LESSONS OF STEEP-SLOPE REVEGETATION FROM THE GOLDEN SUNLIGHT MINE, MONTANA[1]

R. A. Prodgers[2]

Abstract. Effective revegetation on 50% slopes is possible in a semiarid climate. Placer Dome's Golden Sunlight Mine in southwest Montana was a pioneer in 2H:1V slope revegetation. Elements of satisfactory revegetation include nearly two-foot-thick coversoils that combine 30% to 50% rock content for erosion resistance with good texture for plant growth, short-term erosion-control measures such as benches and properly aligned dozer basins, a seed mix that balances strong-establishing species with persisting ones, and seeding equipment that churns and harrows the ground surface following broadcasting. Nitrogen-fixing symbioses also can be important both to increase cover to limit erosion and by increasing productivity and transpiration – important considerations when acid-producing mine waste rock underlies the coversoil. Since steep slopes must be worked almost normal to contours, remedial measures to improve unsatisfactory revegetation are limited when compared to slopes of 3H:1V or less. This makes steep-slope revegetation very dependent on initial revegetation establishment, where weather plays an important role. Since weather during the establishment phase is beyond control, steep-slope revegetation cannot be assured. However, the practices and materials discussed here have proven themselves at the Golden Sunlight Mine.

Additional Key Words: mine reclamation, plant cover, coarse fragments, coversoil, dozer basins, erosion control.

---

[1]Paper was presented at the 2003 National Meeting of the American Society of Mining and Reclamation and The 9th Billings Land Reclamation Symposium, Billings, MT, June 3-6, 2003. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502

[2]Richard A. Prodgers, Plant Ecologist, Bighorn Environmental Sciences, 610 Monroe Ave., Dillon, MT 59725.

Proceedings America Society of Mining and Reclamation, 2003 pp 992-1004
DOI: 10.21000/JASMR03010992

https://doi.org/10.21000/JASMR03010992

Introduction

Placer Dome's Golden Sunlight Mine in Jefferson County, Montana, is one of the pioneers and most skillful practitioners of 2H:1V (50%) slope reclamation on a large scale. This practice usually is associated with waste dump reclamation, starting with waste rock at angle of repose. Reclamation entails regrading the waste rock dump, applying suitable coversoil, taking immediate erosion-control measures, and seeding and fertilizing the slope.

When first proposed over one decade ago, numerous reclamation experts predicted that it could not be done, especially over acid-producing waste rock. They were wrong. It is fair to say, however, that the usual factors associated with revegetation successes and failures in semiarid climates play even more critical roles on steep slopes. This paper discusses some of the practices and plant materials that have contributed to Golden Sunlight's successes, and also the roles of aspect and nature, which cannot be discounted.

In steep-slope revegetation, most practices and materials have both beneficial and negative consequences, which makes it difficult to devise an optimal strategy.

Methods

Although this paper is primarily about practices and materials that have been used successfully at one mine, some revegetation monitoring results are included. The 1990 monitoring was done by mine personnel but methods weren't fully reported. I have tried to use the most pertinent and reliable data. In 2001-2002 monitoring conducted by the author, canopy coverage (Daubenmire, 1959) was estimated to the nearest percent (or as close as possible) in 0.5 m^2 frames systematically placed along "permanent" transects marked by pairs of steel fenceposts. Most transects were 100 m long (328 feet), but transects as short as 90 m (295 fet) were used where field size or configuration required a shorter transect. Each transect was sampled on the left side at 5-m (16.4 feet) intervals, with up to two additional plots randomly located to achieve equal sample sizes of 20 frames/transect in each field. Woody species plant densities were measured but are not reported here.

The Shannon index (often interpreted as equitability or evenness; see Shannon and Weaver, 1949) was calculated from relative cover values using natural logs.

SHANNON INDEX $H' = -\Sigma p_i \ln p_i$

Where: p_i is the relative cover expressed as a decimal.

The unitless numbers take on meaning when compared to native reference vegetation.

Advantages and Disadvantages of Steep Slope Reclamation

Within the context of hardrock mining, the three main advantages of steep-slope reclamation are:

- Reduction in the need for coversoil, assuming equal thickness on slopes of varying pitch. Because soils are often thin in natural settings associated with mineral deposits, the amount of coversoil needed for reclamation may exceed that available in stockpiles. This can require "mining" coversoil off-site, which in a sense exports some impacts while requiring revegetation of the borrow area. Moreover, borrow material from lesser slopes may not have the desired characteristics for steep-slope revegetation.
- The footprint of waste dumps can be minimized through steep-slope reclamation. This minimizes impacts to adjacent healthy lands that otherwise would be buried. Sedimentation from the slopes has been inconsequential in comparison.
- Due to a minimized ratio of slope area to waste rock, the amount of precipitation incident upon the waste dump is minimized compared to lesser slopes. If the waste material is potentially acid-producing when water and oxygen are available, decreasing effective precipitation is a benefit in one respect, although less precipitation is disadvantageous for plant establishment and growth. Steeper slopes also promote more runoff, especially if poorly vegetated. If the waste-rock material is potentially acid-producing, any water that infiltrates and percolates into the dump interior can result in acid production and drainage.

Steep-slope reclamation and revegetation have numerous risks, special requirements, and disadvantages:

- The short-term and long-term potential for soil erosion is great, requiring specific coversoil properties (e.g., rock content, texture) and reclamation practices (e.g., benches, dozer basins).

Golden Sunlight has shown that 2H:1V slope revegetation can limit soil erosion to less than one ton/acre/year (Meissner, Pers. Comm., 2001) based on RUSLE 1.06 (Toy and Foster, 1998).

- Related to the erosion potential, seed mixes must favor strong-establishing species. Often this translates into seeding aggressive introduced species. Permanence is a concern for these species.
- Special seeding equipment is needed to negotiate 2H:1V slopes. Some form of broadcasting is usually the only option.
- The usual effects of aspect are enhanced; on warm aspects it can be very difficult to initiate and maintain satisfactory revegetation.
- Repair can be difficult, requiring hand labor where the use of heavy equipment destroys revegetation.
- Equipment can be run only approximately uphill/downhill. Golden Sunlight Mine has patented a counterweight that fits on the back of a dozer to stabilize it on steep slopes while grading slopes.

Conditions and Practices at the Golden Sunlight Mine

Precipitation at the mine is measured at the facility complex, which lies at about 1,585 meters (5,200 feet) elevation east of a ridge that divides the gold mine. Here precipitation for the past 15 years has averaged 36 cm (14.1 inches), with 12 cm (4.9 inches) occurring in May-June. Probably some of the early west-facing revegetation at elevations of 1,740 to 1,950 meters (5,700 to 6,400 feet) gets a little more average precipitation.

The west-facing slopes are extremely windy, which can impose a severe practical limitation on broadcast seeding. On many days, at least for several hours, effective seeding is impossible. The seed is not merely displaced several meters with no net effect. Instead, winds may be so extreme that some light or fluffy seed and even some mid-weight seed is transported completely outside the target area.

Slope Covers and Construction Practices

Steep-slope revegetation begins with suitable coversoil. A coarse fragment content of 30-50% by volume is desired to limit erosion, but material of about 25% rock content has been used successfully. Coarse fragments should be predominantly gravel with some cobbles. The strongly angled rock fragments associated with bedrock ore deposits are particularly effective in erosion control. Having lots of rock fragments in the soil has a downside: the rooting volume and water-holding capacity of the soil are reduced. Coarse fragments limit soil erosion until an effective plant cover is established and may promote germination of seed at the edges of the coarse fragments. The coversoil must be worked while relatively dry or excessive compaction of the near-surface zone can prevent good plant establishment.

Rock content should be complemented with a texture that promotes good revegetation. The textures present on the slopes discussed in this paper are predominantly good sandy loams with 14-19% clay and secondarily light sandy clay loams with little more than 20% clay.

In some instances, a lime layer or capillary break may be necessary to prevent acidification of the coversoil. Most of the steep-slope revegetation mentioned later in this report was associated with a two-foot layer of coarse oxidized waste rock over sulfide-containing material, with 48 cm (19 inches) of coversoil above the oxide layer. (In practice, the thickness of coversoil was variable and usually exceeded the nominal amount.) The oxide layer was chosen to prevent acidification of overlying coversoils by capillary rise from the sulfide below; to prevent root contact with acid-generating material; and to prevent direct exposure of the sulfide if the entire coversoil eroded away. Later, regulators required that the mine use 60 cm (two feet) of oxide and two feet of coversoil.

Later monitoring showed that acidification of coversoil was minimal even without the oxide layer, and oxidized waste rock was in short supply. Mining more oxidized waste rock would involve additional impacts. The mine proposed replacing the 1.2 meter-thick (four-foot) cover with 0.9 meters (three feet) of coversoil and no oxide layer, citing increased water-storage capacity and greater rooting depth, thus favoring plants in a semiarid environment and minimizing percolation of soil water into underlying acid-generating materials. It is rare for even 0.6 meters (two feet) of coversoil on a 50% slope to be wet to the base in a semiarid climate. A 0.6 meter-thick (two-foot-thick) coversoil of 30-50% rock content is probably a conservative design for 2H:1V slope revegetation.

As soon as the coversoil is placed on the slope, it is susceptible to erosion. When a significant section of slope (the area between benches) is coversoiled, dozer basins are installed immediately. Properly built dozer basins can be very effective in limiting erosion on 2H:1V slopes of about 140 meter (450 feet) length; at the Golden Sunlight Mine they are considered essential. Properly designed and constructed dozer basins are constructed with as straight a dozer blade as possible; U-shaped blades designed to push dirt more effectively result in basins that are deepest at the outer edges. The other essential is that the outer rim of one basin must align vertically on the slope with the central third of the basin downslope. If not properly staggered, a cascade failure can cause gullies.

Sloped benches that intercept overland flow should be located every 60 vertical meters (200 feet) or closer. Some benches at GSM are lined to further channel water off the slope and a French drain is constructed at the inner edge of the bench to transport water off the slope. Water that may pond on a bench above the slope cannot be allowed to exit via the slope.

Revegetation

Without effective revegetation, rocky coversoils become rock pavements, and dozer basins are effective only until they fill with sediments. Because they establish so reliably and have great seedling vigor, the mine relies heavily on introduced grasses. The two most effective grasses in good 2H:1V revegetation at the Golden Sunlight Mine have been crested wheatgrass (*Agropyron cristatum*) and sheep fescue (*Festuca ovina*), both bunchgrasses. Use of crested wheatgrass was later forbidden due to its alleged competitive exclusion tendencies, but its tendency to assume dominance on steep slopes is limited to warm aspects and may be a result of its drought tolerance. It was replaced in seedings by drought-tolerant varieties of pubescent/intermediate wheatgrass (*Thinopyrum intermedium*), such as Mandan and Oahe. They have been partially successful -- but not equally as effective as crested wheatgrass on a variety of sites, although a rhizomatous grass.

Nurse crops usually impede the establishment of perennial species, but they may be necessary on 2H:1V slopes, further highlighting the need for strong-establishing perennials that can endure the competition. Ten or more pounds of barley seed per acre are included in seed mixes for steep slopes. However, the usual first-year weeds (Kochia (*Kochia scoparia*), Russian thistle (*Salsola iberica*), and lambsquarter (*Chenopodium album*)) may be equally effective in controlling erosion while sharing the negative attributes of nurse crops.

Mixing alfalfa with the grasses increases cover, production, transpiration, nutrient-cycling, and palatability. It was seeded in all the revegetation discussed in this paper and complements the usual grasses in rooting habit. The mining company also seeds sweetclover (*Melilotus officinalis*) which, while an invasive species some places, tends to peak the second year and subsequently declines or disappears in revegetation.

Other than legumes, forbs play a minor role in revegetation. Probably the most easily established native forb is yarrow (*Achillea millefolium*), which establishes readily despite its light seed and can contribute to erosion control. Forbs such as blue flax are ineffective for erosion control. Mountain big sagebrush (*Artemisia tridentata* var. *vaseyana*), rubber rabbitbrush (*Ericameria nauseosa*), and fourwing saltbush (*Atriplex canescens*) have been seeded. Saltbush usually establishes best, sagebrush worst. Success with conifer transplants has been slight.

Plant cover and diversity are summarized for five 10-year-old fields in Table 1. Revegetation equaled or exceeded the native reference stands in cover, but not diversity. Revegetation is not undergoing a noticeable amount of "succession."

Seeding is done straight normal to slope contours with a modified Caterpillar tractor. On front is a broadcaster. Fertilizer is mixed with the seed to promote good flow, although it necessitates more frequent filling. On a mass basis, the ratio of fertilizer to seed is about 5:1. The three-feet-wide tracks churn the coversoil. A chain harrow follows. Thus, some seed is on the ground surface, some is shallowly buried, and some is pressed into the ground while some is not. Seeding is usually done from fall to spring when slopes are snow-free.

Climatic Effects

The early 1990s seedings showed that steep-slope revegetation could be successful. For the next half-dozen years, most revegetation was done on benches or 3H:1V slopes. From 2000 to 2002, a major effort was made to finish steep-slope revegetation on over 162 hectare (400 acres) on the west side of the mine, most of it west-facing with some south-facing slopes. Elevations were lower than previous steep-slope revegetation.

Table 1. Reference area and revegetation area summary, Golden Sunlight Mine, 2001. (Reclaimed slopes have 2H:1V slopes and 48 or more cm (>19 inches) of coversoil over 0.6 meters (two feet) of oxide waste rock.)

SITE	PERENNIAL COVER TOTAL	GRASSES	LEGUMES	SPECIES RICHNESS	SHANNON
	--------% Canopy Coverage----------				
L. Half 6200-6300 Test Plot 2	65	41	22	19	1.79
6200 Test Plot 3b	59	40	19	11	1.73
U. Half 6300 Test Plot 2	66	42	23	11	1.67
6300 Test Plot 1	79	34	42	10	1.33
6400 Test Plot 4c	69	41	11	13	1.77
Average	68	42	23	13	1.66
Reference Area 1	64	36	--	21	2.03
Reference Area 2	49	36	--	22	1.96

Recent plant establishment on steep slopes has been less satisfactory than in the earlier years. Perennial seedling densities are sometimes less than one plant per 0.1 square meters (one/ square foot) now compared to four or more plants per 0.1 square meters in early revegetation. The site cannot sustain more than one or two to three plants per 0.1 square meter, but it is better to start with too many than too few.

If anything, planting practices and materials have improved -- except that crested wheatgrass is no longer allowed by regulators in the seed mix. I was asked to evaluate why recent revegetation establishment is inferior to the earlier efforts. This is not a test study and a statistical approach is unwarranted, but it became clear that early revegetation had been remarkably lucky in terms of annual and seasonal (May-June) precipitation, whereas recent revegetation was initiated in a series of dry years.

Table 2. Seasonal Precipitation During the Establishment Phase for Select 2H:1V Fields.

YEAR SEEDED	MAY+JUNE PRECIP.*		DEVIATION FROM NORMAL	FIELDS
Spring 1991	6.3”	16 cm	+28%	High-Grade Test Plots, 5970 Plot B
Fall 1992 Spring 1993	6.8”	17 cm	+38%	Northwest all 6400, 6300 Upper Test Plot 2, 6200 Test Plot 3b, South 6000 Slope Plot A, 5950 Plot D
Spring 2000	4.1”	10 cm	-16%	5200-5700 South Dump,
To Spring	3.2”	8 cm	-35%	Virtually all Remaining
2002	4.3”	11 cm	-12%	Westside Revegetation

* Precipitation in year of expected germination: same year for spring seeding, following year for fall-winter seeding. Elevations higher than facilities probably receive more moisture due to orographic lifting; lower elevations receive less precipitation. Temperatures, of course, are warmer at low elevation, increasing evaporation.

Most of the fields in Table 1 were seeded in the 1991-1993 period when seasonal precipitation consistently exceeded the long-term average by 28-38% (Table 2). The next major seeding effort was between 2000-2002, when May-June precipitation averaged 20% below normal. When comparing revegetation that established with more than 15 cm (six inches) of May-June precipitation to revegetation that established with eight to 10 cm (three or four inches) of precipitation -- in effect only 60% of the water for germination and tiny roots -- one can only expect much poorer establishment in recent years.

Dry conditions are exacerbated by steep slopes and warm aspects. The south- to southeast-facing 1550-1770-meter (5,100-5800-foot) south dump was seeded in spring 2000. It is the most conspicuous of the mine’s revegetation as viewed from Interstate 90. Reference Area No. 1 lies just east of this unit. There bluebunch wheatgrass and needle-and-thread grass account for 56% of relative cover, and weeds (mostly Loesel tumble mustard in 2001) comprise another 27%.

In 2001, total plant cover at the South Dump was high, especially along Transect 1 (Table 3). Most of it was attributable to weeds. Perennial grass cover was just 13% there and 23% along Transect 2. Of course, revegetation is in a state of flux for at least several years, which is why early appraisals of revegetation are unreliable (Prodgers et al., 2000), but in this case the

Table 3. Initial Revegetation Results on a South-Facing Slope, 2H:1V Seeded Spring 2000.

SITE	PERENNIAL COVER TOTAL	GRASSES	LEGUMES	SPECIES RICHNESS	SHANNON
	--------% Canopy Coverage----------				
2001					
5100-5800 South Dump Transect 1	102	13	2	13	1.44
5100-5800 South Dump Transect 2	69	23	2	17	1.66
Reference Area 1	64	36	--	21	2.03
2002					
5100-5800 South Dump Transect 1	47	24	1	10	1.50
5100-5800 South Dump Transect 2	57	40	2	10	1.53

data clearly indicate the effect of seasonal precipitation (and aspect, discussed next) on plant establishment. Since the principal grasses are rhizomatous (thickspike and intermediate wheatgrass), they can respond quickly to favorable resource availability. In 2002, total cover was reduced, but grass cover was up, especially along Transect 1 where weeds predominated in 2001. Alfalfa is a minor component despite being easily established -- warm aspects can be too dry for this legume, and deep roots confer no advantage if the water supply is exhausted within a few centimeters of the surface.

Effect of Aspect

A more long-term look at the effect of aspect is provided by some 1991 south-southwest aspect revegetation tests at the Golden Sunlight Mine. They demonstrated that steep-slope revegetation can initially have greater plant cover than reference areas. The plots are northeast of the South Dump at 5,500 feet elevation. The test area is about 122 meters wide by 30 meters of slope (400 feet by 100 feet). It incorporates several pitches: the western portion is 3H:1V; the next treatment (not monitored) is 2.5:1, and the remainder is 2H:1V. Most of the treatment cells received 0.6 meters (two feet) of oxide with an acid-base account of -7 to -23 topped with 0.6 meters of westside coversoil. It was hydroseeded in 1991 at a rate of 34 kg PLS/ha (30 pounds/acre) with a seed mix consisting of wheatgrasses with lesser amounts of alfalfa (*Medicago sativa*), sheep fescue, Canada bluegrass (*Poa compressa*), and shrubs. Dozer basins were installed.

Southerly aspects are the toughest steep slopes to revegetate satisfactorily. Germination and establishment conditions are very challenging because the near-surface soil can dry so quickly, and temperature extremes are great. Bazzaz (1996, p. 84) graphically illustrates how extreme temperatures at the ground surface compare to the air above and soil below. Even with good establishment, which requires a period of favorable weather, the long-term outlook is perhaps dubious on steep, south-facing slopes.

The test design allows evaluation of the effects of 2H:1V versus 3H:1V slopes. Initially, the 3H:1V slope was dominated by streambank and thickspike wheatgrass (*Elymus lanceolatus* and *E. macrourus*), which were handled as a single taxon in monitoring. Crested wheatgrass was the most common single species, although barely more abundant than the native wheatgrasses. Alfalfa had about half the density of the major grasses individually. Slender and bluebunch wheatgrass (*Pseudoroegneria spicata*) were subordinate but still important. Sheep fescue, Canada bluegrass, and the shrubs (rabbitbrush and saltbush) were very subordinate. Plant cover in 1992 was 58%. By 1994, reported density was half that of two years earlier. The density of crested wheatgrass was unchanged; thickspike-streambank wheatgrass was reduced by half; alfalfa was reduced by about two-thirds, and sheep fescue increased significantly but remained a fairly minor component of the community.

By 1996, plant cover had reportedly increased to 70% while density shrank. Crested wheatgrass was dominant while streambank wheatgrass and sheep fescue were subdominant and a little alfalfa remained.

Today the natives are insignificant. Total plant canopy coverage in 2001 was about 42%. Crested wheatgrass accounted for 65% of relative cover and sheep fescue had another 20% relative cover. Alfalfa was the only other important species with 11% relative cover.

Initially (1991), the 2H:1V slope had less plant cover than the 3H:1V slope, but still almost twice that of the reference area. Crested wheatgrass was dominant, thickspike and streambank wheatgrass each were subdominant, and alfalfa and bluebunch wheatgrass were important tertiary species. By 1994, plant density was reduced by half, but cover remained constant. Crested wheatgrass density was reduced a little, thickspike-streambank wheatgrass was reduced by two-thirds but remained important, alfalfa disappeared, and sheep fescue was reduced by half to play a minor role.

By 1996, a year of about normal precipitation, cover increased from 49% to 64% while density shrank from 4.9 to 4.2 plants/0.1 m^2 frame. Crested wheatgrass completely dominated with 84% of density.

In 2001 the steeper cell had more plant cover than the 3H:1V slope (51% total plant cover vs. 42%). This is partly a function of leveling the frame through which cover is viewed; the amount of ground surface area within the frame is greater on steep slopes. However, if the greater amount of weeds in the 2H:1V plot is factored out, the amount of perennial plant cover in the 2H:1V cell is slightly less than in the 3H:1V cell.

Another notable difference is that crested wheatgrass is about as abundant on the 2H:1V slope as in the 3H:1V area, comprising 61% of plant cover. Alfalfa accounts for just 5% of plant cover and sheep fescue 1%. It seems that sheep fescue and alfalfa cannot compete with crested wheatgrass in the hot, dry environment. Fourwing saltbush comprises 7% of plant cover and weeds 24%. Within the 2H:1V cell, the lower slope now has only about 10% cover of crested wheatgrass, whereas the upper portion has about 50%.

Conclusions

Steep-slope (2H:1V) revegetation can be successfully implemented in a semiarid climate, as the Golden Sunlight Mine has demonstrated. Important elements of good revegetation include 0.6-meter-thich (two-feet-thick), erosion-resistant coversoils with rock fragment content of about 30% to 50%, good textures for plant establishment and growth, effective dozer basins installed immediately after grading, and sloped benches every 60 vertical meters (200 vertical feet) or closer. Strong-establishing plants are a must; alfalfa and tough introduced grasses have proven the best choices here. Seeding practices must mix the seed with loosened soil, not just throw it on the surface. Ten years after plantings, west-facing slopes remain satisfactorily vegetated, but south-facing revegetation seems to be equilibrating at a level below similarly situated native reference plant communities. In a semiarid climate, the role of May-June precipitation in plant establishment is major, and several consecutive years of below-average precipitation can impede revegetation, especially on south-facing slopes.

Literature Cited

Bazzaz, R. A. 1996. Plants in changing environments. Reprinted 1998. Cambridge Univ. Press, Cambridge, England. 320 pp.

Daubenmire, R. 1959. A canopy-coverage method of vegetational analysis. Northwest Sci. 33(1): 43-64.

Prodgers, R.A., T. Keck, and L. Holzworth. 2000. Revegetation evaluations – how long must we wait? Proceedings 2000 Billings Land Reclamation Symposium. March 20-23, Billings, MT. CD ROM.

Shannon, C., and W. Weaver. 1949. The mathematical theory of communication. Univ. of Illinois Press. Urbbana, Ill. 117 pp.

Toy, T., and F. Foster. 1998. Guidelines for the use of the revised soil loss equation (RUSLE) version 1.06 on mined lands, construction sites, and reclaimed lands. The Office of Technology Transfer, Western Regional Coordinating Center, Office of Surface Mining, U.S. Department of Interior, Denver, CO.