State & Transition Models: Moving Beyond Boxes and Arrows

Steve Archer

University of Arizona

Beyond Boxes and Arrows -

Assessing Climate Change/Variability and Ecosystem Impacts/Responses in Southwestern Rangelands

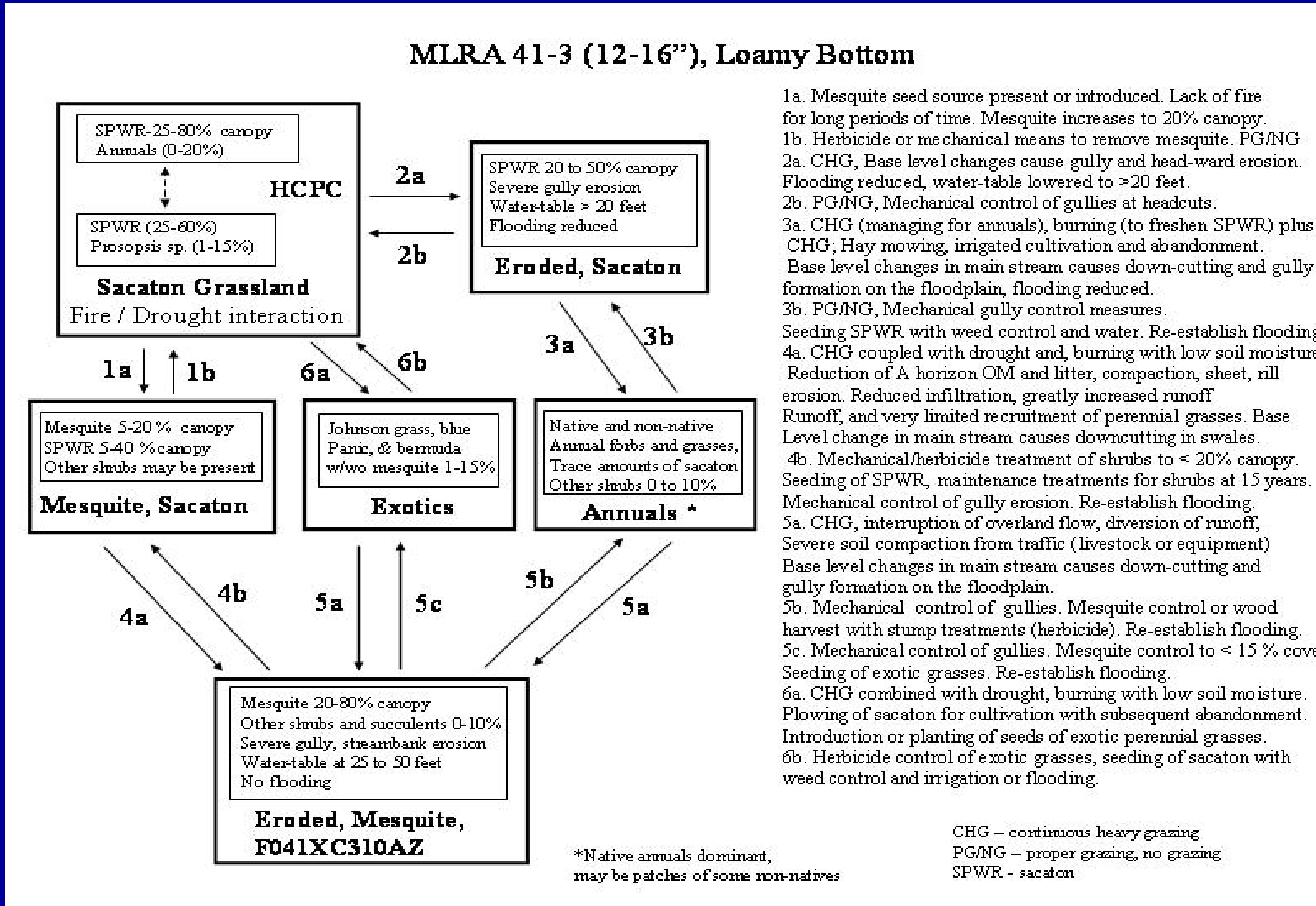
San Carlos - January 25, 2006

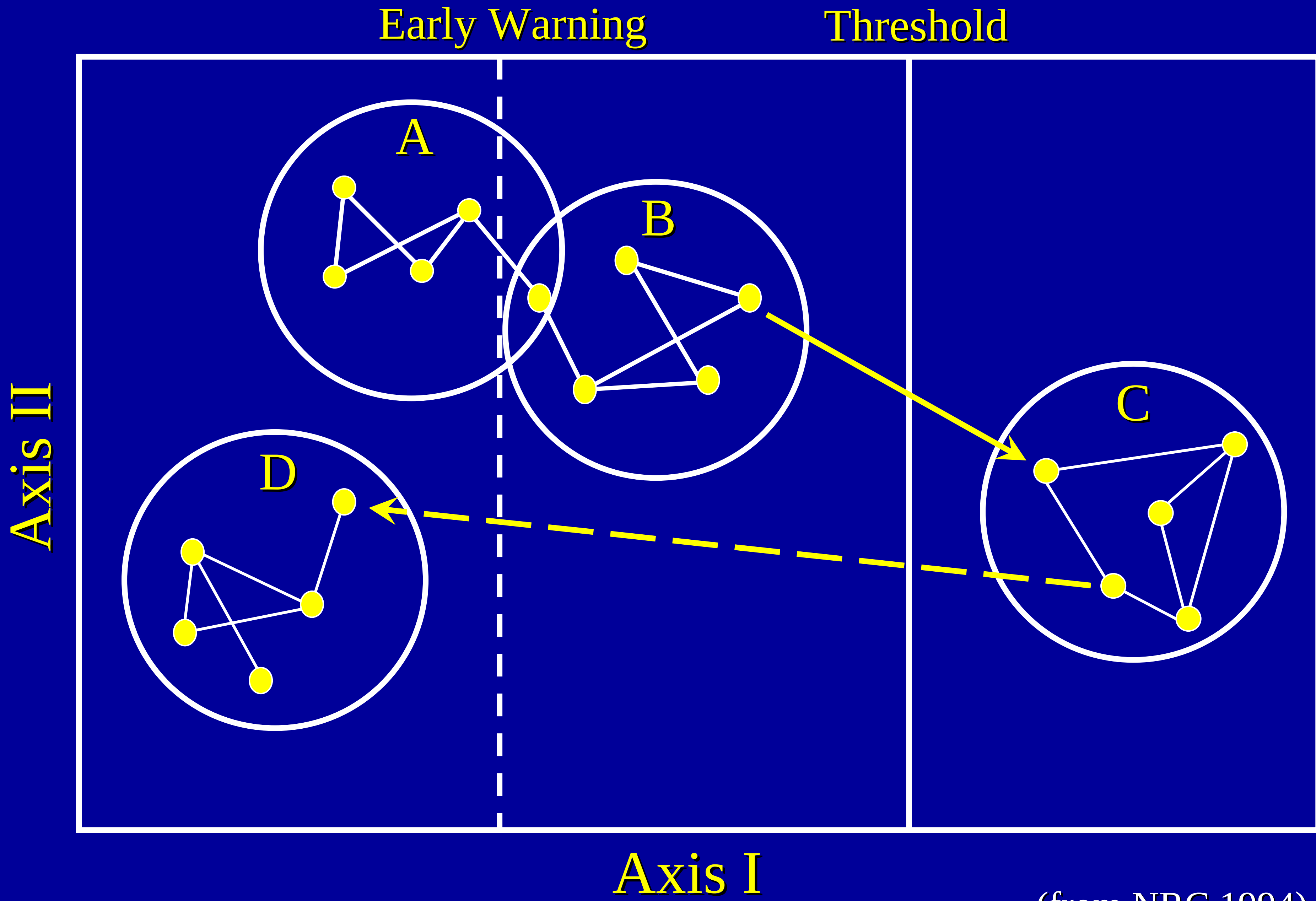
S & T Approach

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……





(from NRC 1994)

S & T Approach

LIMITATIONS

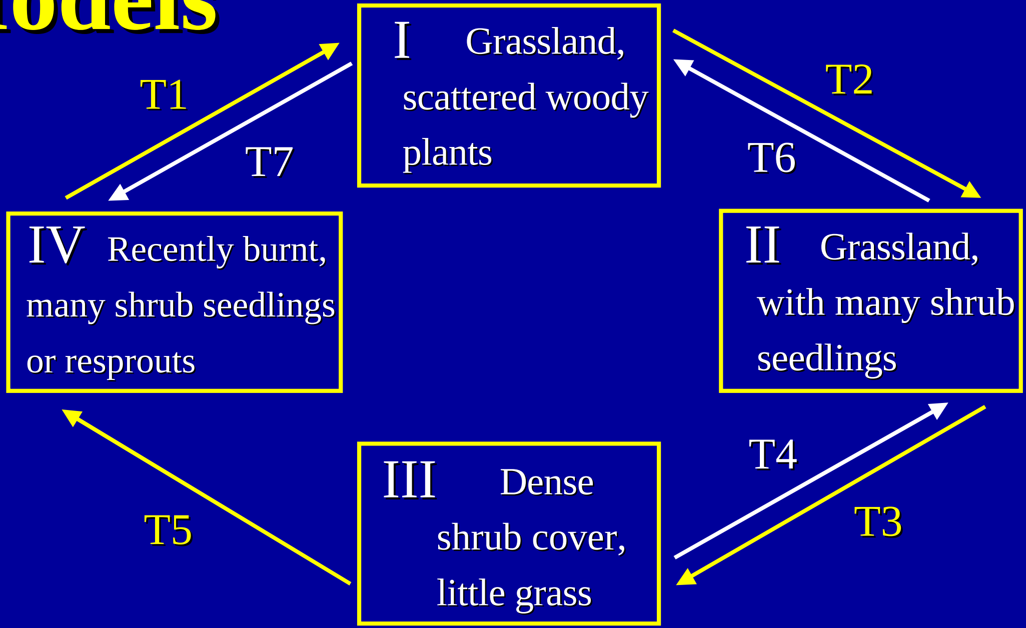
- Heurisic states
- Transition mechanisms poorly understood
- Probability and rate of change seldom known
    - • State longevity?
    - • Likelihood of change to alternate states?
    - • What drives or triggers transitions?

S & T Approach

Beyond Boxes and Arrows……

- ~ Markov Models
- ~ Transition Matrix Models
- ~ Matrix Projection Models

From Westoby *et al*. 1989

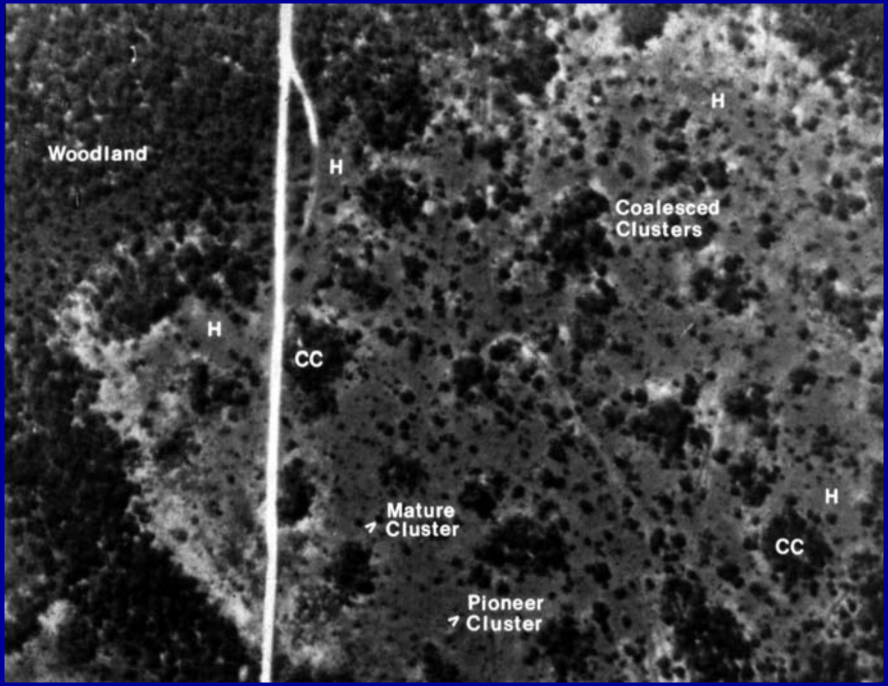


Compute P(change) from a given state to another state(s)

$$\begin{bmatrix} \text{Change} \\ \text{Matrix} \end{bmatrix} \times \begin{bmatrix} \text{Matrix of} \\ \text{Current} \\ \text{States} \end{bmatrix} = \begin{bmatrix} \text{New} \\ \text{State} \\ \text{Matrix} \end{bmatrix}$$

$$\begin{bmatrix}\text{Change Matrix}\end{bmatrix} \times \begin{bmatrix}\text{Matrix of Current States}\end{bmatrix} = \begin{bmatrix}\text{New State Matrix}\end{bmatrix}$$

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

$$\begin{bmatrix} \text{Change} \\ \text{Matrix} \end{bmatrix} \times \begin{bmatrix} \text{Matrix of} \\ \text{Current} \\ \text{States} \end{bmatrix} = \begin{bmatrix} \text{New} \\ \text{State} \\ \text{Matrix} \end{bmatrix}$$

Approach: **Compare 20 x 20 m grids on 1960 aerial photo with those on 1941 aerial photo**

	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	0.56	0.030	0.040	0.029	0.058	0.029
G	0.007	0.006	0.515	0.121	0.115	0.019	0.029
Gm	0.007	0.79	0.242	0.489	0.164	0.112	0.108
M	0.000	0.006	0.061	0.035	0.212	0.032	0.010
P	0.035	0.110	0.152	0.224	0.260	0.575	0.471
H	0.003	0.006	0.000	0.081	0.221	0.184	0.353

[Change Matrix] x [Matrix of Current States] = [New State Matrix]

	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	0.56	0.030	0.040	0.029	0.058	0.029
G	0.007	0.006	0.515	0.121	0.115	0.019	0.029
Gm	0.007	0.79	0.242	0.489	0.164	0.112	0.108
M	0.000	0.006	0.061	0.035	0.212	0.032	0.010
P	0.035	0.110	0.152	0.224	0.260	0.575	0.471
H	0.003	0.006	0.000	0.081	0.221	0.184	0.353

$$\times \begin{bmatrix} 0.56 \\ 0.11 \\ 0.03 \\ 0.26 \\ 0.04 \end{bmatrix} = \begin{bmatrix} 0.54 \\ 0.13 \\ 0.03 \\ 0.23 \\ 0.07 \end{bmatrix}$$

(Wm and Cm not shown)

Stationarity Assumption

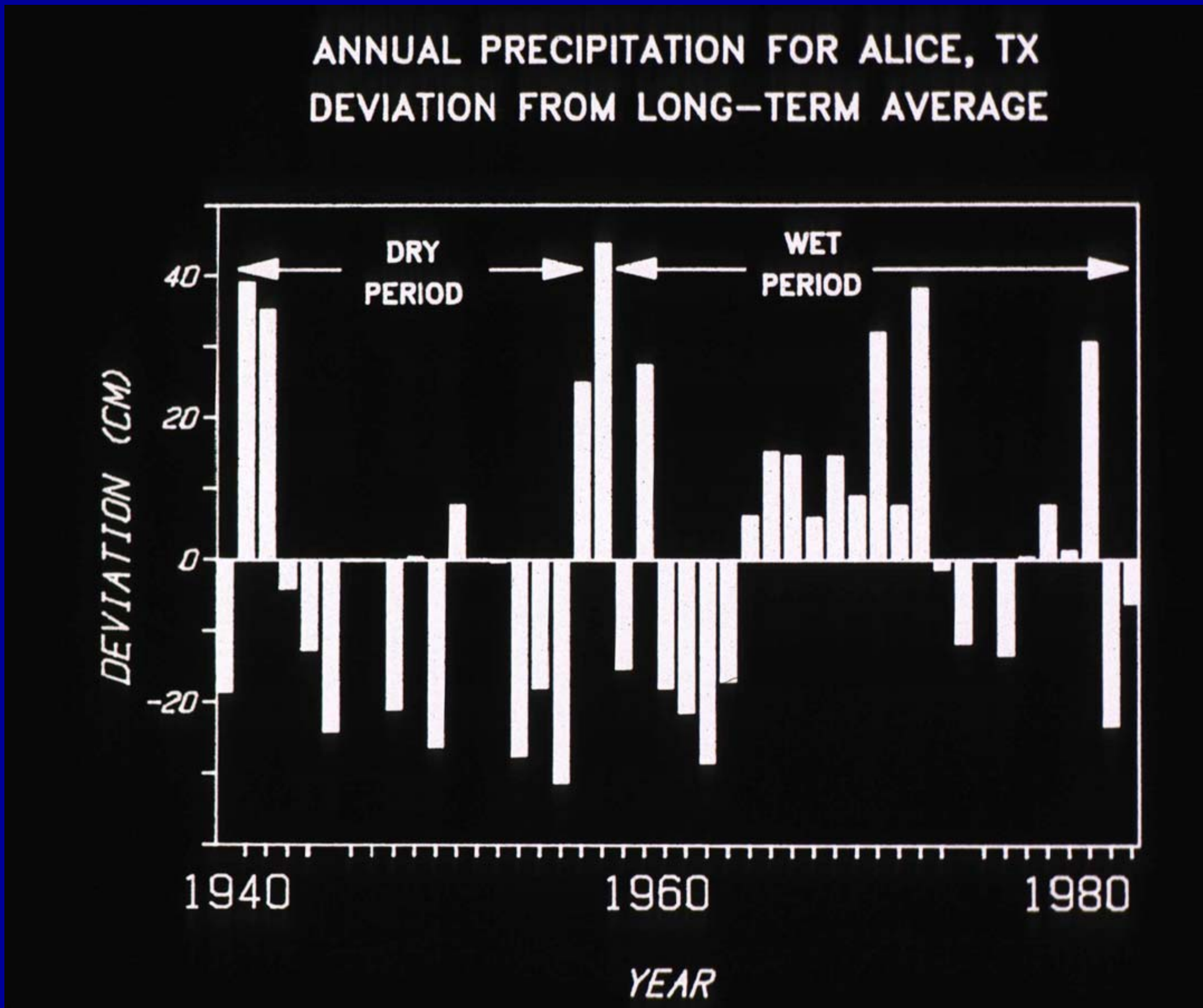
Transitions between states are constant over time

Alternatives

- **Develop a ‘mean transition’**
- **Develop time-specific transitions**

Computed transitions for

- 1941-->1960 (DRY)
- 1960 -->1983 (WET)



DRY MATRIX

	W	Wm	C	Cm	M	P	H
W	0.873	0.232	0.000	0.012	0.000	0.019	0.000
Wm	0.075	0.56	0.030	0.040	0.029	0.058	0.029
C	0.007	0.006	0.515	0.121	0.115	0.019	0.029
Cm	0.007	0.79	0.242	0.489	0.164	0.112	0.108
M	0.000	0.006	0.061	0.035	0.212	0.032	0.010
P	0.035	0.110	0.152	0.224	0.260	0.575	0.471
H	0.003	0.006	0.000	0.081	0.221	0.184	0.353

WET MATRIX

	W	Wm	C	Cm	M	P	H
W	0.970	0.497	0.373	0.132	0.044	0.088	0.019
Wm	0.027	0.429	0.090	0.126	0.65	0.121	0.086
C	0.003	0.000	0.328	0.137	0.196	0.036	0.019
Cm	0.000	0.042	0.119	0.432	0.522	0.170	0.216
M	0.000	0.000	0.030	0.085	0.109	0.104	0.111
P	0.000	0.011	0.060	0.095	0.065	0.447	0.475
H	0.000	0.021	0.000	0.021	0.000	0.036	0.074

$$\begin{bmatrix} \text{Matrix of} \\ \text{Current} \\ \text{States} \end{bmatrix} \times \begin{matrix} \begin{bmatrix} \text{Wet} \\ \text{Change} \\ \text{Matrix} \end{bmatrix} \\ \text{or} \\ \begin{bmatrix} \text{Dry} \\ \text{Change} \\ \text{Matrix} \end{bmatrix} \end{matrix} = \begin{bmatrix} \text{New} \\ \text{State} \\ \text{Matrix} \end{bmatrix}$$

20 y time-steps

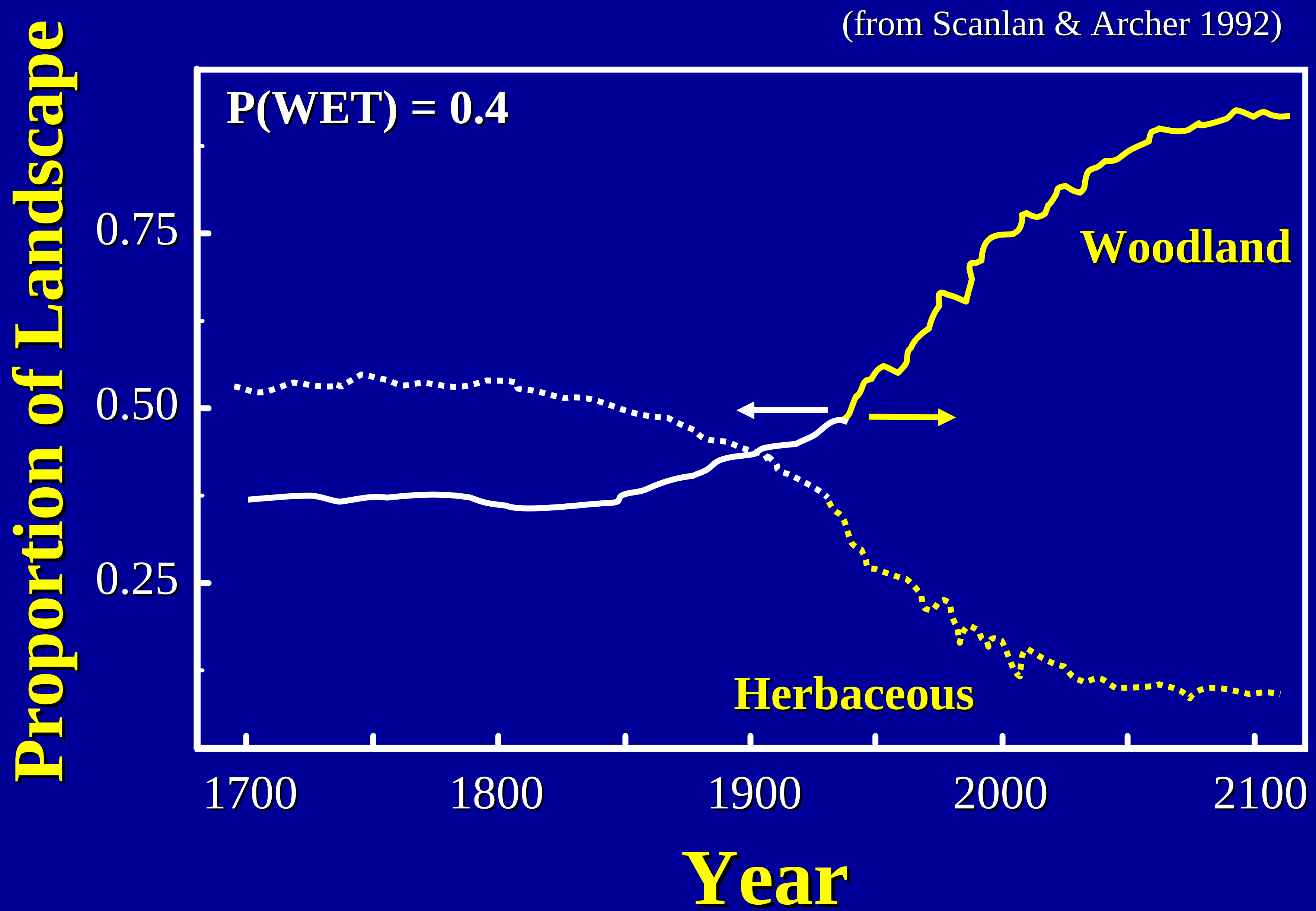
Where are we headed?

- 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)

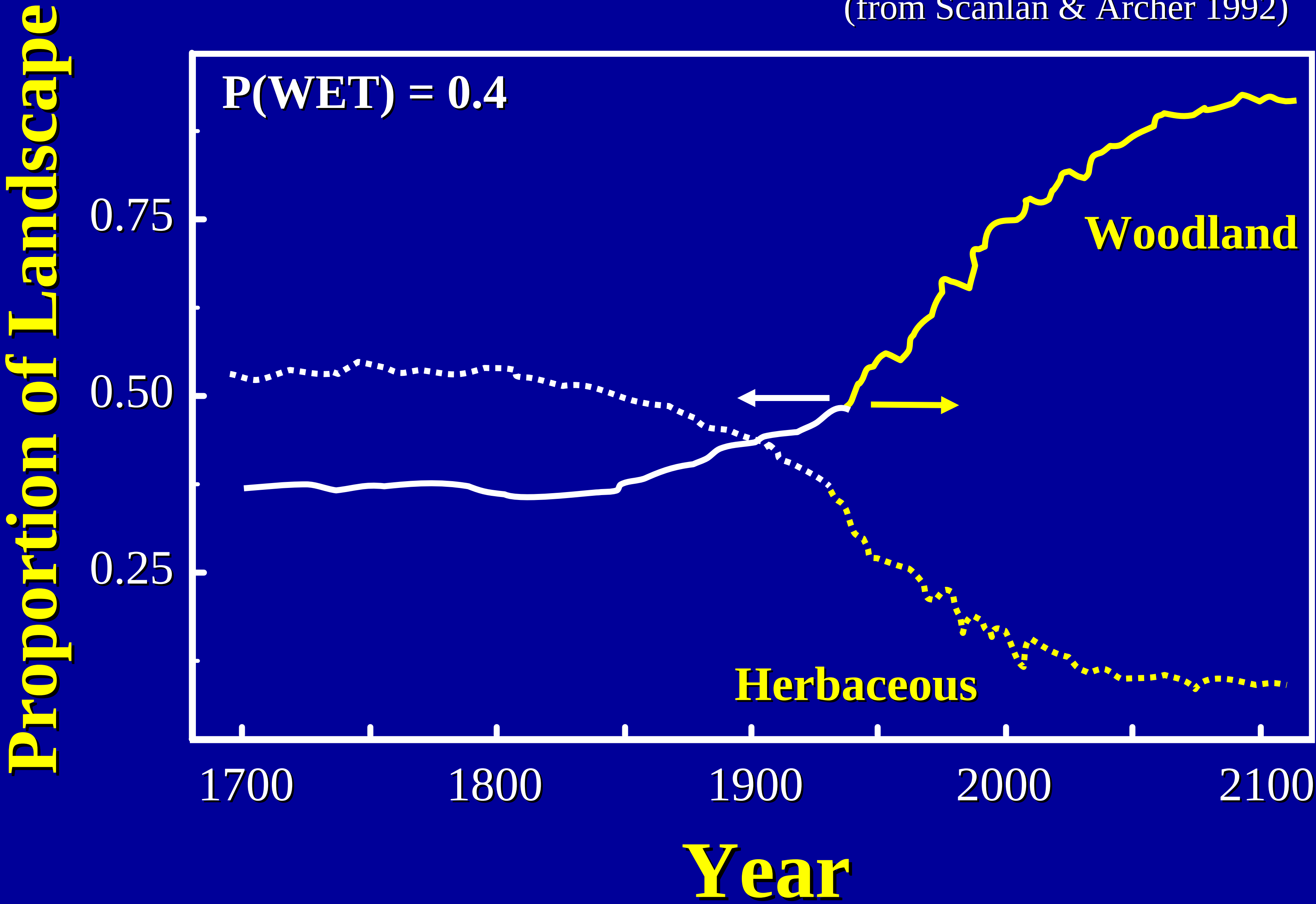
- Run model ‘backwards’ in time
  - How long did it take us to get here?
  - What did things look like pre-settlement?



(from Scanlan & Archer 1992)
P(WET) = 0.4
Proportion of Landscape
0.75
0.50
0.25
Woodland
Herbaceous
1700
1800
1900
2000
2100
Year

Early Warning & Theshold States ?

(from Scanlan & Archer 1992)



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**

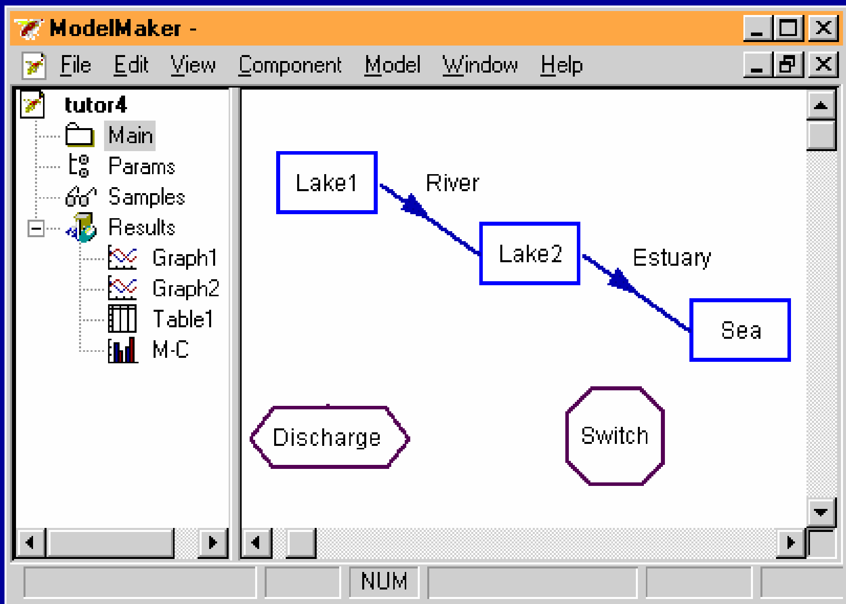
S & T Approach

Beyond Boxes and Arrows……

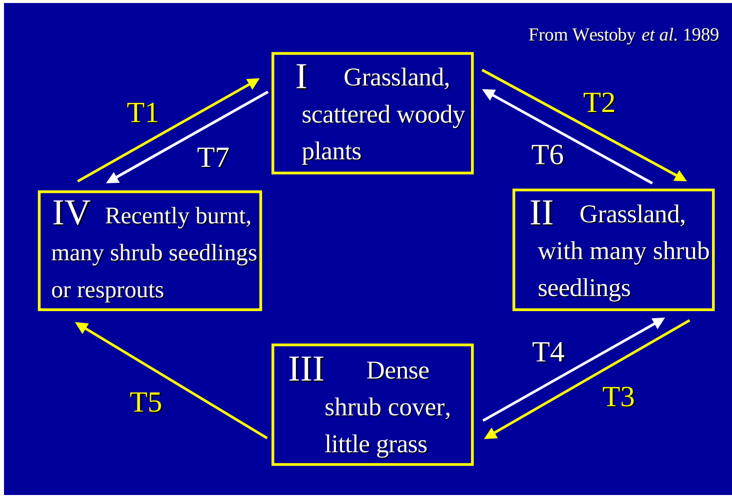
- Dynamic Simulation Models
  - • Data intensive
  - • Highly complex
  - • Difficult to customize for specific needs unless model developer is available
  - • Even then, very time consuming; requires expertise in high-level programming
  - • Research vs management models

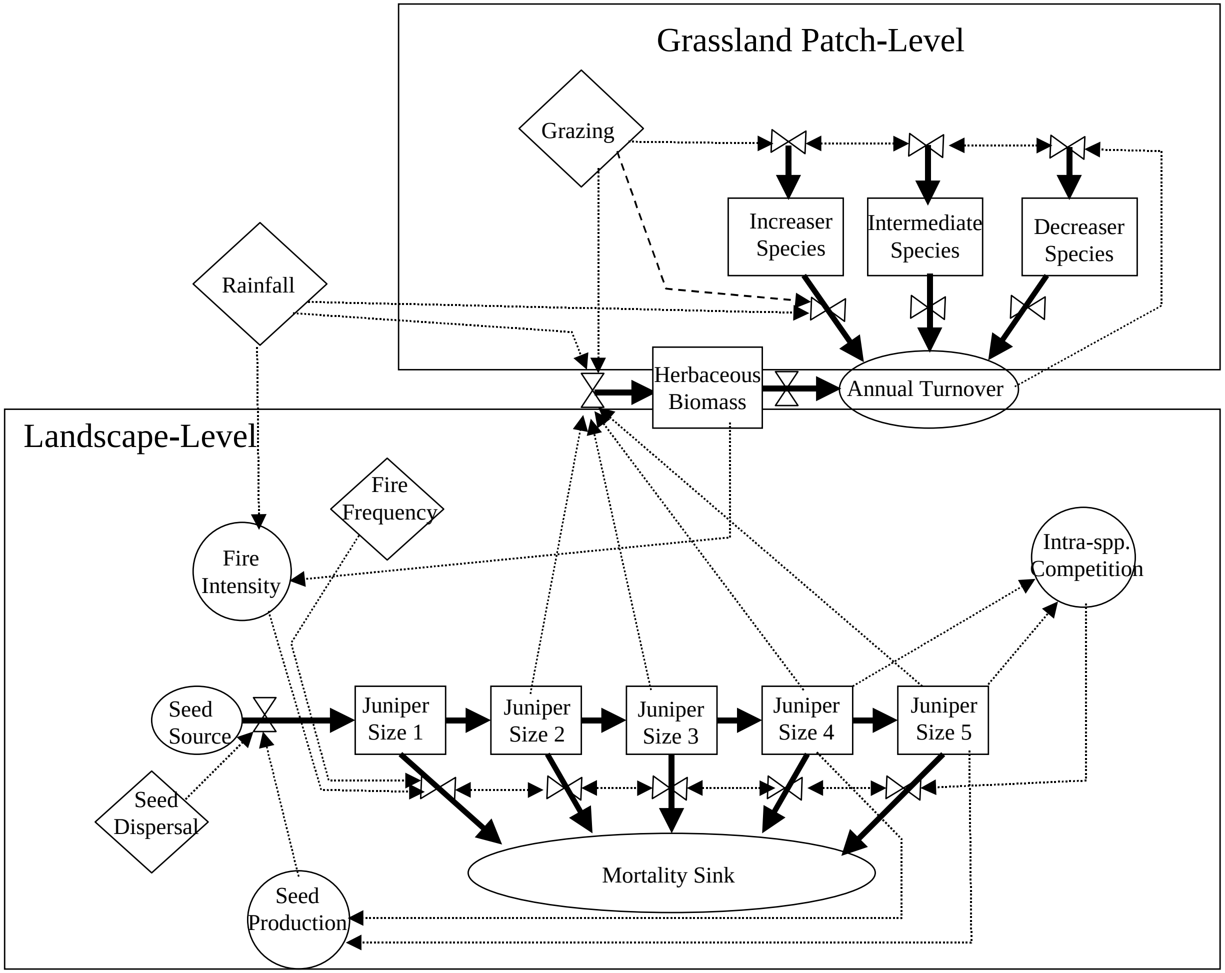
Model Maker

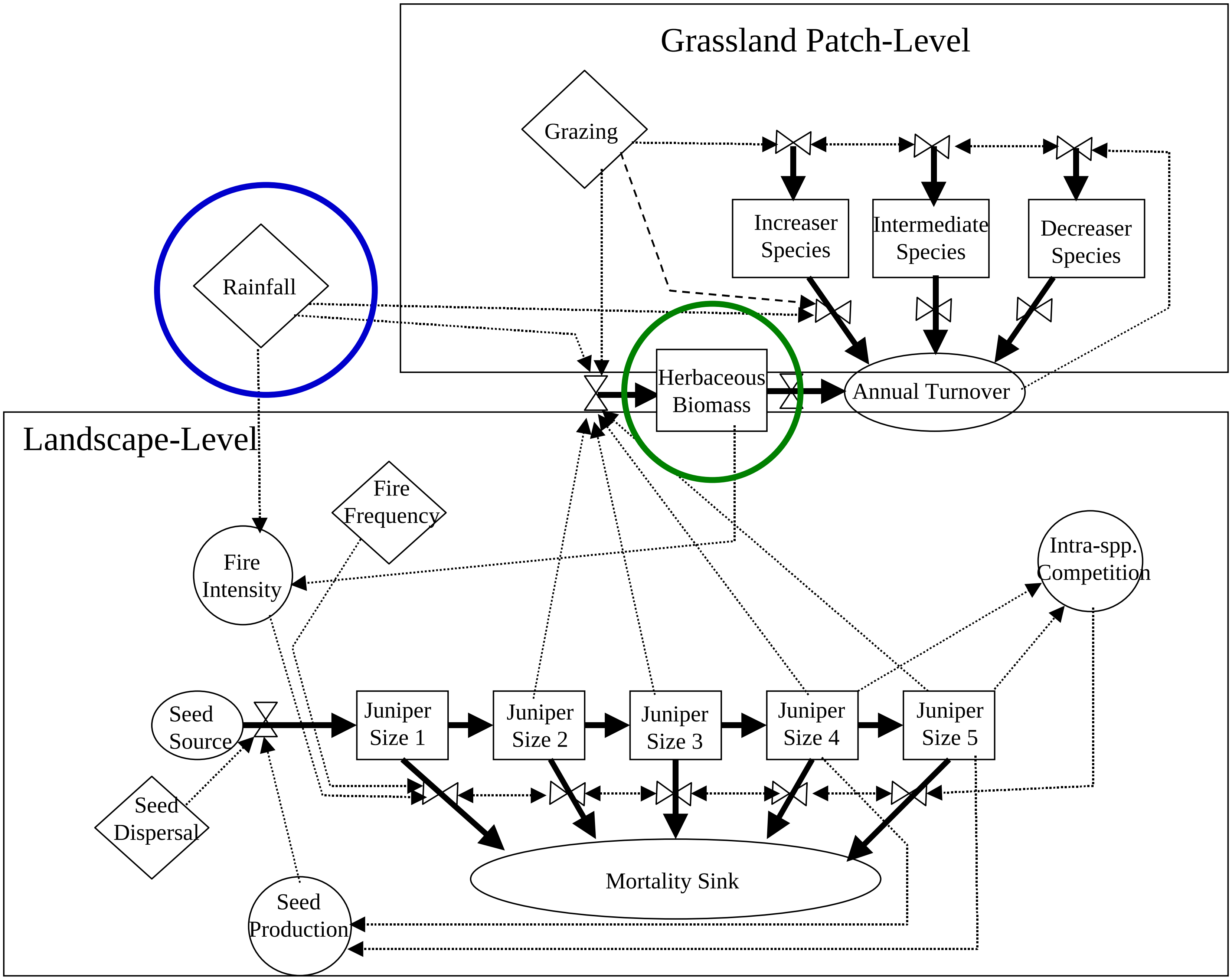
www.cherwell.com/



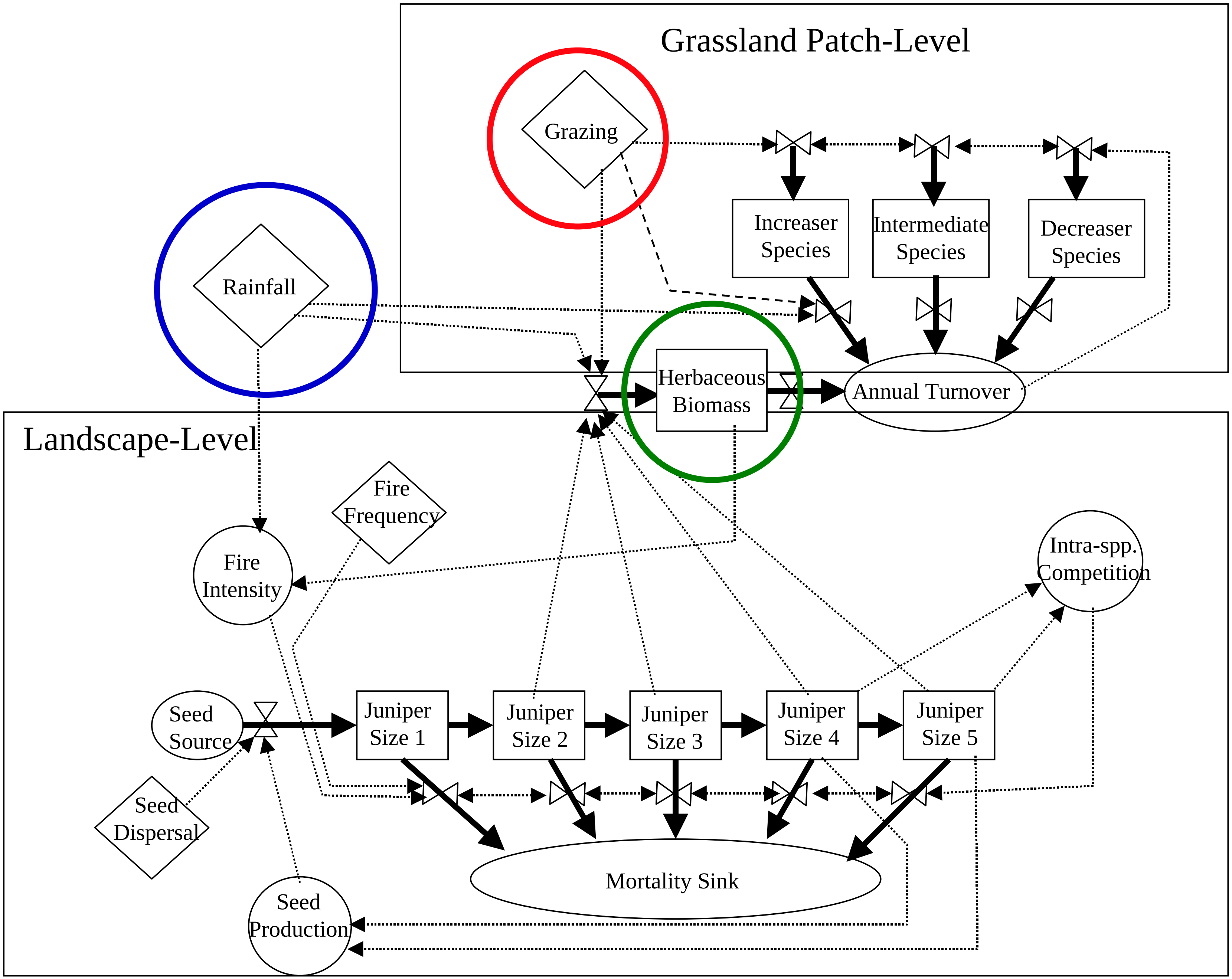
www.hps-inc.com

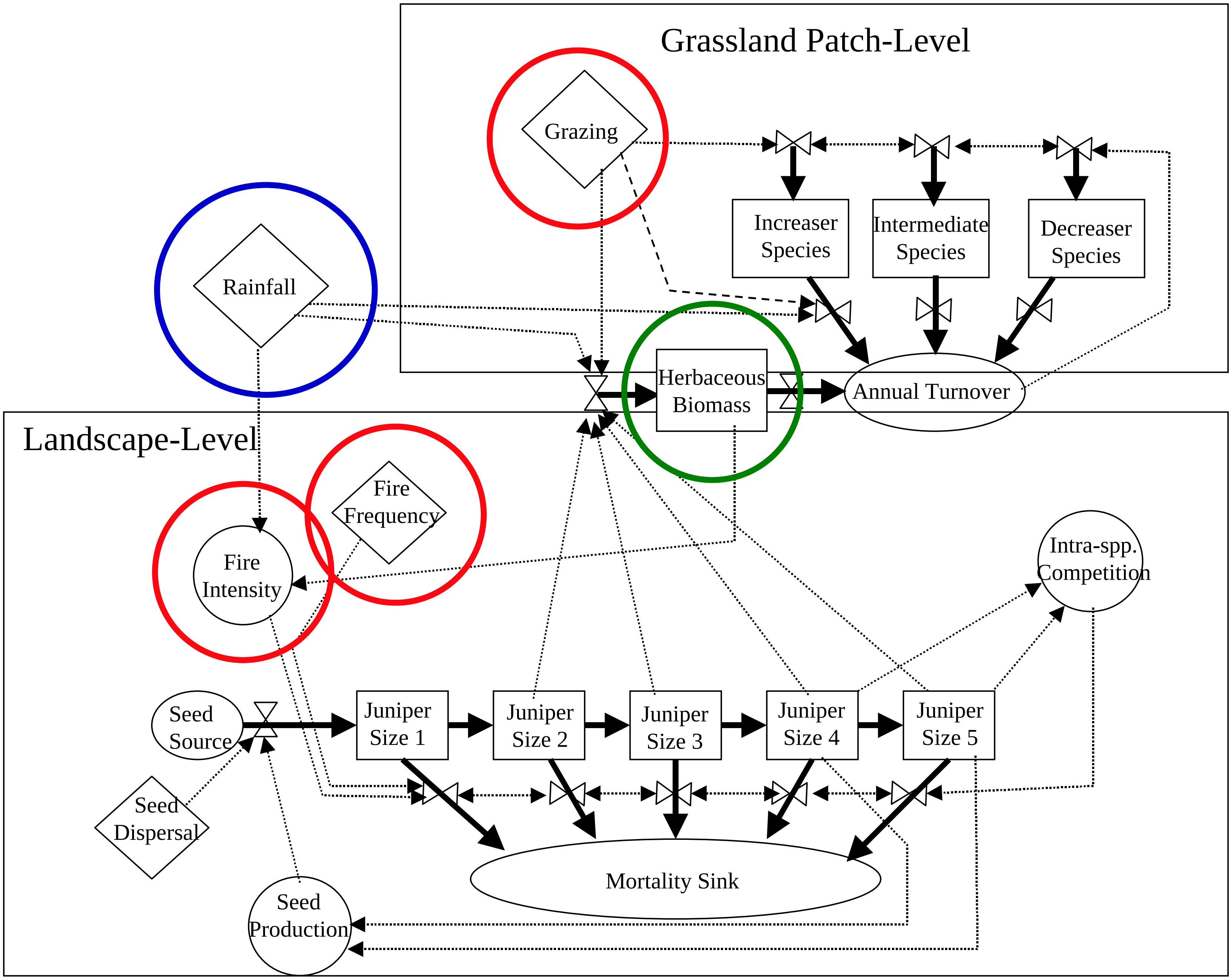

From Westoby et al. 1989
I Grassland, scattered woody plants
II Grassland, with many shrub seedlings
III Dense shrub cover, little grass
IV Recently burnt, many shrub seedlings or resprouts
T1
T2
T3
T4
T5
T6
T7

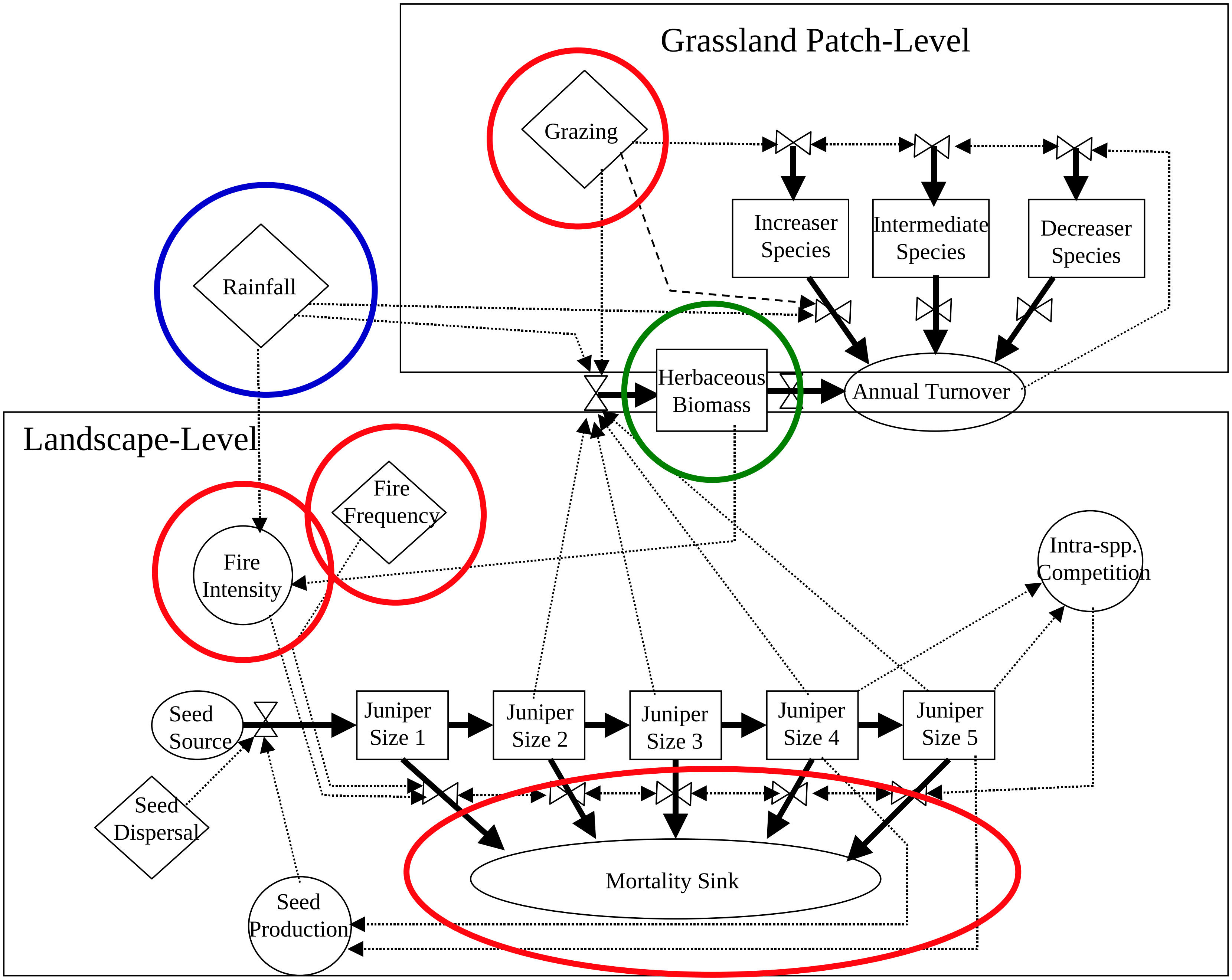

Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production



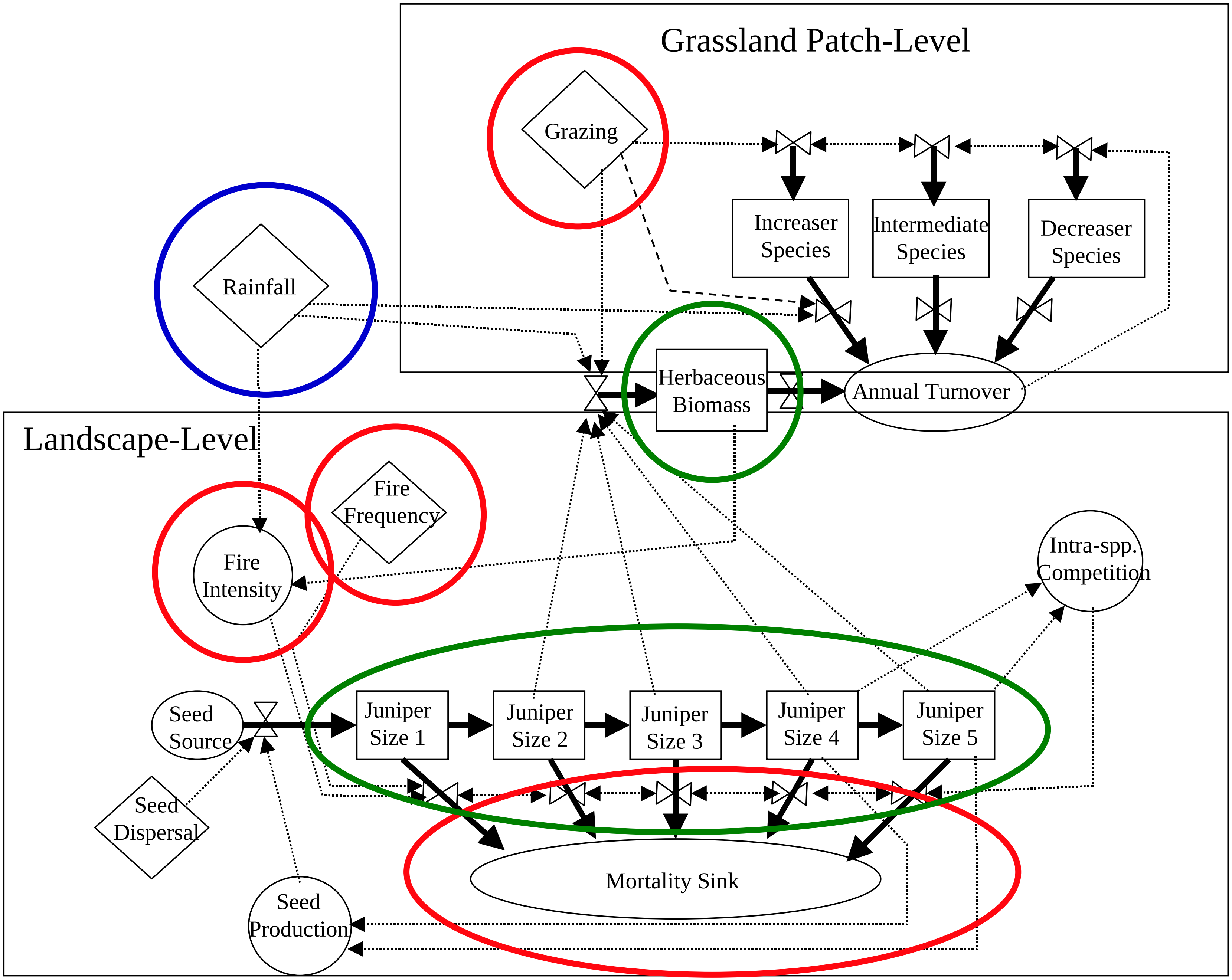
Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production


Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production


Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production

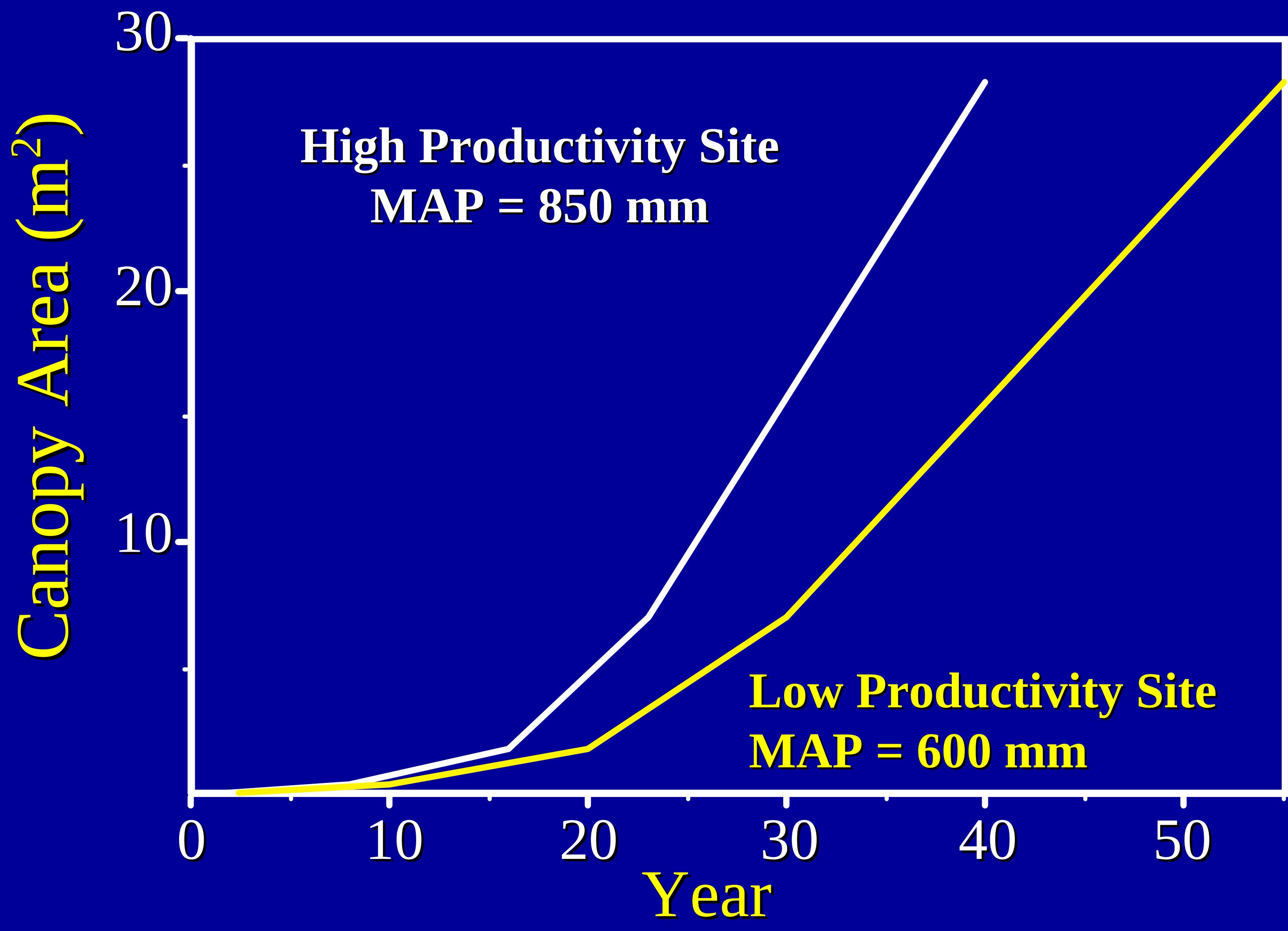


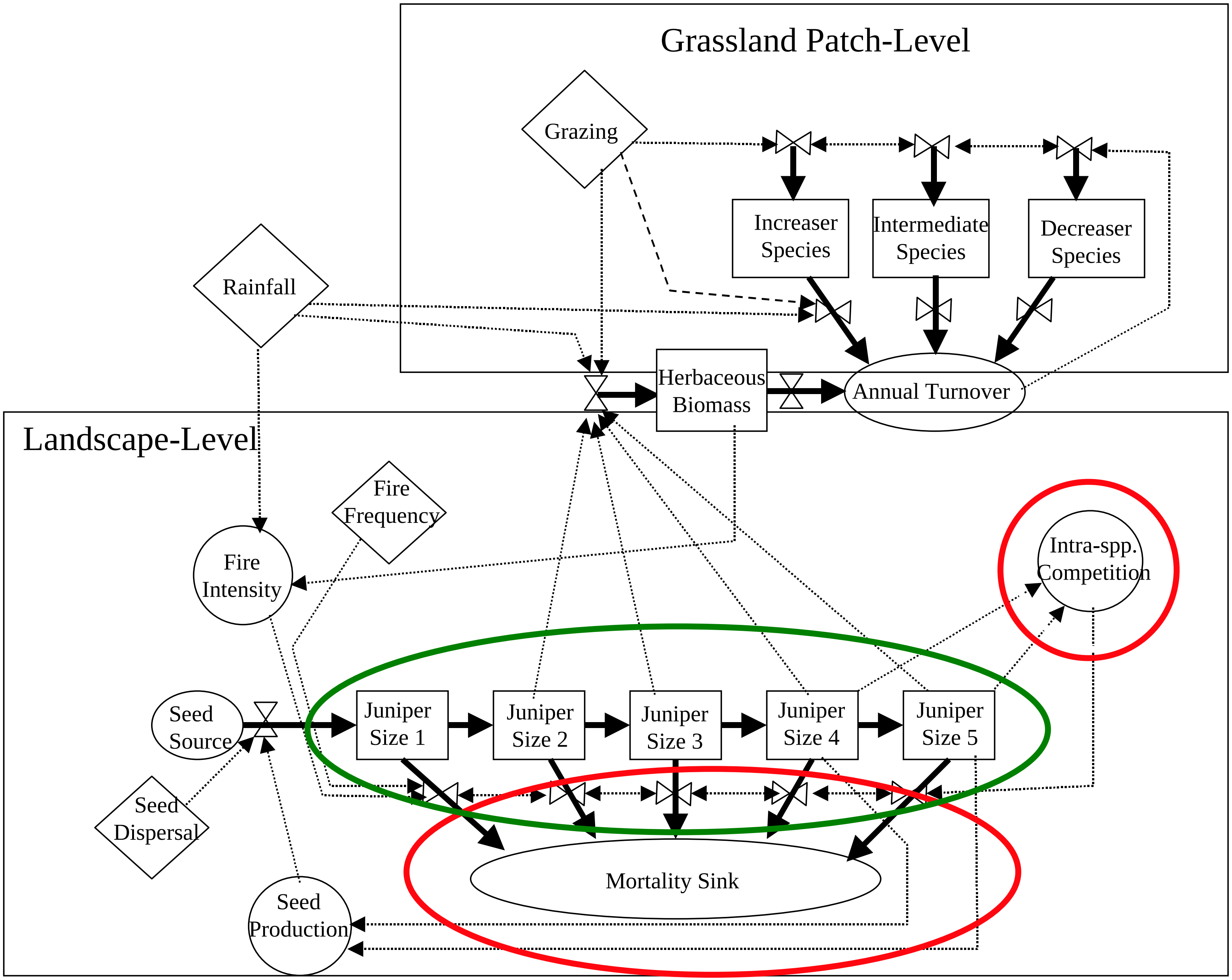
Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production



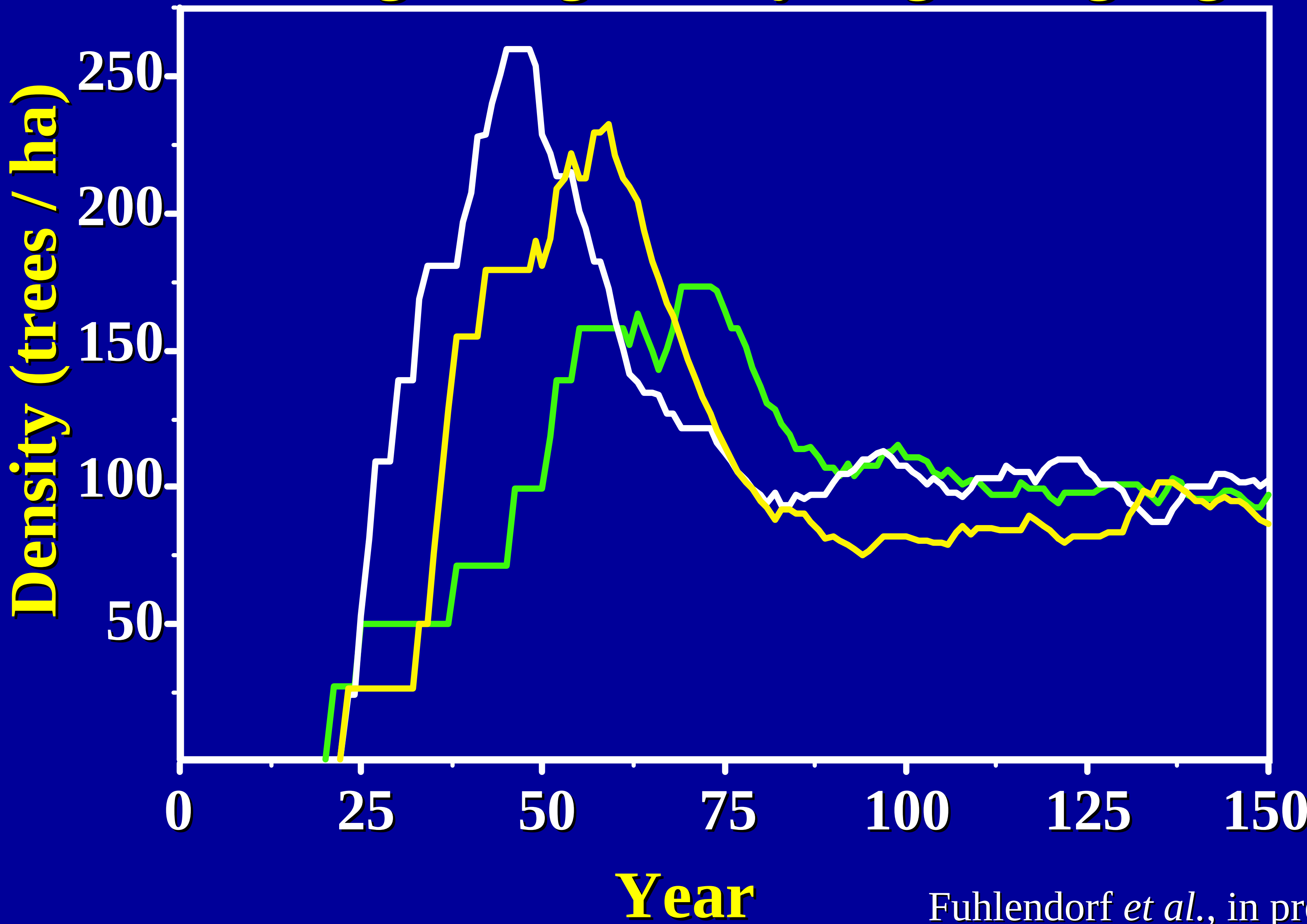
Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production

Fuhlendorf *et al.* in prep.



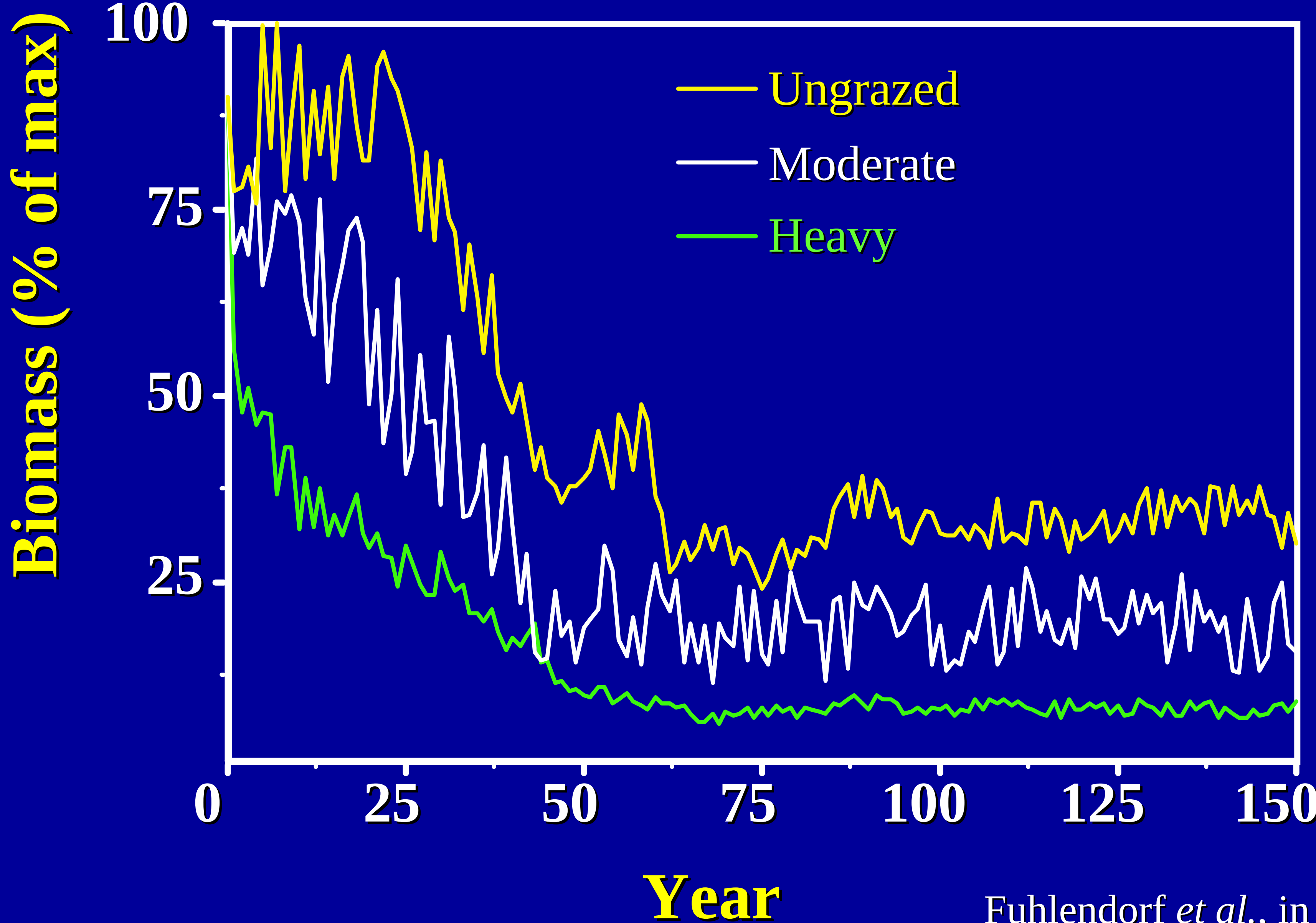

Grassland Patch-Level
Grazing
Increaser Species
Intermediate Species
Decreaser Species
Rainfall
Herbaceous Biomass
Annual Turnover
Landscape-Level
Fire Frequency
Fire Intensity
Intra-spp. Competition
Seed Source
Juniper Size 1
Juniper Size 2
Juniper Size 3
Juniper Size 4
Juniper Size 5
Seed Dispersal
Mortality Sink
Seed Production

With no fire, Juniper increases regard-less of grazing history or grazing regime



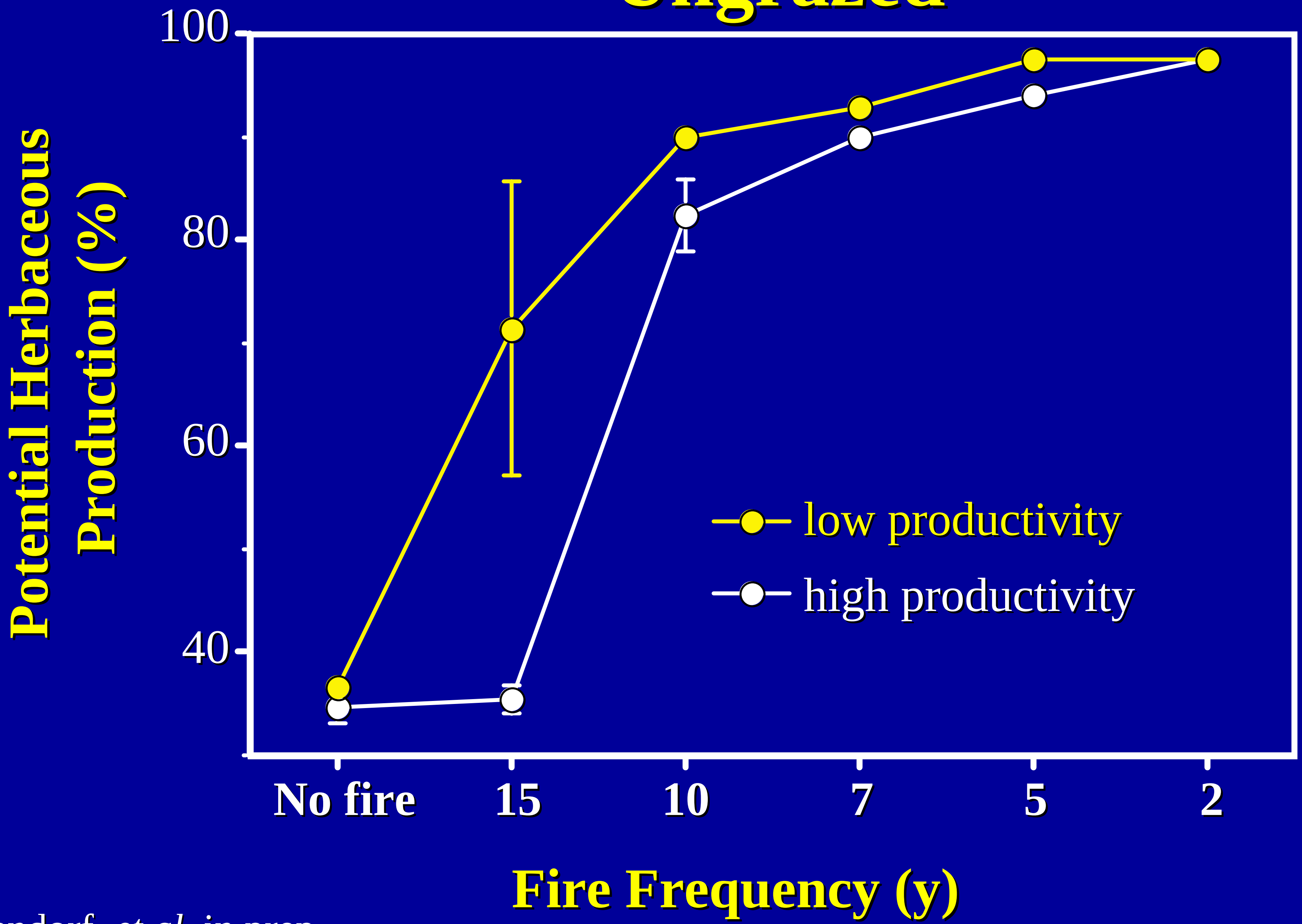
Fuhlendorf *et al.*, in prep.

Herbaceous Production— No Fire



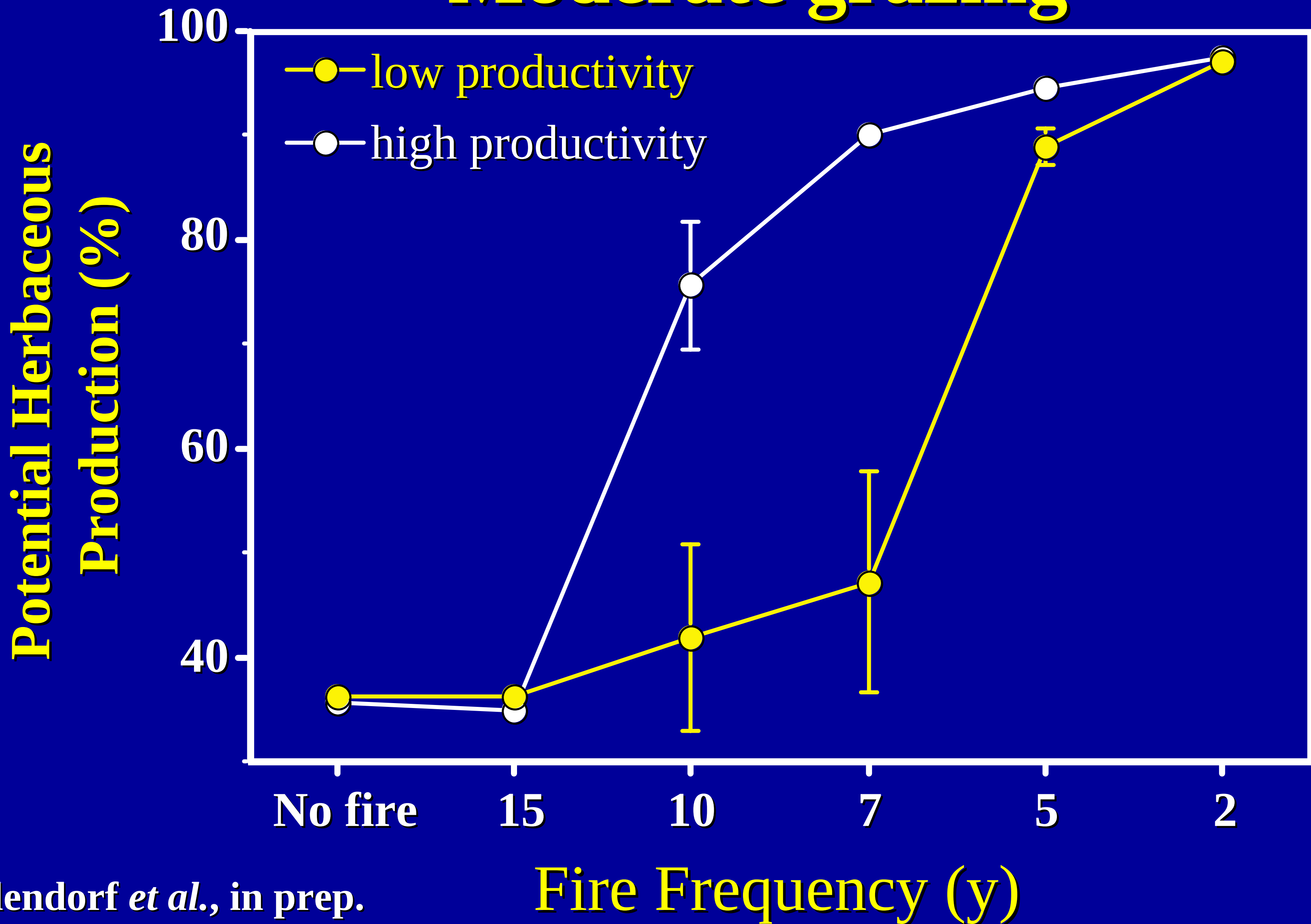
Fuhlendorf *et al.*, in prep.

Ungrazed



Fuhlendorf, *et al.* in prep.

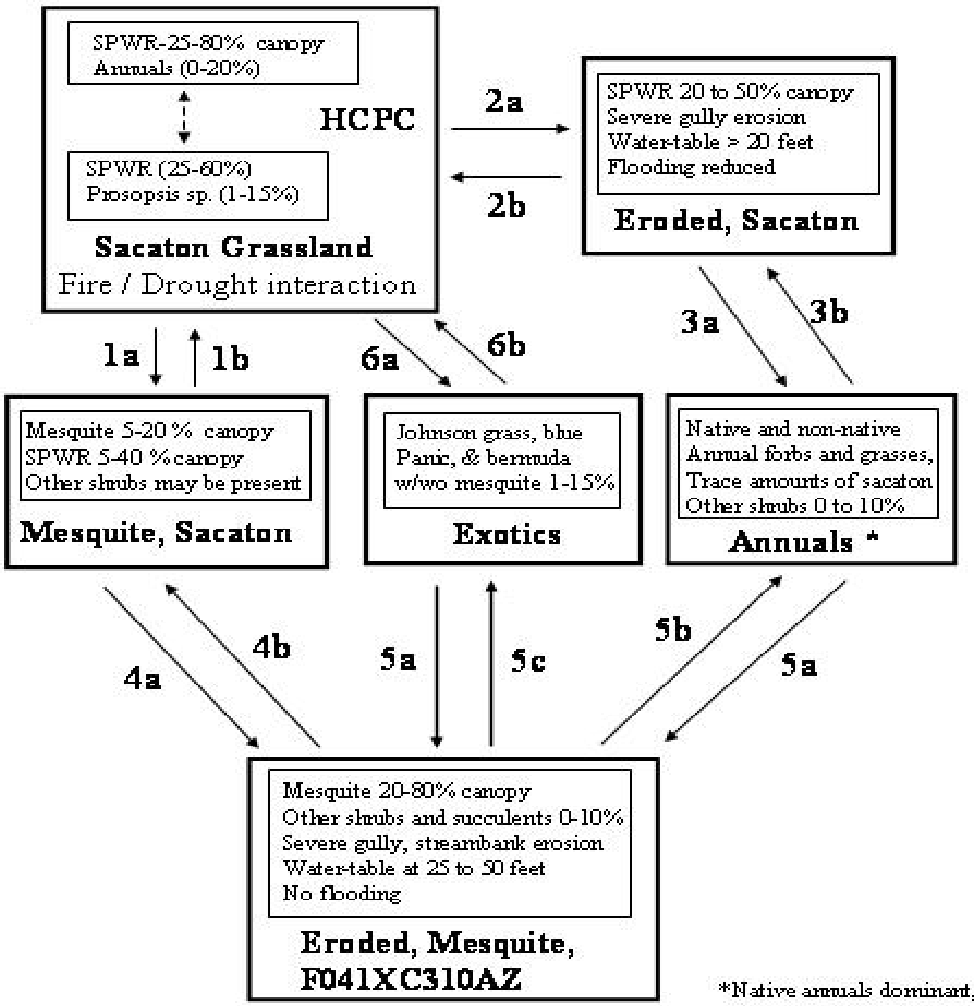
Moderate grazing



Fuhlendorf *et al.*, in prep.

Beyond Boxes and Arrows……

MLRA 41-3 (12-16”), Loamy Bottom



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

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. Seeding 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 downcutting in swales.
4b. Mechanical/herbicide treatment of shrubs to < 20% canopy. Seeding 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 Seeding of exotic grasses. Re-establish flooding.
6a. CHG combined with drought, burning with low soil moisture. Plowing 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.

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