State & Transition Models: Moving Beyond Boxes and Arrows

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Beyond Boxes and Arrows - Assessing Climate Change/Variability and Ecosystem Impacts/Responses in Southwestern Rangelands

San Carlos - January 25, 2006
S & T Approach

**POSITIVE ATTRIBUTES**

- Robust conceptual framework
- Flexible
- Allows for ‘event driven’ change
- Accommodates cyclic & directional change
- Forces us to explicitly state conditions and assumptions
- Explicitly links management and research
Beyond Boxes and Arrows......

MLRA 41-3 (12-16"), Loamy Bottom

1a. Mesquite seed source present or introduced. Lack of fire for long periods of time. Mesquite increases to 20% canopy.
1b. Herbicide or mechanical means to remove mesquite. PG/NG

2a. CHG, Base level changes cause gully and head-ward erosion. Flooding reduced, water-table lowered to >20 feet.
2b. PG/NG, Mechanical control of gullies at headcuts.

3a. CHG (managing for annuals), burning (to freshen SPWR) plus CHG; Hay mowing, irrigated cultivation and abandonment. Base level changes in main stream causes down-cutting and gully formation on the floodplain, flooding reduced.
3b. PG/NG, Mechanical gully control measures.

Seedling SPWR with weed control and water. Re-establish flooding
4a. CHG coupled with drought and, burning with low soil moisture Reduction of A horizon OM and litter, compaction, sheet, rill erosion. Reduced infiltration, greatly increased runoff
Runoff, and very limited recruitment of perennial grasses. Base Level change in main stream causes down-cutting in swales
4b. Mechanical/herbicide treatment of shrubs to < 20% canopy.
Seedling of SPWR, maintenance treatments for shrubs at 15 years.
Mechanical control of gully erosion. Re-establish flooding
5a. CHG, interruption of overland flow, diversion of runoff;
Severe soil compaction from traffic (livestock or equipment)
Base level changes in main stream causes down-cutting and gully formation on the floodplain
5b. Mechanical control of gullies. Mesquite control or wood harvest with stump treatments (herbicide). Re-establish flooding
5c. Mechanical control of gullies. Mesquite control to < 15% cover
Seedling of exotic grasses. Re-establish flooding
6a. CHG combined with drought, burning with low soil moisture.
Fallowing of sacaton for cultivation with subsequent abandonment
Introduction or planting of seeds of exotic perennial grasses.
6b. Herbicide control of exotic grasses, seeding of sacaton with weed control and irrigation or flooding.

*Native annuals dominant, may be patches of some non-natives

CHG - continuous heavy grazing
PG/NG - proper grazing, no grazing
SPWR - sacaton

Sacaton Grassland
Fire / Drought interaction

Eroded, Sacaton

Eroded, Mesquite, F041XC310AZ

Mesquite 5-20% canopy
SPWR 5-40% canopy
Other shrubs may be present

Mesquite, Sacaton

Johnson grass, blue
Panic., & bermuda
w/wo mesquite 1-15%

Exotics

Native and non-native
Annual forbs and grasses,
Trace amounts of sacaton
Other shrubs 0 to 10%

Annuals

SPWR - 25-80% canopy
Annuals 0-20%

HCPC

SPWR (25-60%)
Prosopis sp. (1-15%)

SPWR 20 to 50% canopy
Severe gully erosion
Water-table > 20 feet
Flooding reduced

2a
2b

6a
6b
(from NRC 1994)
S & T Approach

LIMITATIONS

• Heuristic states
• Transition mechanisms poorly understood
• Probability and rate of change seldom known
  • State longevity?
  • Likelihood of change to alternate states?
  • What drives or triggers transitions?
S & T Approach

Beyond Boxes and Arrows......

~ Markov Models
~ Transition Matrix Models
~ Matrix Projection Models

From Westoby et al. 1989

I  Grassland, scattered woody plants
II  Grassland, with many shrub seedlings
III  Dense shrub cover, little grass
IV  Recently burnt, many shrub seedlings or resprouts

T1  T2  T3  T4  T5  T6  T7
Compute $P(\text{change})$ from a given state to another state(s)

\[
\begin{bmatrix}
\text{Change Matrix}
\end{bmatrix}
\times
\begin{bmatrix}
\text{Matrix of Current States}
\end{bmatrix}
=
\begin{bmatrix}
\text{New State Matrix}
\end{bmatrix}
\]
Approach: **Classify vegetation in 20 x 20 m grids on 1941 aerial photo**

- W = Woodlands
- Wm = W margins
- G = Groves
- Gm = G margins
- MC = Mature Clusters
- PC = Pioneer Clusters
- HZ = Herbaceous zones
\[
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**Approach:** Compare 20 x 20 m grids on 1960 aerial photo with those on 1941 aerial photo

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Wm</th>
<th>G</th>
<th>Gm</th>
<th>M</th>
<th>P</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W</strong></td>
<td>0.873</td>
<td>0.232</td>
<td>0.000</td>
<td>0.012</td>
<td>0.000</td>
<td>0.019</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Wm</strong></td>
<td>0.075</td>
<td>0.56</td>
<td>0.030</td>
<td>0.040</td>
<td>0.029</td>
<td>0.058</td>
<td>0.029</td>
</tr>
<tr>
<td><strong>G</strong></td>
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<td><strong>Gm</strong></td>
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<tr>
<td><strong>P</strong></td>
<td>0.035</td>
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<td>0.152</td>
<td>0.224</td>
<td>0.260</td>
<td>0.575</td>
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<tr>
<td><strong>H</strong></td>
<td>0.003</td>
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<td>0.000</td>
<td>0.081</td>
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\end{bmatrix} \]

\[
\begin{bmatrix}
W & Wm & G & Gm & M & P & H \\
W & 0.873 & 0.232 & 0.000 & 0.012 & 0.000 & 0.019 & 0.000 \\
Wm & 0.075 & 0.560 & 0.030 & 0.040 & 0.029 & 0.058 & 0.029 \\
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Gm & 0.007 & 0.790 & 0.242 & 0.489 & 0.164 & 0.112 & 0.108 \\
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\end{bmatrix}
\times
\begin{bmatrix}
0.56 \\
0.11 \\
0.03 \\
0.26 \\
0.04
\end{bmatrix}
= 
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0.54 \\
0.13 \\
0.03 \\
0.23 \\
0.07
\end{bmatrix}
\]

(Wm and Cm not shown)
Stationarity Assumption

Transitions between states are constant over time

Alternatives

• Develop a ‘mean transition’
• Develop time-specific transitions
Computed transitions for

- **1941 --> 1960** (DRY)
- **1960 --> 1983** (WET)
## DRY MATRIX

<table>
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<th>Cm</th>
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## WET MATRIX

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<th>Cm</th>
<th>M</th>
<th>P</th>
<th>H</th>
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</thead>
<tbody>
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<td>0.044</td>
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<tr>
<td>Wm</td>
<td>0.027</td>
<td>0.429</td>
<td>0.090</td>
<td>0.126</td>
<td>0.65</td>
<td>0.121</td>
<td>0.086</td>
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<tr>
<td>C</td>
<td>0.003</td>
<td>0.000</td>
<td>0.328</td>
<td>0.137</td>
<td>0.196</td>
<td>0.036</td>
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<tr>
<td>Cm</td>
<td>0.000</td>
<td>0.042</td>
<td>0.119</td>
<td>0.432</td>
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<td>M</td>
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<td>0.000</td>
<td>0.030</td>
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<td>0.000</td>
<td>0.021</td>
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Matrix of Current States

\[
\begin{bmatrix}
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\text{Dry Change Matrix}
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\times\text{or}\times

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20 y time-steps
Where are we headed?

- Forward projections
- 20 y time-steps
- WET vs DRY transitions randomly selected
- Constraint: \( P(WET) = 0.40 \)
How did we get where we are today?

- Compute ‘reverse transitions’
  
  (1983 --> 1960 and 1960 --> 1941)

- Run model ‘backwards’ in time
  
  - How long did it take us to get here?
  - What did things look like pre-settlement?
P(WET) = 0.4

(from Scanlan & Archer 1992)

Year

Proportion of Landscape

Woodland

Herbaceous
Early Warning & Threshold States?

(from Scanlan & Archer 1992)

P(WET) = 0.4

Proportion of Landscape

Woodland

Herbaceous

Year
What if we ….

• Change the P(WET)?
• Change the sequencing of WET and DRY?
• Compute new transition matrices based on new photo dates?
• Compute transition probabilities based on composition of neighboring cell(s)?
• Incorporate episodic events
S & T Approach

Beyond Boxes and Arrows......

• Dynamic Simulation Models
S & T Approach

Beyond Boxes and Arrows…….

- Dynamic Simulation Models
  - Data intensive
  - Highly complex
  - Difficult to customize for specific needs unless model developer is available
  - Even then, very time consuming; requires expertise in high-level programming
  - Research vs management models
Model Maker
www.cherwell.com/

www.hps-inc.com
Herbaceous Biomass

Landscape-Level

Annual Turnover

Seed Source

Juniper Size 1

Juniper Size 2

Juniper Size 3

Juniper Size 4

Juniper Size 5

Mortality Sink

Intra-spp. Competition

Seed Production

Fire Intensity

Fire Frequency

Rainfall

Grazing

Increase Species

Intermediate Species

Decrease Species

Herbaceous Biomass

Grassland Patch-Level

Grassland, scattered woody plants

Recently burnt, many shrub seedlings or resprouts

Dense shrub cover, little grass

Grassland, with many shrub seedlings

From Westoby et al. 1989

T1

T2

T3

T4

T5

T6

T7

I

II

III

IV

Currently burnt, many shrub seedlings or resprouts

Grassland, with many shrub seedlings

Dense shrub cover, little grass

Grassland, scattered woody plants

II

III

IV
Herbaceous Biomass

Landscape-Level

Annual Turnover

Grassland Patch-Level

Grazing

Intra-spp. Competition

Fire

Intensity

Decreaser Species

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Intermediate Species

Seed Source

Seed Dispersal

Seed Production

Rainfall

Fire Frequency

Mortality Sink

Juniper Size 1

Juniper Size 2

Juniper Size 3

Juniper Size 4

Juniper Size 5

Herbaceous Biomass

Intra-spp. Competition

Rainfall

Fire Frequency

Intra-spp. Competition
Herbaceous Biomass

Landscape-Level

- Annual Turnover
- Seed Source
  - Juniper Size 1
  - Juniper Size 2
  - Juniper Size 3
  - Juniper Size 4
  - Juniper Size 5
- Intra-spp. Competition
- Seed Dispersal
- Seed Production
- Fire Intensity
- Fire Frequency

Grassland Patch-Level

- Grazing
- Mortality Sink
- Herbaceous Biomass
- Annual Turnover
- Seed Production
- Interdependent Species
  - Increaser Species
  - Intermediate Species
  - Decreaser Species

Rainfall

- Decreaser Species
  - Species
  - Decreaser Species

- Increaser Species
  - Species
  - Increaser Species

- Intermediate Species
  - Species
  - Intermediate Species

- Herbaceous Biomass
  - Annual Turnover
  - Seed Source
    - Juniper Size 1
    - Juniper Size 2
    - Juniper Size 3
    - Juniper Size 4
    - Juniper Size 5
Grassland Patch-Level

- Grazing
- Fire
- Rainfall
- Fire Intensity
- Intra-spp. Competition

Landscape-Level

- Seed Source
- Seed Dispersal
- Seed Production
- Herbaceous Biomass
- Annual Turnover
- Intra-spp. Competition

Juniper

- Size 1
- Size 2
- Size 3
- Size 4
- Size 5

Mortality Sink

Additional terms:
- Increase Species
- Intermediate Species
- Decreaser Species
- Annual Turnover
- Intra-spp. Competition
Herbaceous Biomass

Landscape-Level

Annual Turnover

Grassland Patch-Level

Grazing

Intra-spp. Competition

Rainfall

Fire Frequency

Fire Intensity

Mortality Sink

Intra-spp. Competition

Seed Source

Seed Dispersal

Seed Production

Increaser Species

Intermediate Species

Decreasor Species

Juniper Size 1

Juniper Size 2

Juniper Size 3

Juniper Size 4

Juniper Size 5

Decreaser Species

Intra-spp. Competition

Decreaser Species

Intra-spp. Competition

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Juniper Size 5

Intra-spp. Competition

Competition

Intra-spp. Competition

Competition

Intermediate Species

Increases Species

Decreases Species

Intra-spp. Competition
High Productivity Site
MAP = 850 mm

Low Productivity Site
MAP = 600 mm
With no fire, Juniper increases regardless of grazing history or grazing regime.
Herbaceous Production—No Fire

Biomass (% of max)

Year

Ungrazed

Moderate

Heavy

Herbaceous Production

Fuhlendorf et al., in prep.
Potential Herbaceous Production (%) vs Fire Frequency (y)

- Ungrazed

- Low productivity
- High productivity

Fuhlendorf, et al. in prep.
Moderate grazing

Fuhlendorf *et al.*, in prep., in prep.
Beyond Boxes and Arrows......

MLRA 41-3 (12-16”), Loamy Bottom

1a. Mesquite seed source present or introduced. Lack of fire for long periods of time. Mesquite increases to 20% canopy.
1b. Herbicide or mechanical means to remove mesquite. PG/NG
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   Severe soil compaction from traffic (livestock or equipment)
   Base level changes in main stream causes down-cutting and gully formation on the floodplain.
5b. Mechanical control of gullies. Mesquite control or wood
   harvest with stump treatments (herbicide). Re-establish flooding.
5c. Mechanical control of gullies. Mesquite control to < 15% cover
   Seeding of exotic grasses. Re-establish flooding.
6a. CHG combined with drought, burning with low soil moisture.
   Flowing of sacaton for cultivation with subsequent abandonment.
   Introduction or planting of seeds of exotic perennial grasses.
6b. Herbicide control of exotic grasses, seeding of sacaton with
   weed control and irrigation or flooding.

*Native annuals dominant, may be patches of some non-natives

CHG - continuous heavy grazing
PG/NG - proper grazing, no grazing
SPWR - sacaton