Optimizing Mine Soil Amendment with Waste Byproducts using Response Surface Methodologies

presented by
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Road Map

1. Waste byproducts as amendments
2. Overview of response surface methodologies
3. Applying RSM: Optimizing waste byproduct amendments for revegetating gold mine tailings and quarry substrates
Mine Soil Constraints

**Infertility**

- Add nutrients:
  - Organic amendment
  - Fertilizer

**Physical Constraints**

- Break-up soil (tillage)
- Promote aggregation (organic matter)

**Toxicity**

- Increase pH (lime)
- Add complexing agents:
  - Organics (compost)
  - Inorganic sorbent (iron oxides)
Organic and Liming Amendments

- **Organics**
  - Adds nutrients and organic matter
  - Biosolids, composts, agronomic waste, manures, papermill sludges, wood chips, etc.

- **Soil Acidity/pH Amendments**
  - Increased pH reduces metal bioavailability and improves nutrient retention
  - Fly ash, wood ash, FGD sludge, etc. (20 – 80% CCE)
  - Used in conjunction with lime
Mineral Soil Conditioners

- **Foundry sand**
  - Modify soil texture

- **Steel slag**
  - Combined alkaline soil amendment, sorbent and micronutrient source

- **Dredged materials**
  - Modify soil texture or form soil profile

- **Phosphogypsum**
  - Enhance soil aggregation, offset sodicity and aluminum toxicity

- **Water Treatment residuals**
  - Modify soil texture and sorb trace metals
Application Rates

• **Organic Amendments**
  – Meet plant N requirements
  – Increase soil organic matter content (2 – 5%)
  – **But**, wastes can have imbalanced nutrients or high moisture content (↑ transport costs)

• **Acidity/pH Amendment**
  – Balance acidity using calcium carbonate equivalents (CCE)
  – **But**, wastes can have soluble salts, boron, heavy metals

• **Mineral Soil Conditioners**
  – Site and objective specific, but usually up to 100 Mg/ha
  – **But**, wastes can have soluble salts and trace metals
Response Surface Methods

**Purpose:**
Predict operating conditions that yield an optimum response in one or more response factors

**Benefits:**
- Optimization-specific experiments
- Fewer experimental units and lower cost than factorial designs

**Drawbacks:**
- Assumes all factors are important (i.e. no treatment comparison)
- Requires advanced software for design and analysis
Research Objectives:

Verify response surface methodologies can be used for optimizing soil amendments

- Greenhouse experimentation
- Two case studies:
  - Abandoned gold mine tailings (metal-contaminated)
  - Quarry overburden (infertile)
Response: Vegetation Performance

Aboveground Biomass (Shoots)
- Maximize

Belowground biomass (Roots)
- Maximize

Root : Shoot ratio
- Balanced (~1.0)
Response: Cost

**Total Cost** = Materials + Quality Loss

- **Materials** = Purchase + Transport
- **Quality Loss** = Monetization of performance using Taguchi quality loss function
Case Study 1: Phytostabilization of abandoned gold mine tailings
- Municipal solid waste compost (OM & Nutrients)
- Wood chips (C:N adjustment)
- Steel slag (As adsorbent & Alkalinity)

Case Study 2: Quarry substrate revegetation
- Municipal solid waste compost (OM & Nutrients)
- Alkaline stabilized biosolids (Nutrients & Alkalinity)
- Wood chips (C:N adjustment)
Case Study 1: Phytostabilization of Abandoned Gold Mine Tailings
Study Site: Montague Gold Mine

c. 1865 – 1940
Arsenopyrite Deposit
Mercury Amalgamation
As (mg/kg): 2,600 – 43,000
Hg (mg/kg): 650 – 6,700
pH ~ 4.5 - 5.5
Sample Collection Areas
Montague Tailings

Upper

Oxidized
As available

Amend

Reduced
As bound

Lower
Component-Amount Design

- MSW Compost: 30 – 100 Mg/ha
- Wood chips: 0 – 10 Mg/ha
- Steel slag: 0 – 35 Mg/ha

Amendments varied independently
- Main effects
- Interactions

Logistics:
- Transport
- Application
- Incorporation
Greenhouse Experiment

- Seeded with tufted hairgrass (*Deschampsia cespitosa*)
- Incubated 50 days post-germination
- Measured above- and below-ground biomass
- Analyzing tissue and soil heavy metals
Response Surface Model

Shoot Biomass  Root Biomass  Root:Shoot Ratio  Total Cost

Maximum desired
Peak observed

Maximum desired
Peak not observed

~1.0 desired
Trough observed

Minimum desired
“Plateau” observed

Optimum:
85 Mg/ha MSW compost, 24 Mg/ha steel slag and 2 Mg/ha wood chips
Case Study 2: Optimizing Organic Amendment Mixes for Quarry Soil Reclamation
Sample Collection Areas

Rock Fines

Overburden

Image © 2014 DigitalGlobe
Quarry Soils

Rock Fines – Blocks 1 and 2

Overburden – Blocks 3 and 4

Compact Infertile: <0.5% OM
Mixture-Amount Design

Blended Amendment

Amount:
30 – 100 Mg/ha

Mixture:
0 – 100% MSW Compost
0 – 100% Biosolids
0 – 10% Wood chips

Assess blending behavior and influence of total application

Why? Logistics:
• Storage
• Availability
• Incorporation
Greenhouse Experiment

Seeded with Nova Scotia Highway Mix:
40% red fescue | 20% timothy | 15% tall fescue | 15% perennial ryegrass | 15% kentucky bluegrass

Biomass harvested 50 days following germination

100 Mg/ha
100% MSW Compost
Shoots

50 – 90 Mg/ha: High proportion biosolids, lower proportions MSW and Wood

Optimized Amendment:

Rate = 60 Mg/ha

Composition = 80% biosolids, 18% compost, 2% wood

Roots

70 – 100 Mg/ha: High proportion biosolids, lower proportions MSW and Wood

Root: Shoot

30 – 70 Mg/ha: High proportion biosolids, lower proportions MSW and Wood

Total Cost

<80 Mg/ha: High proportion biosolids, lower proportions MSW and Wood
Summary

1. Response surface methods (RSM) worked well for amendment optimization in greenhouse

2. RSM-based optimization can improve project performance and economics
   - Avoid under/over-application and potential toxicity

3. Field validation is required and ongoing
   - Quarry: RSM design in field – compare against greenhouse
   - Tailings: Temporal stability ± mycorrhizal fungi
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1. Fit statistical model for each response

2. Fit individual desirability functions

3. Maximize overall desirability

Optimum: 85 Mg/ha MSW compost, 24 Mg/ha steel slag and 2 Mg/ha wood chips
Optimum: 60 Mg/ha amendment composed of 80% biosolids, 18% MSW compost and 2% wood chips
Experimental Designs

E.g. B = biosolids (Mg/ha); F = fly ash (Mg/ha)

ANOVA-based:

\[ Y = X_0 + aB + bF + cBF + \varepsilon \]

Most common!
Most appropriate?

Fixed: categorical (treatments)
Random: continuous (linear)

Response surface methods (RSM):

\[ Y = X_0 + aB + bF + cB^2 + dF^2 + eBF + \varepsilon \]

All Continuous! (Required for optimization)
Model Comparison

![Graph showing model comparison]

- **Linear Model**: $y = 0.0429x + 6.7898$  
  - $R^2 = 0.10188$

- **Quadratic Model**: $y = -0.0059x^2 + 0.7628x - 8.85$  
  - $R^2 = 0.95306$

**Variables**:
- **Yield (kg/ha)**
- **Biosolids application rate (Mg/ha)**
### Example: Plant Response to Biosolids

![Graph showing plant response to biosolids application rate]

**Yield (kg/ha)** vs **Biosolids application rate (Mg/ha)**

- **Polynomial Effect**: "Curvature" in response due to phytotoxic compounds
- **Interaction Effect**: Different response at different rates of additional factor

**Amendment Toxicity**: Difficult to estimate. Experiments required.