3 times per year (Joshua Tree National Park *unpublished data*).

Fences and Other Physical Barriers

Most restoration sites in sparsely vegetated desert environments require physical barriers to facilitate restoration success. Barriers can be exclusionary and prevent continued disturbance at a site from grazing or vehicle trespass (Brooks

1995, 1999). Temporary fencing can be developed to exclude specific species, such as rabbits, rodents, lizards, and deer, which might eat or damage vegetation. Grantz and Vaughn (2001) recommend barriers to modify sediment transport, such as wind fences, silt fences, and furrows. In Little Morongo Canyon at the southern boundary of the Mojave Desert, earthen berms were installed to reduce surface runoff during high rainfall events. These berms proved ineffective, however, during intense rainfall in 2004–2005 and may have exacerbated flooding and erosion.

Barriers can be constructed from a variety of materials. In addition to earthen berms, materials can include weed-free straw bales, rock, gabions, and vegetation. Rock walls and dams can slow the rate of water flow and erosion on steep slopes, but may also have detrimental effects because of the reduced overland flow to surfaces downslope. The BLM Ridgecrest Field Office frequently uses check dams on closed roads and slopes to reduce erosion. Gabions, wicker or wire mesh baskets filled with mud balls or rocks, can facilitate revegetation while blending in with the surrounding terrain. Straw bales, in addition to preventing erosion, can restrict motorized vehicles from unauthorized roads. Vegetation is very effective as a barrier for reducing dust in wind-prone areas. Most information about live vegetation as a barrier comes from work done in the Antelope Valley, Los Angeles County, where Grantz and Vaughn (2001) found that *Atriplex canescens* (fourwing saltbush) appears to be the best choice for rapid live fencing (Grantz 1998; Grantz et al. 1998; Grantz and Vaughn 2001). *Proposopis glandulosa* (mesquite), *Larrea*, and *Isomeris arborea* (bladderpod) windbreaks planted and watered monthly at the NTC and Marine Corps Air Ground Combat Center in Twentynine Palms, California, between 1997 and 1998 had high survival rates eight months after planting. No data was available on the long-term effectiveness of these projects.

Any time that barriers and fencing are installed as a permanent feature, efforts should be made to reduce its visual impact.

Ground surface treatments

Soil Manipulation: While soil can be used to create barriers, it can also be manipulated in other ways to facilitate the success of restoration projects. In the Mojave Desert, soil has been re-contoured to concentrate the flow of water to planted areas, to reduce erosion and sediment transport by flattening and terracing hill slopes, and to catch moisture and seeds in surface depressions called pits. In addition, restoration projects have used redistributed topsoil and decompaction methods to facilitate the natural regeneration of shrubs, grasses, and forbs.

Soil Salvage: Many disturbed sites have lost important soil surface structure, nutrient content, and, in some cases, topography. All of these factors can exacerbate erosion. Because organic material is very limited in arid climates, soil salvage can be very useful in accelerating recovery. Topsoil can be salvaged from construction sites, in tandem with vegetation, which is very cost effective. If project goals include the conservation of topsoil, this can be done by stripping the top 100–150 mm of soil. Soil salvage conserves soil organic matter and surface bulk density. When applying salvaged topsoil, the natural contour should be restored to reduce future soil erosion and lessen the contrast with adjacent areas.

Decompaction: Severely disturbed desert soils may be highly compacted, which reduces water infiltration and nutrient cycling (Webb et al. *this volume*). Ripping (deep plowing) and harrowing (surface plowing), are methods used in the Mojave Desert to alleviate compaction. Decompaction on slopes has had varying success in desert restoration projects (Montalvo et al. 2002; Scoles and DeFalco 2003). Although ripping may improve soil bulk density at the surface, it can also break up a caliche layer, unnaturally desiccate the soil, and make shrub regeneration nearly impossible. Decompaction can also lead to increased erosion. Soils with high silt content, for example, are easily eroded by winds. Hydromulch, or matting, can help stabilize the soil. As with any soil-disturbing activity, invasive plant species may become established; monitoring and implementation of an integrated weed management program may be necessary.

Mulching: Between 2002 and 2005, the BLM completed revisions to the California Desert Conservation Area Plan (Bureau of Land Management 1999). The amendments determined which off-highway vehicle (OHV) trails will remain open as part of a permanent route network—thousands of miles of OHV routes are slated for closure. The cost of container stock and work crews to revegetate these routes is beyond the institutional capacity and financial means of the BLM. Because of this, managers must optimize natural processes and target restoration funds efficiently across large areas. Mulching is a common technique and currently the primary method used to facilitate natural revegetation and halt travel on closed routes. Mulching roughens soil surfaces and accelerates the regeneration of native shrub and bunchgrass species. Mulching can improve water infiltration and retention, reduce wind velocity at the soil surface, reduce soil temperature, lessen runoff, protect the soil from raindrop splash, and reduce chemical crusting of the soil (Munshower 1994).

Mulching can also minimize the visual differences between the closed trail and the adjacent native vegetation, and thus discourage vehicle riders from veering off of clearly marked, designated OHV routes (fig. 16.3). Beyond the line of sight from the designated OHV route, restoration proceeds at natural rates without additional restoration efforts.

Horizontal Mulching: Horizontal mulching makes use of vegetation to cover surfaces of OHV trail beds so that formerly bare surfaces no longer attract the notice of passersby on vehicles. Shrub and tree branches can be laid along slope

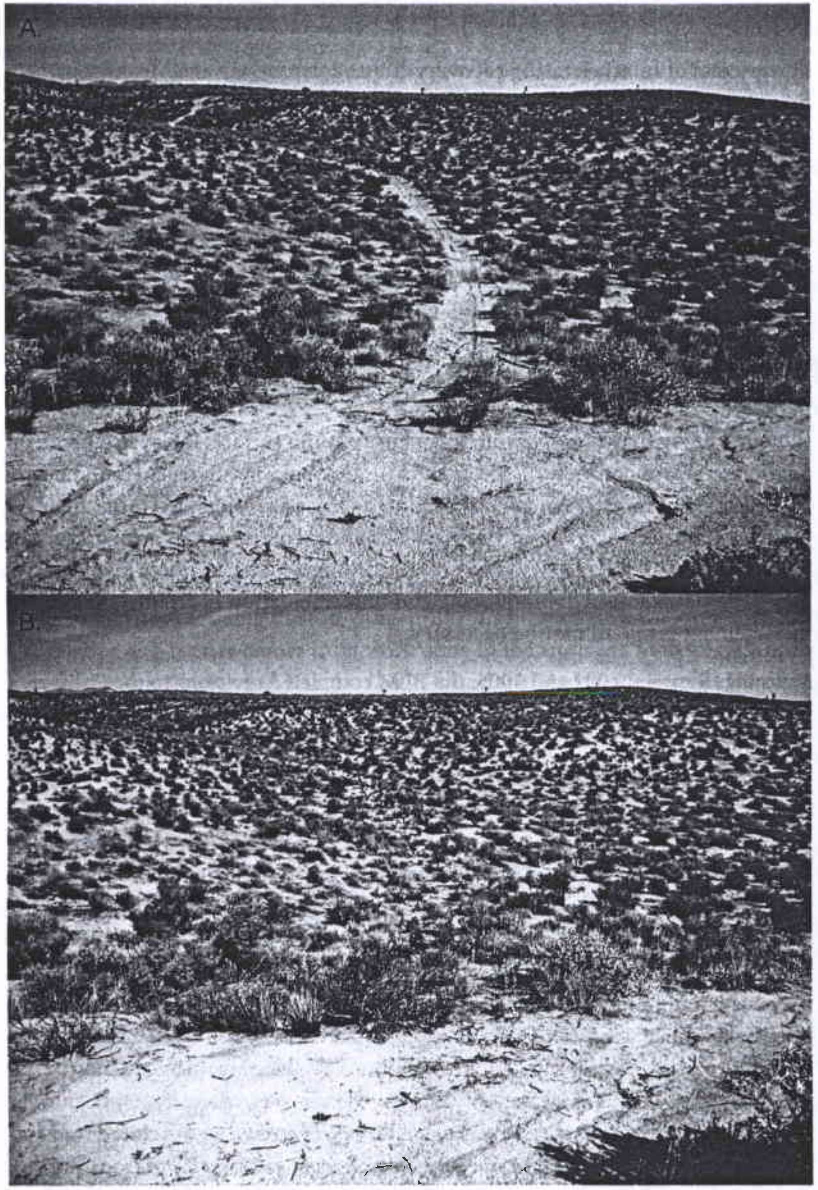

Fig. 16.3. Photographs documenting restoration along a trail in the Jawbone-Butterbredt Area of Critical Environmental Concern in Kern County, California. *A*, was taken in the autumn of 2005 before vertical mulching practices. *B*, was taken in the autumn of 2005 after vertical mulching practices (photographs courtesy of Ronald Gartland, BLM California Desert District archives).

contours and over disturbed soil. This type of mulching has been shown to increase soil fauna, increase the rates of biological processes, and reduce moisture loss due to evaporation, in addition to the advantages listed above (Ludwig and Tongway 1996; Tongway and Ludwig 1996).

Vertical Mulching: Vertical mulching consists of straw, sticks, or brush, tied in bunches and buried upright in the soil. Materials that have been used include broom corn, straw, reeds, and brush from existing vegetation. Material selection depends on the severity of disturbance at the site, other restoration methods being utilized, the project's goals in terms of aesthetics, and the availability and cost of materials (Bainbridge 1994). Vertical mulching slows runoff and increases infiltration by allowing water to seep into the soil around stems of the buried material. Fairbourn (1975) found that vertical mulch can increase soil moisture more than 20%. Vertical mulching also provides shade and cover for seedlings and below-ground organic matter as it decomposes (Bainbridge 1994).

Bureau of Land Management staff have buried bunches of rice straw halfway into road beds to imitate the appearance of desert bunch grass. Because of the improvisational and creative nature of vertical mulching, this method needs to be documented more fully and communicated more widely. Ecologists with the BLM and USGS are presently studying the long-term effectiveness of vertical mulching at both deterring unauthorized OHV travel and promoting natural revegetation. Joshua Tree National Park has summarized their vertical mulch and closed road techniques in several unpublished protocol handbooks.

Rock Mulching: Rocks can also be used to obscure disturbed areas and restore ecological function. Rock mulch promotes water retention from dew and rainfall, and creates a rough surface with pockets that capture seeds and can facilitate germination. Like other mulches, rocks reduce soil moisture evaporation and wind and water erosion (Walker and Powell 2001). Rocks that resemble the native material can be used to camouflage disturbed sites by restoring the texture and color of the ground surface.

Early restoration projects at the BLM Barstow Field Office and JTNP used variations on these mulching techniques, and involved experimenting with rock mulches ranging in size from coarse gravel to large boulders. Restoration crews have improved their techniques by using brooms to smooth the surfaces between the trail beds and the undisturbed surfaces and by partially burying larger rocks. At Lake Mead National Recreation Area (NRA), rock stains and soil colorings, such as Permeon™, have also been used to obscure tire tracks on desert pavement.

Mulching to Sequester Excessive Nitrogen. A major concern to ecologists in the Mojave Desert is the increasing nitrogen deposition from urban sources (Allen et al. *this volume*). Results from studies in other parts of California show that mulching with a combination of sucrose and straw/wood chips provides carbon and increases the carbon to nitrogen (C:N) ratio (Cione et al. 2002; Corbin and

D'Antonio 2004). One useful effort would be to see whether a shift in the C:N ratio can be used to give native annuals and grasses a competitive advantage as a means to suppress nonnative plants, especially *Bromus* ssp. (brome grasses) and *Erodium cicutarium* (redstem stork's bill) (Brooks 1998).

Continuing support for diverse mulching techniques on BLM lands in the California portion of the Mojave Desert comes from the California Department of Parks and Recreation Off-Highway Motor Vehicle Recreation Division (OHM-VRD). California state law has promulgated that at least $7 million of OHM-VRD funds be applied to restoration projects, a considerable portion of which is dedicated to the closing and restoration of redundant vehicle routes in the Mojave Desert.

Irrigation

Restoration publications generally highlight restoration work conducted in temperate ecosystems, where annual precipitation is fairly predictable and outplanting and irrigation of plants is easier than in arid ecosystems. Because water can determine the outcome of a restoration project, understanding hydrology is essential for successful restoration projects in the Mojave Desert.

Many restoration projects in the Mojave Desert occur in remote areas where access is limited and materials and equipment sources are distant. Nearby water sources often do not exist, or are restricted to use by wildlife. In these cases, five options are available: (1) use a restoration prescription that does not require water other than natural rainfall, (2) include physical structures, such as berms and rainwater catchments, to increase infiltration and the amount of precipitation that reaches the site, (3) construct an irrigation system to convey water and supply water to the site, (4) use water-retaining gels, and (5) a combination of methods.

Irrigation Systems: Irrigation systems are usually part of a restoration prescription when container-grown plants are used. Irrigation is often the most expensive component of a restoration project. Travel to remote sites incurs fuel, labor, and vehicle maintenance costs. Experience at JTNP shows that transplants may require irrigation for as long as two years.

The Soil Ecology and Restoration Group has experimented with irrigation techniques such as surface watering using berms, pitting, and treeshades, as well as deep pipe drip systems and porous capsule drip systems. They have also studied the effectiveness of systems adapted from other desert cultures, such as wick irrigation, used in India (Bainbridge and Virginia 1991), and clay pot irrigation, used for centuries in China and Pakistan (Bainbridge 2001).

When using an irrigation system, the amount of water and the scheduling of water deliveries need to be efficient and timely. Because labor and truck delivery costs can be prohibitively high, temporary irrigation systems are sometimes necessary.

Water-Absorbing Soil Amendments: Soil amendments can also be used to increase the amount of water available to plants. One type of water-absorbing amendment is a polyacrylamide-based polymer that slowly releases water to the plant at the root zone. These polymers, also referred to as root-watering crystals, planting gels, and water-retention granules, are long-chained organic compounds that molecularly bind water molecules. The water is released as soil bacteria decompose the molecular chains (Fischer 2004). These gels may hold up to as much as 1,000 times their weight in water (Staton 1998).

The water supplied by the gels reduces the physiological shock to transplanted stock, promotes the growth of seedling root systems, and aids plants in withstanding desert droughts. Both fine- and medium-textured gel granules are available. Bare-root seedlings are usually dipped in a mixture of fine granules and water before planting. Previously saturated, medium-textured gels are then mixed with desert soils poured into the planting hole. Subsequent watering or irrigating will replenish the water held by the gels.

Polyacrylamide, however, can potentially contaminate groundwater as it degrades to an acrylamide monomer, which is toxic to humans, animals, and plants (Jha 2004). An alternative nontoxic gel is DriWater®, which is 98% water and 2% cellulose and alum—food-grade ingredients. Generally, when used as a soil amendment, a one-quart gel pack is placed in a vertical tube near the plant root (Fischer 2004). According to the manufacturer, this product lasts up to 90 days, as opposed to the longer-lasting polymers mentioned above. Gel packs, however, are susceptible to animal consumption and removal.

DriWater® has been used at the Lake Mead NRA and the Mojave National Preserve. Joshua Tree National Park conducted a small study ($n = 27$, sample size was limited due to budget constraints) of DriWater® effectiveness in 2004. Gel pack tubes were filled at the time of planting and 3, 6, and 9 months postplanting. After 2 years, 20 of 27 nursery shrubs planted were still alive. Soil erosion caused 3 of the 7 deaths. In a nearby planting, also in 2004, 61 of 75 shrubs transplanted with gel pack watering tubes survived 2 years postplanting, and 35 of 35 shrubs died when just receiving surface water. Plants without gel packs received supplemental water once every six weeks in the summer of 2004, and only once in the summer of 2005. Gel pack plants received supplemental water once in the summer of 2005 (Joshua Tree National Park *unpublished data*).

THE HISTORY OF MOJAVE DESERT RESTORATION

Beginning in the mid-1800s the human population in the Mojave Desert began to grow as explorers, immigrants, and pioneers moved west (Hughson *this volume*). For decades, the residents of the newly created agricultural and mining communities held no sense of long-term stewardship. When key resources became depleted, people simply moved on, leaving abandoned towns and mining sites—areas which now provide invaluable information about natural recovery processes

(Wells 1961; Webb and Wilshire 1980; Webb and Newman 1982; Webb et al. 1988). A general perception of the Mojave Desert as desolate and worthless continued well into twentieth-century and accounts, in part for the creation of military training bases and hazardous waste dumps (Reith and Thomson 1993).

In the past 25 years the human population has exploded (Lovich and Bainbridge 1999; Hughson *this volume*). Only recently has the value of preserving the natural state of the Mojave Desert become a priority. Active restoration is a relatively recent concept in the Mojave Desert; threads of knowledge have only emerged in the last 50 years, and no long-term, finely tuned plan for sustained use or active restoration has been formulated.

Los Angeles Aqueduct Restoration, 1968–1972

The first carefully documented active restoration project in the Mojave Desert followed construction by the Los Angeles Department of Power and Water of a second aqueduct barrel to transport water from Owens Lake and Oiyee Reservoir in southern Inyo County, California, across BLM land to Los Angeles. During construction, bulldozers bladed a 40–45 m right-of-way on both sides of the aqueduct access road, which left areas scraped of topsoil, occasional hills of piled topsoil, and strips of soil studded with cement rubble at the edges of the bladed areas. Aerial photographs 35 years after construction still reveal a stark contrast in soil surface color between the undisturbed and disturbed areas (fig. 16.1).

To mitigate the damage, several revegetation experiments were conducted using seeds, transplanting, soil ripping, and irrigation. The species selected for revegetation included *Larrea* and *Ambrosia*, which dominated the area, and other native shrubs, including *Ericameria nauseosa* (rubber rabbitbrush), *Hymenoclea salsola* (cheesebush), *Lepidospartum squamatum* (California scalebroom), *Grayia spinosa* (spiny hopsage), *Krascheninnikovia lanata* (winterfat), *Atriplex polycarpa* (cattle saltbush) and *A. canescens*. The success of the experiments varied with species, and was generally low (Lovich and Bainbridge 1999). The overall conclusion of these experiments, according to Kay and Graves (1983), is that revegetation efforts should focus on the visually dominant species—*Larrea*, in this case.

A series of 24 Mojave Revegetation Notes were published between 1970 and 1972, and again after return visits in 1979 and 1988, which describes and evaluates the restoration methods and species selection. Sites with topsoil removed fared poorly or failed altogether in the first decade, a time of severe drought in California. However, the second decade prompted rapid natural revegetation of shrubs on scraped sites (Kay 1988). The soil ripping created linear strips that appeared to favor nonnative annual *Schismus* grasses. Shrubs on hills of piled topsoil, however, showed notable long-term success. Complex vegetation islands consisted of unusual combinations of pioneer and late-seral species from the original species mix.

Revegetation at Joshua Tree National Park

Restoration efforts at JTNP first began in the 1970s, when park rangers began removing nonnative *Tamarix ramosissima* (salt cedar) from remote springs and oases. In 1986, JTNP staff founded the Center for Arid Lands Restoration (CALR), a plant nursery and information hub for restoration technology. Initially, the CALR served a large-scale realignment project along 7 miles of road from Interstate 10 to the JTNP Cottonwood Visitor Center. Funded by a small grant from the Federal Highways Program, the CALR became the first facility in the Mojave Desert region to grow native Mojave Desert species for restoration projects. Since its establishment, the CALR has supplied hard-to-get container stock to the San Bernardino National Forest, the BLM's California Desert District field offices, California State Parks, Marine Corps Air Ground Combat Center, Fort Irwin National Training Center (NTC), local nonprofit organizations, as well as to Death Valley National Park and the Mojave National Preserve. Databases maintained by JTNP on propagation methods and requirements for 90 perennial species are available through CALR to restoration practitioners (Joshua Tree National Park *unpublished data*).

In the late 1990s, park managers tried direct seeding of abandoned borrow pits with poor results. Insufficient seed application rates, combined with a lack of reliable moisture, rodent predation, and continued slope erosion were the likely culprits. As often happens with limited funds and high staff turnover, the outcomes of these trials were not studied further, and this could still be a viable method at select sites.

Between 1989 and 1999, most JTNP revegetation and mine reclamation projects used container stock of various sizes and species. Careful monitoring and documentation of germination and outplanting has made it possible for JTNP to share successful methods for seed collection, propagation, planting, and site maintenance. In addition, invention of the "tall pot" has improved long-term shrub survival in the harsh conditions of the Mojave Desert. Designed to focus growth on roots rather than shoots, the original tall pot was made of Schedule 35 PVC pipe, 152 mm in diameter, cut to 760 mm in height, and enclosing 13.6 L by volume. The tall pot and its successors (in dimensions appropriate to specific shrub species) have enabled the nursery to produce desert shrubs with extensive, healthy root systems. Emphasis on the development of deep roots has consistently proved much more effective for plant survival. Species such as *Hymenoclea* and *Ambrosia* can become very leggy and fleshy in the nursery, and they are highly subject to herbivory by lizards, ants, and rodents; all outplants are protected with chicken wire for up to 3 years postplanting to prevent herbivory.

Past projects in the lower, drier areas of the park relied heavily on the use of *Larrea* because of its ability to survive with minimal watering and extremely limited natural precipitation. Other early seral species successfully used in harsh conditions included *Hymenoclea*, *Ambrosia*, and *Isomeris arborea*.

In the late 1990s, JTNP staff inventoried and assessed closed roads and abandoned mine lands parkwide, particularly along park boundaries and points of access. Spatial and tabular databases allowed managers to prioritize restoration practices and initiate them as funds became available. After several years of applying various methods, vertical mulching, pitting, and recontouring proved to be the most cost-effective. Ultimately, 167 miles of road were closed to vehicle traffic, and 14 sites were rehabilitated 200 feet or less from the intersection with an open road (Joshua Tree National Park *unpublished data*). Refinement of methods continued as JTNP began extensive road realignment and parking lot expansion within Joshua tree woodland communities. Concerns over nonnative species invasion, off-road vehicle activity along road edges, and the loss of numerous large *Yucca brevifolia* and *Y. schidigera* created new restoration opportunities. Operations shifted from the exclusive use of container stock to salvaging live plants wherever possible. Plants unsuitable for live salvage were harvested for use as mulch.

In addition to these projects, JTNP has collected over 15 years of information on germination and survivorship of planted species. Germination information is also housed at the CALR; a good deal of this information has been added to the latest revision of the U.S. Department of Agriculture's Woody Plant Seed Manual at http://www.nsl.fs.fed.us/wpsm/.

The Soil Ecology and Restoration Group at San Diego State University

The Soil Ecology and Restoration Group (SERG) at San Diego State University began conducting research in the Mojave Desert in 1991, and has been at the forefront of restoration at challenging Mojave Desert sites, in particular by undertaking novel applications in restoring OHV hill climb areas at Red Rock Canyon State Park in Kern County, and in revegetating upland sites heavily impacted from military maneuvers at the NTC. In addition to innovative irrigation systems adapted from ancient desert cultures, SERG has also developed techniques for efficiently channeling and capturing rainfall to supply those systems (Edwards et al. 2000). In addition, they emphasize the importance of summarizing past land use and disturbance as part of developing successful restoration prescriptions.

Unlike other restoration groups, SERG has emphasized improvements to soil fertility through management of microbial ecology and soil-plant processes. The group combines information about specific sites with academic research and produces valuable knowledge on below-ground ecological processes. Graduate students have provided new information on all aspects of soil, with special emphasis in two areas: (1) the effects of nodulation and soil productivity on *Prosopis glandulosa* var. *torreyana* (honey mesquite) (Darby 1993; Kay 1989; Thomas 1995) and *Larrea* (Sorensen 1993); and (2) the effects of metals, such as selenium, on nitrogen fixation in *Astragalus crotalariae* (Salton milkvetch) (Kramer 1989).

The SERG faculty, staff, and students have also created a useful online extension service that introduces and illustrates restoration technologies. A series of SERG Restoration Bulletins outlining desert restoration techniques is available online at http://www.sci.sdsu.edu/SERG/techniques.html. By carefully documenting restoration projects and making the technologies and results available to the public, SERG scientists provide a valuable and rare source of information to both interested individuals and public land managers.

UNIQUE CHALLENGES IN ACTIVE RESTORATION IN THE MOJAVE DESERT

The Urban-Desert Interface

The human imprint on the Mojave Desert has increased dramatically in the past 25 years and shows no signs of abating soon (Lovich and Bainbridge 1999). The human population in the cities of San Bernardino County, California, quadrupled between 1980 and 2005 (State of California 2006), from 81,749 to 326,020. Similarly, over the same period, Clark County, Nevada, grew in population from 463,087 to 1,796,380 (Hardcastle *undated*).

The urban-desert interface, where the wild landscape and the anthropogenic landscape meet, is particularly vulnerable to repeated disturbance. Public lands nearest urban areas are subject to the greatest anthropogenic impacts and have the greatest need for restoration. Due to continuing disturbance, restoration at a given site may have to be repeated. Maintaining the pristine appearance of the landscape within scenic viewsheds is important because it contributes to the value of real estate and to a sense of community identity and land stewardship.

An issue of increasing concern, which is affected by restoration at the urban-desert interface, is human health and well-being. Vegetation cover and soil stability are important for reducing dust emissions and conserving air quality worldwide; disturbance of soil and vegetation cover generates airborne dust. Numerous mineral, fungal, and pollen allergens have adverse effects around the world. Illnesses associated with desert dust include silicosis (Hirsch et al. 1974), bronchial asthma (Ezeamuzie et al. 2000), and allergic rhinitis (Dowaisan et al. 2000; Behbehani et al. 2004).

No published research studies exist on the effects of desert dust on the health of Mojave Desert communities; most documentation of the affects to human health from desert dust comes from China, Israel, and Kuwait. Studies in Kuwait (Al-Dowaisan et al. 2004) of desert fungal spores and plant pollen point to desert plants in the Chenopodiaceae family and mesquites (genus *Prosopis*) as triggers for widespread asthma in Kuwaiti communities. Chenopodiaceae species are frequently a major, if not dominant, component of shrub colonization of disturbed sites at the urban-desert interface in the Mojave Desert. Recent research from Spain (Colas et al. 2005; Garde et al. 2005) and Kuwait (Al-Dowaisan et al. 2004) also underscores the allergenic sensitivity of residents in semiarid communities to the pollen of *Salsola* ssp. (Russian thistles or tumbleweeds), invasive exotic species in the Chenopodiaceae family, also commonly found on disturbed sites in the Mojave Desert.

The role of desert restoration at the urban-desert interface has not received attention from public land managers, although they are aware of the impacts at the interface as precursors to expanded impacts from illegal vehicle travel and noxious weed invasions. Joshua Tree National Park, which has the poorest air quality of all national parks in the United States, also has housing development adjacent to some of its boundaries. Designing robust desert vegetation communities along the west and south margins of JTNP to effectively ward off nonnative plant invasions and, at the same time, improve air quality, is now a priority.

Riparian Restoration

Freshwater streams and accompanying riparian forests and woodlands are rare in the Mojave Desert. Their structural complexity provides habitat for multiple vertebrate species, including the federally listed Mohave tui chub (*Gila bicolor mohavensis*), arroyo toad (*Bufo microscaphus californicus*), Southwestern Willow Flycatcher (*Empidonax traillii* ssp. *extimus*), and Least Bell's Vireo (*Vireo bellii pusillus*). The Colorado, Virgin, Mojave, and Amargosa rivers are the major watersheds, having at least partially perennial streamflow. Restoration and maintenance of the native biological diversity along these rivers is critical.

Efficient restoration and habitat management in these desert riverine ecosystems is a challenge for federal land management agencies. The Mojave River watershed, for example, stretches from the San Bernardino National Forest to the Mojave National Preserve. Multiple federal, state, county, and city agencies, as well as interest groups with a stake in Mojave River restoration, must collaborate for meaningful watershed management. There is the possibility that restoration projects will be implemented piecemeal, and thus be subject to greater likelihood of long-term failure.

The complexity of perennial stream restoration can be seen in the history of the Mojave River segment in the BLM Afton Canyon Area of Critical Environmental Concern. Since 1992, the BLM Barstow Field Office has targeted exotic *Tamarix* ssp. populations and restoration of native plant communities comprised of *Populus fremontii* (Fremont cottonwood), *Salix* ssp. (willows), and *Prosopis glandulosa* (honey mesquite) and *Prosopis pubescens* (screwbean mesquite). Innovative and complex methods utilized herbicides, pole plantings, shrub seeding, and prescribed fire (Egan 1999; West 1996) to reduce *Tamarix* cover and capacity to recolonize after initial removal on 121 hectares.

Multiple partners, such as American Forests and Quail Unlimited, contributed funding to support restoration work in Afton Canyon. The conversion of vegetation back to native species was successful until January and February 2005. On January 11, 2005, the U.S. Army Corps of Engineers, Los Angeles District, authorized an all-time maximum release of 470 m^3 s^{-1} of water from the Mojave River Dam on the north side of the San Bernardino Mountains. Downstream, the Silverwood Reservoir also released water. The resulting inundation of the Afton Canyon riparian woodlands negated, in the course of a few days, the progress of more than 10 years of restoration. Almost immediately, the Mojave Desert Resource Conservation District was applying for funding to promote reestablishment of native riparian vegetation.

Because infrequent flash floods direct the disturbance regimes in riparian areas, restoration efforts are sometimes erased. Maintaining streams and riparian vegetation in native conditions requires repeated and rapid management responses if the natural functioning of desert rivers is a goal. Short-term restoration accomplishments between catastrophic floods must be the basis for determining the success of restoration in Mojave Desert riparian areas.

Wildland Fire

Other research addresses the connection between nonnative plants and the accumulation of fine fire fuels (Brooks and Pyke 2001; Dudley *this volume;* Brooks *this volume*). The increasing human presence in the Mojave Desert merits a closer analysis of the fire frequency on federal public lands since 1980, particularly at the urban-desert interface and in higher elevation woodlands within National Forests—in particular the Inyo, San Bernardino, Sequoia, and Toiyabe National Forests. Many wildland fires originate at higher elevations and spread downslope to BLM or national park lands with pinyon-juniper or Joshua tree woodlands.

The structural complexity of higher elevation Mojave Desert woodlands make them important habitats for species such as Gray Vireo (*Vireo vicinior*), which is designated as sensitive by the BLM, and can be found on the northern slopes of the San Bernardino Mountains in California. Fires in 1994 and 1999, originating from the San Bernardino National Forest, spread onto BLM lands to the north. California juniper woodlands burned during the fires and, to date, no juniper regeneration has been noted in the Juniper Flat Area of Critical Environmental Concern or elsewhere in the burned areas. Focused restoration of desert woodlands and the desert/chaparral interface will be key to reconstructing nesting habitat for Gray Vireos and other neotropical migrant species. Collaboration across agency management boundaries in the San Bernardino Mountains and elsewhere in the Mojave Desert is a key part of conservation biology and restoration response to wildland fire.

Wildlife and Rare Plant Habitats

Specific active restoration measures and prescriptions do not exist for wildlife habitat for most species of concern in Mojave Desert ecosystems. Most conservation measures proposed thus far are general and passive in nature. Fencing critical habitat and reliance on natural rates of soil and vegetation recuperation are currently the principal focus for wildlife habitat and rare plant management. Public expectations that wildlife biologists will improve the habitats of threatened and endangered species appears to exceed current agency capabilities. Greater attention to the processes, composition, and structure of Mojave Desert ecosystems as factors in population biology is warranted. Now is the time to synthesize information from research studies on wildlife species such as the desert tortoise (*Gopherus agassizii*) and to develop practices to enhance the supply of annual plant species known to provide high-quality forage (e.g., Jennings 2002; Martin and van Devender 2002; Oftedal et al. 2002). Management of air quality, in particular of dust from OHV trails, may also be critical to maintaining viable populations of rare plants such as *Astragalus jaegerianus* (Lane Mountain milkvetch). Wildlife biologists and botanists have been slow to specify which features of soil, vegetation, and topography (all of which are focal elements in restoration projects), should be enhanced to recreate Mojave Desert habitats. Hypotheses from wildlife biologists and rare plant specialists need to be translated into adaptive management experiments. Recently, USGS wildlife biologists have begun analyzing the distribution of spring annual plant species to guide efforts to augment seed bank supplies of species especially favored by desert tortoises.

A few examples do exist where restoration ecologists have put into practice specific restoration actions to benefit wildlife. At JTNP, restoration ecologists relocated dead and downed yucca species in road construction projects to adjacent undisturbed areas to maintain habitat for the desert night lizard (*Xantusia vigilis*) (Cox and Rodgers 2003). These microhabitat specialists live exclusively among the stems of *Yucca* and *Agave* species (Bezy 1989). Vertical mulch distribution and structure were applied in desert tortoise habitat, which also benefited more common species such as the desert spiny lizard (*Sceloperus magister*) and kangaroo rats (*Dipodomys* ssp.). Shallow pits to collect seeds and water were created to promote higher propagation of the annual forbs favored by desert tortoise. However, there is no data on the effectiveness of this technique (Joshua Tree National Park *unpublished data*).

Plant ecologists and wildlife biologists are now discussing ways that restoration of vegetation benefits plants that are critical for population rebound. Only now are managers and scientists discussing specific restoration practices for improving desert tortoise forage and sources of seeds for rare mammals such as the Mohave ground squirrel (*Spermophilus mohavensis*). Unexpectedly, restoration measures to reduce the proportion of nonnative and less nutritious forb and grass species in desert tortoise critical habitat may require the application of sugar. This treatment in steppe and chaparral ecosystems has been shown to increase the C:N ratio, and thus renders nitrogen deposition from air pollutants unavailable to invasive plant species that otherwise thrive in nitrogen-enriched sites. This shift in the C:N ratio then makes sites more suitable for the native legume species that provide better nutrition for desert tortoises.

Wilderness Areas

The 1994 California Desert Protection Act designated nearly 1.42 million hectares of BLM land in the California desert as wilderness, as well as designating national park status for Death Valley National Park, Joshua Tree National Park, and the Mojave National Preserve. Restoration in federally designated wilderness is often constrained by regulations that exclude the use of motorized equipment. However, many agencies are now recognizing that restoration requires flexibility when it comes to working in wilderness areas. The problem of restoration in wilderness is particularly acute where wilderness areas are close to Mojave Desert cities such as Ridgecrest and Yucca Valley. Over the decade since passage of the Act, the California Off-Highway Motor Vehicle Recreation Commission has funded restoration of OHV trails inside BLM wilderness areas that adjoin other BLM lands with designated OHV routes. Some of the most challenging restoration sites remain unaddressed, however, because the technology for restoring disturbed, steep slopes has not been worked out, given the constraints on the tools permitted in wilderness areas. A restoration analysis of abandoned mine lands in JTNP produced a list of tools that included, at a minimum, small generators, power augers, welding equipment, and helicopters (Joshua Tree National Park *unpublished data*).

MANAGING FOR SUCCESSFUL ACTIVE RESTORATION

Management of restoration programs is constantly growing and improving. The following sections outline some directions for management that could amplify the benefits of ecosystem restoration efforts and encourage creativity and efficiency in acquiring knowledge and applications for desert restoration.

Increase Public Awareness and Environmental Education

Most people who now live in the Mojave Desert have not lived there very long—they do not always have a strong connection with the land. Involving people in restoration projects enhances a sense of place in several ways. Volunteers become informed supporters of restoration projects and knowledgeable restoration practitioners. In urban-desert interface areas, at sites most in need of intensive restoration, volunteers can provide site preparation and irrigation as revegetation projects become established. Without public involvement, public land managers will never have enough labor and financial support to make restoration successful. Community stewardship on the part of volunteers is essential. Ecological restoration can serve as a tool for informing people about Mojave Desert ecosystems and for creating a modern, indigenous knowledge base.

Making restoration methods and technology a core part of curriculums in high schools and community colleges could also inform Mojave Desert residents, and young people in particular, about the function and management of ecosystems. Victor Valley Community College in Victorville, California, for example, offers students a flexible curriculum in natural resource management with an emphasis on Mojave Desert ecosystems. Courses include nursery management, plant propagation, soil rehabilitation, mine reclamation, and restoration project design. Such educational programs build expertise in local communities. Students such as these are also ideal candidates for public agencies, which in the past have had high turnover rates.

Create a Bioregional Plan

A comprehensive, bioregional restoration and conservation plan is needed to create common goals, consolidate resources, and to offset adverse impacts due to development. Questions to be addressed include: Where can people conserve the natural landscape and its resources, restore damaged lands, and maintain the complexity, diversity, and resilience of the Mojave Desert? Will cost-benefit analysis be the sole determinant? What are the explicit and implicit assumptions of economic decisions?

The bioregional plan could make restoration more efficient because it would transcend boundaries and present restoration issues at multiple spatial scales. Efforts on the part of public land managers can reinforce one another and maximize overall benefits to watersheds and landscapes. The inclusion of state parks would make planning more comprehensive and gain greater participation. Private conservation organizations can add expertise, political leverage, and resources to facilitate community awareness and involvement.

Conserve Information and Experience

The public expects land management agencies to be proficient in both the basic science and specific applications of restoration. Given that desert restoration has a short history in the Mojave Desert, managers and restoration practitioners have much to learn. Conserving institutional memory about ecosystem restoration for land management agencies is critical to accumulating and transmitting knowledge. Documenting restoration projects fully, returning to monitor the outcomes, and widely communicating the results are critical to keeping agencies aware and learning. Rapid turnover of agency staff makes conservation of institutional memory haphazard and makes agencies vulnerable to making and repeating mistakes, thus inviting public criticism.

The following example illustrates another reason to conserve information and personnel. Kay (1988) showed that the failure of initial restoration actions at some sites along the second Los Angeles aqueduct resulted from a severe drought in the mid-1970s. However, by 2005, Berry et al. (2005) found that, in time, sites had regenerated, with canopy area comparable to that of nearby undisturbed vegetation. The initial goal of restoring shrub canopy cover was met, but at a rate not in concert with restoration expectations. While canopy cover may be the same, the composition of the plant species remains different. If the monitoring, first established by Kay and continued until 1988, had been extended to 2005, we might have a better understanding of the relationship between natural revegetation and climate. Ongoing monitoring of restoration in the medium- and long-term (> 5 years) is important to understanding restoration planning at multiple time scales. Measures of success or failure may indicate quite different results at different times.

Solutions to the problem of conserving institutional memory are not difficult to implement. First, professional and interdisciplinary training of restoration ecologists is essential. Rather than treating restoration in the Mojave Desert as an orphan activity, agencies can learn from forest restoration on less arid public lands. Structured thinking and the incorporation of experimental treatments into the design of restoration projects promote learning. While many projects have been undertaken on public lands, few practitioners have published the results of their efforts. It is crucial that individuals share their successes and failures if large-scale, active restoration is to be successful.

Practice Adaptive Management

Adaptive management experiments are critically important to advancing practical knowledge of desert restoration methods. Adaptive management is defined as a systematic approach to continually improving restoration policies and practices by learning from the outcomes of past and current projects. Prescriptions are designed so that, even if they fail, they will provide useful information for the future. The advantages of adaptive management are: (1) it addresses gaps in available scientific and technical information; (2) it provides examples of the success or failure of tested practices; and (3) it provides a basis for statistically validating and objectively evaluating restoration results. Incorporating tests of hypotheses and technologies in restoration spurs innovation, efficiency, and rapid learning by agencies and the concerned public.

Tend Soil Fungi and Soil Bacteria to Facilitate Restoration

Attention to soil physical properties and chemistry in restoration appears to increase revegetation success. However, much of the Mojave Desert, and in particular the lands managed by the BLM, has not been surveyed for soil characteristics. The lack of available information about local soils and the lack of land managers with expertise in soil science, microbiology, and hydrology presents a continuous challenge. An area currently neglected in restoration projects is management of subsurface biotic resources to enhance soil fertility, soil-water relations, and soil formation.

For example, arbuscular-mycorrhizal (AM) fungi stabilize desert soils and enhance plant acclimatization and growth by reducing drought stress and facilitating nutrient acquisition (Carrillo García et al. 1999; Requeña et al. 2001). Arbuscular-mycorrhizal propagules develop around plant roots and promote "islands of fertility" that speed the pace of colonization and increase the survival of desert plants (Azcón Aguilar et al. 2003). Work by U.S. Department of Agriculture mycologists in Corvallis, Oregon, and soil scientists at the Universidad Autónoma de Baja California Sur in La Paz have contributed to an understanding of these dynamics in the Sonoran Desert. Bacteria and fungi both facilitate fertility and adaptive colonization of desert plants, particularly cacti species, in rocky areas (Carrillo García et al. 2001; Puente et al. 2004a, 2004b). Titus et al. (2002) have started to analyze AM fungi and their role in the establishment of native shrubs in the Mojave Desert. The potential for more efficient restoration in the most difficult sites in the Mojave Desert may improve with mastery of desert microbial ecology.

DISCUSSION AND CONCLUSIONS

While active desert restoration is a large financial and management commitment, there are some cases where accelerating the restoration process is worthwhile. For instance, investing in obscuring a road junction halts off-highway vehicle disturbance and allows natural recovery to take place on the remaining stretch of abandoned road. Disguising access points leading to abandoned mines or former encampments improves safety and visitor protection on public lands. Restoration "landscaping," in conjunction with construction activities, can control traffic in fragile areas and may reduce the potential for invasion by nonnative plant species.

The most successful projects utilize new and innovative materials and techniques, and often new or adapted inventions. There is a wide body of information on past restoration efforts in the Mojave Desert. However, much of it consists of unpublished materials found at agency offices. It is important that this information be made available to ecologists and land managers. A "Mojave Desert Restoration Bibliography" would be of great use to practitioners in the field. While many management prescriptions may be new or cutting-edge in the Mojave, restoration has occurred far longer in other arid regions of the globe, such as China, Tibet, and Mongolia. Gathering information from around the world would be an invaluable addition to the existing literature.

Federal public land managers are now the principal trustees for conservation of Mojave Desert natural resources. Increasingly, federal land managers must meet regional expectations of excellent air quality, attractive landscapes, and access to recreation opportunities, as well as national expectations for conservation of biological diversity and intact ecosystems. Meeting the public's often contradictory expectations will require more intensive land stewardship on the part of federal land managers. Restoration of sites, watersheds, and landscapes will increasingly command management attention to offset the impacts of humans on federal public lands.

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APPENDIX 16.1

Additional Resources for Restoration of Disturbed Sites in the Mojave Desert

A recovery and restoration timetable, produced by the U.S. Geological Survey, is a useful tool when choosing between active restoration and natural recovery (http://biology.usgs.gov/s+t/SNT/noframe/gb151.htm).

Bauder and Larigauderie (1991) provided an early overview of the technologies and results of restoration efforts in the Mojave Desert.

The Desert Lands Restoration Task Force (DLRTF), under the Desert Manager's Group (DMG), developed a guide for restoration practices titled "A Beginner's Guide to Desert Restoration" (Bainbridge et. al. 1995).

Similar guides and decision-making tools have been developed at Joshua Tree National Park (Joshua Tree National Park *unpublished data*), the BLM Ridgecrest Field Office (Gartland and Weigand 2003), and the Soil Ecology and Restoration Group (Bainbridge 1999, http://www.serg.sdsu.edu/SERG/index.html).

Racin (1988) published a report on revegetation of slopes along US Highway 395 in Inyo and Mono Counties, California, with native plant seedlings.

The Mojave Desert

Ecosystem Processes and Sustainability

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