Understanding and mitigating soil legacies to improve restoration success

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Targeting legacies in restoration

- **Intact Native Site**
- **Degraded, Some Invasion**
- **Degraded, Extreme Invasion**

Attempt to ameliorate legacy effects that impede restoration

Modified from Whisenant 1999
Need to target legacy effects explicitly

Heneghan et al. 2008 Rest Ecol
Can we change rate of legacy decay?

- Legacy development
- Legacy decay

Strength of Legacy vs. Time

- Invader introduction
- Invader removal
- Goal is to increase the rate of decay
Targeting legacies in restoration

Ecosystem Attributes

Native Scrub

Disturbed Scrub

Scrub Converted to Pasture

Í Natives
Δ Soil microbes
È C,N

No natives
È Δ Soil microbes
È C,N
Δ Structure

Invasive Removal, Microbial Inoculation, Native Seed Addition
Restoration
community & ecosystem goals

• Mitigate structural, biogeochemical, and microbial legacies

• Initiate self-sustaining native populations
Restoration sites
- disturbed
- pasture

Native sites
- undisturbed
scrub patches
Restoration treatments: herbicide
Restoration treatments: 
soil microbial addition
Plots were set up in fall 2006 and tracked through spring 2010.
Measuring restoration success

- Return site characteristics?
- Reduce nutrient legacies?
- Improve plant recovery?
Measuring restoration success

• Return site characteristics?

• Reduce nutrient legacies?

• Improve plant recovery?
Success on some (visible) fronts: plant removals largely restore structure.
Success on some (visible) fronts: plant removals largely restore structure.
Success on some (visible) fronts: plant removals largely restore structure.

![Graph showing non-native cover percentages]
Success on some (visible) fronts: plant removals largely restore structure
Success on some (visible) fronts: plant removals largely restore structure

![Graph showing success on some fronts with plant removals]
Success on some (visible) fronts: plant removals largely restore structure.
Success on some (visible) fronts: plant removals largely restore structure.
Measuring restoration success

• Return site characteristics?
  – Yes, site cover, openness, & soil crust aggregation were improved in degraded sites

• Reduce nutrient legacies?

• Improve plant recovery?
Measuring restoration success

• Return site characteristics?
  – Yes, degraded site cover, openness, & soil crust aggregation were improved

• Reduce nutrient legacies?

• Improve plant recovery?
Soil N differs among veg types

Total Inorganic N

Microbial Biomass N

 Ug g⁻¹

Control  Control  Control

NATIVE SCRUB  DISTURBED SCRUB  CONVERTED PASTURE

Hamman & Hawkes 2013 Rest Ecol
Microbial additions have little effect on N.

Hamman & Hawkes 2013 Rest Ecol
High N persists after veg removal

**Total Inorganic N**

**Microbial Biomass N**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>NATIVE SCRUB</th>
<th>DISTURBED SCRUB</th>
<th>CONVERTED PASTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>+Mic</td>
<td>Control +Mic</td>
<td>Control +Mic +Herb</td>
</tr>
<tr>
<td>+Mic</td>
<td></td>
<td>+Herb</td>
<td></td>
</tr>
</tbody>
</table>

Hamman & Hawkes 2013 Rest Ecol
Treatments do not change N legacies

Total Inorganic N

Microbial Biomass N

Control  +Mic  +Herb  +Herb +Mic

NATIVE SCRUB  DISTURBED SCRUB  CONVERTED PASTURE

Hamman & Hawkes 2013 Rest Ecol
Measuring restoration success

• Return site characteristics?
  – Yes, degraded site cover, openness, & soil crust aggregation were improved.

• Reduce nutrient legacies?
  – No. May need more time. Possibly remove topsoil if N reduction is necessary.

• Improve plant recovery?
Measuring restoration success

• Return site characteristics?
  – Yes, degraded site cover, openness, & soil crust aggregation were improved.

• Reduce nutrient legacies?
  – No. May need more time. Possibly remove topsoil if N reduction is necessary.

• Improve plant recovery?
The cast of characters

Hypericum cumulicola***
Eryngium cuneifolium***
Lechea cernua*
Lechea deckertii
Polygonella basiramia***
Paronychia chartacea**
More germination in native sites

Proportion Germination (± 1 SE)

NATIVE SCRUB

DISTURBED SCRUB

CONVERTED PASTURE
More germination in native sites
Microbial additions alone do not improve germination

Proportion Germination (± 1 SE)

NATIVE SCRUB

DISTURBED SCRUB

CONVERTED PASTURE
Plant removals improve germination only in pastures
Plant removals with microbial additions recover germination in disturbed sites.
Substantial native background recruitment, but not in pastures

Open space, moisture, and non-native veg cover explain 38% of variation in recruitment
Background recruitment of non-targeted species

*Polanisia tenuifolia*

*Stipulicida setacea*

*Cnidosculus stimulosus*

*Polygonella robusta*
Opportunities created for recruitment of non-targeted species in pastures

Open space and soil aggregation explain 43% of variation in non-target recruitment
What does this mean for population viability?

• Demographic modeling of taxa to estimate population growth rates

• Started with one of the most abundant plant species, *Polygonella basiramia*
Polygonella population growth rates increased with restoration treatments

<table>
<thead>
<tr>
<th>VEGETATION</th>
<th>TREATMENT</th>
<th>Δ LAMBDA RELATIVE TO CONTROLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbed Scrub</td>
<td>Microbes</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Herbicide</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Herbicide+Microbes</td>
<td>+2.8%</td>
</tr>
<tr>
<td>Converted Pasture</td>
<td>Microbes</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Herbicide</td>
<td>+2.5%</td>
</tr>
<tr>
<td></td>
<td>Herbicide+Microbes</td>
<td>+1.1%</td>
</tr>
</tbody>
</table>
Measuring restoration success

• Return site characteristics?
  – Yes, degraded site cover, openness, & soil crust aggregation were improved.

• Reduce nutrient legacies?
  – No. May need more time. Possibly remove topsoil if N reduction is necessary.

• Improve plant recovery?
  – Yes, but veg-specific effects on germination, establishment, and population trajectories.
The probability of successful restoration differs among sites.
Can we open up the soil black box?

• How do microbial communities differ among native, disturbed, and pasture sites?
• Do those differences persist?

• Can we use what we learn to further enhance restoration success?
Focus on fungi

• Root fungi
  – Involved in nutrient and water uptake

• Soil fungi
  – Responsible for decomposition and nutrient recycling in soil

• Both abundant in this ecosystem and should play important functional roles given the low nutrient, xeric soils
Can we open up the soil black box?

• How do **fungal** communities differ among native, disturbed, and pasture sites?

• Do those differences persist?

• Can we use what we learn to further enhance restoration success?
Soil fungi had little overlap among veg types regardless of treatment.
Native sites have lower diversity and fewer fungi

NMS Axis 1 ($r^2 = 0.600$)

NMS Axis 2 ($r^2 = 306$)

Increasing fungal richness & abundance

Native

Disturbed

Pasture

Hyphal abundance (mm g$^{-1}$ soil ± 1 SE)

Fungal Richness (# OTUs ± 1 SE)
Strongest fungal legacy in pastures

NMS Axis 1 ($r^2 = 0.600$)

NMS Axis 2 ($r^2 = 306$)

Native
Disturbed
Pasture

Glinka & Hawkes, in review
Can we open up the soil black box?

• How do **fungal** communities differ among native, disturbed, and pasture sites? Do differences persist?
  – Yes! There are strong differences over three years, likely related to changes in soil organic matter.

• Can we use what we learn to further enhance restoration success?
Can we open up the soil black box?

• How do **fungal** communities differ among native, disturbed, and pasture sites? Do those differences persist?
  – Yes! There are strong differences over three years, likely related to changes in soil organic matter.

• Can we use what we learn to further enhance restoration success?
Manipulating specific fungi
Cultured fungi reflect whole community patterns

Native

Disturbed

Pasture

NMS Axis 2 ($r^2=0.256$)

NMS Axis 3 ($r^2=0.250$)

Sikes & Hawkes, unpublished
Cultured root fungi and soil fungi are phylogenetically distinct.

Sikes & Hawkes, unpublished
Select fungi for amendments

- Fungi selected for variable function based on prior tests of competition and decomposition
- 8 root and 5 soil fungal isolates per site type
Testing fungal effects on restoration efforts

Disturbed Pasture

Control

Control

Herbicide

Root fungi

Soil fungi

Control

Control

Home Site Fungi

Native Scrub Fungi
Overall native plant germination was dominated by three species:

- **Aristida gyrans**
- **Schizachyrium niveum**
- **Palafoxia feayi**

Other species include:

- **Polygonella robusta**
- **Lechea cernua**
- **Sabal etonia**
No variation in *Aristida* in the absence of fungi

Sikes et al. unpublished data
Fungal effects on *Aristida* were highly context dependent

![Germinants](image)

Control

DISTURBED

PASTURE + Herbicide

PASTURE

Sikes et al. unpublished data
Aristida germination inhibited in disturbed sites by fungi from native scrub

Sikes et al. unpublished data
Fungi from pastures improved *Aristida* germination in pastures with veg removed

Sikes et al. unpublished data
Fungi had no effect on *Aristida* germination in pastures when grasses were not removed

Sikes et al. unpublished data
Without fungi, *Schizachyrium* germination varied little across sites

Sikes et al. unpublished data
Fungi from disturbed sites improved *Schizachyrium* germination in disturbed sites

Sikes et al. unpublished data

![Graph showing germination rates in different treatments.](image)
In pastures, root fungi from native scrub improved *Schizachyrium* germination

Sikes et al. unpublished data
*Palafoxia* germination lower in pastures without fungi

Sikes et al. unpublished data
Fungal effects on *Palafoxia* are also highly context dependent

Sikes et al. unpublished data
Can we open up the soil black box?

• How do **fungal** communities differ among native, disturbed, and pasture sites? Do those differences persist?
  – Yes! There are strong differences over three years, likely related to changes in soil organic matter.

• Can we use what we learn to further enhance restoration success?
  – Potentially, but it is not straightforward and may be both species- and site-specific
Different approaches overcome legacies to different degrees

Ecosystem Attributes

Native Scrub

Invasive Plant Removal + Soil Inoculation

Specific microbe additions for some species

Ecosystem State

Disturbed Scrub

Invasive Plant Removal

Scrub Converted to Pasture
When should we address legacy effects?

- Amount of effort should be based on the balance of resources required, potential efficacy, and degree of need

- Many new studies coming out manipulating microbes and finding improved restoration, but the field is still in its infancy

- General rules?
Thank you!

- Hawkes Lab
  - Erin Brault
  - Clare Glinka
  - Nick Johnson
  - Ben Sikes
- Archbold Biological Station
  - Eric Menges
  - Hilary Swain
  - Patrick Bohlen
  - Stacy Smith
- USDA NRI Managed Ecosystems Program
- Smith Fellows Program
Four of these species were also differentially sensitive to microbes.