Revegetation of Mine Wastes in Arid Environments: Linking Above- and Below-Ground Performance
Legacy Mine Operations

Raina M. Maier
Department of Environmental Science
University of Arizona, Tucson, AZ
rmaier@arizona.edu

National Institute of Environmental Health Sciences
Superfund Research Program

The University of Arizona Superfund Research Center

Center for Environmentally Sustainable Mining

Outline

- The challenge of sustainable mining
- Legacy sites: lessons learned at our remediation field site
- Modern sites: applying these lessons to improve current remediation practices
- CESM, a partnership approach: working with the mining industry to understand and solve remediation challenges

Residual mine waste is one of the largest waste streams in the world

Recent accidents world-wide highlight the importance of improving the science and engineering of treating these waste streams:

36 Major Mine Tailings Dams Failures since 2010
(https://www.wise-uranium.org/mdaf.html)
Corrego do Feijao tailings dam failure, Brazil (2019) – 12 million m^3, 259 deaths
Yichun Luming Mining Co, China (2020) 2.53 million m^3

The mining industry and investors are very concerned. New thought and guidance just released:
August 20, 2020: ICMM (International Council on Mining and Metals), UNEP (UN Environment Programme), and PRI (Principles for Responsible Investment)
https://globaltailingsreview.org/global-industry-standard/

Vale, which owns the Brumadinho mine just came out with a "Request for Information – Future of Tailings"

Mt. Polley, Canada

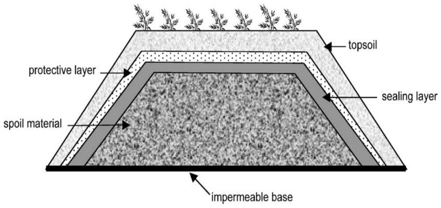
Corrego do Feijao, Brazil. Before and after.
(Courtesy of Estado en Minas | Twitter.)

Residual mine waste is one of the largest waste streams in the world

Reclamation Strategies:

Cap and plant

- Full topsoil cover
- Vegetative growth within topsoil
- Physically isolates mine tailings from environment



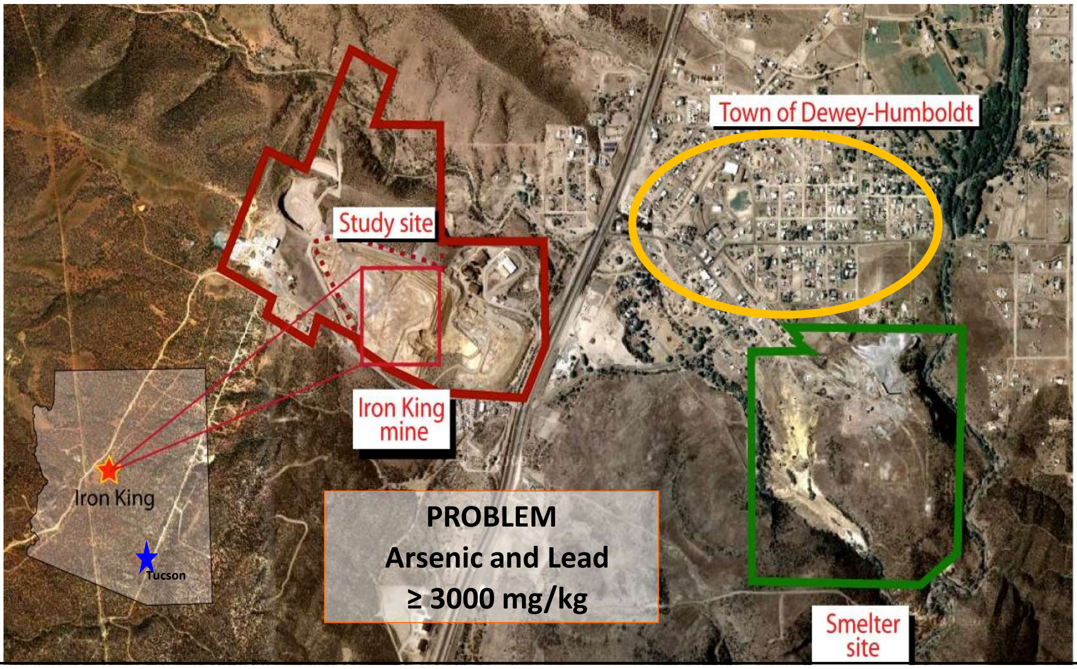
Johnson and Hallberg, 2005. Sci. Total Environ.

Phytostabilization

- Soil amendments improve fertility
- Vegetative growth within mine tailing material
- Stabilizes mine tailing material from fluvial and aeolian erosion

Mendez and Maier, 2008. Environ. Health Perspec.

Legacy site example: The Iron King Mine and Humboldt Smelter Superfund Site



PROBLEM
Arsenic and Lead
≥ 3000 mg/kg

Pyritic mine wastes

- **Left over crushed sulfidic ores from mineral processing**
- **Characterized by:**
  - Heavy metals
  - Acidic pH
  - Lack of nutrients

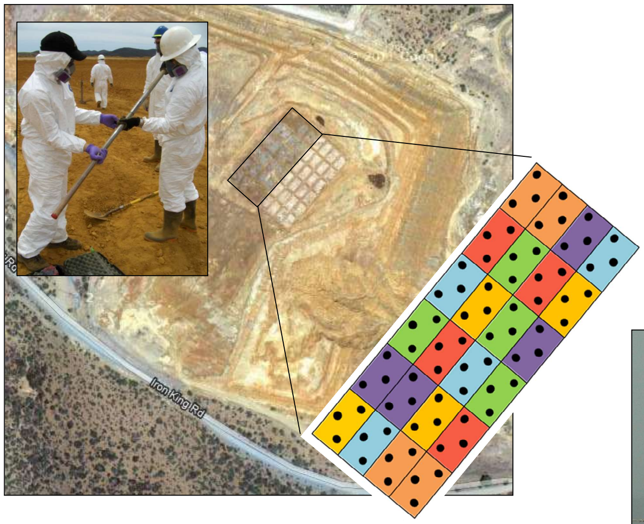

1950

ADMMR Photo Archive, Arizona Geological Survey

Iron King
Mine Tailings


Today

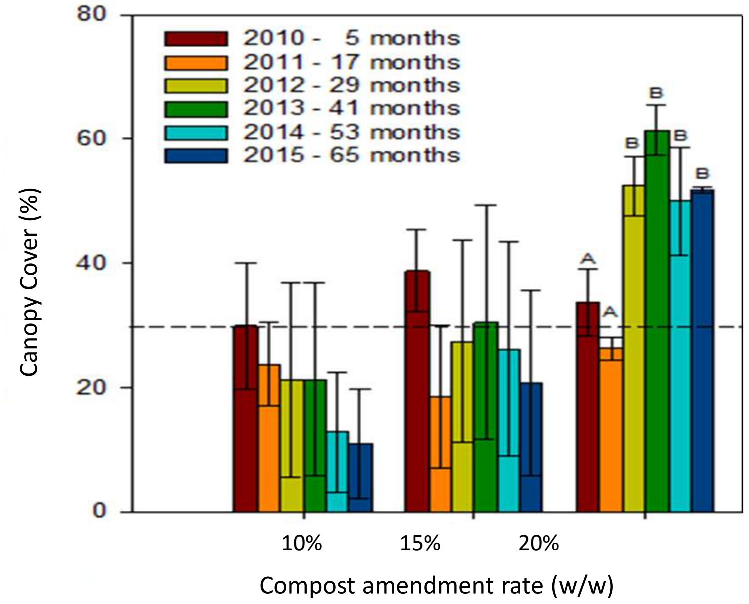
Field Study- Iron King Mine and Humboldt Smelter Superfund site



- ▨ 0% Compost
- ▨ 10% Compost + seeds
- ▨ 15% Compost + seeds
- ▨ 20% Compost + seeds
- ▨ 15% Compost, no seeds
- ▨ 20% Compost, no seeds

Compost-assisted direct planting
Based on greenhouse work

IKMHSS field trial - Initiated May 18, 2010



Unamended irrigated control – 29 months

29 Months

Off-site vegetation

Gil-Loaiza et al., 2016. Sci. Total Environ.

Results Show

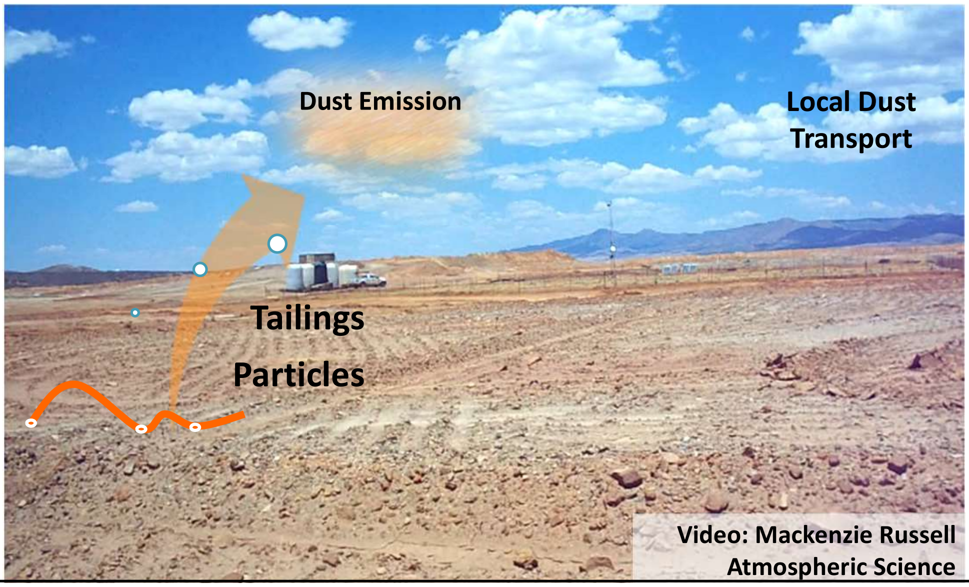
A **single application** of compost immediately increased pH and **improved** levels of **nutrients** (C and N).

Greenhouse results **scaled effectively** to the field for **key parameters:** amount of compost required, pH, carbon, nitrogen and neutrophilic heterotrophic counts.

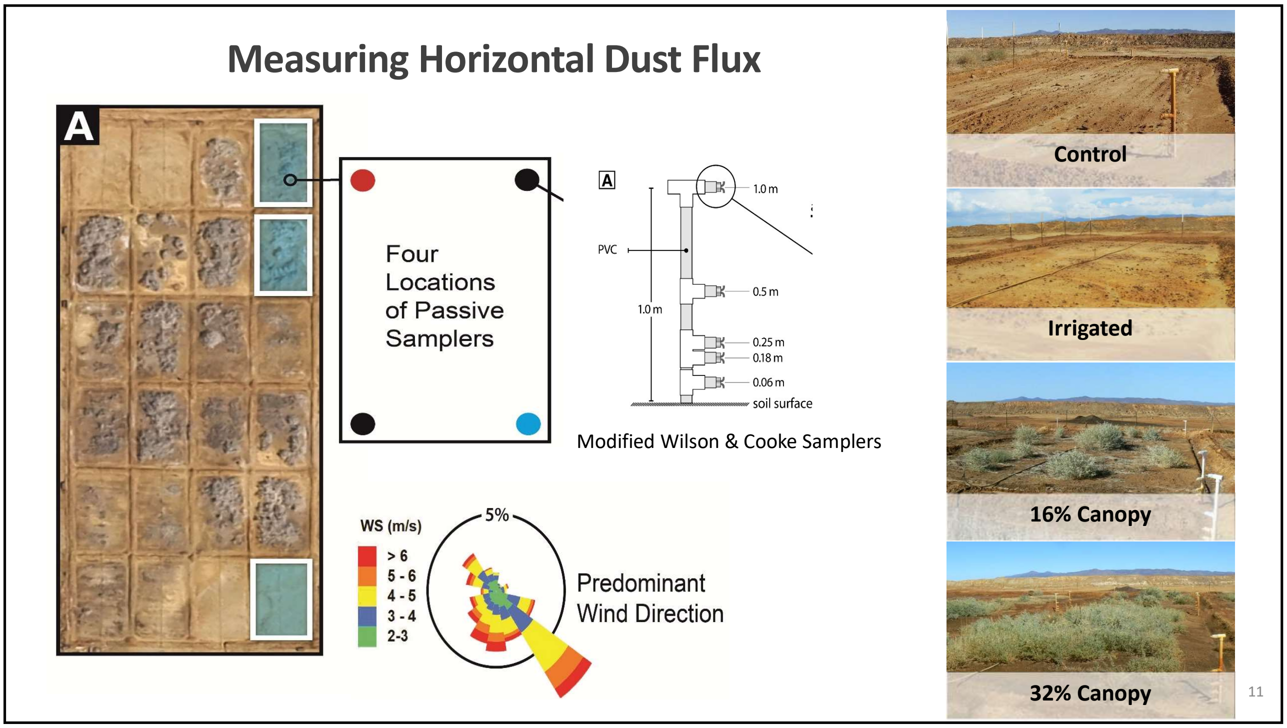
Compost transitioned a highly **disturbed matrix** into a substrate able to **support plant** germination, and growth for six years, however, during this time, erosion and ponding accelerated acidification processes in localized areas indicating that remediation must be monitored and supplemented over the long term.

Solis-Dominguez et al., 2012, ES&T; **Gil-Loaiza** et al., 2016, Sci Total Environ; **Root** et al., 2015, Appl. Geochem.; **Valentin-Vargas** et al., 2014, Sci. Total Environ.; **Hammond** et al., 2020, Geochim. Cosmochim. Acta; **Hottenstein** et al., 2019, Front. Microbiol., **Honeker** et al., 2019, Front. Microbiol.

Dust Emission at the Iron King Mine and Humboldt Smelter Superfund Site



Video: Mackenzie Russell Atmospheric Science

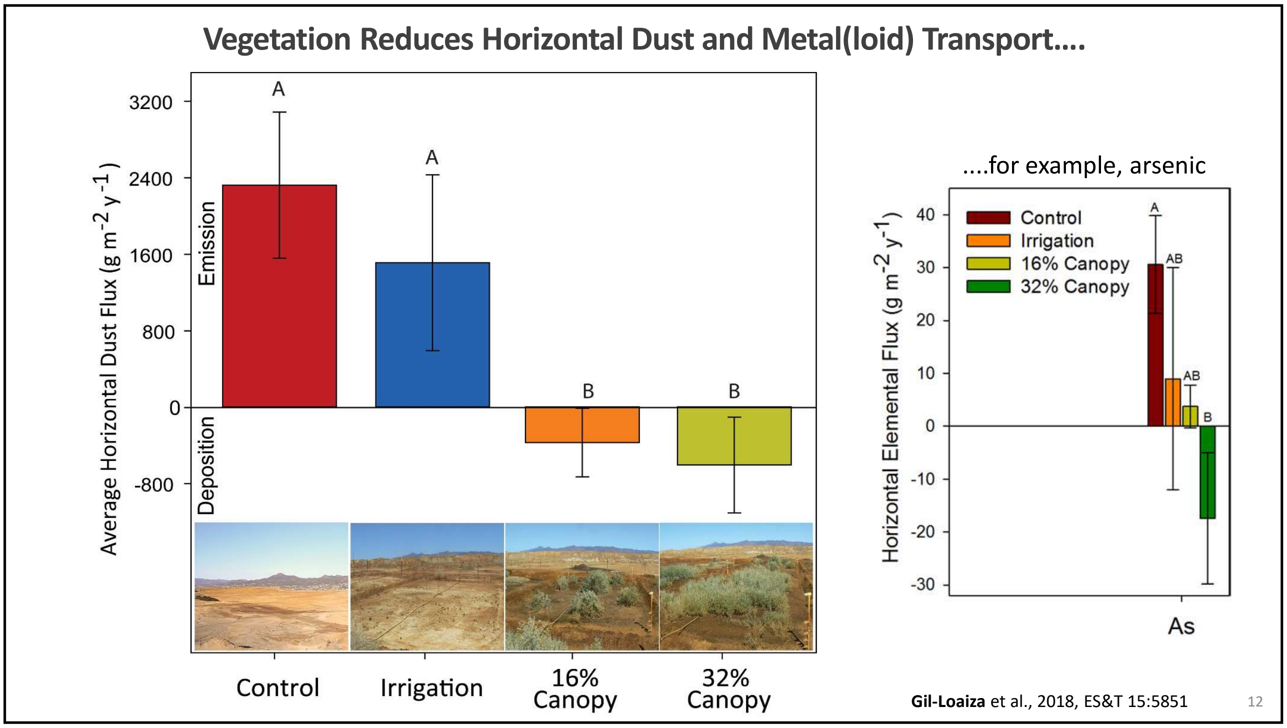


Measuring Horizontal Dust Flux

Four Locations of Passive Samplers

Modified Wilson & Cooke Samplers

Predominant Wind Direction



Vegetation Reduces Horizontal Dust and Metal(loid) Transport....

....for example, arsenic

Gil-Loaiza et al., 2018, ES&T 15:5851

Research suggests for legacy acid-generating sites that the tailings microbiome governs the success or failure of the plant cover

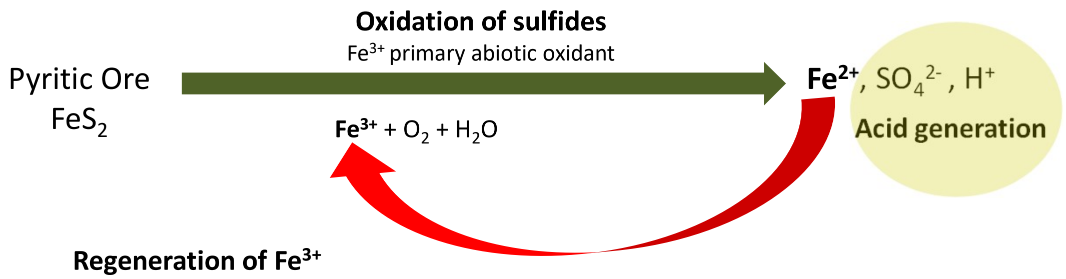
A story of warring microbes

Mendez *et al.* [**2008**] *Appl Environ Microbiol*; Gadd *et al.* [**2010**] *Microbiol*; Chen *et al.* [**2013**] *Environ Microbiol*; Baker & Banfield [**2003**] *FEMS Microbiol Ecol*; Solis-Dominguez *et al.* [**2011**] *Sci Total Environ*

Mine tailings: a stable and healthy environment for:

- Acidophilic microbial communities
- Energy supplied by reduced iron and sulfur in pyritic ore

Biogeochemistry of pyrite dissolution



Oxidation of sulfides

Fe^{3+} primary abiotic oxidant

Pyritic Ore

FeS_2

Fe^{2+}, SO_4^{2-}, H^+

Acid generation

Fe^{3+} + O_2 + H_2O

Regeneration of Fe^{3+}

$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$

- With oxic and pH > 4.5 conditions reaction is catalyzed abiotically (slowly)
- In increasingly acidic conditions, oxidation reaction is mediated biologically (rapidly)

Acidic mine tailings and acid drainage

- Caused by exposure of metal sulfide minerals to oxygen
- Releases heavy metals in highly acidic water to the environment
- Plants do not grow at < pH 5

- Can last for decades to centuries

Jerry McBride, The Durango Herald

Warring Microbes

Iron King Mine tailings field study 2010 to 2017

Time zero

1 year

3 years

Compost amendment

- Adds C, N, and other nutrients
- Adds plant growth promoting microbes
- Enhances soil qualities such as texture which increased water holding capacity

But…….. difficult to establish sustained plant growth

Research Objective

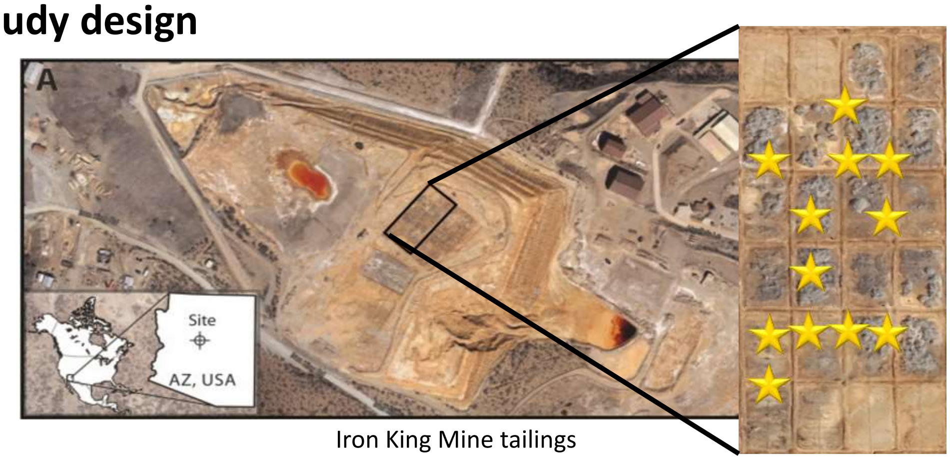
To understand the taxonomic composition dynamics of microbial communities in extremely acidic mine tailings during a six-year compost-assisted revegetation field study

Using the Iron King Field Trial, we examined changes in the soil microbiome over a six-year time period.

Additionally, a Microcosm Experiment was performed to identify microbial taxa involved in developing and maintaining acidic conditions when reduced iron and sulfur are present were examined in a controlled microcosm enrichment study.

Hottenstein et al., 2019, Front. Microbiol. doi.org/10.3389/fmicb.2019.01211

Field study design

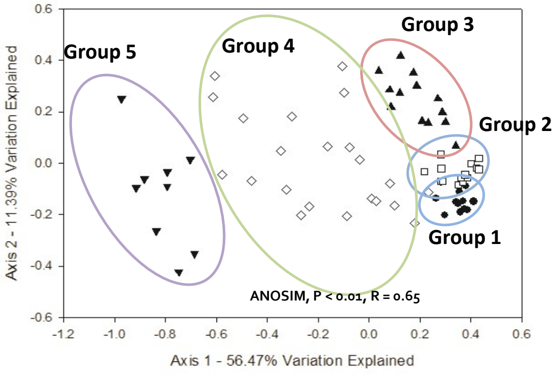


Iron King Mine tailings

- Study initiated in 2010
- Soil cores collected annually: 2010 to 2014, 2016
- Geochemical parameters measured: pH, plant cover
- Microbiome analyzed via iTag sequencing of the 16s rRNA gene

Field microbiome and biogeochemical progression

Grouping statistics



Microbial taxa divided into 5 groups related to increasing acidity and decreasing plant cover

Taxonomic analysis

Group

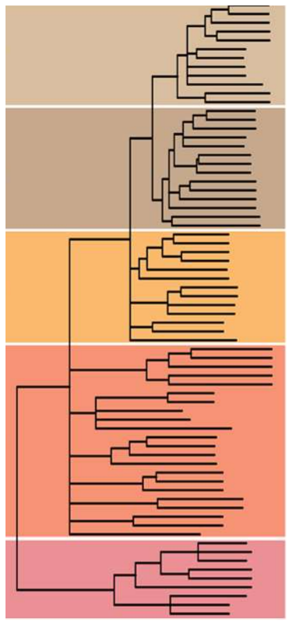
1

2

3

4

5



Field microbiome progression

Acidophilic Fe and S oxidizers

Plant growth promoting microbes

Unassigned

Taxonomy (Family)

Group

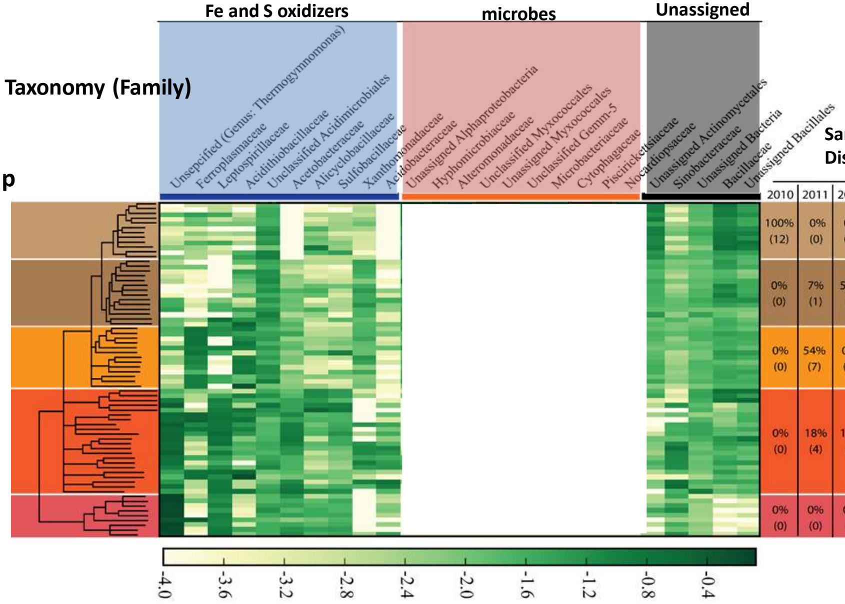
1

2

3

4

5



Sample Distribution (%)

2010	2011	2012	2013	2014	2016
100% (12)	0% (0)	0% (0)	0% (0)	0% (0)	0% (0)
0% (0)	7% (1)	50% (7)	21% (3)	7% (1)	14% (2)
0% (0)	54% (7)	0% (0)	23% (3)	23% (3)	0% (0)
0% (0)	18% (4)	18% (4)	14% (3)	23% (5)	27% (6)
0% (0)	0% (0)	0% (0)	22% (2)	33% (3)	44% (4)

Microcosm design

Artificial soil matrix

- 85% quartz sand, 15% bentonite/kaolinite clay
- Amended with iron, sulfur, or iron and sulfur
- Inoculated with 1% mine tailings from compost-amended treatment at field site

Sampled every 2 weeks to capture iron and sulfur oxidizing communities

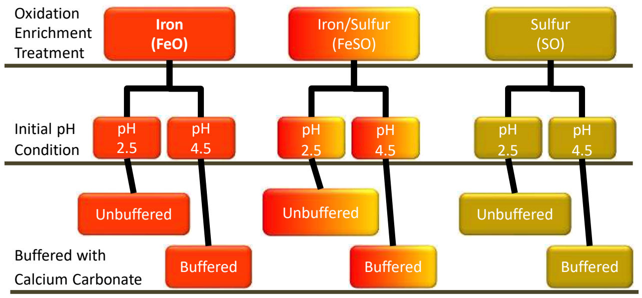
- DNA extracted and sequenced for microbial community analysis

---

Microcosm culture experiments

Experiment 1: Showed that acidification is biotic, not abiotic

Experiment 2: Identify microbial communities involved in moderately acidic and highly acidic pH conditions



Oxidation Enrichment Treatment

Iron (FeO)

Iron/Sulfur (FeSO)

Sulfur (SO)

Initial pH Condition

pH 2.5

pH 4.5

pH 2.5

pH 4.5

pH 2.5

pH 4.5

Unbuffered

Unbuffered

Unbuffered

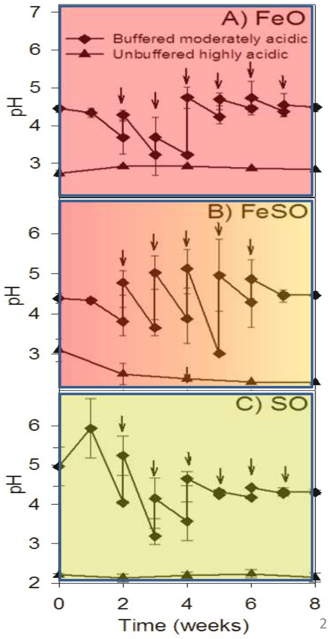
Buffered with Calcium Carbonate

Buffered

Buffered

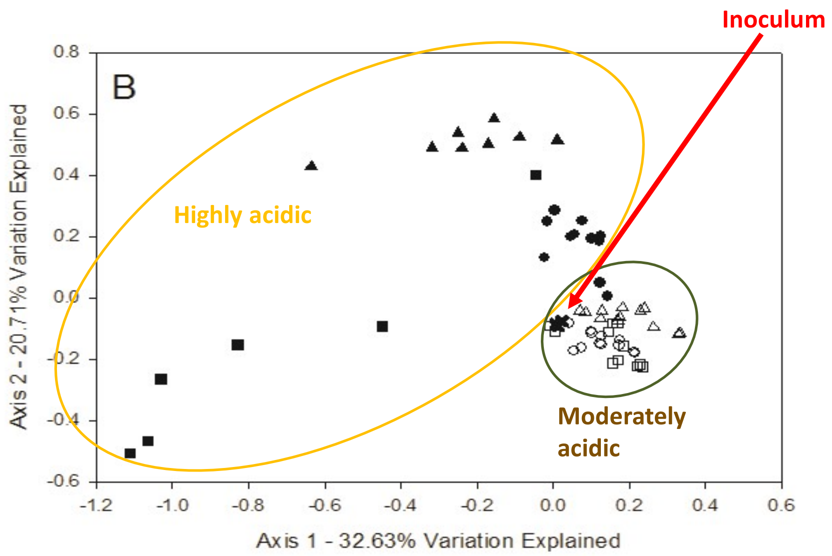
Buffered

Outcome: Distinct moderately acidic and highly acidic enrichment pH conditions were established



Hottenstein et al., 2019, Front. Microbiol. doi.org/10.3389/fmicb.2019.01211

Microcosm taxonomic composition



Inoculum

Highly acidic

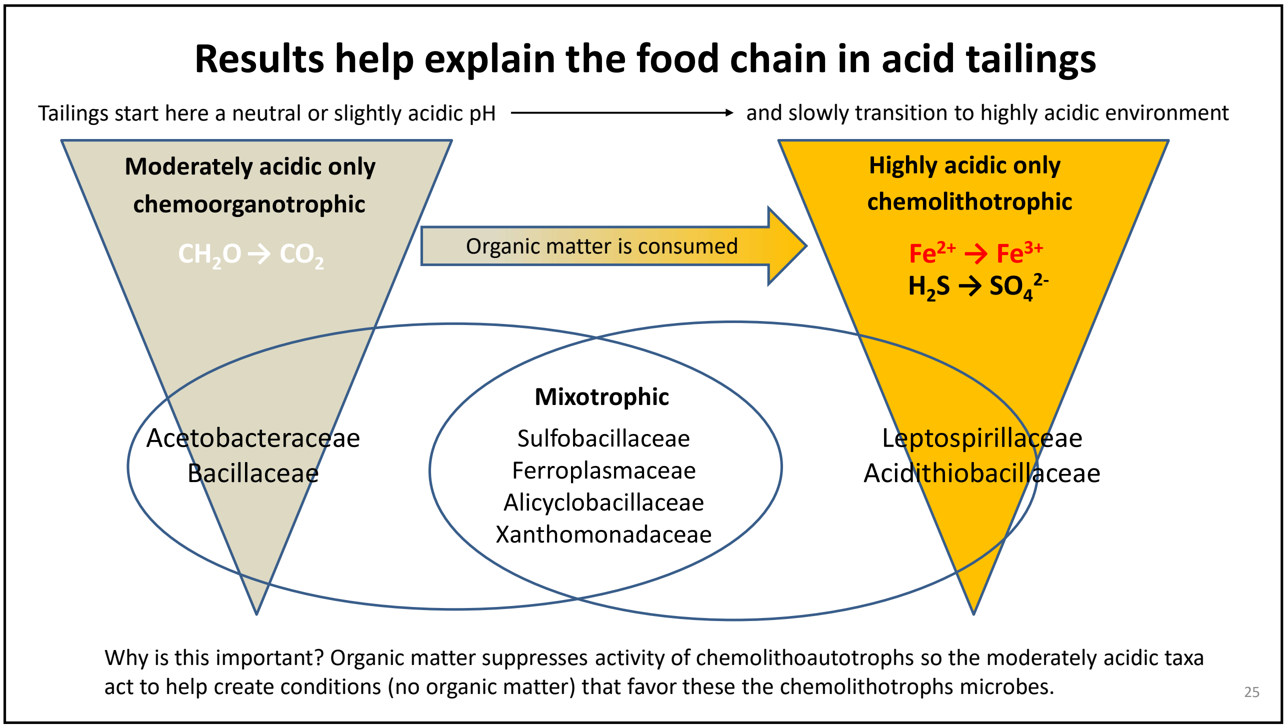
Moderately acidic

Outcome: Dominant taxa different in moderately acidic vs. highly acidic conditions

Microcosm taxonomic composition

Microbial Taxa and Abundance		Moderately Acidic Conditions			Highly Acidic Conditions		
Family	Most abundant genus (%)	FeO	FeSO	SO	FeO	FeSO	SO
Acetobacteraceae	Acidiphilium (68%)	**9.7%**	**1.5%**	**8.1%**	12.9%	0.0%	0.0%
Xanthomonadaceae	Unassigned (85%)	**6.3%**	**7.6%**	**2.6%**	0.0%	0.0%	0.0%
Alicyclobacillaceae	Alicyclobacillus (48%)	**6.9%**	**51.2%**	**5.6%**	4.8%	1.1%	0.0%
Bacillaceae	Unassigned (78%)	**6.5%**	**5.7%**	**7.2%**	2.2%	0.1%	0.9%
Sulfobacillaceae	Sulfobacillus (99%)	0.1%	0.1%	0.4%	**10.8%**	**53.2%**	**1.8%**
Leptospirillaceae	Leptospirillum (100%)	0.0%	0.0%	0.0%	**29.9%**	**14.6%**	**3.9%**
Ferroplasmaceae	Ferroplasma (100%)	0.0%	0.0%	0.0%	**0.3%**	**8.7%**	**84.0%**
Acidithiobacillaceae	Acidithiobacillus (100%)	0.9%	**21.3%**	0.0%	0.9%	**15.9%**	0.0%

Outcome: Dominant taxa different in moderately acidic vs. highly acidic conditions



Results help explain the food chain in acid tailings

Tailings start here a neutral or slightly acidic pH → and slowly transition to highly acidic environment

Moderately acidic only
chemoorganotrophic
$CH_2O \rightarrow CO_2$

Organic matter is consumed

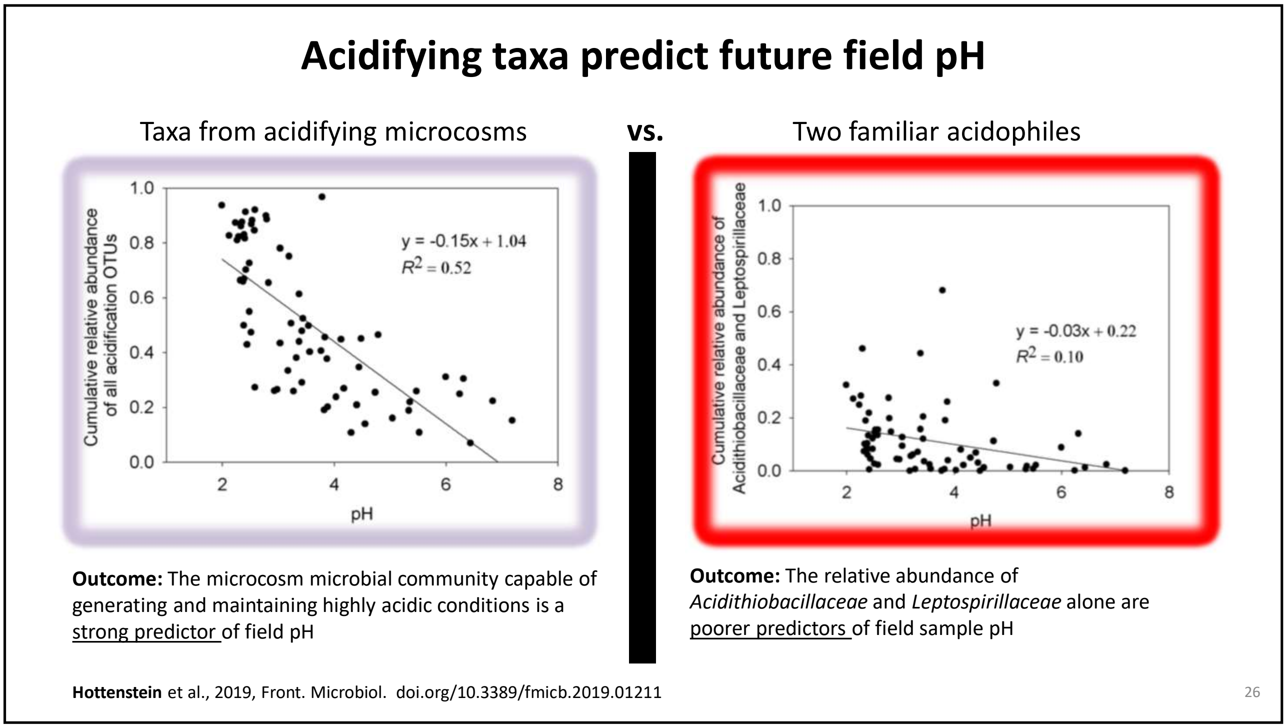
Highly acidic only
chemolithotrophic
$Fe^{2+} \rightarrow Fe^{3+}$
$H_2S \rightarrow SO_4^{2-}$

Acetobacteraceae
Bacillaceae

Mixotrophic
Sulfobacillaceae
Ferroplasmaceae
Alicyclobacillaceae
Xanthomonadaceae

Leptospirillaceae
Acidithiobacillaceae

Why is this important? Organic matter suppresses activity of chemolithoautotrophs so the moderately acidic taxa act to help create conditions (no organic matter) that favor these the chemolithotrophs microbes.



Acidifying taxa predict future field pH

Taxa from acidifying microcosms **vs.** Two familiar acidophiles

Outcome: The microcosm microbial community capable of generating and maintaining highly acidic conditions is a strong predictor of field pH

Outcome: The relative abundance of *Acidithiobacillaceae* and *Leptospirillaceae* alone are poorer predictors of field sample pH

Hottenstein et al., 2019, Front. Microbiol. doi.org/10.3389/fmicb.2019.01211

Conclusions

- Mine tailings acidification is a complex process that can be controlled by organic matter addition.
- Legacy sites will required long-term monitoring and perhaps additional management. The tailings microbiome is a biomarker of mine tailings status.
- Combined insights of soil microbiome dynamics with above ground plant growth may better assure sustained plant growth for long-term success of mine tailing reclamation.

University of Arizona Center for Environmentally Sustainable Mining

Translating Innovation into Practice

Revegetation of Mine Wastes in Arid Environments: Linking Above- and Below-Ground Performance:
Active Mine Operations

Julia Neilson, PhD
jneilson@email.Arizona.edu
Director, Center for Environmentally Sustainable Mining
University of Arizona Dept. Environmental Science

EPA Webinar
August 12, 2020

Center for Environmentally Sustainable Mining

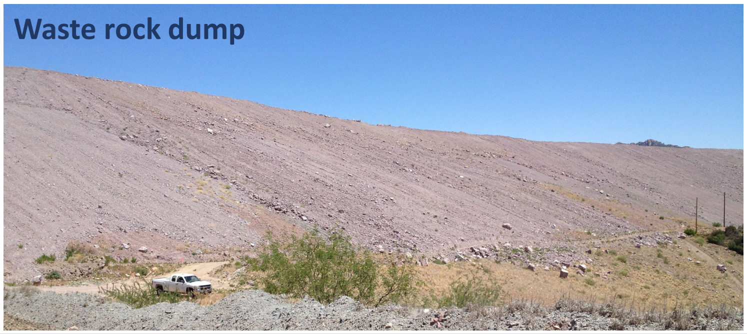
Superfund Research Program

Modern Copper Mine: Operations Footprint

- Excavation and extraction of mineral ore
- Mine tailings storage facilities
- Waste rock deposition
- Economic mineral recovery causes major land disturbance

Mine Waste Deposition

Mine Tailings Storage Facility



Waste rock dump

<u>Tailings</u>

- Waste remaining after ore extraction (typical copper content < 0.5%)
- Fine particle size distribution
- Storage facilities occupy 100s of acres

<u>Waste Rock</u>

- Excavated rock with copper concentration too low for economic extraction
- Course particle size distribution

Mine Waste Reclamation Research Objectives

- Dust control of fine particulate matter that can cause respiratory complications

- Develop more effective and efficient revegetation tools to return mine waste to a productive state following mine closure: accelerated ecosystem regeneration
- Address revegetation knowledge gaps to facilitate consistent ecosystem regeneration.

Case Study 1: Revegetation of Mine Tailings Storage Facility

Standard technology

- **Soil cap**: depth varies with tailings chemistry (6-36")
- **Seed mix**: native grasses, shrubs, and trees
- **Seed application**: drill or hydroseed

Challenges to sustainable plant establishment

- Semiarid region: limited precipitation and high evapotranspiration
- Low nutrient/low water holding capacity material
- Available soil capping material highly variable
- Metrics of revegetation progress are poorly understood

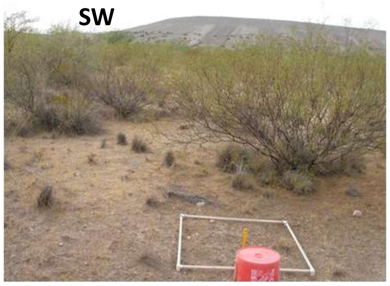
Research Focus

Develop belowground biogeochemical indicators to be used as predictive tools by the mining industry to quantify

- Assess soil cover quality
- Revegetation progress

Assessment of Variable Plant Establishment

- 600-acre reclaimed tailings storage facility (TSF)
- Tailings capped with 12 in. soil
- Drill seeded with a complex mixture of native perennial grasses, forbs, shrubs, and trees
- Site evaluation: 5 years after seeding
- SW and NW quadrants of TSF were capped with soil excavated from different depths



vs

Sample Year 1	% Plant Cover
1NE	17 B
1NW	17 B
1SE	15 B
1SW	42 A

ANOVA; p< 0.001, Tukey HSD

Lydia Jennings, Catherine Fontana

Evaluation of Below-Ground Soil Indicators

Below-ground indicators

Biological (Soil microbiome):
- DNA Biomass
- Bacterial abundance
- Microbial diversity
- Microbial community composition

Chemical:
- pH
- Electrical Conductivity (salinity)
- Total Nitrogen
- Organic Carbon
- Bioavailable Phosphorus

Physical:
- Soil Texture Analysis
- Particle Size Distribution

Total Nitrogen

Sample Year 1	TN (mg/g)
1NE	0.155 B
1NW	0.165 B
1SE	0.151 B
1SW	0.311 A

DNA Biomass

Sample Year 1	DNA Biomass (ng/g dry soil)
1NE	175 B
1NW	302 B
1 SE	426 B
1 SW	2488 A

ANOVA; p< 0.001, Tukey HSD

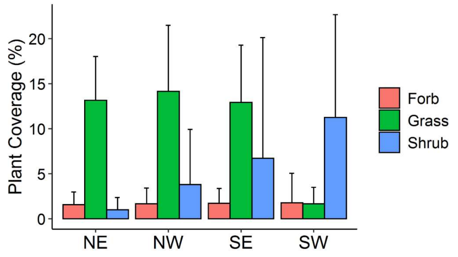
- **Total nitrogen**
  Native soil 0.46 ±0.17 mg N/g soil
- **DNA Biomass**
  (includes bacteria, archaea, and fungi)
  Native soil = 2900 ng DNA/g soil

Above-ground Assessment

Plant Community Composition

(10 Years after Seeding)

Species Composition



Case Study 1: Summary

Metrics that associate with robust plant establishment
- Below-ground increases in soil nitrogen and biomass
- Above-ground plant community transition to increased shrub cover

Cover material source (quality) impacts plant establishment

Case Study 2: Revegetation of Mine Waste Rock Dump

Site Evaluation

- Seeded Slope(**D**):
  - Hydroseeded in 2012 with native seed mix
  - No soil cover
  - Seed mix: 6 perennial grasses, 3 perennial forbs, and 4 shrubs
- Above-ground plant establishment and below-ground substrate development monitored for 5 years
- Seeded slope (**D**) compared to unseeded slope (**N**)

Lia Ossanna, Karen Serrano, Catherine Fontana

Initial Below-ground Comparison

(2014: 2 years after seeding)

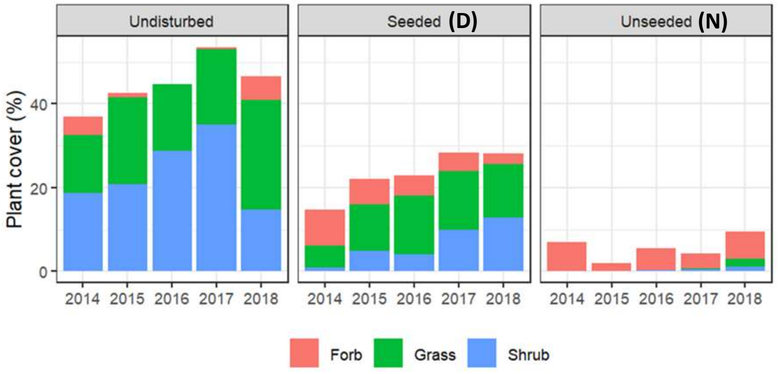
	Undisturbed (OS)	Seeded (D Slope)	Unseeded (N Slope)
pH	6.83 ± 0.32 b	9.22 ± 0.44 a	9.28 ± 0.184 a
EC (ds/m)	0.251 ± 0.157 a	0.144 ± 0.031 b	0.162 ± 0.053 b
Total nitrogen (mg/g)	1.562 ± 0.644 a	0.065 ± 0.033 b	0.049 ± 0.015 b
DNA biomass (ng/g)	6822 ± 2628 a	31 ± 84 b	11 ± 20 b
Fines (%)	34 ± 8	30 ± 7	29 ± 7
Pebbles (%)	37 ± 13	41 ± 8	43 ± 9
Cobbles (%)	29 ± 6	31 ± 7	28 ± 13

ANOVA; p< 0.001, Tukey HSD

Fines:	< 2mm
Pebbles:	2 mm-3 in
Cobbles :	3 – 10 in

Plant Community Composition

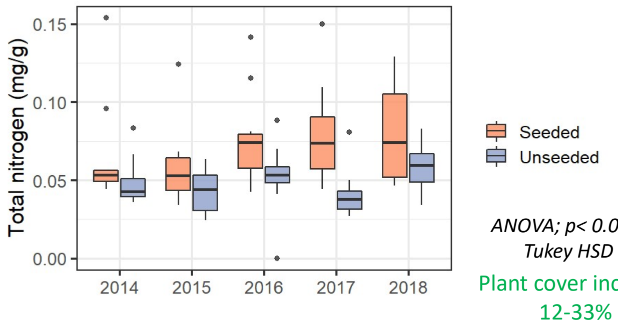
(2-6 Years after Seeding)



- Undisturbed site vegetation: average of 44% cover
- Seeded D Slope: Plant cover increased from 12% in 2014 to a high of 33% in 2017
- Seeded D slope relative shrub cover increased from 4% to 43%
- Unseeded N slope: plant cover below 10%

Temporal Assessment of Below-Ground Soil Indicators

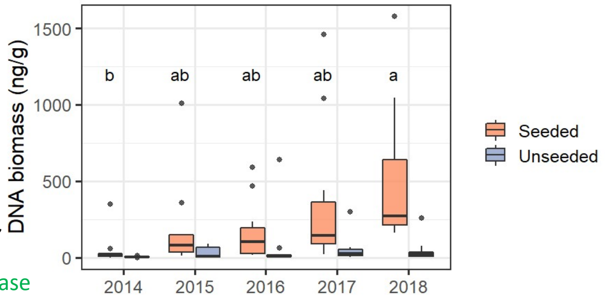
Total Nitrogen



ANOVA; p< 0.001, Tukey HSD

Plant cover increase 12-33%

DNA Biomass



- Total Nitrogen: steady, but insignificant increase observed on Seeded Slope; no increase on unseeded slope. *Undisturbed areas, 1.56±0.64 mg TN/g dry soil*
- DNA Biomass*:* Seeded Slope 2018 biomass is significantly higher than 2014; no change observed on unseeded slope. *Undisturbed areas*, *6822±2628 ng DNA/g dry soil*.
- Seeded slope site variation (size of box plot) increases with time.

Targeted Study of Plant Influenced Substrate

(Shrub vs Grass Effect)

Shrub-influenced waste rock development

Grass-influenced waste rock development

Below-ground Comparison

(6 years after seeding)

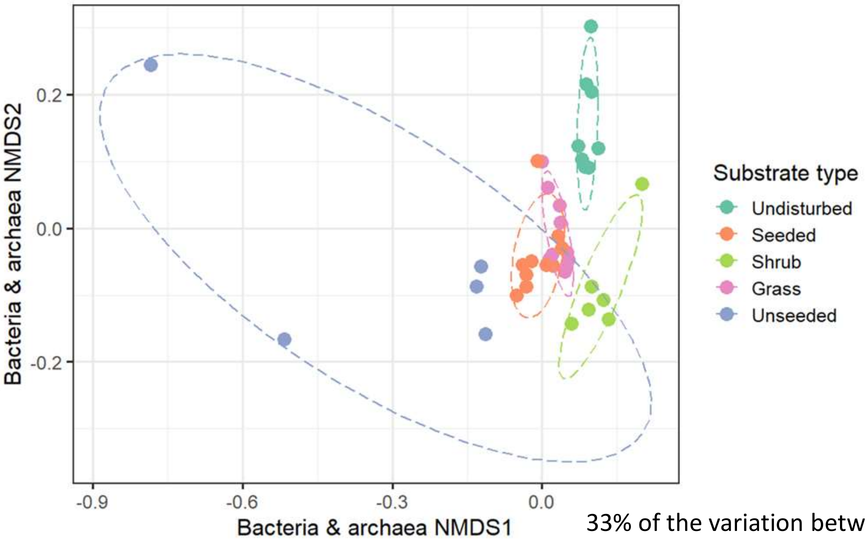
Fertility Measure (per g substrate)	Undisturbed	Seeded (D Slope)	Shrub Rhizosphere	Grass Rhizosphere	Unseeded (N Slope)
Org Carbon (mg/g)	14.2 a	1.4 c	7.5 b	1.7 c	0.8 c
Bioavailable P (ug/g)	22.5 a	3.2 bc	7.8 b	3.3 bc	2.0 c
Total N (mg/g)	1.3 a	0.09 c	0.6 b	0.12 c	0.05 c
Biomass (ng/g)	9250 a	671 c	4162 b	1610 c	28 c
Bacterial abundance (log copies/g)	8.53 a	7.36 b	8.24 ab	8.11 ab	5.20 c
Bacterial/archaeal richness	2761 a	1293 b	2190 a	2080 b	221 c
Fungal richness	634 a	164 bc	262 b	280 b	12 c
N-cycling gene abundance*	5.15 ab	3.34 bc	6.52 a	4.52 ab	0.91 c

*Quantification of *amo*A bacterial gene; bacterial conversion of ammonium to nitrite

ANOVA; p< 0.001, Tukey HSD

Bacteria/Archaea Community Composition

(6 years after seeding)



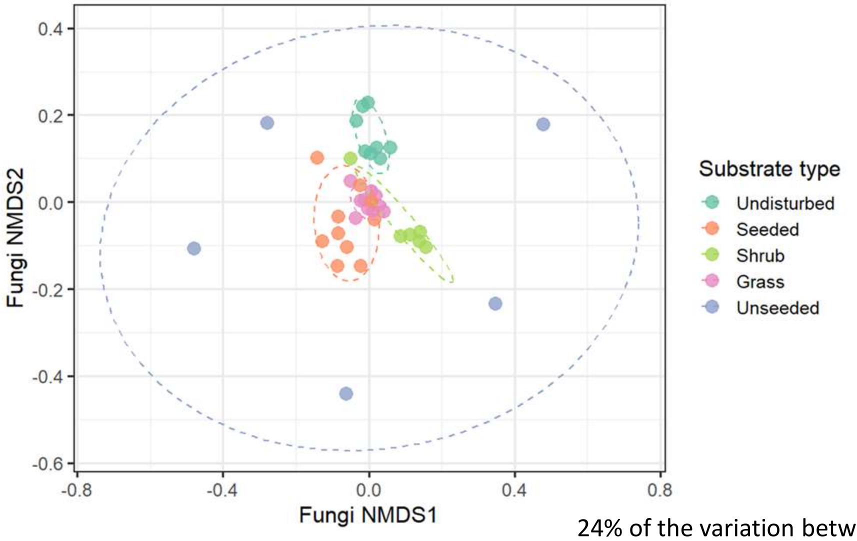
<u>Significant variation observed between the composition of the following communities</u>

- Unseeded waste rock vs natural undisturbed site
- Shrub- vs grass-influenced waste rock

33% of the variation between bacterial communities is explained by the substrate type

Fungal Community Composition

(6 years after seeding)

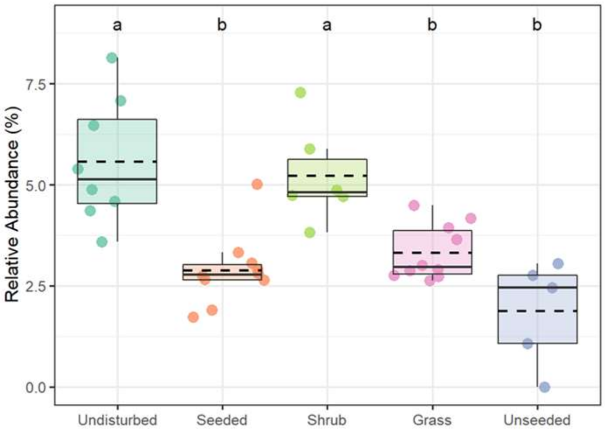


- Greater overlap is observed between fungal community composition than for bacteria/archaea
- The unseeded fungal community is distinct from the plant-influenced communities

24% of the variation between bacterial communities is explained by the substrate type

Differences in Nitrogen Cycling Potential

(6 years after seeding)



ANOVA; p< 0.001, Tukey HSD

- Relative abundance of putative nitrogen-cycling bacterial/archaeal phylotypes
- Shrub-influenced substrate has a significantly higher relative abundance of nitrogen-cycling microbial phylotypes then grass-influenced or unseeded substrates
- The relative abundance of nitrogen-cycling phylotypes in shrub-influenced waste rock is not significantly lower than the undisturbed native soils.

Case Study 2: Summary

1. Temporal patterns observed in Case Study 2 affirm metrics identified in Case Study 1
    - A temporal increase in plant cover is associated with a belowground increase in nitrogen and biomass
    - A temporal increase in plant cover is associated with increased relative percentage of shrub cover
2. No significant above-ground plant establishment or below-ground fertility development was observed on unseeded waste rock over 6 years of monitoring.
3. The waste rock microbial community differs significantly from that of the natural vegetated soil; unseeded waste rock is characterized by a lack of nutrient cycling microbial capacity important to plant sustainability
4. Shrub establishment accelerates soil fertility development relative to grass establishment.

Significance of Mine Waste Revegetation Research Results

Results from these studies provide metrics to monitor revegetation progress and data to inform revegetation management decisions

Industry research partners identify significant environmental areas of concern for research development.

Future research directions

- Develop metrics for cover material evaluation; characterize the effect of cover material excavaton source and depth on plant establishment
- Evaluate significance of month of seeding to plant establishment
- Evaluate microbial amendments such as mycorrhizal fungal inocula

Center for Environmentally Sustainable Mining (CESM)

Develop educational and research initiatives that address environmental issues related to mining activities in arid and semi-arid environments

https:/superfund.Arizona.edu/cesm

- A technical advisory committee (TAC) informs and evaluates CESM activities and research priorities
- CESM TAC includes multiple industry representatives from copper and rock products companies and consulting
- CESM provides an avenue for research translation from academia to industry and addresses technologies to enhance sustainable mining practices
- Neutral tech transfer to state and national policy makers and regulators.

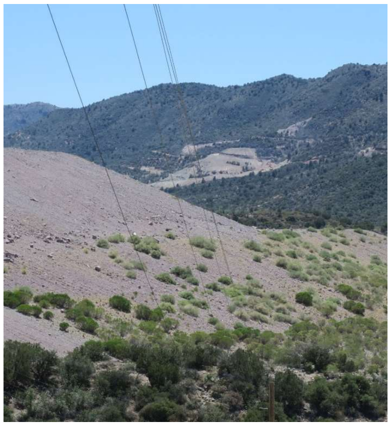
Center for
Environmentally
Sustainable Mining

CESM UA-Industry Academic Revegetation Research Cooperative

- Revegetation research cooperative
- Formed in 2013
- Member industries – ASARCO Mission Mine; KGHM Carlota Copper; Rio Tinto Resolution Copper; BHP Copper, Inc.
- Specific focus

  Develop belowground biogeochemical indicators of revegetation progress to be used as predictive tools by the mining industry

- Management application
  1. Evaluate quality of capping materials
  2. Quantify revegetation progress



Center for Environmentally Sustainable Mining

Ultimate Goal

Provide the mining industry with technological tools to make revegetation a data driven science

ACKNOWLEDGMENTS

Faculty
Dr. Alicja Babst-Kostecka
Dr. Eric Betterton
Dr. Jon Chorover
Dr. Elise Gornish
Dr. Eduardo Saez

Staff, Post-Docs, Students
Alaina Adel
Mary K. Amistadi
Travis Borillo
Lauren Bozeman
Dr. Yongjian Chen
Dr. Janae Csavina
Omar Felix
Catherine Fontana
Jason Field
Ariel Friel
Emalee Eisenhauer
Dr. Asma El Ouni
Xiaodong Gao
Dr. Juliana Gil-Loaiza
Catherine Gullo
Zhilin Guo
Dr. Corin Hammond
Gail Heath
Dr. Sarah Hayes
Dr. David Hogan
John Hottenstein
Linnea Honeker
Shannon Heuberger
Lydia Jennings
Shuqiong Kong,
Jessica Ledesma
Viviana Llano
Billy Linker
Karis Nelson
Lia Ossanna
Shawn A. Pedron
Michael Pohlmann
Benjamin Rivera
Dr. Robert Root
Mackenzie Russell
Yiamar Rivera
Richard Rushforth
Karen Serrano
William J. Scott
Harrison Smith
Mira Theilmann
Lane D. Undhjem
Alexis Valentin
Kayla M. Virgone
Yadi Wang
Scott White

Funding:
Amer Soc Microbiology Undergrad Research Fellowship
Arizona Technology and Research Initiative Fund (TRIF)
ASARCO Mission Mine
BHP Copper, Inc
KGHM Carlota Copper Company
Resolution Copper Mining, LLC
UA Undergraduate Biology Research Program
NIEHS Superfund Research Program Grant P42 ES04940
NIH EHS TRUE (Undergraduate Research Experiences)
NSF Graduate Research Fellowship Program

Partners:
Arizona Department of Environmental Quality
Arizona Department of Health Services
ATSDR Region 9
EPA Region 9
Jesse Dillon/Cedar Creek Associates
North American Industries, Stephan Schuchardt

THE UNIVERSITY OF ARIZONA Superfund Research Center

Center for Environmentally Sustainable Mining