USDA Forest Service
Tonto National Forest
Arizona

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Process Memorandum to File

Revegetation Meta-Analysis to Support the Chapter 3 Soils and Vegetation Section

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Prepared by:
Mandy Bengtson, Ph.D.
Regional Scientist, Soil Ecologist
SWCA Environmental Consultants

Purpose of Process Memorandum

The purpose of this process memorandum is to provide detail on the development and execution of revegetation meta-analysis that is described in Section 3.3 of the Resolution Copper Project and Land Exchange Draft Environmental Impact Statement (DEIS). This process memorandum covers the following:

- The objectives of the revegetation meta-analysis
- Revegetation meta-analysis approach and methods
- Limitations of the revegetation meta-analysis
- Outcomes of the revegetation meta-analysis

Key Process Steps

Meta-analysis Objectives

The objective of the revegetation meta-analysis is to help constrain the potential range of outcomes of revegetation efforts for the Resolution Copper Project and Land Exchange (the project), including actions during the construction and operation phases to the post-closure/reclamation phase. While many research studies and previous revegetation efforts have been completed and documented throughout the region, the rates of revegetation success are highly variable and strongly dependent on several controlling environmental variables (e.g., precipitation or water availability, climate, soil or revegetation substrate, reclamation techniques, etc.). No single case study is, therefore, sufficient to project potential rates of revegetation success. The meta-analysis approach was developed and executed to document the range in possible revegetation success outcomes for the project.

Meta-analysis Approach and Methods

The first step in this meta-analysis was to gather relevant case studies from published scientific literature, technical reports, and semi-quantitative field observations. Results from these studies were compiled, and two key attributes were recorded from each study:

1. the number of years since reclamation commenced
2. the minimum and maximum observed percent vegetation cover

The following attributes for each case study were also recorded (when sufficient data were available):

- The metric of vegetation measurement (if percent vegetation cover was not reported)
- The mean value for the vegetation measurement (if minimum and maximum were unavailable)
- Reclamation and/or revegetation methods
- Application of irrigation or supplemental watering in revegetation treatments

- Vegetation species planted or seeded
- Location of case study
- Reclamation substrate or cover material (if applicable)
- Reclamation setting (e.g., tailings storage facility, drill pads, roads)
- Climate of case study
- Year(s) of case study
- Other notes

Some case studies reported data from multiple years, providing multiple vegetation cover observations to inform the analysis. If more than one treatment type was reported for a given year in a study, the minimum and maximum values (of all treatment types) were provided for that year. The results from each study were combined into a single plot for visual interpretation.

The resulting analysis provides a minimum and maximum percent vegetation cover from each study (at all time points for which data are available). For this meta-analysis, only revegetation case studies from Arizona and New Mexico (primarily from mining or mineral exploration activities) were included, which reflect characteristics in vegetation communities, climate, soils, and disturbance types similar to the project area. Only those studies for which the following information was available were included in the meta-analysis: (1) the number of years since reclamation commenced, and (2) the minimum and maximum observed percent vegetation cover.

A table detailing the results, notes, and citations (as applicable) from the compiled case studies is included in Attachment 1. All case studies included in the final meta-analysis are indicated by **bold text** in the table.

Meta-analysis Limitations

There are potential limitations to the meta-analysis approach and the level of reliable interpretations that can be derived. Limitations that should be considered in interpreting outcomes of the meta-analysis include the following:

- Revegetation success from the case studies was highly variable, which translates to a high degree of uncertainty in potential revegetation outcomes.
- This study is semi-quantitative and does not reflect any quantitative modeling efforts or outcomes.
- The results of this analysis may not reflect yet unknown reclamation techniques that could be developed over the life of the project.
- The nature and degree of disturbance would strongly influence the rates of revegetation success, which would differ across project facility components and over the life of the project.

- Reclamation and revegetation efforts would be ongoing and would vary based on project phase and project component. Therefore, the meta-analysis does not reflect outcomes for specific components or phases but simply provides a range of possible revegetation outcomes that could be expected at a given time after reclamation has commenced for that project component.

Meta-analysis Outcomes and Interpretations

Reclamation and revegetation efforts would occur across all phases of the project, during which time vegetation would be established through seeding or direct planting of seedlings within reclamation areas. The proposed reclamation practices detailed in the General Plan of Operations (GPO) include closing and sealing the mine shafts, removing surface facilities and infrastructure, and establishing self-sustaining vegetative communities using native local species on the disturbed surface facility areas through revegetation methods (Resolution Copper 2016).

The precise short- and long-term impacts of revegetation efforts within various portions of the facility over the life of the project are challenging to determine. Environmental factors (e.g., precipitation, temperature, topography, existing native and non-native seedbank), type and magnitude of disturbance, and reclamation methods (e.g., planting/seeding methods, weed management, soil salvage or capping media) all strongly influence rates and success of revegetation. Currently, insufficient data are available to accurately model or predict rates of revegetation success. This meta-analysis constrains the level of variability in vegetation cover that could be expected at a given time after reclamation and revegetation efforts have commenced for a project component.

Results of the meta-analysis are shown in Figure 1. Data for this analysis included case studies from reclamation areas in Arizona and New Mexico (many of which were mine or mineral exploration sites). Case studies were compiled from (1) a literature review and (2) ocular estimates of vegetation cover from reclamation sites near the project area. Each vertical bar in Figure 1 represents the range in vegetation cover observed from a single year in a given case study. Some case studies provided multiple years of data. The combined results of all analyzed case studies illustrate the range in observed vegetation cover (percent vegetation cover) that has been recorded previously and could be reasonably be expected from the project's revegetation efforts. Because of the data limitations from the available case studies, vegetation cover by native versus non-native plant species were not differentiated, and vegetation cover is not compared with undisturbed reference conditions. Therefore, in some instances, non-native species could be dominant and account for the majority of the measured vegetation cover. Furthermore, the ecological potential of a site (as compared to relevant reference conditions) is not considered. Despite these data limitations, the meta-analysis demonstrates the following relationships (from Arizona and New Mexico case studies), which provide some constraint for the outcomes of revegetation efforts proposed for the project area:

- Vegetation cover (by native and non-native species) of 8 percent or greater is consistently established by Year 10. This level of vegetation growth would provide some soil cover and erosion control functions.

- Vegetation can be as low as 0 percent, as observed in in Year 1 for one case study, or as high as 100 percent 4.5 years post-reclamation in another case study, with significant variation among and within the years after reclamation.
- According to the case studies illustrated in Figure 1, vegetation cover may plateau around Year 12; however, analysis of additional case studies is needed to confirm that trend.

The revegetation response is expected to be influenced by the nature of the surface disturbance, while irrigation or active soil management interventions could enhance revegetation success, thereby reducing erosional losses and net negative impacts to soil productivity. Outcomes of this meta-analysis, including these additional considerations, will be discussed in the project DEIS.

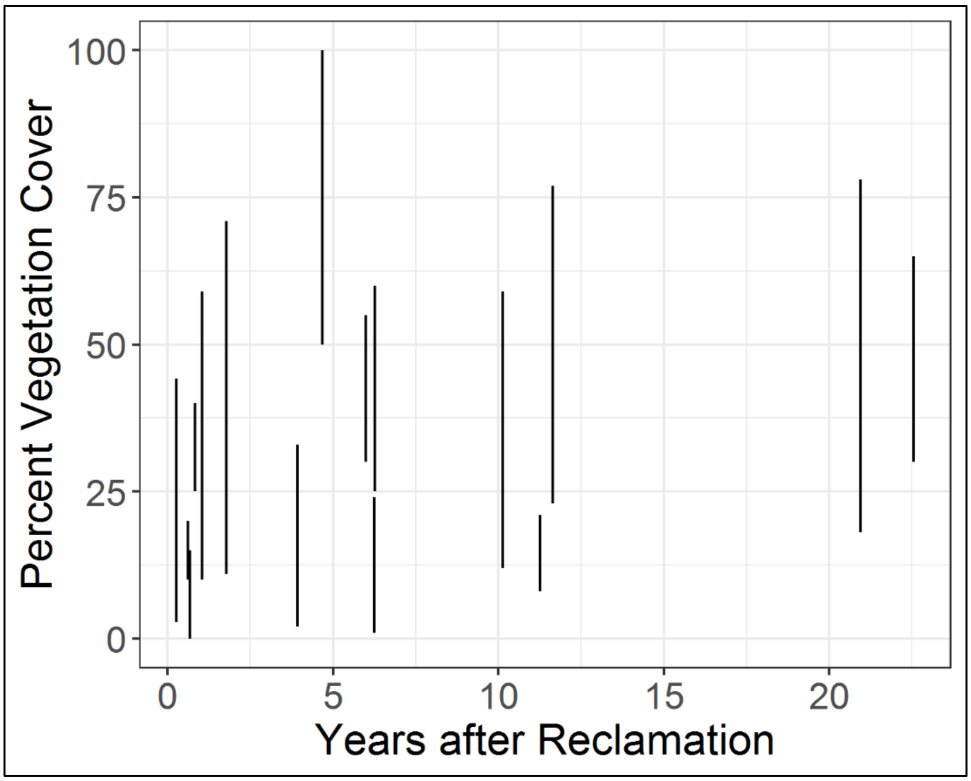

Figure 1. Meta-analysis summary. Each vertical bar in Figure 1 represents the range in vegetation cover (percentage) observed from a single year (shown in years after reclamation) from a given case study. Data shown include only case studies in Arizona and New Mexico.

Literature Cited

Resolution Copper. 2016. *General Plan of Operations Resolution Copper Mining*. Superior, *Arizona*: May 9.

ATTACHMENT 1

Case Studies Considered in Meta-Analysis

Case Study	Full Citation	Metric of Vegetation Measurement	Years to Reach Vegetation Metric	Minimum Vegetation Value Reported (using metric of vegetation measurement)	Maximum Vegetation Value Reported (using metric of vegetation measurement)	Mean Vegetation Value Reported (using metric of vegetation measurement)	Reclamation or Revegetation Methods	Irrigation (Yes/No)	Vegetation Species Planted or Seeded	Location	Reclamation Substrate	Reclamation Setting (Tailings, Drill Pad, Roads, etc.)	Climate	Year(s) of Study	Other Notes
(Bashan et al. 2012)	Bashan, Y., B.G. Salazar, M. Moreno, B.R. Lopez, and R.G. Linderman. 2012. Restoration of eroded soil in the Sonoran Desert with native leguminous trees using plant growth-promoting microorganisms and limited amounts of compost and water. *Journal of Environmental* Management 102(2012):26-36.	Survival (%)	2.5	58.0	100.0	5	Planting of three different leguminous tree species (with/without bacterial/AM fungal inoculation); compost with cow manure and wheat straw	Yes	Transplanting trees: mesquite amargo (*Prosopis articulata*), and yellow and blue palo verde (*Parkinsonia microphylla* and *Parkinsonia florida*).	Northwestern Center for Biological Research (CIBNOR) in El Comitan, Baja California Sur, Mexico (Sonoran Desert)	Native soils sediment dump areas (variable soil textures)	Eroded site (no longer supporting native vegetation)	Arid	2004–2009	
(Day and Ludeke 1981)	**Day, A.D., and K.L. Ludeke. 1981. The use of legumes for reclaiming copper mine wastes in the Southwestern USA. *Minerals and the Environment* 3(1):21-23.**	**Vegetation Cover (%); mean cover for each plant species and soil material**	**1**	**10**	**59**	**44**	**Broadcast seeded by hand, used spike tooth chaindrag smooth surface and loosen seedbed along berms containing each soil material. Treatments varied but included some straw application after seeding; nitrogen added with 1 cm of irrigation water six times each growing season.**	**Yes**	**Blue lupine (*Lupinus* sp.), *Sesbania* sp., alfalfa (*Medicago* sp.)**	**Tucson, Arizona (Cyprus Pima Mining Company)**	**Overburden**	**Copper mine soils**	**Desert**	**1974, 1975**	**Also report trials in desert soil, which performed the best in terms of plant growth. Used subplots with only one species planted in each, so ground cover cannot be added together.**
(Glenn et al. 2001)	Glenn, E.P., W.J. Waugh, D. Moore, C. McKeon, and S.G. Nelson. 2001. Revegetation of an abandoned uranium millsite on the Colorado Plateau, Arizona. *Journal of Environmental Quality* 30(4):1154-1162.	Plant Growth (m^3 per plant)	3	0.3	0.4		Ripped soil, then planted, irrigated first summer only with 20 L/plant/week	Yes	Fourwing saltbush (*Atriplex canescens*). Also, direct seeding of native forbs, grasses, shrubs	Former uranium mine near Tuba City, Arizona			Arid		
(Johnson 1998)	Johnson, N.C. 1998. Responses of *Salsola kali* and *Panicum virgatum* to mycorrhizal fungi, phosphorus and soil organic matter: Implications for reclamation. *Journal of Applied Ecology* 35:86-94.	Aboveground Biomass (g within 25 × 25–cm plot)	0.4	0.3	58.0		Treatment included with/without mycorrhizal inoculation, organic matter compost	Yes	Seeding of *Salsola kali* and *Panicum virgatum*	Jackson County Iron (taconite mine), near Black River Falls, Wisconsin	Slurry tailings	Taconite mine tailings	Humid	1985	
		Plant Height (cm)	0.4	13.0	61.0										

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(Johnson 2018)	Johnson, J. 2018. Site Visit Notes: Cottonwood Tailings, GSF 1 and 2, Kennedy Ranch, FMI Drill pad I, Drill pad off FR 650, DSF. Phoenix, Arizona: SWCA Environmental Consultants. March 25.	Vegetation Cover (%)	1	10.0	20.0		Hydroseeded and recontouring		Desert scrub area	Forest Road (FR) 650 (site 1), Arizona		Drill pad		2013, 2017	Invasive plant removal helped, post-planting. Disturbance occurred in 2011.
		Vegetation Cover (%)	5	30.0	55.0		Hydroseeded and recontouring		Desert scrub area	Off FR 650, Arizona		Drill pad		2013, 2018	Invasive plant removal helped, post-planting. Disturbance occurred in 2011.
		Vegetation Cover (%)	1	0.0	15.0		Seeded		Early successional desert scrub	Off FR 650 (site 2), Arizona		Drill pad		2017	Non-native control has kept non-natives down, but only forbs were observed after 1 year.
		Vegetation Cover (%)	1	25.0	40.0		Seeded, recontoured			Off FR (DSF tailings), Arizona	Tailings (or near tailings)	Drill pad		2017	Large numbers of cattle bed in area, grazing has significantly impacted vegetation and soils.
		Vegetation Cover (%)	4.5	50.0	100.0		Hydroseed			Pinto Valley, Arizona (GSF 1 and 2)	Slurry tailings with soil cap	Joint Storage Facilities 1 & 2			Soil cap helped success.
		Vegetation Cover (%)	5.5	25.0	60.0		Ripped and hydroseeded. No tree/shrubs seeds to allow plants with local genetics to colonize the site		Sonoran desert scrub area	Off FR 650 #8 intersection (FMI Drillpad 1), Arizona		Drill pad		2012–2013	More trees/shrubs; fewer grasses and forbs, as it is grazed
		Vegetation Cover (%)	22	30.0	65.0		Furrowed with mule (in wilderness area)		Native/non-native grassland with scattered trees/shrubs	Kennedy Ranch, Arizona		Unknown		1996	Similar rain pattern and elevation to Carlota Mine. Riparian areas along site were not reclaimed.

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(Lawson 2011)	**Lawson, H.M. 2011. Grassland Revegetation for Mine Reclamation in Southeast Arizona. M.S. thesis, School of Natural Resources and the Environment, University of Arizona, Tucson.**	**Canopy Cover (%)**	**0.5**	**2.8**	**44.2**		**Field testing methods near Rosemont mine; methods included: top-dressed soils (topsoils) derived from sandy loam soils derived from Arkose and Gila Conglomerate and placed on the sites; treatments included smooth vs. rough surfaces and surface mulch, incorporated mulch, and no mulch. No irrigation was applied.**	**No**	**Semi-desert grassland seed mix (see Table 1 in the document)**	**Southeast Arizona, soil borrow sites near Rosemont Mine**	**Sandy loam soils derived from Arkose and Gila Conglomerate**	**Soils (proxy for reclamation)**	**Arid**	**2009–2010**	**Density of plants and basal cover were both recorded; Also recorded for cool-season period, but not reported here, as canopy cover was only recorded during warm season.**
(McNearny 1998)	McNearny, R.L. 1998. Revegetation of a mine tailings impoundment using municipal biosolids in a semi-arid environment. Paper presented at Proceedings of the 1998 Conference on Hazardous Waste Research, May 18–21, 1998, Snowbird, Utah.	Vegetation Cover (%)	1	26.7	49.4		Drill seeding and biosolids application	N/A	Drill seeding of perennials and legumes (see seed mix list in Table 1 of report)	Kennecott Utah Copper Corporation tailings impoundment, Magna, Utah,	Copper tailings	Tailings impoundment slopes	Semi-arid	1994–1996	
		Vegetation Cover (%)	2	44.6	61.1										
(Martínez-Ruiz and Fernández-Santos 2005)	Martínez-Ruiz, C., and B. Fernández-Santos. 2005. Natural revegetation on topsoiled mining-spoils according to the exposure. *Acta Oecologica* 28(2005):231-238.	Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	1	55.0	80.0		Natural propagules from 'topsoiled' cover material (arkose material)	No	No seeding	Uranium in west-central Spain Spain (40°37'N, 6°38'W)	Uranium-mining spoils (slate bedrock); slag heaps with substrate cover (arkose material, sandy loam texture)	Uranium-mining spoils (dump slopes)	Semi-arid Mediterranean	1994–1996 (survey period)	Chronosequence study; uses absolute cover (note may be above 100% cover in some cases)
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	2	65.0	80.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	3	70.0	125.0										

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		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	4	150.0	190.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	5	75.0	125.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	6	110.0	125.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	7	100.0	200.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	8	110.0	135.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	12	210.0	250.0										

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		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	13	125.0	175.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	14	175.0	180.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	15	140.0	160.0										
		Vegetation Cover (% Absolute Cover [includes % cover for all species, and therefore commonly exceeds 100%])	16	80.0	140.0										
(Milczarek et al. 2003)	Milczarek, M., J. Vinson, T.M. Yao, J. Word, B. Musser, and R. Mohr. 2003. Monitoring the performance of mono-layer evapotranspirative covers in response to high precipitation and extended drought periods in the Southwestern United States. Paper presented at Sixth International Conference on Acid Rock Drainage, July 14–17, 2003, in Cairns, Australia.														Earlier results of Milczarek et al. (2011)

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(Milczarek et al. 2011)	Milczarek, M.A., F.M. Steward, W.B. Word, M.M. Buchanan, and J.M. Keller. 2011. Final results for the Morenci tailings experimental reclamation plots. Paper presented at the Conference: VI International Seminar on Mine Closure, Lake Louise, Canada.	Vegetation Cover (%), average of treatment (ranges represent different treatments)	1	11.0	71.0		Experimental monolayer evapotranspiration cover system (variable thickness); organic matter amendments; mulch added, seed mixes	No	Native seed mix	Morenci Mine (Clifton, Arizona), Madrean Archipelago (Chihuahuan and Sonoran Deserts)	Bare tailings and Gila Conglomerate cover	Tailings dam	Semi-arid	1997–2009	Study aimed at understanding infiltration limitations and deep percolation in the evapo-transpiration cover; Experiment 5 (reference conditions) left out of study; not all studies measured in Years 11 and 12.
		Vegetation Cover (%), average of treatment (ranges represent different treatments)	4	2.0	33.0										
		Vegetation Cover (%), average of treatment (ranges represent different treatments)	7	1.0	24.0										
		Vegetation Cover (%), average of treatment (ranges represent different treatments)	10	12.0	59.0										
		Vegetation Cover (%), average of treatment (ranges represent different treatments)	11	8.0	21.0										
		Vegetation Cover (%), average of treatment (ranges represent different treatments)	12	23.0	77.0										

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(Mummey et al. 2002)	Mummey, D.L., P.D. Stahl, and J.S. Buyer. 2002. Microbial biomarkers as an indicator of ecosystem recovery following surface mine reclamation. *Applied Soil Ecology* 21(2002):251-259.	Vegetation Cover (%)	5			22.5	Seeded, stockpiled soil placed to depth of 20–30 cm after being stored for 10+ years.		Sites dominated by *Agropyron smithii* and *Agropyron crestatum* (although the latter was unseeded)	Pathfinder Uranium Mine, Shirley Basin, southeastern Wyoming	Stripped and stockpiled topsoil (for 10+ years) placed to depth of 20–30 cm	Surface mining site	28 cm annual precipitation, 16°C to 26.3°C temperature range	Year of study not provided; occurred during or before 2001.	
		Vegetation Cover (%)	19			35									
(Munk et al. 2006)	Munk, L., M. Jaworski, M. Jojola, and D. Romig. 2006. Upward migration of constituents in soil covers at semi-arid mine sites. Paper presented at Seventh International Conference on Acid Rock Drainage, March 26–30, 2006, in St. Louis, Missouri.														Results detailed in Romig et al. (2006)
(Romig et al. 2006)	**Romig, D., L. Munk, and T. Stein. 2006. Leaf area and root density measurements for use in cover performance evaluations on semi-arid reclaimed mine lands. Paper presented at Seventh International Conference on Acid Rock Drainage, March 26–30, 2006, in St. Louis, Missouri.**	**Vegetation Cover (%)**	**20**	**18.0**	**78.0**		**Methods not available; paper discusses native soils covering a tailings facility, so there was likely some kind of 'top dressing' (topsoil cover) applied.**	**N/A**	**Revegetated; site currently covered in warm-season grasses, forbs, shrubs.**	**Southwestern New Mexico (1,900 meters elevation)**	**Soils derived from Gila Conglomerate (loamy sand to silty clay loam)**	**Tailings site**	**Semi-arid**		**Vegetation cover provided as site characterization information (not as part of the study)**
(Rosario et al. 2007)	Rosario, K., S.L. Iverson, D.A. Henderson, S. Chartrand, C. McKeon, E.P. Glenn, and R.M. Maier. 2007. Bacterial Community Changes during Plant Establishment at the San Pedro River Mine Tailings Site. *Journal of Environmental Quality* 36(2007):1249-1259.	Transplant Survival	1.5		80		Revegetation trial in historic mine tailings area; transplants of fourwing saltbush (*Atriplex canescens*), with/without compost	Yes	Transplants of fourwing saltbush	Boston mill mine tailings site (active 1879–1887 near the San Pedro River National Conservation Area, south of Fairbanks, Arizona	Tailings material (from silver/gold ore production)	Historic mine tailings	Arid		Examined changes in bacterial communities among treatments
		Plant Canopy Volume (m^3) per 7.5- to 12-m plots	1.5	0.008	0.010										

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(Schmidt 2002)	Schmidt, A. 2002. Strip-Mine Rehabilitation in Namaqualand. M.S. thesis, University of Stellenbosch, Stellenbosch, South Africa.	Vegetation Cover (%)	1			17.2	Several treatments: leveled and left for natural succession; leveled and tilled and left to recover on its own; leveled and tilled and left to recover with addition of Australian saltbush (*Atriplex semibaccata*) species	No	*Atriplex semibaccata* (sown), *Atriplex nummularia* (planted), plus any natives self-recruiting	Gypsum strip mine near Vanrhynsdorp in Western Cape Province of South Africa	Overburden with topsoil placed back after strip mining	Gypsum strip mine	Desert, 145.5 m annual precip, average annual temp (min–max): 8.7°C–23.4°C	2000–2001	Four different treatments done on the 16-year-old sites
		Vegetation Cover (%)	4			32.8									
		Vegetation Cover (%)	8			21.4									
		Vegetation Cover (%)	16	11.4	39.0										
(Vinson et al. 1999)	Vinson, J., B. Jones, M. Milczarek, D. Hammermeister, and J. Ward. 1999. Vegetation success, seepage, and erosion on tailings sites reclaimed with cattle and biosolids. Paper presented at 16th National Meeting of the American Society for Surface Mining and Reclamation, August 13–19, 1999, in Scottsdale, Arizona.	Biomass (lb/acre)	≤1	12.1	96.9		Variable methods: with/without Gila conglomerate cap, native/non-native seeding, biosolids, cattle grazing, bioflora	No	Native/non-native seed mixes	Morenci Mine (Clifton, Arizona), Madrean Archipelago (Chihuahuan and Sonoran Deserts)	Bare tailings and Gila Conglomerate cover	Embankment tailings	Semi-arid	1998–1999	Complementary or same study as Milczarek et al. (2011); results show results of first year of seeding.
		Seedling Germination Rate (%)	≤1	3.4	8.7										

Note: **Bold text** indicates case study data were included in final meta-analysis.