Steep Slope, In-Place Reclamation of Abandoned Coal Gob Piles in Sugarite Canyon, Raton, New Mexico

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The Sugarite gob (coal mine waste) reclamation projects, in which gob piles were reclaimed in place without significant earthmoving, are not geomorphic reclamation projects in the strict sense of the word. However, the in-place design approach is akin to a geomorphic design approach in that both methods work to create geomorphically stable landforms, albeit on different time scales. At Sugarite, rather than using earthmoving equipment to almost instantly shape mature geomorphic landforms, the power of nature, primarily in the form of precipitation, gravity, sunlight, vegetation, and other living organisms, is harnessed to slowly move the reclaimed landforms toward greater geomorphic stability and ecological functionality.

At Sugarite, this approach builds on and extends what nature has done through landsliding, erosion, and weathering of the steep gob piles since mining began in 1901 and ceased in 1944. Geomorphic design as compared to Sugarite in-place design might be analogous to the comparison between the Natural Channel Design (Rosgen, 1996) or GeoFluv™ design (GeoFluv, 2009) approaches where earthmoving equipment is used to shape restored stream channels and landforms, and the Induced Meandering method of letting “water do the work” to restore streams (Zeedyk & Clothier, 2009) (Zeedyk, 2009).

The historic Sugarite coal mines are located in northeastern New Mexico, about four miles northeast of Raton and three and a half miles south of the Colorado border in Sugarite Canyon State Park. Reclaimed areas encompass about 22 acres in five large and three small gob piles. The approximate center of the gob piles is at 36°56’38” N 104°22’57” W.

Sugarite Canyon State Park receives visitors attracted by its natural beauty and numerous recreational opportunities and those interested in mining history (Sugarite Canyon State Park). Park rangers and others conduct tours of the remains of the mining camp several times during the year and the mining camp and mining facility ruins are open for self-tours as well. A couple of the Park’s designated hiking trails with historic interpretive signage pass directly by some of the gob piles, which are also visible from the state highway that passes through the Park.

The original decision to reclaim the steep, dangerous gob slopes at Sugarite in place resulted largely from a directive from the New Mexico Historic Preservation Division (HPD) to avoid significant disturbance of the gob piles. HPD’s goal was to preserve the gob piles as historic landscape features at an important historic coal mining site, especially given its high public visibility in a popular State Park.

The decision for in-place reclamation also resulted from the design team's insight that the extremely narrow, steep walled Sugarite Canyon offered almost no opportunities to flatten slopes or reshape gob piles on-site and that full or partial removal of the gob piles to an off-site reclamation location would still leave the challenge of steep slope reclamation. The native soils that would have been uncovered have quite likely been chemically altered by decades of being overlain by gob materials. Therefore off-site reclamation would likely have been significantly more expensive than reclaiming the gob in place and would still have required in-place, steep slope reclamation of difficult soils.

<u>Design Challenges and Practices</u>

Some of the first design tasks were to determine the chemical and physical characteristics of the gob material, the gross landform stability of the gob piles, and the plant species that would be used to revegetate the gob material. It was also necessary to understand how cultural and climatic conditions at the site would affect the final design.

Gob materials at Sugarite are largely heavy clays weathered from shale removed from two underground coal mines on opposite sides of the canyon, with some coal and sandstone fragments. The gob exhibits a moderate degree of sodicity (sodium adsorption ratios, or SARs, are generally in the range of 11 to 43 and average 23.4), slight salinity (electrical conductivity ranges from 0.39 to 13.2 and averages 4.4 mmhos/cm), and slight acidity (pH ranges between 4.2 and 7.8 and averages 5.8). The material is high in clay content, ranging from 22 to 64 percent and averaging 39 percent clay.

Key factors limiting spontaneous vegetation establishment seemed to be:

(i) the sodic, collapsed clays on steep slopes, leading to rapid runoff of rain water, formation of numerous rills and gullies, sheet erosion, low levels of soil moisture storage, and a smooth soil surface with very few niches for seeds to sprout;

(ii) the black color of the gob, leading to extremely hot daytime soil surface temperatures in the summer; and

(iii) the gob's acidity in a semi-arid environment where native plants are better adapted to alkaline conditions.

A few native plants had managed to sparsely colonize the gob piles, most notably New Mexico locust (*Robinia neomexicana)*, rubber rabbitbrush (*Ericameria nauseosa*), and curlycup gumweed (*Grindelia squarrosa*), but not in sufficient cover densities to significantly reduce daily temperature variations of the gob surface or to ameliorate the difficult soil conditions.

The gob piles are very steep, with slopes averaging about 1.9:1. Significant portions of the gob piles face south, west and southwest, exacerbating high daily soil surface temperature variations and drying of the soil. All the larger gob piles exhibit signs of landsliding. Historic photographs indicate that gob landslides were occurring during mining operations (see photograph below). In fact two of the smaller gob piles were formed as the result of either landslides or mudflows from the larger gob piles above them. As indicated on historic aerial photographs, one major gob landslide occurred as late as the 1980s, indicating that the larger gob piles are continuing to destabilize through ongoing weathering of the shale and deep downcutting of gullies. Engineering analysis of slope stability, however, indicated that the gob piles are reasonably secure from further major mass wasting through landsliding.

Narrow, deep gullies with almost vertical banks had formed in every large gob pile, in places as much as 20 feet deep. The network of gullies had left the gob piles with drainage densities many times greater than that of the surrounding heavily forested landscape. Such high drainage densities indicate that runoff from the gob piles to Chicorica Creek was extremely flashy and rapid and carried high sediment loads from surface and gully erosion.

The semiarid continental climate at Sugarite is characterized by short, warm summers and long, cold winters. Precipitation averages about 20 inches annually, with most rainfall occurring in July and August, although weather records indicate that intense storms can also occur in late spring and early autumn. Elevations of the gob range from about 6,960 feet above sea level along the floodplain of Chicorica Creek to 7,280 feet near the now closed mine entrances on both sides of the canyon.

The main guiding principle adopted early in project design was to capture precipitation and slow runoff wherever possible and to infiltrate the water into the gob. In this way precipitation and runoff can support the vegetation that maintains the long-term erosional stability of the slopes, while guiding their geomorphic evolution to more stable forms and shapes. This process of geomorphic evolution is expected to take decades and perhaps longer for full expression as stable landforms.

Another major design principle was to build as much biodiversity into the reclamation as possible early on in the project. Vegetative biodiversity provides landscape resilience against the perturbations of drought, wildfire, hot summer temperatures, deep winter freezes, intense rainfall events, and herbivory by elk, deer, and rodents. Vegetative biodiversity also promotes soil microorganism diversity, diversity of animals that use the site both above and below the ground, and the cycling of nutrients by both wide and deep rooted vegetation. Using a wide range of species during seedling planting and seeding (see seedling and seed mix lists below) also addressed the initial uncertainty about which native plants could adapt to conditions on the gob piles.

Soil characteristics could be modified in the short term to allow for the initial few years of vegetation establishment by incorporation of gypsum and wood waste to counteract the gob's sodicity, lime to adjust for acidity, and slow release organic fertilizer to start nutrient cycling on the gob piles. Straw bales and other organic materials with high carbon-to-nitrogen ratios were placed primarily to slow, stop, and infiltrate rainfall and runoff. However such carbonaceous materials also serve as materials to counteract sodicity (by enabling leaching of sodium ions in the soil), provide mulch cover to reduce daytime soil surface temperatures, and provide carbon for soil fertility. A vegetative cover consisting primarily of deeply rooted trees, shrubs and forbs seemed necessary to reestablish nutrient cycling in the soil and reduce the potential for shallow land slipping through root reinforcement of the gob matrix (Gray & Leiser, 1982).

In the late fall of 1995 and early springs of 1996 and 1997, New Mexico Abandoned Mine Land Program (AML) staff conducted small scale trials using straw bales placed along contour on 20-inch wide, hand-dug terraces. Live, adventitious rooting cuttings, primarily a mix of locally sourced willow (*Salix*) species, with some narrowleaf cottonwood (*Populus angustifolia*), box elder (*Acer negundo*), and snowberry (*Symphoricarpos albus*), were placed along the terraces underneath and behind the bales. Although the bales clearly helped to infiltrate precipitation and runoff, the cuttings had difficulty coping with the sodic, slightly saline soils and droughty soil conditions and most died in the first year except in the most mesic areas of the gob piles. In 1996, small trials were conducted by packing gullies with dead branches, to slow water and enhance sedimentation in narrow gullies, while providing a carbon and nutrient source. These proved successful, as were initial trials of aspen excelsior sediment control logs in shallower gullies.

The pilot construction project in 1999 on two acres of Gob Site A2N was built on the experience and knowledge gained from the trial plots. Straw bale terraces were placed along contour at eight-foot contour intervals, with closely spaced plantings of one-year old, greenhouse-grown, native seedlings along the upslope edges of the straw bales. Native species that showed promise in being able to grow on the gob material were used. The larger and deeper gullies (from about four-feet to 20-feet deep) were packed with branches sourced from local ponderosa pine forest thinning operations. Twenty-inch diameter sediment control logs were placed in the smaller gullies on four- and eight-foot contour intervals. The site was hydroseeded with a bonded fiber matrix which, in a two-step application process, provided mulch for the seed first sprayed onto the slopes.

Straw bales seemed to work well on the flatter slopes. On slopes steeper than about 1.5:1, which comprised a good portion of the gob piles, the bales decomposed before the seedlings could become well established and, in some steep slope areas, the seedlings became smothered by gob materials eroded from upslope. Establishing vegetation through hydroseeding also showed limited success, although the solutions to better establishment were initially unclear. No seedlings were planted at the sediment barrier dams and very few seeded plants established in the gullies, indicating that something needed to be done to better stabilize the shallower gullies.

<u>Reclamation Discoveries</u>

Subsequent projects were built on the successes and failures of the techniques tested in earlier phases of work. There were several significant discoveries made during the evolution of steep slope, in-place gob reclamation. One was that the eight-foot vertical spacing for on-contour barriers, such as straw bales, with seedling plantings was too great and needed to be reduced to four-foot contour intervals, with exception of the flattest slopes. Too much runoff was generated between the barrier rows, leading to seedling washout or burial in sediment and to bare eroding slopes between the rows of straw bales. The excelsior sediment barrier dams spacing also needed to be tightened from four- and eight-foot to two-foot contour intervals and planted with seedlings for improved vegetative success in gullies. These final vertical spacing parameters for vegetative erosion barriers are similar to spacing guidelines developed in the field of soil bioengineering (Gray & Sotir, 1996).

Trials of 12-inch diameter coir (coconut husk fiber) rolls, as a replacement for straw bales on slopes steeper than 1.5:1, indicated that they were a good substitute. Coir rolls are better able to cope with the higher velocity runoff on those slopes, last significantly longer, and lead to better establishment and vigor of the seedlings planted along their upper edges. Six-inch diameter coir wattles (wattles are packed less densely with coir than rolls) were placed just above the rows of seedling plantings at coir rolls to protect them from upslope sediment.

But even coir rolls were found to have their limits. On slopes steeper than about 0.75:1, excavation of the narrow terraces needed for their installation quickly led to shallow land slipping that wiped out the coir roll terraces and their seedling plantings. In 2011 at one area with significant areas of slopes steeper than 0.75:1, the AML Program experimented with the use of rectangular coir blocks, nine inches by sixteen inches in cross-section, staked directly onto the slope without terracing, on contour at three-foot vertical spacing, and with plantings of seedlings immediately above them. Initial results have been encouraging and a second installation of coir blocks at the 1980s gob landslide scarp was completed in 2013.

Watering the seedlings for two to three months after planting in the spring significantly increased six-month survival rates (from 56% in the pilot project, where they were not watered except at the time of planting, to between 67% and 87% in later phases of work). Placed at ten and twelve inches on center along coir roll and straw bale terraces respectively, the average density of planted seedlings is about three thousand seedlings per acre. More New Mexico locust was planted than any other species of tree or shrub. There are several reasons for this: New Mexico locust had already proven its ability to thrive on the gob piles prior to reclamation; it provides good erosion control because exposed roots will sprout; surviving root crowns and rhizomes will sprout following fire; and its scrubby, thorny nature discourages visitors to the State Park from climbing on the steep and dangerous gob piles.

The AML Program also learned that to be successful in establishing vegetation on the gob by hydroseeding it was necessary to incorporate gypsum and wood waste into the gob beforehand. This was first tested on one of the few flat slopes accessible by machinery and later utilized over much larger areas, primarily by hand incorporation, to a minimum of six inches. For worker safety, hand incorporation of amendments was limited to slopes 1.5:1 and flatter.

Another important observation was that concentrating vegetation in gullies was essential to overall success in erosion and sediment control. Heavy growth of vegetation could be achieved in the naturally wetted gully bottoms and serves to slow runoff and filter sediment out of storm flows. This sediment buildup is slowly raising the base of the gullies while the steeper, generally higher and more erodible parts of the landform are dropping in elevation, leading to a slow smoothing and rounding off of the landforms.

Now 15 years after the first trials on the gob and several construction and maintenance projects between 1999 and 2013, vegetation has become well established on the gob, erosion has been significantly reduced, and natural cycles continue to reshape the gob to more stable forms. Coal fragments and fans of black clay deposits are now difficult to find in Chicorica Creek at the base of the gob piles.

A few years after work began, beavers moved in to build and maintain at least three ponds along Chicorica Creek below the gob pile furthest upstream. The Creek and small lakes upstream are stocked with trout and Park Rangers have commented that fishing in the creek below the gob piles has noticeably improved since reclamation began. The steep banks of the deepest gullies in the piles remain bare but some flattening of the gully side slopes is beginning to be seen. All but the deepest and narrowest of the gullies planted with seedlings exhibit a dense cover of vegetation and are often flanked by bare, steep gob banks full of rills episodically feeding sediment into the bottom of the gullies. It will be interesting to compare how the branch-packed gullies without vegetation evolve over time compared to gullies with vegetation plantings.

Effects of Drought

Since beginning reclamation work, the project site has withstood several years of drought and a storm event with rainfall totaling about three-inches on October 12, 2008 (Western Region Climate Center, 2013). Intensity and duration of that storm are unknown, although the 10-year, 24-hour storm event at the site is 3.29 inches (NOAA National Weather Service).

Recent drought years include 2002, which was the worst drought year for forests in the Southwest United States in the last 1,000 years as measured by the Forest Drought Stress Index (FDSI). In the Southwest, the FDSI is a function of pre-growth season precipitation in November through March and air temperatures (or more precisely, vapor pressure deficits) in the previous August through October and in May through July during the growing season. FDSI is estimated through correlation with tree ring analysis. Other recent years of high regional FDSIs include 2006, 2011, and 2012 (Williams). With the trends for continued warming in the Southwest and perhaps for a moderate decrease in precipitation, it is likely that drought stress on trees (and other vegetation) will continue to increase.

Except perhaps in 2006, when records indicate near normal precipitation (see table below), this regional drought stress seems to have been expressed locally at Sugarite. Regional drought stress may be locally muted in Sugarite by its deep, narrow canyon setting and cold air drainage effects. Despite the recent drought, good reclamation results have been achieved, at least visually, including establishment and growth of vegetation and diminishment of erosion and sedimentation. Note that no scientific measurements of reclamation results, other than six-month survival analysis of planted seedlings, have been taken. The most visible impact of drought was some dieback of New Mexico locust on the gob piles noted in 2012.

Table 1: Annual Precipitation Records at the Nearest Two Official Weather Recording Stations during Years of Reclamation Activities (Western Region Climate Center, 2013)

Year	At Raton Filter Plant (inches)	At Lake Maloya (inches)	Average of Two Weather Stations[1] (inches)
1999	22.11	28.77	25.44
2000	16.00	18.68	17.34
2001	14.08	13.40	13.74
2002	12.45	17.76	15.11
2003	14.10	17.39	15.75
2004	28.74	27.70	28.22
2005	20.54	22.01	21.27
2006	21.90	20.26	21.08
2007	13.97	20.86	17.41
2008	15.81	19.02	17.41
2009	14.80	19.15	16.98
2010	18.82	20.41	19.62
2011-13	*	*	-
Annual Average[2]	17.62	22.98	20.30

[1] Calculated values. Note that the Sugarite reclamation site is approximately halfway between the two weather stations.
[2] Average total annual precipitation for periods of record: 1953 to 2012 at Raton Filter Plant and 1942 to 2012 at Lake Maloya.
*Records are incomplete in 2011, 2012, and 2013.

The Track Wildfire of June 2011, which burned several thousand acres of forest and grasslands near Raton, came within 130 yards of the northernmost reclaimed gob pile in Sugarite Canyon and required that the construction contractor evacuate the job site for two weeks. Fortunately it did not burn across the Sugarite gob piles.

It is clear that this style of reclamation is vulnerable to fire during establishment of vegetation, particularly because of its reliance on heavy inputs of high carbon materials, particularly straw bales, coir rolls and wattles, and gully packing with dead branches. The AML Program became acutely aware of fire's potential impact on the Sugarite reclamation when this same wildfire burned through one corner of a small gob reclamation site in nearby Yankee Canyon. There coir rolls and straw bales placed several years before burned, killing almost all of the seedlings planted along them. Once these carbonaceous materials decay, the reclaimed landscape should become significantly more fire resistant, particularly because surviving root crowns and rhizomes of the heavily planted New Mexico locust sprout following fire (USDA Forest Service).

Major Lessons

I believe that the primary lesson of the Sugarite gob reclamation projects that is applicable to geomorphic reclamation and disturbed land reclamation in general is the importance of understanding how water moves and wants to move across a particular landscape, both along and below its surface. I suggest that we, as reclamation designers, do everything reasonable to slow water movement on the landforms we are establishing to maximize infiltration into the soil, both at the time of initial reclamation efforts and in the long-term. Properly designed, mechanisms that slow and infiltrate water maximize water and mineral cycling (Ripl & Eiseltova, 2010; Tane, Catchment Habitats and Landscape Ecosystems; Tane, Landscape Ecostructures for Sustainable Societies; Tane, Terraquaculture). Especially in a landscape with diverse aspects and degrees of slope, slowing and lengthening the movement of water through landforms encourages the growth of a diverse cover of vegetation, which shades and mulches the soil and protects it from erosion. On steep slopes, woody vegetation also reinforces the soil mass against shallow landsliding.

Secondly, a diverse vegetative cover combined with increased water storage in soils and landforms become key components in establishing sustainable, resilient, and drought resistant landscapes. Diverse vegetative cover promotes proper cycling and recycling of water and nutrients, the damping of daily surface and near surface temperature variations, and the dampening of soil and air moisture level fluctuations. Vegetation and slow water movement on reclamation landscapes also aid in the capture, redistribution, and use of the fertility moving onto the reclaimed sites from forested areas above them through leaf, bark, and needle fall.

I believe that reclamation designers can do more to incorporate these concepts into their designs. Provisions to slow and lengthen flow paths of water across reclaimed landforms, both above and below the surface, can be made everywhere. Where feasible, the major drainages can be lined with shrub and tree vegetation, floodplains reconnected to their stream channels and rehydrated, and small ponds and wetlands established (Berger & Brown, 2008) to slow water movement and to provide long-term water storage and natural fertility management on a landscape scale. Trees and shrubs in riparian zones serve to secure the banks of streams and water bodies, shade the water, filter run-off before it enters the stream, and provide habitat.

Forested areas, with a preponderance of deciduous trees where possible, can be established on hilltops and ridges in reclaimed landscapes (where not already present as they are at Sugarite) as a long-term source of nutrients for the reclaimed land below them. Living things (i.e., bacteria, fungi, protists, plants, and animals) in, on, and above the soil will also create and distribute fertility across the landscape. Many animals, including wildlife and livestock in some instances, will carry fertility from the lower, better watered areas of the landscape to the higher, forested parts through their daily movement from water and browse to upper shaded resting areas.

In short, slowing, infiltrating, and storing water in the soil and in small impoundments and the use of diverse landforms and vegetation types should be primary components in the design of mined and disturbed land reclamation to provide resilient reclamation landforms and vegetative covers that are better able to respond to perturbations, that moderate microclimates, and that increase connectivity to the surrounding landscape.

Table 2: Primary Species Planted as One-Year Old Seedlings at Sugarite
(10-cubic-inch containers and bareroot)

New Mexico locust (*Robinia neomexicana*)
Four-wing saltbush (*Atriplex canescens*)
Skunkbush sumac (*Rhus trilobata*)
Woods rose (*Rosa woodsii*)
NM Forestiera (*Forestiera neomexicana*)
Rocky Mt. juniper (*Juniperus scopulorum*)
Ponderosa pine (*Pinus ponderosa*)
Curl-leaf mountain mahogany (*Cercocarpus ledifolius*)
Piñon pine (*Pinus edulis*)
Gambel oak (*Quercus gambelii*)
Chokecherry (*Prunus virginiana*)
Native plum (*Prunus americana*)
Shrubby cinquefoil (*Potentilla fruticosa*)
Douglas fir (*Pseudotsuga menziesii*)
Serviceberry (*Amelanchier alnifolia*)
Mountain snowberry (*Symphoricarpos oreophilus*)

Table 3: Primary Species Seeded at Sugarite
Grasses:
Sideoats grama (*Bouteloua curtipendula*)
Blue grama (*Bouteloua gracilis*)
Bottlebrush squirreltail (*Elymus elymoides*)
Thickspike wheatgrass (*Elymus lanceolatus ssp. lanceolatus*)
Slender wheatgrass (*Elymus trachycaulus ssp. trachycaulus*)
Newhy hybrid wheatgrass (*Pseudoroegneria spicata x Elytrigia repens*)
Arizona fescue (*Festuca arizonica*)
Great Basin wildrye (*Leymus cinereus*)

Beardless wildrye (*Leymus triticoides*)
Switchgrass (*Panicum virgatum*)
Western wheatgrass (*Pascopyrum smithii*)
Galleta grass (*Pleuraphis jamesii*)
Bluebunch wheatgrass (*Pseudoroegneria spicata ssp. spicata*)
Little bluestem (*Schizachyrium scoparium*)
Alkali sacaton (*Sporobolus airoides*)
<u>Forbs:</u>
White yarrow (*Achillea millefolium*)
Purple prairie clover (*Dalea purpuresa var. purpurea*)
Maximilian sunflower (*Helianthus maximiliani*)
Sulphur-flower buckwheat (*Erogonum umbellatum*)
Winged wild buckwheat (*Erogonum alatum*)
Birdsfoot trefoil (*Lotus corniculatus*)
Rocky Mountain Penstemon (*Penstemon strictus*)
Mexican Hat (*Ratibida columnifera*)
Scarlet globemallow (*Sphaeralcea coccinea*)
<u>Shrubs:</u>
Fringed sagebrush (*Artemisia frigida*)
Prairie sage (*Artemisia ludoviciana*)
Fourwing saltbush (*Atriplex canescens*)
Winterfat (*Krascheninnikovia lanata*)

<u>Note:</u> In recent seeding at Sugarite, the AML Program has experimented with including deep rooted, annual tillage radish (*Raphanus sativus*) in the seed mix to reduce soil compaction through biological tillage. After a season of growth the radishes are winter killed and, as they decompose, they increase soil organic matter and leave holes in the surface that allow water and air to infiltrate the soil.

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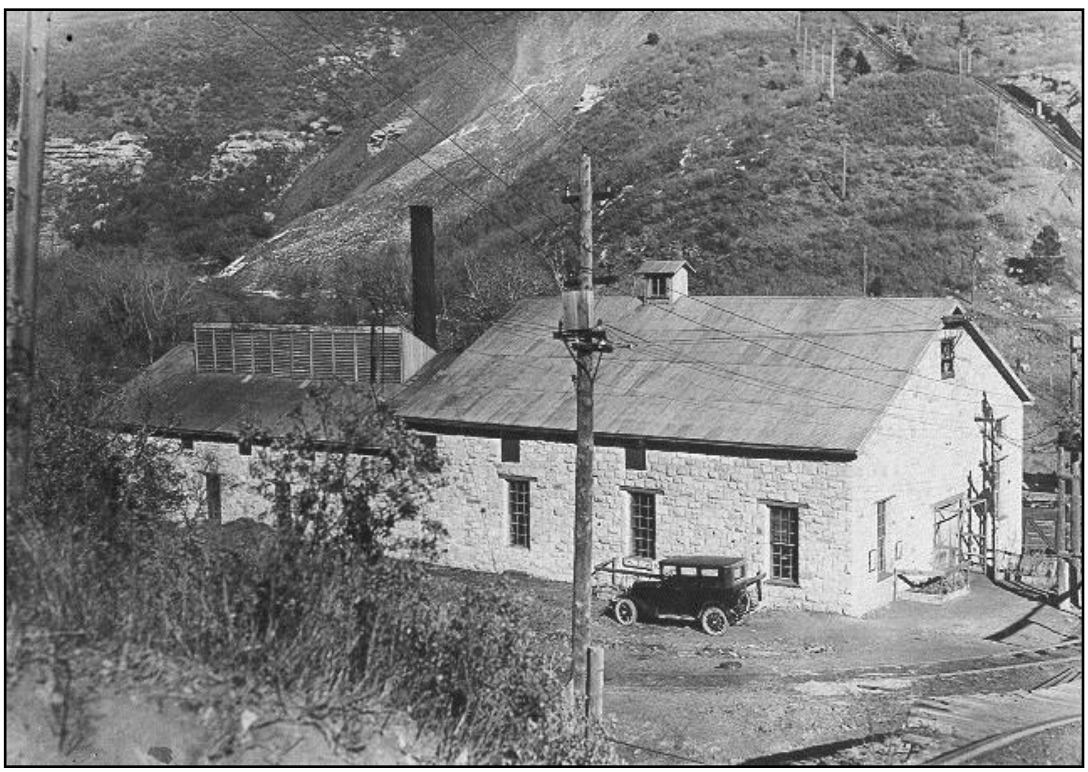
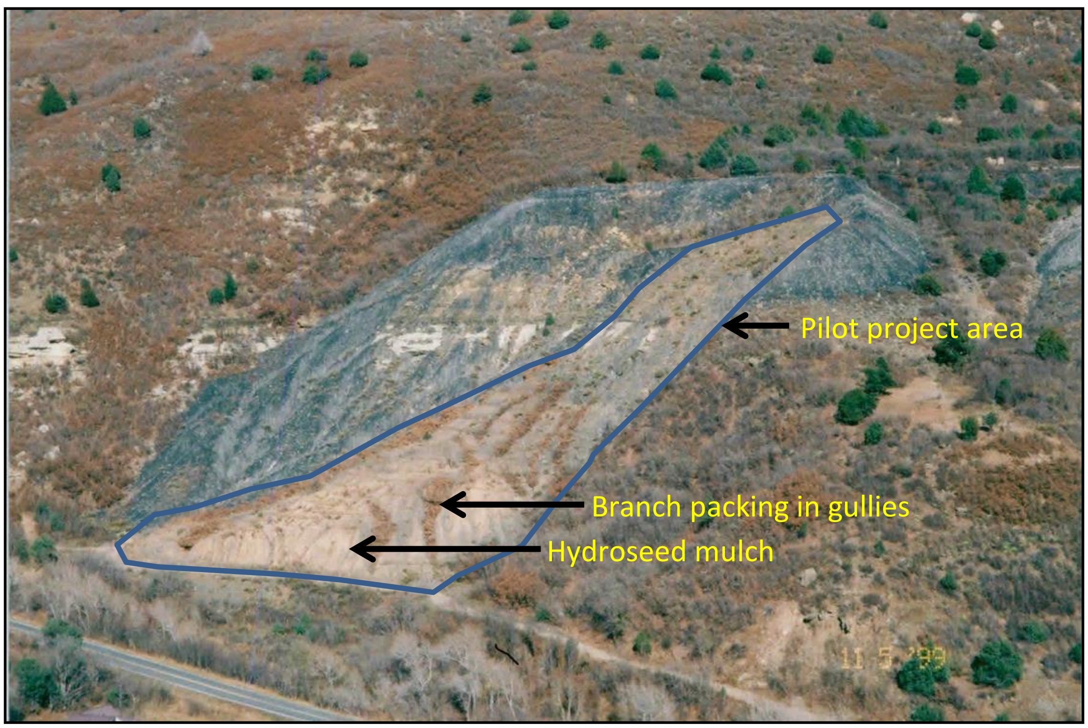
<u>Photographs</u>

Sugarite coal miners, ca. 1918



Historic photo of the power house at Sugarite, no date.
Note the landslide at Gob Site A2N visible in background.

Trial installation on Gob Site A2N of straw bales with live cuttings
at the base of the bales a few months after installation, 1997



Gob Site A2N reclamation a few months after completion of pilot project, 1999

Branch packing in large gully, looking upstream, 1999

Branch packing at same location, 2010

Newly installed branch packing in small, deeply incised gully, looking upstream, 2005

Aspen excelsior sediment logs in gully and straw bale and
coir roll terraces on gob slope prior to seedling planting, 2010

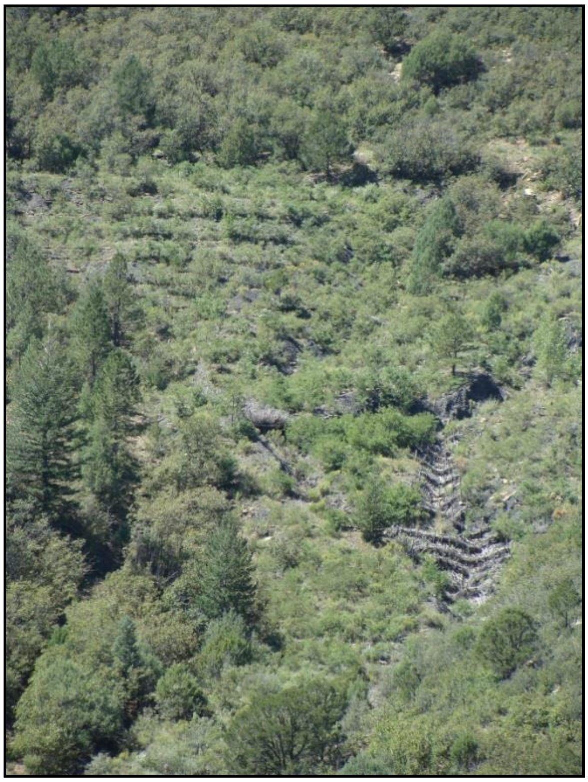
Coir block and coir roll installations on extremely steep slope prior to seedling planting, 2011

East-facing Gob Site A1, August 2001


Gob Site A1, September 2010

West-facing Gob Site A2N during pilot project, 1999

Gob Site A2N, 2011



Close-up of Gob Site A1, 2010

Gully with sediment logs, 2010

Close-up of Gob Site A2N, 2010

Closely spaced seedling plantings along straw bale terrace, 2010

Yellowing of leaves and dieback of New Mexico locust, July 2012

Coal gob in Chicorica Creek, 1997

Same location in Chicorica Creek, 2006.
Vegetation has since nearly completely covered the gravel bar.

Animal impact on mineral cycle, Gob A2N, 2010

Beaver pond in Chicorica Creek below Gob Site A2N, 2010