Digital Soil Assessment of Landscape-Scale Forest Restoration Using a Species Distribution Model

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Red Spruce Ecosystem

- **Historic extent:** ~600,000 ha in West Virginia (Rentch 2007)
  - Extensive logging in between 1860’s and 1920’s removed much of the spruce forests
  - Wildfires, pests, and conversion to pasture hindered spruce regrowth

- **Current extent:** ~24,000 ha in West Virginia (Adams et al. 2001)
  - One of the most endangered forest types in Central Appalachians (Noss et al. 1995)
Red Spruce Restoration

• Red spruce forests provide multiple ecosystem services
  – Water storage
  – Soil carbon sequestration
  – Habitat for sensitive, threatened, and endangered species

• Broad interest in restoring red spruce forests
  – State and federal governments and non-governmental organizations
  – Focus on landscape connectivity
Pedoecological Mapping

- Ecosystem-level state factor model (Jenny 1961, 1980)
  \[ l, v, s, a = f (L_0, P_x, t) \]

- Soils and vegetation community co-evolve
  - Similar drivers
  - Strong interactions

- Disturbance can degrade spodic horizons
  - Depodzolization
Impetus for Research

- Observed spodic soil properties reflect greater conifer extent before “Great Cut” (1860’s-1920’s)
  - Recent observations in West Virginia indicate greater distribution of spodic soil properties than existing inventories

- Many areas now under hardwood that have spodic soils used to be conifer
  - Disturbance has shifted community states

- Digital soil mapping methods can be employed to improve soil survey products (e.g., to guide forest management and restoration)
Previous Work

• Random Forest (Nauman et al., 2015)
  – Full model (n=322)
    • Out Of Bag error = 29.5%
  – Independent validation
    • Training set (n=208)
    • Test set (n=114)
    • 0.57 probability threshold
    • Error = 30%
  – Independent plot data (n=24)
    • 88.1% accuracy
• 70-88% accuracy
Species Distribution Models

• Recent work by forest ecologists has led to the application of species distribution models (SDM) to predict the current (and future) geographic distribution of red spruce in the Central Appalachians

• SDM identify species-environment relationships to estimate the geographic range of a species (Daniel 2014)
  – Based on the concept of the ecological niche
  – Derived from the environmental conditions where the species is known to exist
  – Determine which environmental variables or conditions are important to the species

• SDM $\rightarrow$ DSM
Study Area

- **Hardwood-conifer ecotone**
  - Higher elevations (880-1320 m)
- **Upland soil map units**
  - Devonian-age acidic shale and siltstone
- **Stratified random sample**
  - Vegetation, slope gradient, slope curvature
  - 322 field soil profile descriptions
- **Environmental variables**
  - Topographic layers (30-m DEM)
  - Remote sensing layers (Landsat Geocover)
- **Spodic expression**
Spodic Intensity (SI) Index

<table>
<thead>
<tr>
<th>Rating</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>No evidence of podzolization</td>
</tr>
<tr>
<td>0.5</td>
<td>Very weak expression of podzolization</td>
</tr>
<tr>
<td></td>
<td>• There is only slight physical evidence of podzolization. A slightly</td>
</tr>
<tr>
<td></td>
<td>redder hue and higher value is present at the top of the B horizon, but</td>
</tr>
<tr>
<td></td>
<td>the hue is less than one Munsell hue redder than an underlying horizon.</td>
</tr>
<tr>
<td></td>
<td>The soil is non-smeary.</td>
</tr>
<tr>
<td>1.0</td>
<td>Weak expression of podzolization</td>
</tr>
<tr>
<td></td>
<td>• Spodic materials are present, but they do not meet the criteria for a</td>
</tr>
<tr>
<td></td>
<td>diagnostic spodic horizon. A weakly expressed Bs horizon is present. The</td>
</tr>
<tr>
<td></td>
<td>Bs horizon is one Munsell hue redder than an underlying horizon. Bhs</td>
</tr>
<tr>
<td></td>
<td>material is usually absent. An albic E horizon is not present. The spodic</td>
</tr>
<tr>
<td></td>
<td>materials are sometimes weakly smeary.</td>
</tr>
<tr>
<td>1.5</td>
<td>Moderate expression of podzolization (spodic intergrade)</td>
</tr>
<tr>
<td></td>
<td>• Spodic materials do not meet the criteria for a diagnostic spodic</td>
</tr>
<tr>
<td></td>
<td>horizon. A moderately expressed Bs horizon is present, often with pockets</td>
</tr>
<tr>
<td></td>
<td>of Bhs material. An albic E horizon is not present. The spodic materials</td>
</tr>
<tr>
<td></td>
<td>are often weakly smeary.</td>
</tr>
<tr>
<td>2.0</td>
<td>Strong expression of podzolization (Spodosol)</td>
</tr>
<tr>
<td></td>
<td>• A diagnostic spodic horizon is present usually underlying an albic E</td>
</tr>
<tr>
<td></td>
<td>horizon. A Bhs or Bh horizon is continuous across at least 85 percent of</td>
</tr>
<tr>
<td></td>
<td>the pedon. The spodic materials are often moderately smeary.</td>
</tr>
</tbody>
</table>

Color, smeariness, presence and persistence of E/Bh/Bhs/Bs horizons
Spodic Intensity (SI) Index

SI = 0

SI = 1

SI = 2
Maximum Entropy Species Distribution Modeling (MaxEnt)

- **Baysean**
  - Identifies the geographic distribution using the constraints defined by the available data while making the fewest assumptions

- **Presence-only data**
  - Approximate the “fundamental niche” for spodic soil properties
  - Absence data may be problematic because of disturbance, depodzolization

- **Environmental variables**
  - Continuous (e.g., elevation)
    - Linear, quadratic, product, threshold, hinge
  - Categorical (e.g., geology)

- “MaxEnt is by far the most popular presence-only SDM in use today.” (Daniel 2014)

http://www.cs.princeton.edu/~schapire/maxent/
Maximum Entropy Species Distribution Modeling (MaxEnt)

Model Evaluation

• Area Under the Curve
  – Plot of sensitivity vs. specificity
  – Number of presence points correctly predicted vs. number of absence points incorrectly predicted

AUC = 0.957
Variable Importance

• All covariates
  – Elevation
  – Relative Height indices
  – TWI
  – Landsat bands (green, MIR, NIR)
  – Eastness

• Only terrain covariates
  – Elevation
  – Relative Height indices
  – TWI
  – Northwestness
  – Plan Curvature

• Random Forest (Nauman et al., 2015)
  – Eastness, Northwestness
  – Landsat Middle Infrared band
  – Convergence
Variable Importance

- Variable influence on model gain (improvement) when that only that variable is used or when only that variable is omitted
1.0

0.0

Spodic Probability

Random Forest Model (Nauman et al., 2015)

MaxEnt Model
MaxEnt Model

Random Forest Model (Nauman et al., 2015)

Spodic Probability

0.0

1.0
(Historic) Spruce Distribution

- >1300 m: Spruce most dominant
  - Minor aspect influence
  - 1200 m
  - Moderate aspect influence
  - 1000 m
  - Strong aspect + mid-lower slope positions
  - 900 m
  - Cold air drainages in narrow valleys
- 509 m: Lowest red spruce from witness tree records
Suitability for Red Spruce Restoration

Red Spruce Suitability: Spodic Soil Properties
- Very Suitable
- Well Suited
- Moderately Suited
- Low Suitability
- Poor Suitability

Drainages