Rethinking remediation technologies for desertified landscapes

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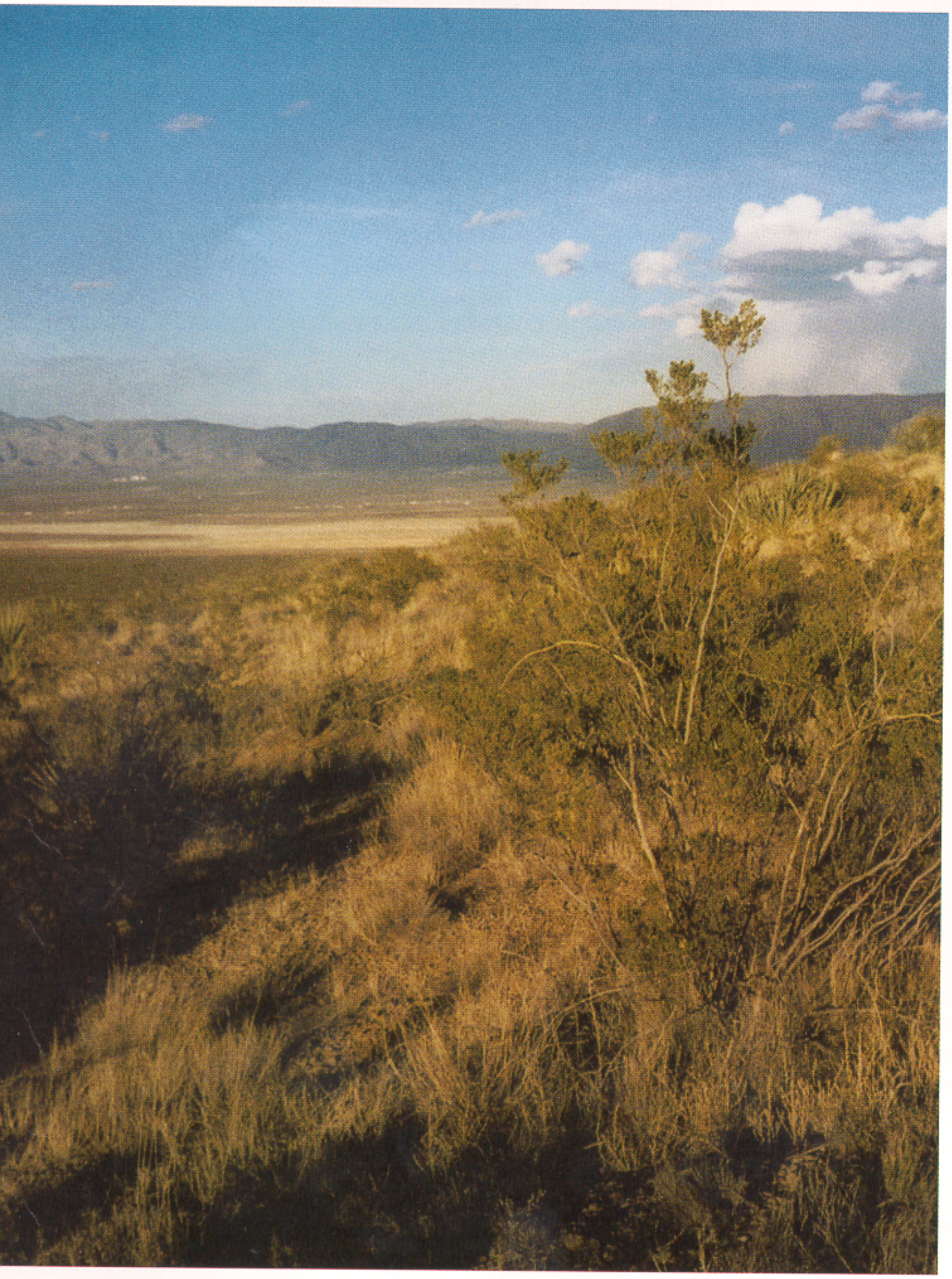

Creosotebush invading black grama grassland above the Jornada Experimental Range

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Shrub-dominated communities have replaced native grasslands throughout much of the arid Southwest during the past 120 years. Most currently available remediation technologies are uneconomical due to large inputs of energy, fertilizers, herbicides and labor, or are ecologically ineffective due to harsh environments and the highly competitive nature of these native shrubs. Our analysis of these historical remediation technologies together with new information on ecosystem processes has led us to pursue an ecologically-based approach in which more limited inputs are targeted to promote natural processes of regeneration. Advantages to this approach include lower costs, reduced reliance on agronomic practices, and maintenance of natural landscape features. Disadvantages include longer time required for desired changes to occur, and a need for increased understanding of arid land processes.

Historical and ecological context

The landscapes of the southwestern United States, like many arid regions of the world, are extraordinarily dynamic (Figure 1). Short-term increases in the frequency and intensity of droughts have triggered landscape-scale shrub invasions of desert grasslands at least three previous times during the past 4000 years (Van Devender 1995). The impacts of these changes in climate on the survival and competitiveness of individual species varied across the landscape as a function of soils and landscape position. Thus, even during the most intense periods of drought, a patchy mosaic of shrub- and grass-dominated communities has been maintained.

While the prehistoric record indicates that shrubs have dominated the region at various times in the past, the rate and intensity of change during the post-U.S. Civil War period have been extreme. For example, the ratio of desert grassland to shrubland in the northern region (Trans Pecos) of the Chihuahuan Desert in the past 140 years has gone from 2:3 to a present-day ratio of 1:7 (Hendrickson and Johnston 1986). This shift has significant cascading effects on a host of important processes at local, regional, and global scales (Schlesinger et al 1990). The shift from grass- to shrub-dominated landscapes is frequently associated with lower plant cover which leads to higher rates of soil erosion.

The causes for these recent changes are subject to considerable debate (Grover and Musick

1990). The significance of acute episodic disturbances on vegetation dynamics is becoming increasingly recognized as an important factor in stimulating change (Neilson 1987). Prolonged drought, unmanaged livestock grazing, and increased seed dispersal of invasive woody native species and exotic herbaceous perennials are recognized as main factors (Buffington and Herbel 1965). The relative importance of each of these factors is widely debated (e.g. Conley et al. 1992). Other forces of change include alterations in historical fire frequency (Brown and Minnich 1986), increased atmospheric CO^2 levels, and the introduction of feral and exotic herbivores (horses, African antelope) other than livestock.

Regardless of the responsible forces, the changes extend far beyond the visible shifts in plant community composition. The shrub-island conceptual model of change proposes that shrub invasion occurs in response to one or, more frequently, several extreme events or disturbances. A self-reinforcing process of increasing resource concentration beneath shrub canopies and resource depletion in the interspaces solidifies the competitive advantage of shrubs over perennial grasses (Schlesinger et al. 1990). Both wind and water play a role in within-site redistribution and export of soil and water resources in these communities. These processes frequently lead to a near-complete redistribution of the A horizon in many areas (Figure 2; Connin et al. in press) and a net reduction in the silt content in sandy basin soils in which aeolian processes dominate (Gibbens et al. 1983). Prior grass-dominated communities are unlikely to be reestablished without intervention, due in part to the alteration of shrub interspaces to the extent that they become unsuitable environments for seedling establishment.

Currently available technologies

Most currently available remediation technologies employ an agronomic approach in which an attempt is made to kill or physically remove shrubs throughout a management unit which may or may not be physiographically-based. Large areas have been cleared using heavy machinery including bulldozers and tractors. Clearing is generally followed by reseeding with grasses. The combination of vegetative cover removal, intense surface disturbance and typically low seedling establishment rates frequently leaves the soil exposed to wind and water erosion for several years. Collateral damage to cultural resources is also a concern, particularly when deep-tillage implements are used to rip roots out of the soil. Herbicide-based programs have the advantage of minimizing soil surface disturbance but are limited by low rates of success, negative impacts on water supplies and non-target species, and high purchase and application costs. Even when successful, many of these systems revert to shrub-dominated systems within several decades (Herbel et al. 1995).

Figure 1. The dynamic nature of southwestern rangelands over periods ranging from months to millennia can be attributed in part to the variability in moisture availability

The economic costs of currently available technologies are exceedingly high. The costs are frequently further inflated by the need to reseed in one or more subsequent years. In an analysis of a wide variety of seeding trials conducted over a six-year period, Ethridge et al. (1997) found that none of the 14 species evaluated generated a positive economic return. In this analysis, benefits were measured in terms of increased beef production and no attempt was made to include costs other than labor and purchased inputs.

In summary, most existing technologies rely on traditional agronomic approaches to replace shrubs with desired forage species uniformly across the landscape. These approaches have high cost:benefit ratios, high environmental costs, and a low long-term success rate. In contrast, remediation systems of the future must be designed with recognition of multiple societal values including soil, water and air qualities, biodiversity and aesthetics. They must require minimal external inputs, comply with a myriad environmental regulations, and be cost-effective.

Ecologically-based remediation: the art of the possible

The criteria listed above for future systems represent a tall order. In order to succeed, we must increasingly rely on what might be considered to be "internal inputs" by working to promote existing processes which favor the establishment of desired species. The proposed approach is based on the following premises:

(1) biological integrity of both above- and

Figure 2. Soil surface buried by dune formed around mesquite shrub
Note: The A horizon has been completely lost from the unvegetated interspace at the right side of the photo. This change has been associated with a loss of silt-sized particles from these former grasslands (see Hennessy et al. 1986)

below-ground systems, in addition to the short-term establishment of desired species, is necessary to buffer against future disturbances,

(2) resource redistribution over time at the community and landscape levels plays an important role in both desertification and restoration processes,

(3) restoration efforts should focus on relatively fertile sites best suited for re-establishment of the native community, and

(4) planting technologies should be based on readily-available "natural" dispersal systems.

Implicit in this approach is the recognition that the restoration of pre-European settlement plant communities may not be desired or even possible at some, if not all, sites because of the permanent (on a human time scale) loss of soil and/or genetic resources (Figure 2) and the invasion and/or expansion of other species. The definition of desired plant communities depends on the functions which a particular landscape serves, or may serve in the future. These functions will often, but not always, include preservation of habitats and native species. The recognition that historic changes may limit options and the acknowledgment that human societies impose multiple values on both public and private lands allow ecologically-based remediation to address a much broader range of landscapes. This perspective also frees ecologically-based remediation from the debates over what represents the "pre-settlement plant community" that are associated with the word "restoration." The approach is in a very real sense an art that seeks to use science to identify and release the possibilities locked within the existing soil and plant communities.

The basic approach (Figure 3) applies at both the research and management application levels. At the research level, a class of site is selected that appears to have a high potential for change in the desired direction in response to limited inputs in Stage I. These sites should also be located in areas where natural expansion of the vegetation is likely to occur. The current limitations to recovery are then identified in Stage II. These limitations may be described in terms of both properties and processes and include spatial and/or temporal availability of water and nutrients, soil temperature, soil surface stability, disturbance frequency, and soil and litter chemistry. In Stage III, biological and physical properties and processes which can be easily manipulated to remove the limitations are identified. Targeted inputs are applied in Stage IV to initiate remediation. These inputs may be directed to change resource availability directly or through a modification in the density and activity of selected functional groups of organisms. The inputs may include materials, substrates, organisms or simply a change in the disturbance regime. Stages II-IV are then repeated to develop systems to promote natural expansion of the vegetation.

At the management application level, a similar process is followed. Site-specific information is gathered and synthesized with research data from similar sites and general knowledge of the natural history of the area, including the current and historic disturbance regime. While the simplified conceptual model presented in Figure 3 is linear, the actual process of developing a remediation plan is highly iterative and involves incorporating diverse knowledge and observations as illustrated in the examples below. Ideas for inputs and interventions may come from a knowledge of the life history and community interactions of specific organisms, from observations of the relationships between different landscape units, or from historic or even pre-historic land-use practices.

Decisions about which inputs and interventions to apply may be aided by simulation models which provide a structure within which available information can be synthesized and applied. Increasingly comprehensive models that incorporate life history traits and interactions among plants for resources, as well as effects of factors such as soil texture and grazing on vegetation dynamics are available (Coffin and Lauenroth 1990) and have been used successfully to address recovery problems in shortgrass steppe communities of eastern Colorado (reviewed in Coffin et al. 1996). In addition to guiding management decisions, this type of model may be used at the research level throughout the first three stages outlined in Figure 3.

For example, a model could be used to evaluate a number of sites with different characteristics, and select the sites most likely to respond favorably to limited inputs or the sites expected to be most sensitive to changes in different kinds of inputs (Stage I). For these sites, the model could be used to identify the factors that currently limit recovery of desired species (Stage II). The model could then be used to investigate the consequences of altering these limitations through manipulations of different biological and physical processes. The model could also be used to select those manipulations with the highest probability of achieving the desired objective with the lowest costs and risk of negative impacts (Stage III). Patches of different sizes, shapes, and spatial configurations could be simulated to determine the optimum combination of disturbances needed to increase site stability and promote vegetation change. An advantage of using a simulation model is that a number of different alternatives as well as a large range in parameter values can be investigated at a relatively small cost. More expensive and time-consuming field manipulations can then be focused on properties and processes which are currently poorly parameterized and which, based on the output of the current model, have a potentially large impact on the outcome.

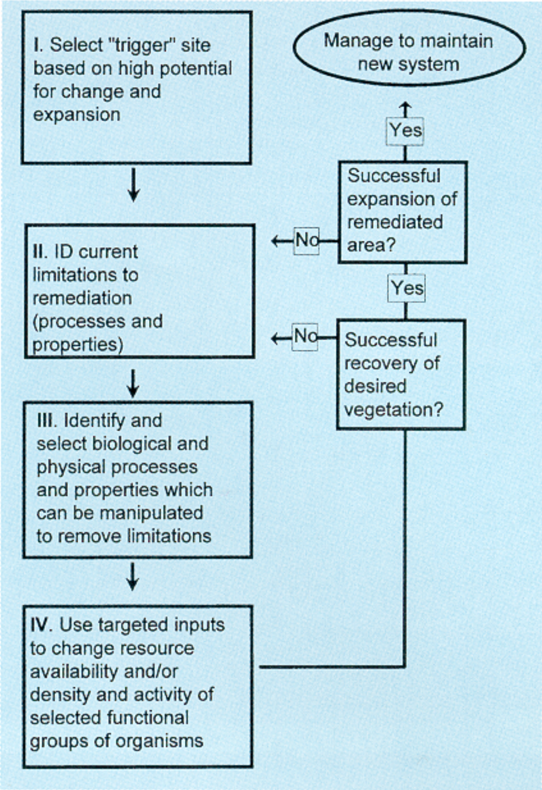

Figure 3. Conceptual model for development and application of an ecologically-based approach to rangeland remediation

Examples

There are a number of examples of how components of this new approach are being developed and applied (see, for example, recent work by Whisenant 1996). The following two examples draw on current work at the USDA, ARS Jornada Experimental Range in south-central New Mexico. They have been organized to follow Figure 3 using the roman numerals in each box as references.

Example: seed dispersal. Surface soils of many sites with a high potential for remediation based on soil and microclimate characteristics (I) commonly lack critical species in the seed bank. This can be caused by a lack of species in either adult or seedling populations, the relatively short life span of many of these seeds, and high soil erosion and deposition rates (II). Traditional seeding approaches are not cost-effective because they are expensive and because seeds are often consumed by predators including ants and rodents, or germinate prematurely in microsites or at times which are unfavorable for seedling establishment. However, seeds are generally distributed naturally to favorable microsites by wind, water, and animals (III). Water, livestock and rodents are all currently being explored as potential seed dispersal agents (Fredrickson et al. 1996).

The "gully seeder" (Figure 4; Barrow 1992) is designed to release seeds into a normally dry rill or gully only after sufficient rainfall has occurred to generate runoff and (in most cases) to saturate the soil (IV). The seeds are protected in the bottle from predators until the critical precipitation event. Many seeds are then deposited in potentially favorable microsites for establishment where litter deposition provides an insulating mulch, and nutrient and water availability are higher. This approach is unique in that it turns a normally negative feature of this dynamic environment (unpredictable and frequently extreme rainfall) into an advantage.

Animal dispersal of seeds can be enhanced by feeding the seeds directly to livestock (IV; Figure 5; Barrow and Havstad 1992). In addition to providing a source of nutrients, cattle dung patches effectively cap the soil, reducing temperatures and increasing soil water availability during dry periods. Kangaroo rats may also be used as effective dispersal agents by exploiting their inefficient caching behaviors (Fredrickson et al. 1996).

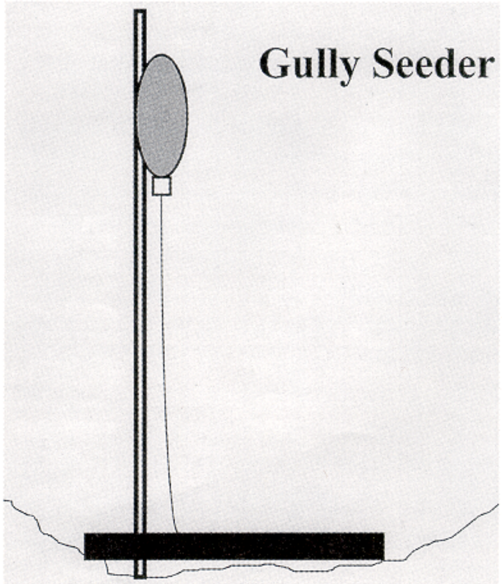

Figure 4. Diagram of gully seeder

NOTE: The seed-filled bottle is mounted upside-down on a fence post which is placed in an area of episodic water flow, such as an arroyo. The seeds are released when flowing water moves the log, pulling the stopper out of the bottle.

Figure 5. Seedling emerging from a cattle dung patch

Example: soil water infiltration. Shrub interspaces and devegetated sites on heavier-textured basin soils should have a relatively high potential for remediation based on high rates of run-on of water and nutrients from higher landscape positions (I). However, infiltration rates in these sites are so low that during intense storms, more water flows off than is received from precipitation alone, eliminating the potential to capture additional resources (II). Earlier experiments using machinery to create low (7.5 - 15 cm) dikes demonstrated that enhancing water infiltration can lead to significant increases in vegetative cover in these areas (Figure 6; M. Walton et al., unpubl. data). Infiltration can be increased by promoting biological processes which increase the density of surface-connected macropores, increase soil surface roughness and reduce the susceptibility to physical crusting. Soil-dwelling termites are ubiquitous in southwestern deserts and generate surface macropores which quickly conduct water into the profile (Figure 7; Herrick and Lal 1995), while lichens and other cryptogams can increase surface roughness and overcome soil physical crusting in unvegetated areas (III). Targeted applications of organic matter, including cattle dung, dairy manure and sewage sludge, may be used to trigger a rapid increase in infiltration rates (IV). Observations of several biosolids applications throughout the region, however, suggest that termite utilization of these materials may be limited by composition and physical structure.

Conclusions

The conceptual approach described here is not a panacea. Permanent (on a human timescale) losses of soil resources and invasion of highly competitive shrub species which may persist for decades in the soil seedbank may limit the range of possible endpoints. Effectively targeting limited inputs to favor processes which benefit one group of plant species over another requires a much greater knowledge of ecosystem processes than we currently have. Nevertheless, recent small-scale successes and a number of relatively unexplored options, including soil-plant-microorganism relationships, suggest that ecologically-based approaches have a high potential to cost-effectively promote remediation of degraded arid and semi-arid rangelands.

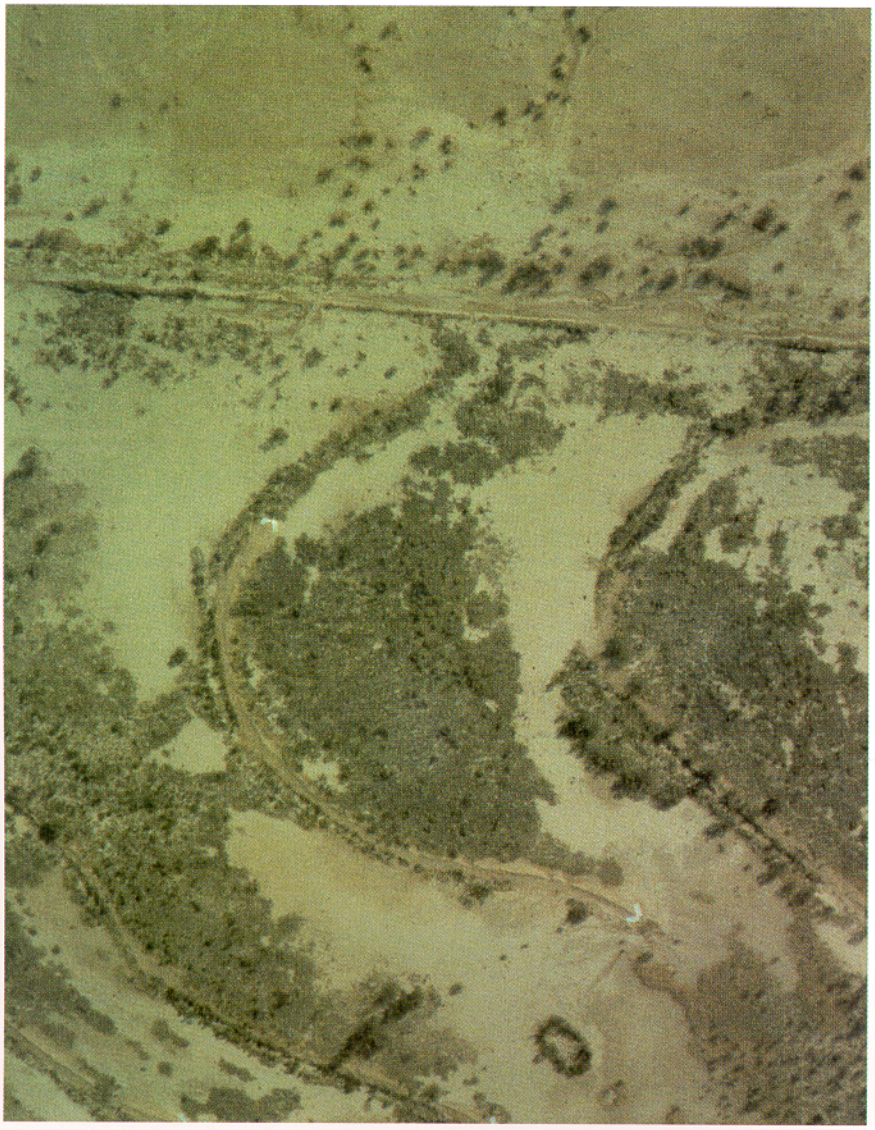

Figure 6. Vegetation establishment behind 7.5 cm-high dikes established along the contour in 1976

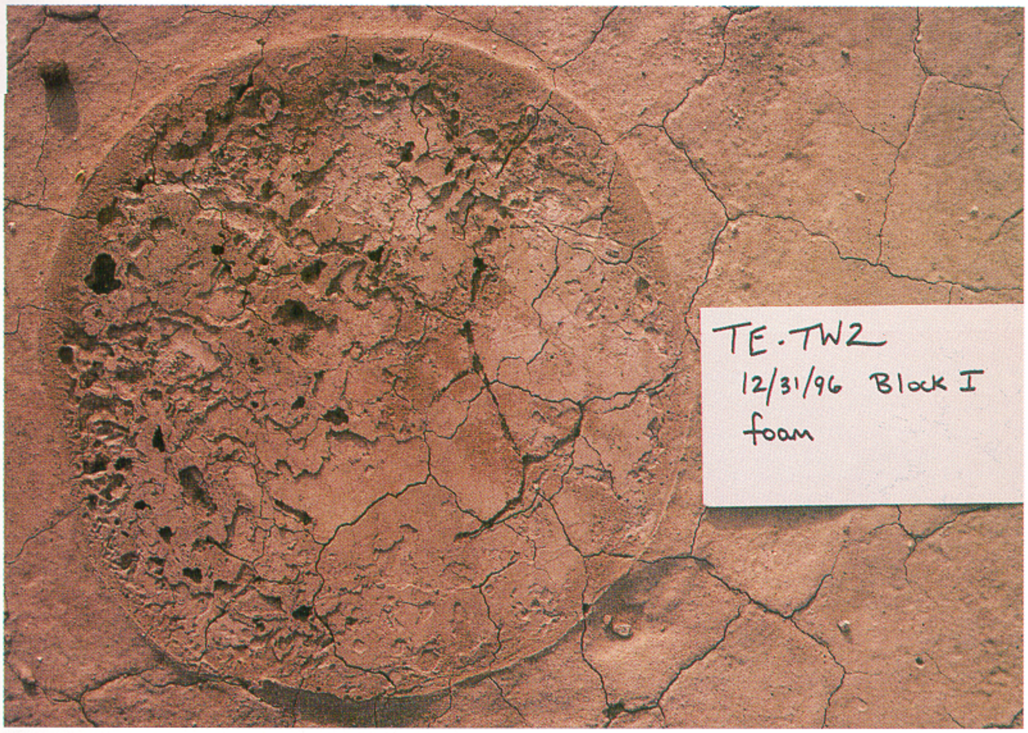

Figure 7. Macropores created by soil termites in a highly compacted soil

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