Choosing Efficient Treatment Options for Invasive Plants by Assessing Costs and Benefits in a Spatial Risk-Based Optimization Framework

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Center for Environmental Science
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Treated under
Emergency Stabilization & Rehabilitation and Burned Area Rehabilitation Programs

Source Data: USFS, BLM
Native-Dominated Site
Cheatgrass- & Medusahead-Dominated Site
A decision-support tool to help allocate restoration effort to maximize social benefits

- Address the question: Where should restoration efforts be concentrated?
Research Approach

1. Characterize management problems and response options
2. Identify ecosystem services affected and frame benefits analysis
3. Evaluate data available to inform assessment of benefits, costs & risks
4. Develop risk-adjusted cost-effectiveness framework for decision support
5. Test integrated simulation optimization for comparing options and assessing uncertainty
Framing Benefit Assessment

• Which areas can / do provide benefits in terms of ecosystem services?
• What damages / costs are avoided by restoring now at various locations?
• How confident are we that restoring will generate future streams of benefits?
• How urgent is treatment at this site?
## Benefits: Costs Avoided with Cheatgrass Management

<table>
<thead>
<tr>
<th>Ecosystem Service</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1 = \text{Recreational Antelope Hunting}$</td>
<td>Increased costs, reduced bag rates, reduced quality of experience.</td>
</tr>
<tr>
<td>$b_2 = \text{Production of animal forage for commercial ranching}$</td>
<td>With fire - lost profits – if no substitute land, reduces productivity and/or increases costs. BLM policy to shift ranchers off burned areas for 2-3 yrs. Without fire - Increased variability of returns (?)</td>
</tr>
<tr>
<td>$b_3 = \text{Property protection}$</td>
<td>Increased risk of property damage due to fire with cheatgrass</td>
</tr>
<tr>
<td>$b_4 = \text{Existence values}$</td>
<td>Sage / sage grouse are characteristic species at risk. Loss of sage appears irreversible without human intervention.</td>
</tr>
</tbody>
</table>
Treatment options to prevent cheatgrass domination

Intensity

• No treatment
• Aerial seeding only (mix of native/non-native)
• Aerial seeding + chaining
• Aerial seeding + chaining + herbicide
• Aerial seeding + chaining + drill-seeding

• Intensive sheep grazing
Evaluate Risk-Adjusted Cost-Effectiveness

1. Benefits of Successful Restoration
2. Probability of Successful Restoration
3. Costs of Treatment

\[
\text{Cost - Effectiveness} = \frac{\Delta \text{Benefits} \times \text{Probability of Success}}{\text{Costs of Treatment}}
\]
Comparing Restoration Options

Cost

Benefits

No
Low Benefits
High Costs

Yes
High Benefits
High Costs

Low Benefits
Low Costs

High Benefits
Low Costs
Burned Area Restoration Optimization Model

**Objective**
Maximize benefits of multiple ecosystem services subject to a given budget constraint

\[ B_t = \sum_i \sum_j w_j (b_{ij}^{\text{with}} - b_{ij}^{\text{without}}) \]

- \( i \) = Location \( i \), (sum over subset of fires)
- \( j \) = Benefit \( j \) (brec, bforage bprop, bexist)
- \( t \) = 2-3 years following restoration

**Control Variables**

- \( k \) = treatment, the level of preventative/restorative treatment provided to burned area \( i \)
- \( w \) = weights assigned to benefits \( j \)

**Budget Constraint**

\[ TC_i = \sum_k FC + JC_k \cdot JT_i + TCA_{ik} \cdot A_i \]

- \( FC \) = Fixed Costs
- \( JC_k \) = Journey (Travel) Cost, personnel and equipment
- \( JT_i \) = Journey Time (hours)
- \( TCA_{ik} \) = Treatment Cost per Acre
- \( A_i \) = area treated (acres)
- \( k \) = treatment(s)
Estimating Change in Benefits with Treatment

\[ b_{ij} = f (b_{\text{max}ij}, S_i, C_i) \]

- \( b_{\text{max}ij} = \) maximum possible site benefits
- \( S_i = \) probability of success (desirable plants dominant in year 2-3)
- \( C_i = \) contiguity / connectedness of native vegetation proxy for fire risk to neighboring lands
Assessing Site Restorability

Restorability:

\[ S_i = P(r_i, \tau_k) \]

- \( r_i \) = site recoverability
- \( \tau_k \) = treatment effectiveness
- \( k \) = treatment
Recoverability and restorability based on % neighborhood in cheatgrass (holding all else constant)
Calculating Risk-Adjusted Site Benefits

Restorability (S)

- Restorability (S)
  - Treatment intensity \( k \)
  - Treatment result
    - Landscape condition: good, poor

On-site Benefit response (per acre)

- Benefits
  - % Native veg

Benefits

- b\(_{\max(i)}\)

On and Off-Site Benefit response (total fire)

- Benefits
  - b * C
  - % Native veg

% Native Veg

- Low r
- High r

P(Success)

- Treatment intensity \( k \)
- P(Success)\(_{ik}\)

% native veg
Benefits vs. % native vegetation

$B_{ij} = \frac{b_{max_i} \times \%\text{native}}{k_j + \%\text{native}}$

More responsive benefit

Less responsive
Effect of Fire on Landscape Connectivity

Mean Contiguity = 0.666
Largest Patch Index = 75.2

Mean Contiguity = 0.576
Largest Patch Index = 31.7
Measuring $b_{\text{max}}$

- Site quality
- Landscape quality
- Scarcity / replaceability / substitutability
- Risk of service disruption
Site Quality: Grazing
Quality Indicator

Source data: BLM
Site Quality: Sage Grouse Habitat
Accessibility: Travel Time to Site
Accessibility: Population within 1.5 Hours of Site

177,642 people within green area
Results
## Restorability Regression Analysis

### Results (ordinal logit)

<table>
<thead>
<tr>
<th>Reduced Success (negative coefficients)</th>
<th>Enhanced Success (positive coefficients)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• % Infested</td>
<td>• Elevation*</td>
</tr>
<tr>
<td>• Herbicide use</td>
<td>• Herbicide x %Infested*</td>
</tr>
<tr>
<td>• Drill seeding</td>
<td>• Drill seeding x %Infested</td>
</tr>
<tr>
<td></td>
<td>• Native seeds*</td>
</tr>
<tr>
<td></td>
<td>• Fencing</td>
</tr>
<tr>
<td></td>
<td>• Spending per acre</td>
</tr>
<tr>
<td></td>
<td>• Fire size</td>
</tr>
</tbody>
</table>

* Coefficients significant at > 95%
Seed Choice and Project Success
## Treatment Cost Empirical Modeling

**Dependent variable = Treatment cost per acre**

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>(Constant)</td>
<td>6.763</td>
<td>.524</td>
<td>12.898</td>
</tr>
<tr>
<td></td>
<td>ln (fire size)*</td>
<td>-.304</td>
<td>.071</td>
<td>-.441</td>
</tr>
<tr>
<td></td>
<td>drill seed dummy</td>
<td>.646</td>
<td>.200</td>
<td>.344</td>
</tr>
<tr>
<td></td>
<td>herbicide dummy</td>
<td>.386</td>
<td>.216</td>
<td>.218</td>
</tr>
<tr>
<td></td>
<td>state dummy (ID)*</td>
<td>-1.368</td>
<td>.322</td>
<td>-.756</td>
</tr>
<tr>
<td></td>
<td>native dummy*</td>
<td>.675</td>
<td>.248</td>
<td>.359</td>
</tr>
<tr>
<td></td>
<td>WUI dummy</td>
<td>-.192</td>
<td>.446</td>
<td>-.045</td>
</tr>
<tr>
<td></td>
<td>slope class</td>
<td>-.042</td>
<td>.327</td>
<td>-.013</td>
</tr>
<tr>
<td></td>
<td>protected area</td>
<td>-.305</td>
<td>.273</td>
<td>-.117</td>
</tr>
<tr>
<td></td>
<td>fencing dummy</td>
<td>-.292</td>
<td>.245</td>
<td>-.141</td>
</tr>
<tr>
<td></td>
<td>Ln (airport travel time)</td>
<td>-.297</td>
<td>.205</td>
<td>-.186</td>
</tr>
</tbody>
</table>
Costs vs. Risk-Adjusted Benefits

- Options
- RISKOptimizer Selected Options
- Agency Selected Options

Costs vs. Benefits Diagram

- Total Treatment Costs
- Benefits

Costs range from $0 to $400,000

Benefits range from 0 to 1,400

Legend:
- Options
- RISKOptimizer Selected Options
- Agency Selected Options
## Optimization Output vs. Management Decisions

equal weights to benefits

<table>
<thead>
<tr>
<th></th>
<th>Total Acres Treated</th>
<th>Total Change in Benefit Units</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RISKOptimizer</td>
<td>48,140</td>
<td>626,439</td>
<td>$999,500</td>
</tr>
<tr>
<td>Treated Sites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agency Treated</td>
<td>25,850</td>
<td>67,149</td>
<td>$1,254,000</td>
</tr>
<tr>
<td>Sites</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lessons Learned

• **Assessing Restorability**
  – Need data on *untreated* sites to distinguish recovery rate from restoration rate

• **Assessing Benefits**
  – Managers want to incorporate all benefits not just monetized benefits
  – Benefit indicator calculations are time-consuming but can be automated
  – Further research needed to ensure benefit measures adjust to changing scarcity
  – Static analysis can incorporate concepts of benefit persistence
  – Data not available to quantitatively assess reduction in fire risk
  – Dynamic model required to directly assess value of increasing fire-free interval
Why we decided to try RISKOptimizer Software

• Deals explicitly with uncertainty regarding inputs/processes/outcomes

• Combines simulation & optimization

• Moderate-cost ($500) software tool that can be implemented as an Excel add-in
RISKOptimizer Software Overview

- Combines Monte Carlo simulation with genetic algorithm-based optimization in models that contain uncertain factors

- Can find optimal solutions to problems that are “unsolvable” using standard linear and non-linear optimizers
Impact of Uncertainty on Simulation/Optimization

Example 1: Certain Input Variables
B = change in EBI with Treatment  B = 500
C = cost of treatment  C = $100

Results
B/C = 5

Example 2: Uncertain Input Variables – only 2 possible values per input
B = 300 or 500  C = $50 or $150

Results
B/C = 6  300/$50  B/C = 10  500/$50
B/C = 2  300/$150  B/C = 3  500/$150

Example 3: Uncertain Input Variables – site-specific probability of values
E.g., B = (500, 200-600)  C = $(100, (10))

Results
B/C = f(B,C) which will differ for each site
RISKOptimizer Software Overview

Allows the user to describe the range and probability distributions for each uncertain factor, and then

1. **Runs** full simulations for each possible trial by selecting factor values based on probabilities

2. **Stops** simulating and selecting factor values after a selected time period or number of iterations

3. **Picks** the solution that best fits the distribution of the target cell being maximized or minimized
General Approach

Step 1  **Enter all factors** (inputs, outputs, weights, constraints, etc.),

Step 2  **Define all processes** (relationships among factors)

Step 3  **Identify which factors are uncertain** and their expected range and probability distributions.

Step 4  **Identify the target cell** to be maximized
       • Weighted sum of our four benefit indicators.

Step 5  **Identify adjustable cells** (control variables):
       • Weights on each benefit indicator (defined by the user)
       • Treatment intensity at each area (solved by the program)

Step 6  **Identify constraints**
       • “Hard” – budget
       • “Soft” – policy choices that limit the optimization

Step 7  **Assign a weight to each benefit** (user preferences)

Step 8  **Run the program and assess results**

Step 9  **Perform sensitivity tests** on assumptions, weights, etc.

Step 10 **Interpret results** and develop recommendations
Cheatgrass Optimization Model

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OBJECTIVE</td>
<td>Maximize sum of weighted benefit indicators from all sites</td>
</tr>
<tr>
<td>CONSTRAINTS</td>
<td>Hard -- Total cost for all treatment cannot exceed $1,000,000</td>
</tr>
<tr>
<td></td>
<td>Soft -- Varies based on policy decisions (e.g., restrictions on treatment or spending allocations)</td>
</tr>
<tr>
<td>CONTROL VARIABLE</td>
<td>Treatment intensity at each site:</td>
</tr>
<tr>
<td></td>
<td>0 = no treatment</td>
</tr>
<tr>
<td></td>
<td>1 = seeding (native/non-native)</td>
</tr>
<tr>
<td></td>
<td>2 = seeding and herbicide</td>
</tr>
<tr>
<td></td>
<td>3 = seeding, herbicide, and drill seeding/harrowing</td>
</tr>
<tr>
<td></td>
<td>4 = seeding, herbicide, drill seeding/harrowing, and follow-up treatment</td>
</tr>
<tr>
<td>MODEL PROCESSES</td>
<td>Effects of post-fire treatment on cheatgrass cover</td>
</tr>
<tr>
<td></td>
<td>Effects of landscape factors on site benefits</td>
</tr>
<tr>
<td></td>
<td>Effects of landscape factors on treatment success</td>
</tr>
<tr>
<td></td>
<td>Effects of site/landscape characteristics on site treatment costs</td>
</tr>
<tr>
<td></td>
<td>Effects of cheatgrass cover on site benefits</td>
</tr>
<tr>
<td></td>
<td>Effects of cheatgrass cover on landscape benefits</td>
</tr>
<tr>
<td>SENSITIVITY ANALYSIS</td>
<td>Adjust relative weights of benefit categories</td>
</tr>
<tr>
<td></td>
<td>Assess and compare constraint penalties (shadow prices)</td>
</tr>
</tbody>
</table>
RISKOptimizer Progress Watcher

![Graph showing progress of Excel RO_input_101606.xls]

- **Result** column lists the outcomes for each trial.
- **Values** table displays the values for specific columns.
**Sample RISKOptimizer Output**

### PROGRAM INPUT

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recreational/Hunting</td>
<td>0.25</td>
</tr>
<tr>
<td>Grazing</td>
<td>0.25</td>
</tr>
<tr>
<td>Property Protection</td>
<td>0.25</td>
</tr>
<tr>
<td>Habitat/Existence Value</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### PROGRAM OUTPUT -- Optimal Solution

#### OPTIMAL BENEFIT SOLUTION

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>Change in Benefit Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Recreational/Hunting Benefits</td>
<td>108,608</td>
</tr>
<tr>
<td>Change in Grazing Benefits</td>
<td>168,172</td>
</tr>
<tr>
<td>Change in Property Protection Benefits</td>
<td>2,670</td>
</tr>
<tr>
<td>Change in Habitat/Existence Value Benefits</td>
<td>346,989</td>
</tr>
<tr>
<td>Total change in benefits</td>
<td>628,439</td>
</tr>
</tbody>
</table>

#### PROGRAM SOLUTION

<table>
<thead>
<tr>
<th>Treatment Type</th>
<th># Fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Treatment</td>
<td>26</td>
</tr>
<tr>
<td>Aerial seeding only</td>
<td>17</td>
</tr>
<tr>
<td>Aerial seeding + chaining</td>
<td>11</td>
</tr>
<tr>
<td>Aerial seeding + chaining + herbicide</td>
<td>5</td>
</tr>
<tr>
<td>Aerial seeding + chaining + drill-seeding</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average fire size per treatment type</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Treatment</td>
<td>2,601.6</td>
</tr>
<tr>
<td>Aerial seeding only</td>
<td>2,628.3</td>
</tr>
<tr>
<td>Aerial seeding + chaining</td>
<td>184.9</td>
</tr>
<tr>
<td>Aerial seeding + chaining + herbicide</td>
<td>262.2</td>
</tr>
<tr>
<td>Aerial seeding + chaining + drill-seeding</td>
<td>12.7</td>
</tr>
</tbody>
</table>
Conclusions

1. Details are important to managers, so site-specific analysis for comparing benefits, costs, risks are most useful

2. Benefit response functions are not well understood; but screening-level economic analysis based on first principles of ecology and economics can work

3. Data are sufficient to perform screening level analysis, but results are sensitive to the functional form of benefits

4. Weights on benefits are only critical when benefits compete; when they do, weights can significantly change the optimal allocation of treatment effort and treatment intensities

5. A simple decision framework that is based on costs and various types of benefits, incorporates uncertainty, and provides a means for testing hypotheses regarding competing and complementary benefits is most useful.

6. Decision-support tools that follow sound economic principles and reveal underlying assumptions and value judgments provide a better basis for both expert and stakeholder involvement in decision-making and promote cost- and risk-conscious solutions