Evaluation of forest management objectives: creating spatially heterogeneous structure and reducing fire behavior

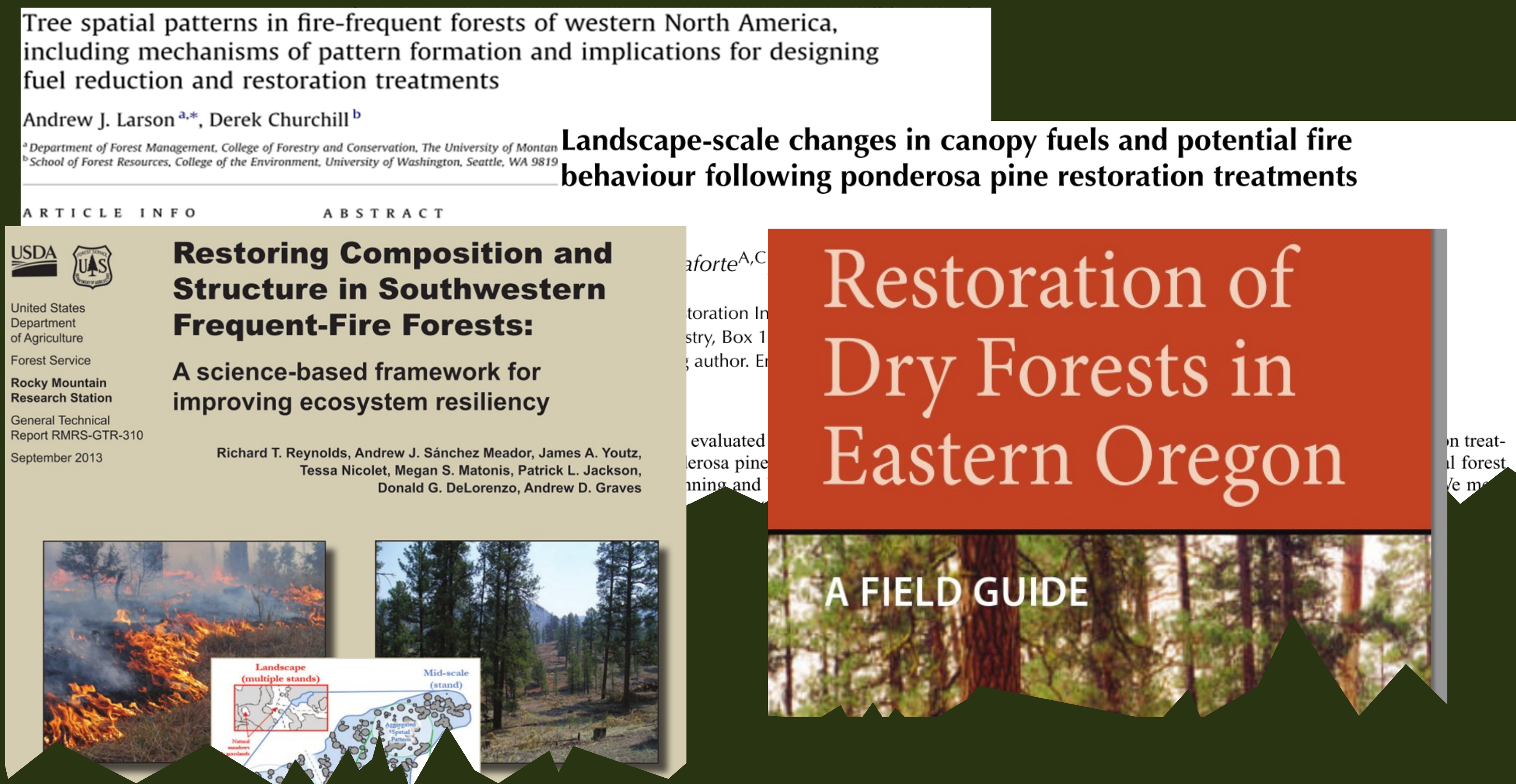
Chad Hoffman, Mike Battaglia, Yvette Dickinson, Justin Ziegler, Emma Vakili, William Mell

Outline

- background
- Restoration and spatial heterogeneity
- Restoration and fire
- Some general conclusions and future research

Restoration thinnings

Much ado about forest restoration these days…



Forest restoration: an issue of pattern and process

The process of assisting the recovery of an ecosystem …focuses on reestablishing, the composition, structure, pattern and ecological processes necessary to facilitate an ecosystems sustainability, resilience, and health….USDA FS (2012)

But….

The desired ecological processes or services we are attempting to restore can arise from a variety of forest structures, compositions and patterns

This suggests that we need to understand the mechanisms by which various forest structures, compositions and patterns alter ecosystem services and processes.

Some bad news…
or opertunities

- Limited research that directly links forest structure, composition and pattern to ecosystem services and processes
- Non spatial modeling methods (mostly)
- Difficulty monitoring spatial patterns for adaptive management
- Non spatial objectives and/or lack of clear ecosystem services and processes

- Historical silviculture promoted homogeneity, need to develop treatment methods that promote heterogeneity
  - Need to change forestry education

More bad news….and opportunities

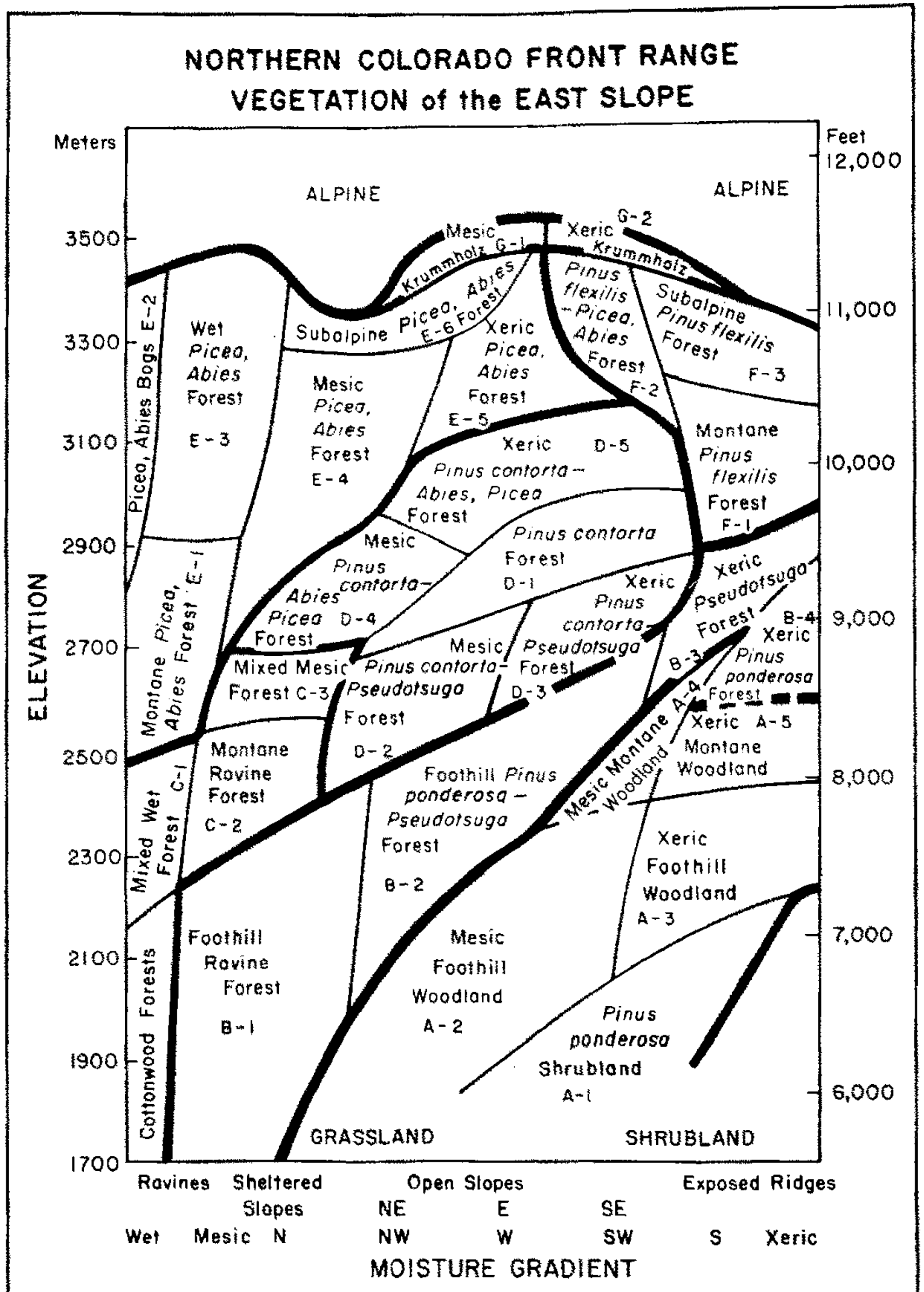
- Increasingly diverse objectives
  - Reduce uncharacteristic fire hazard (System dependent)
  - Improve aesthetics
  - Improve wildlife habitat
  - Improve forest health
  - Increase understory plant diversity and cover
  - Increase ecological resilience (and resistance
  - Improve clean water and air
  - ….

Our research approach

- Focus on:

1. Quantifying spatial patterns of vegetation at different scales
2. Develop monitoring and modeling methods to deal with spatial scales
3. Link pattern to process
   (especially fire behavior and micrometeorological variables)

Restoration in dry forest types in Colorado


NORTHERN COLORADO FRONT RANGE
VEGETATION of the EAST SLOPE
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ALPINE
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Krummholz
Subalpine Picea, Abies E-6 Forest
Picea, Abies Bogs E-2
Wet Picea, Abies Forest E-3
Mesic Picea, Abies Forest E-4
Xeric Picea, Abies Forest E-5
Pinus flexilis - Picea, Abies Forest F-2
Subalpine Pinus flexilis Forest F-3
Montane Pinus flexilis Forest F-1
Xeric D-5 Pinus contorta - Abies, Picea Forest
Mesic Pinus contorta - Abies Picea D-4 Forest
Pinus contorta Forest D-1
Xeric Pinus contorta - Pseudotsuga Forest D-3
Xeric Pseudotsuga Forest B-4
Montane Picea, Abies Forest E-1
Mixed Mesic Forest C-3
Mesic Pinus contorta - Pseudotsuga Forest D-2
B-3
Xeric Pinus ponderosa Forest A-5
A-4
Montane Ravine Forest C-2
C-1
Mixed Wet Forest
Foothill Pinus ponderosa - Pseudotsuga Forest B-2
Mesic Montane Woodland
Xeric Montane Woodland
Xeric Foothill Woodland A-3
Cottonwood Forests
Foothill Ravine Forest B-1
Mesic Foothill Woodland A-2
Pinus ponderosa Shrubland A-1
GRASSLAND
SHRUBLAND
Ravines
Sheltered Slopes
Open Slopes
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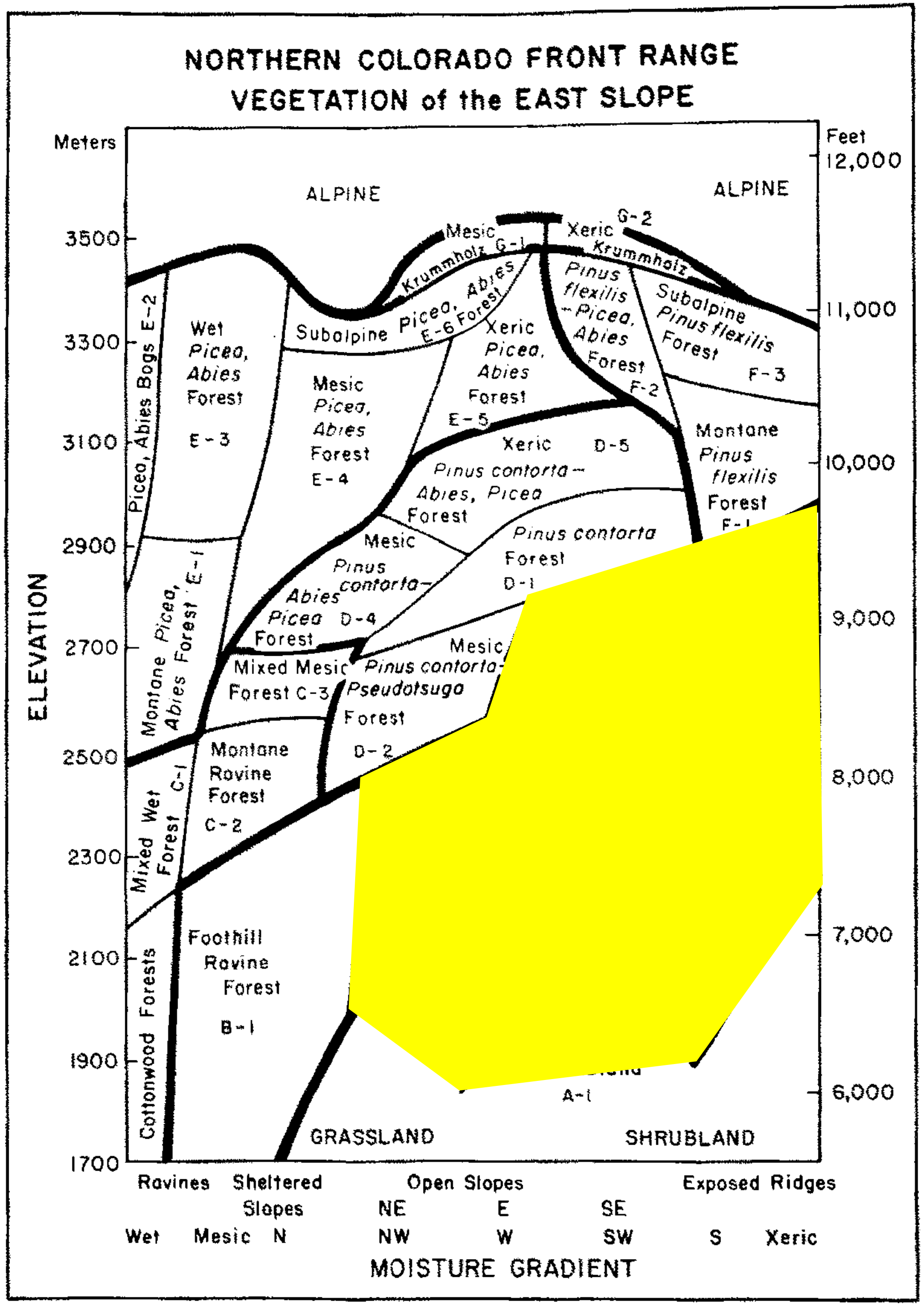
MOISTURE GRADIENT

Peet (1981)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Peet (1981)

Restoration thinnings

Restoration thinnings seek to reduce hazardous fire behavior in a manner that enhances spatial diversity

- Prevent large scale crown fires – more mixed and low severity
- Remove continuous forest fuels – create patches, openings, and individual trees
  - Ideally providing all other the other ecosystem services we want

What is structural complexity?

Complexity: characterization of how components of a system are intricately arranged.

Forest Structural complexity: characterization of how *trees* of a *stand* are intricately arranged.

What is structural complexity?

Complexity is *Dimensional*:

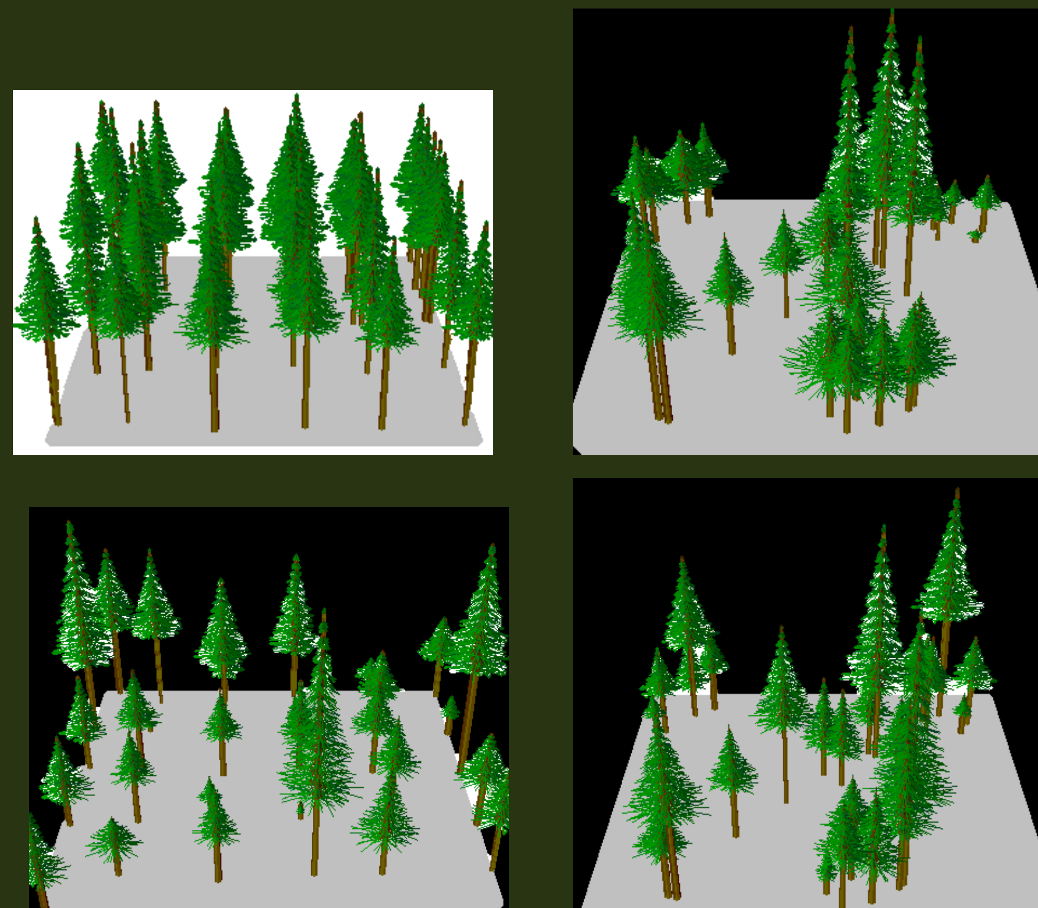
Horizontal— spatial relations of trees *“Aggregation”*

Low | High

Low

Vertical—
mingling of differently sized trees
“Canopy diversity”

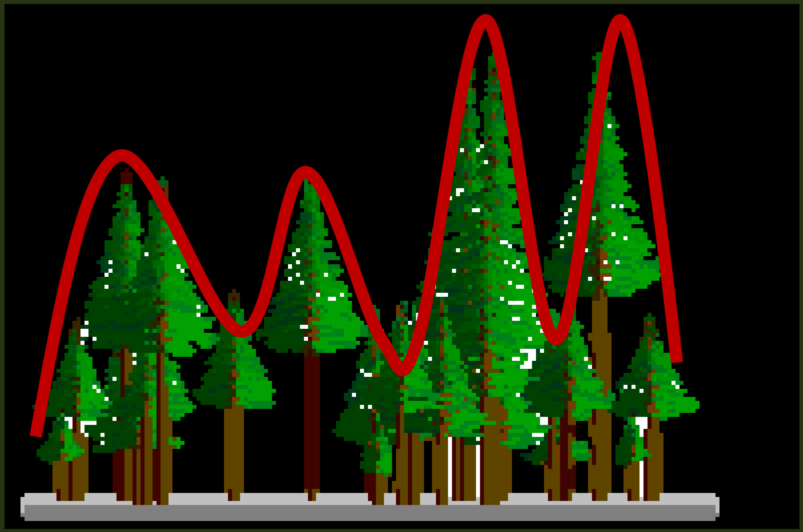
High

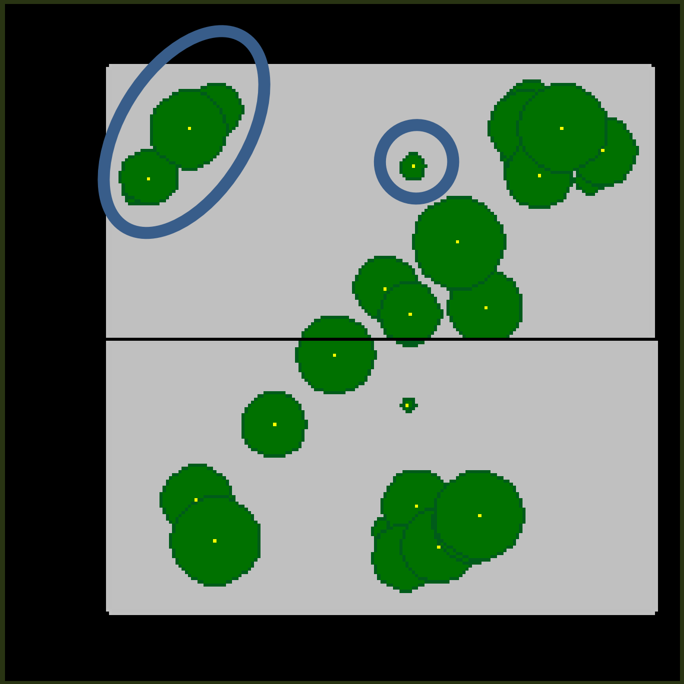


What is structural complexity?

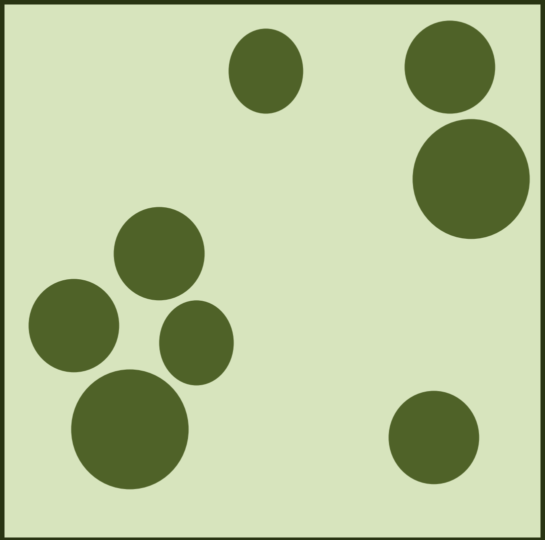
Complexity is *Scaled*:

- **Stand-level**—spatial properties characterizing the area of a stand
- **Patch-level**—spatially enumerating within-stand features
- Landscapes – spatial properties characterizing many stands

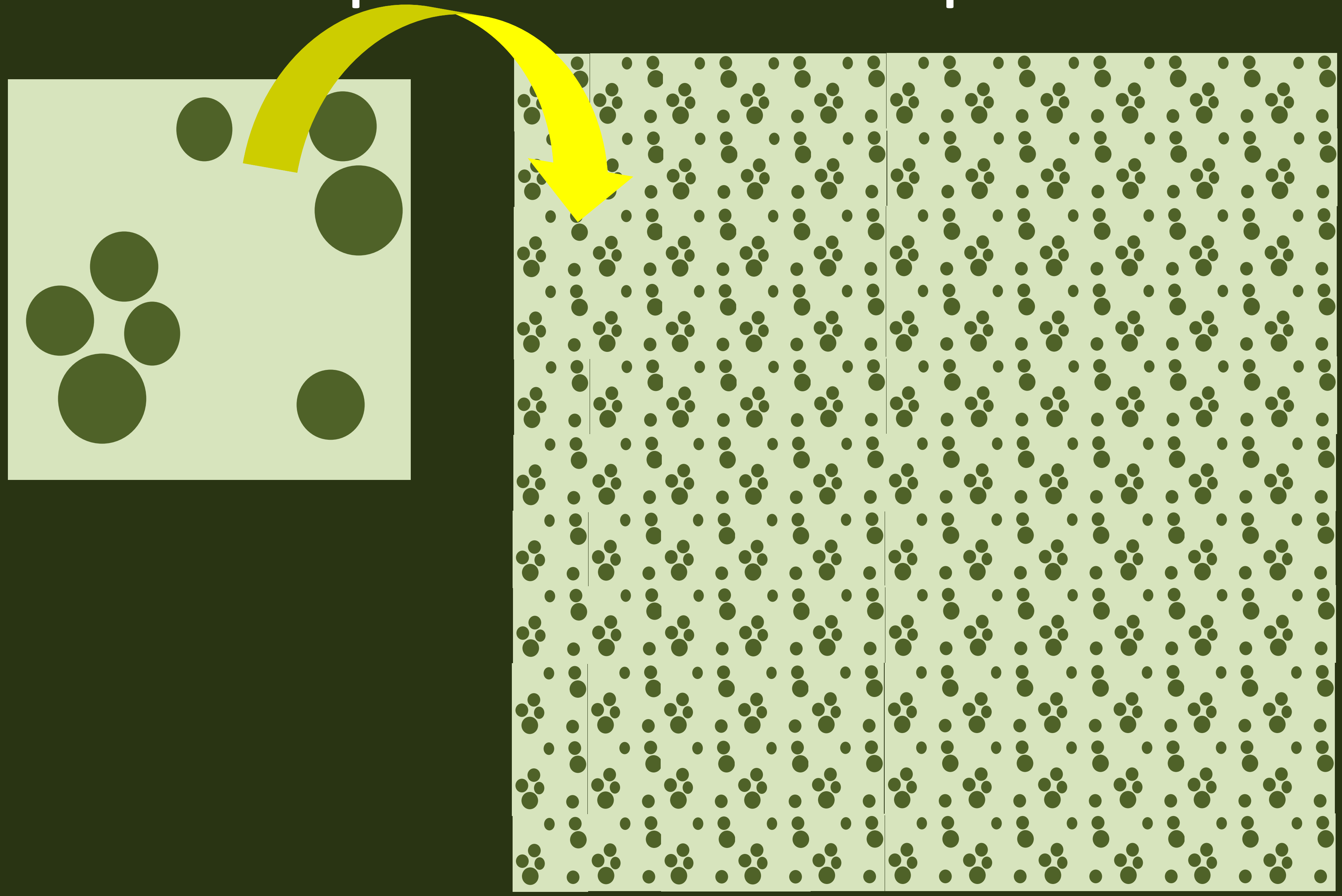




Landscape scale: nested patterns



Landscape scale: nested patterns



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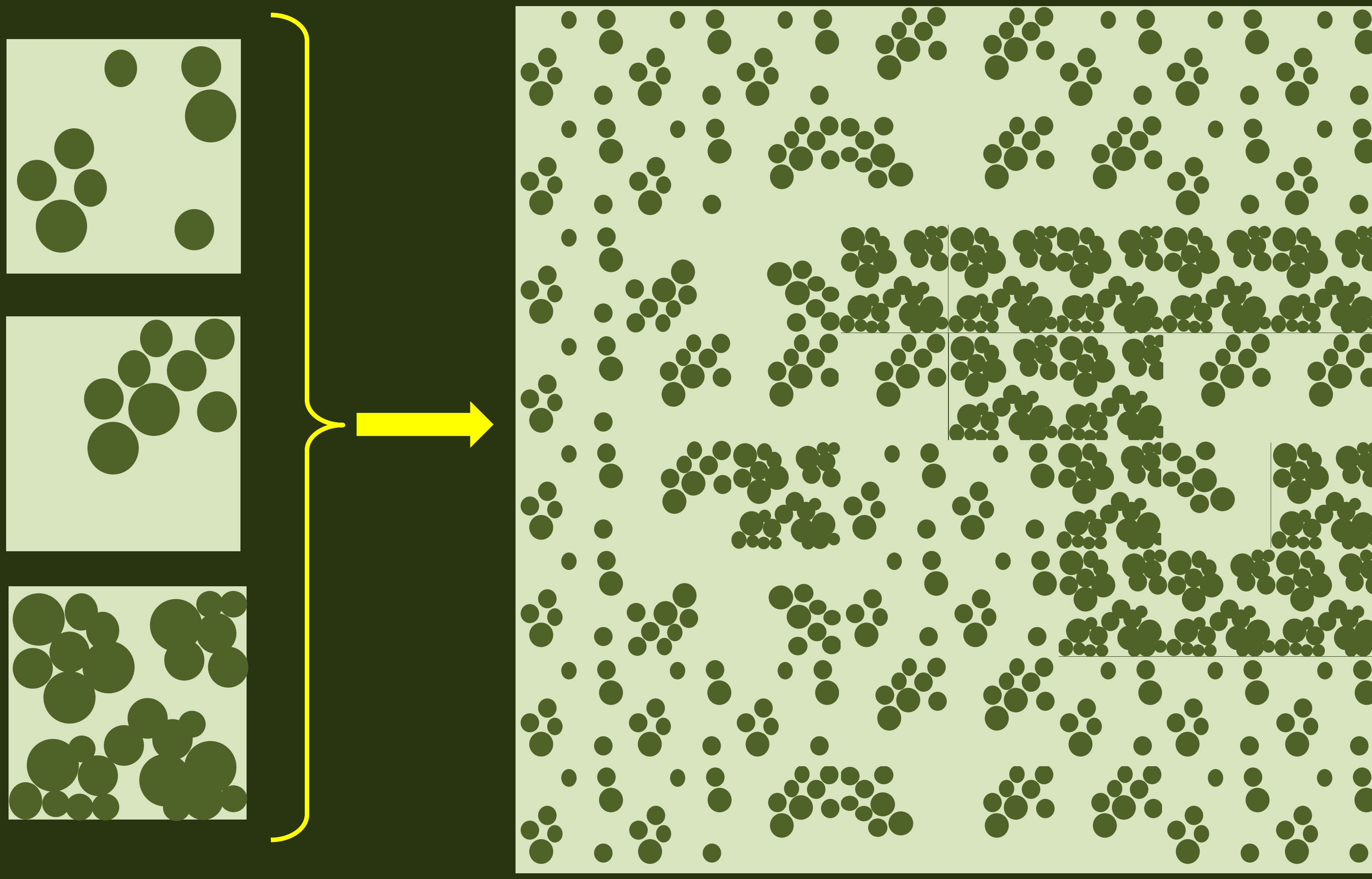
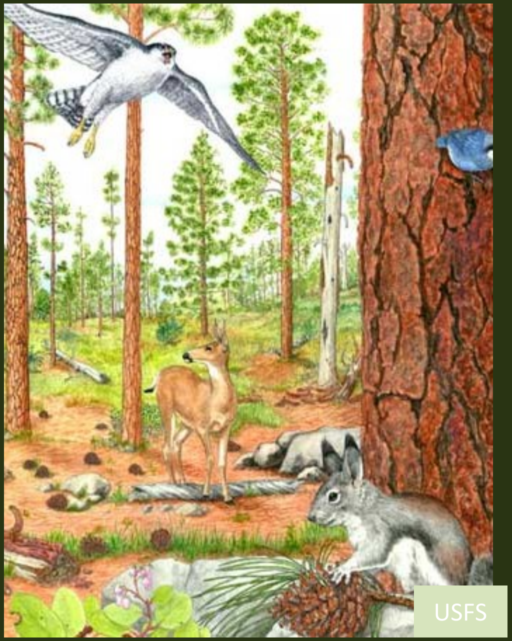


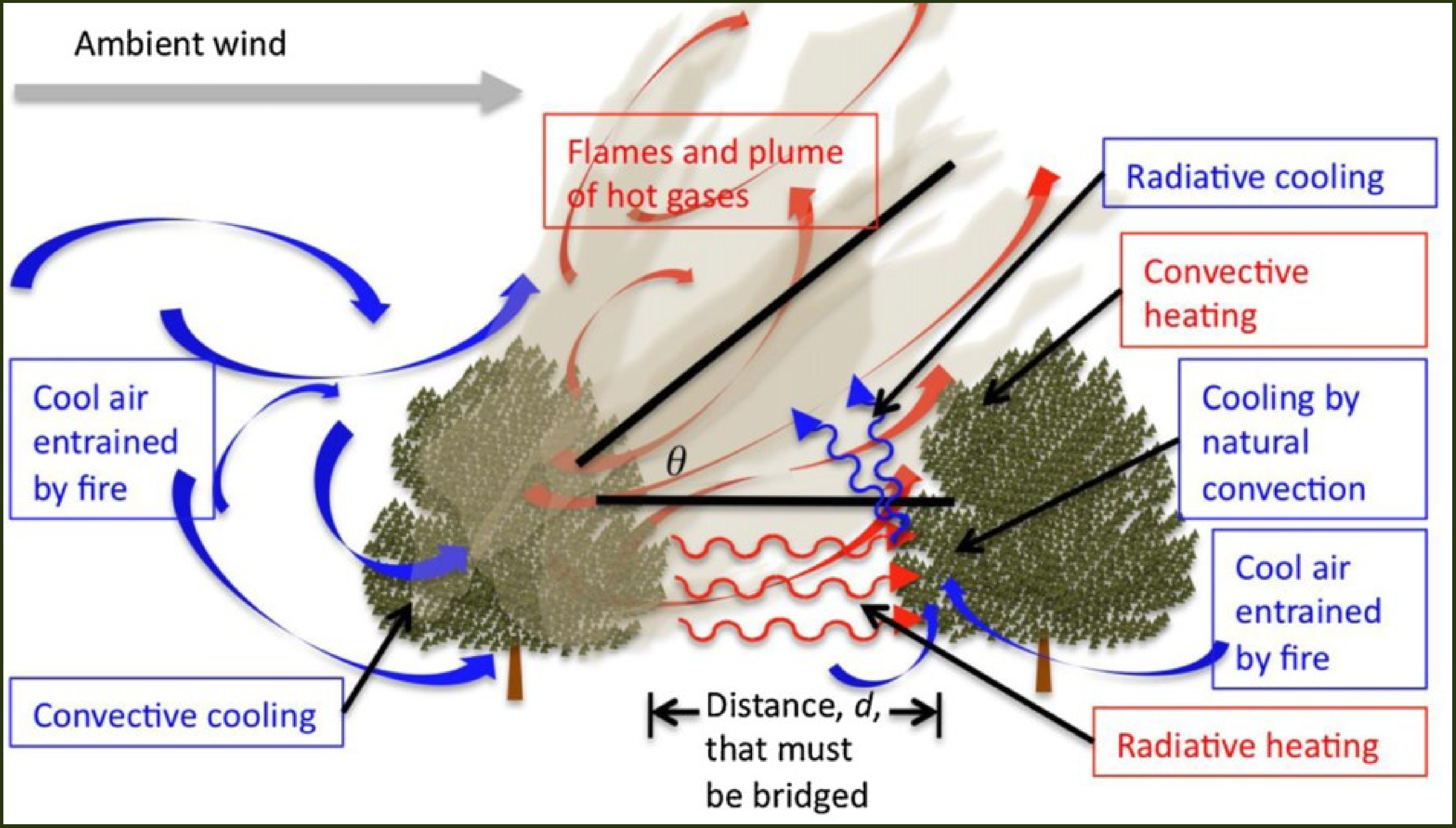
Impacts of altered structure

Structure  function



The fire environment

- Spatially and temporally dynamic
- Depends on complex interactions among the fire, fuels and atmosphere



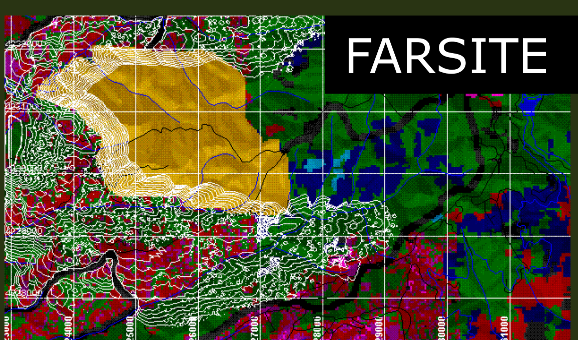
Current approaches to modeling wildfires

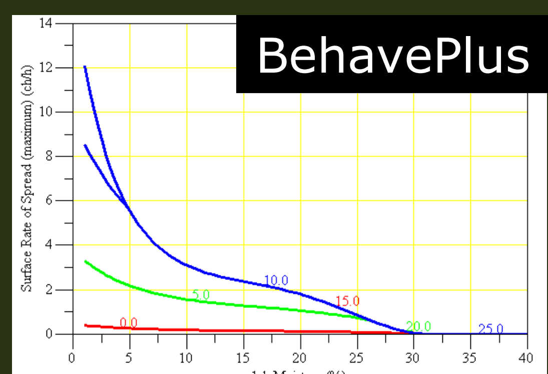
Current modeling approaches

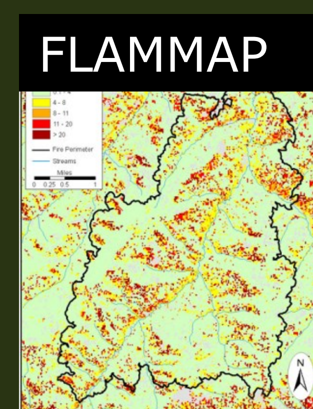
(Behave, Nexus, Farsite, FlamMap, ARCFuels, FFE-FVS)

Rothermel family of models (empirical and semi-empirical models)

- Surface fire rate of spread (Rothermel 1972)
- Crown fire rate of spread (Rothermel 1991)
- Crown fire initiation and spread (Van Wagner 1977)







Current approaches to modeling wildfires

Simplifying assumptions of the Rothermel family of models

- Fuels are assumed to be continuous and homogeneous
- Quasi-steady state rate-of-spread
- Mechanisms of heat transfer not explicitly addressed
- Homogenous environment and topography
- No fire-fuel-atmospheric interactions

Inconvenient truths about wildland fuels

Fuels are neither continuous nor homogeneous.

Clumpy in nature with voids at multiple scales and are highly variable in composition, structure and arrangement

Inconvenient truths continued

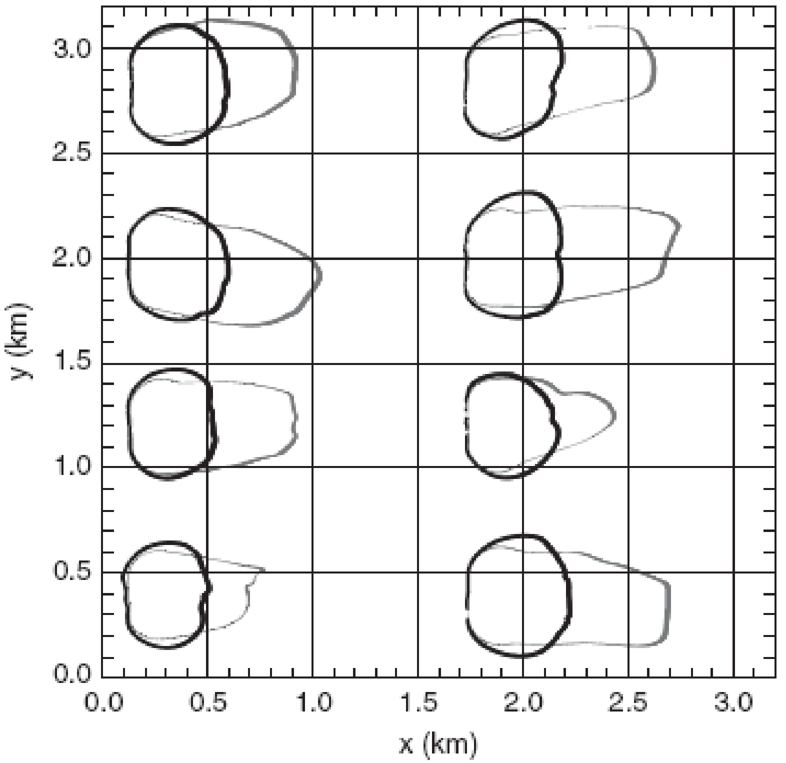
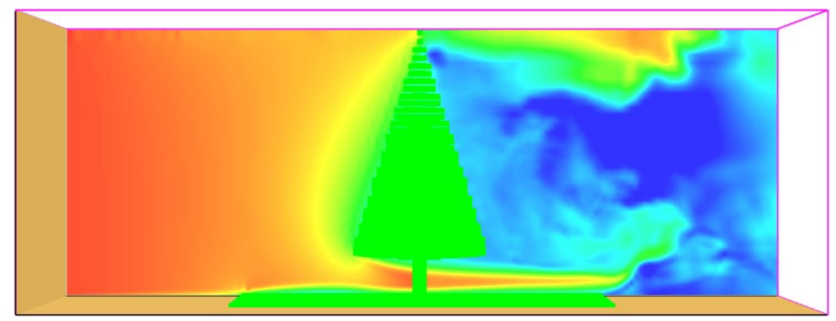
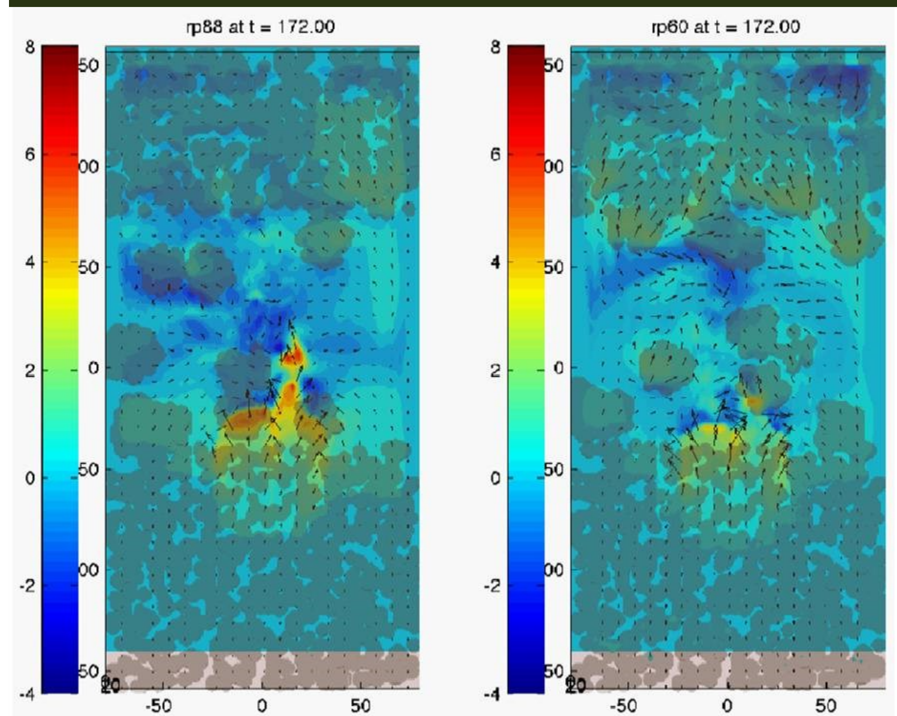


Fig. 5. The eight fire lines in the 'one-way coupling' case (black line), and the eight fire lines in the 'two-way coupling' case (grey line), in the convective boundary layer (CBL) at 5 min after the fires started. Initial fire line length (L_{ig}) was 200 m.





What do these inconvenient truths really mean

- Cannot capture fuel heterogeneity at various scales
  - i.e. an unknown uncertainty around model predictions
- Do not address couplings (i.e. fire behavior triangle), which control fire behavior and can produce rapid changes in rates of spread
- Do not adequately characterize potential threats to firefighter safety or effectiveness of suppression actions
- Have limited ability for predicting ecological effects of fire (due to lack of heat transfer mechanisms included)
- Considerable uncertainty in predictions - particularly when we implement treatments that deviate from the idea of big boxes of fuel!

- Can not help us link forest pattern to process!

Physics based fire behavior models

Two main models

1) FIRETEC

Los Alamos National Lab – Rod Linn

Very strong with wind field, topography

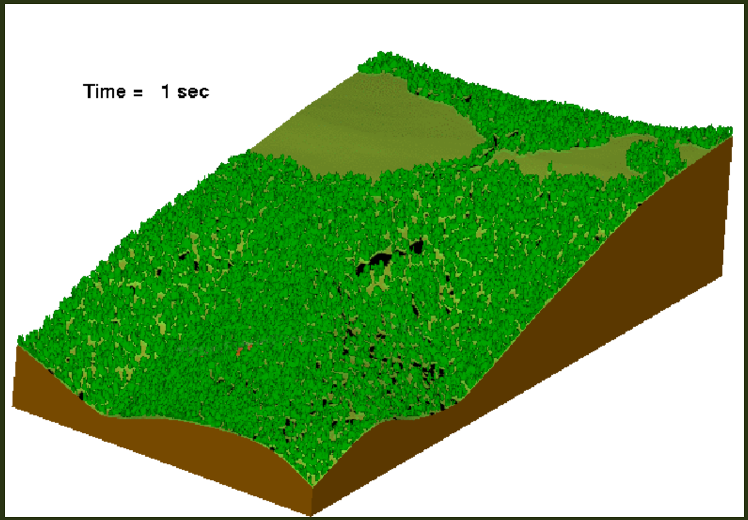
2) Wildland Urban Interface Fire Dynamics Simulator (WFDS)

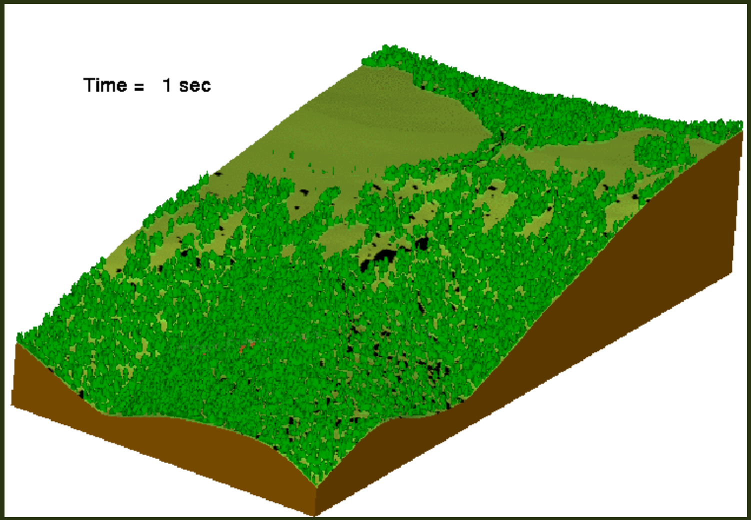
N.I.S.T. -- William Mell

Structure fire origins, adapted for wildland fire

Dynamic fire behavior models

Computational fluid dynamics (CFD) model of fire-driven fluid flow which solves a form of the Navier-Stokes equation through time on a 3-dimensional grid



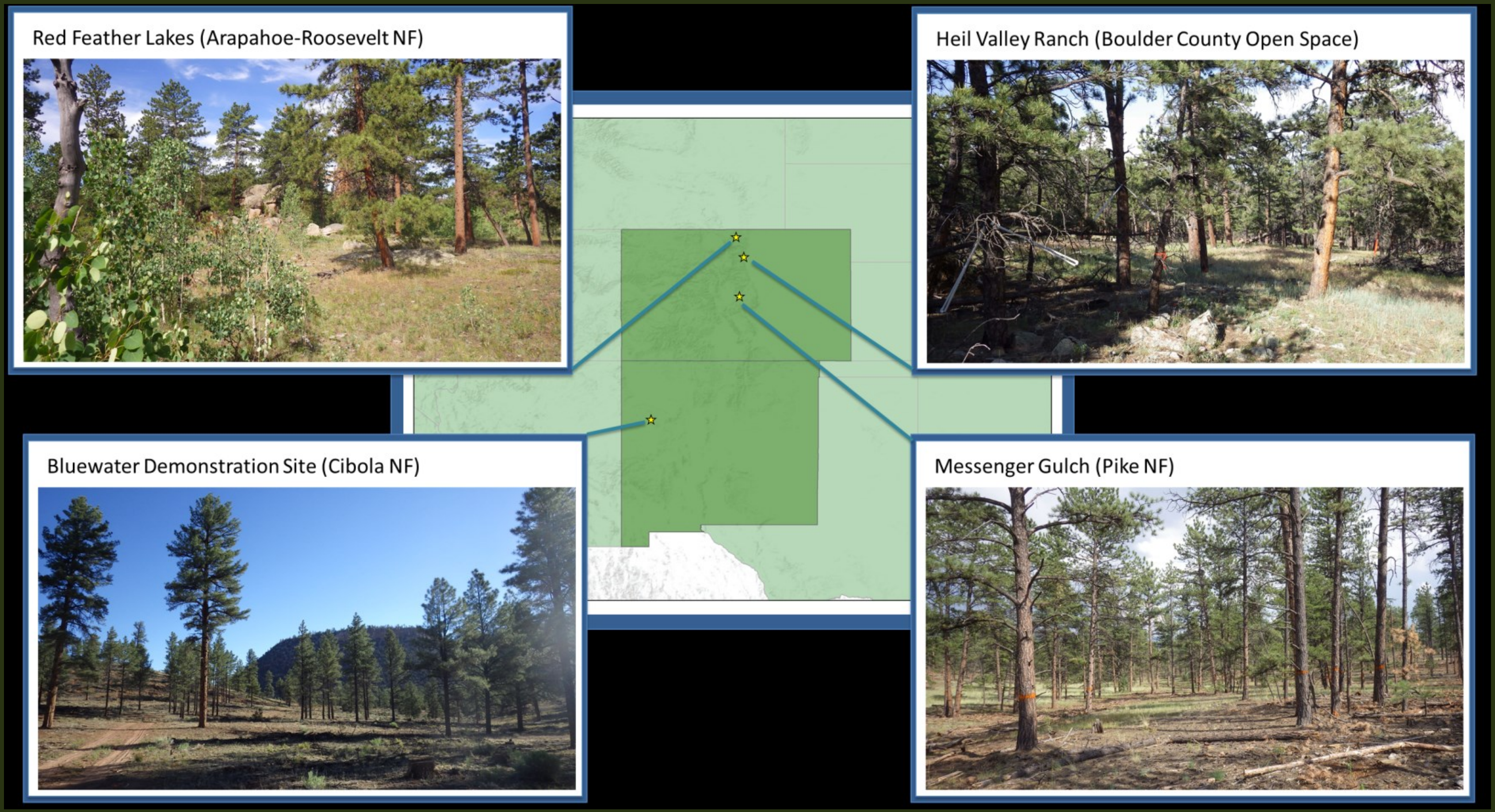


Projects and objectives

- Assessing current and post-treatment forest structure
  - Surface fuels (ongoing work)
  - Canopy fuels
- Assessing changes in fire behavior following restoration treatments

Assessing changes in surface fuels

- Data collected on 4 sites (to date)



Surface Fuels: Methods

- Surface fuels were inventoried within a nested plot design with a combination of the photoload technique (Keane and Dickinson 2007) and sample collection (see Figure 1).

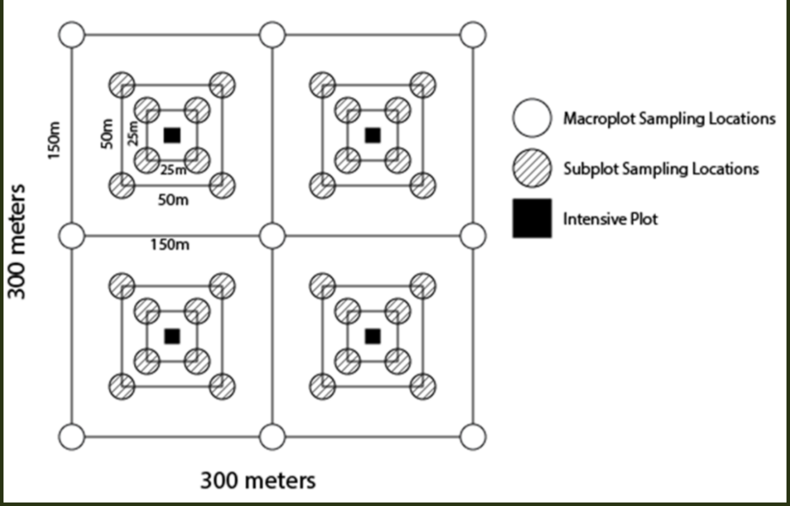
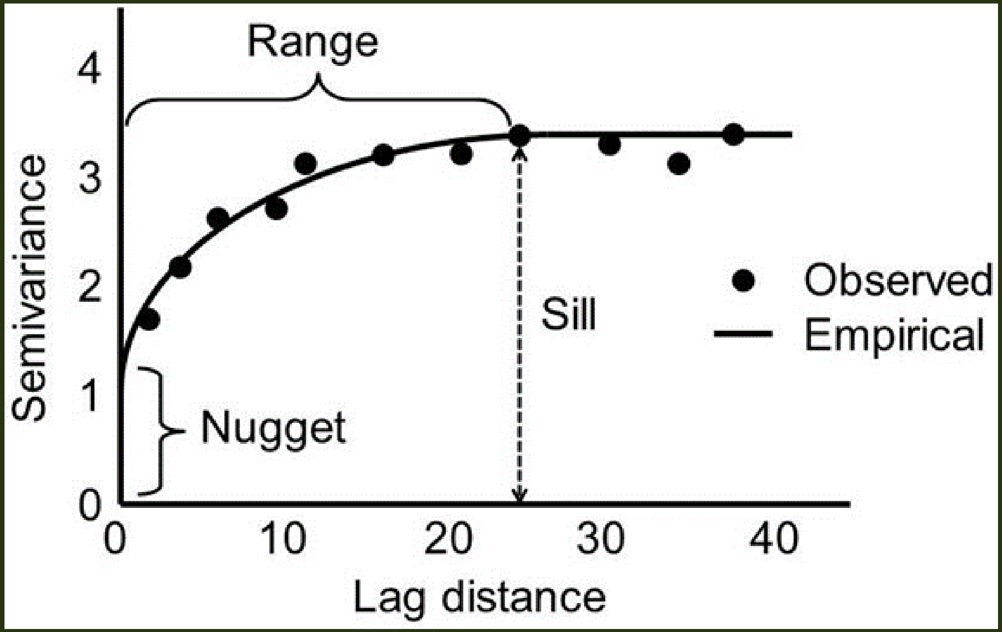


Figure 1a: Field crew working in the intensive plot

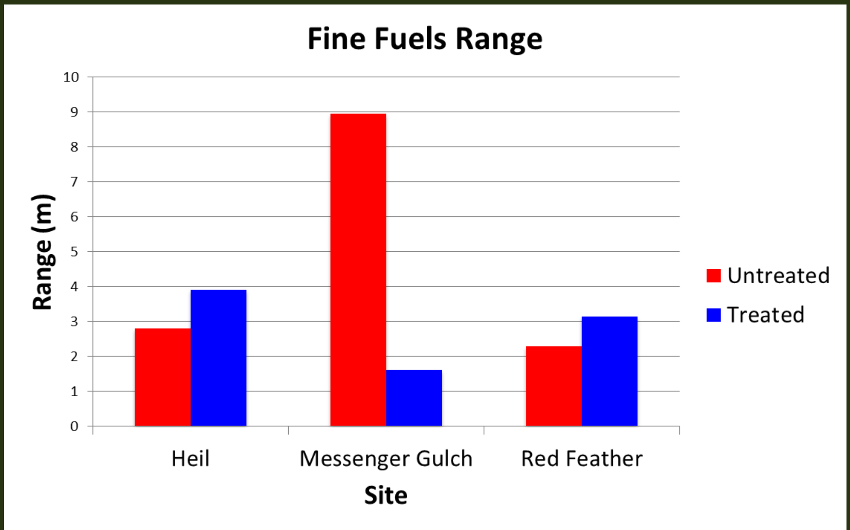
Figure 1b: 1-m frame used for 1-hr, 10-hr, and 100-hr fuel estimates using the photoload technique

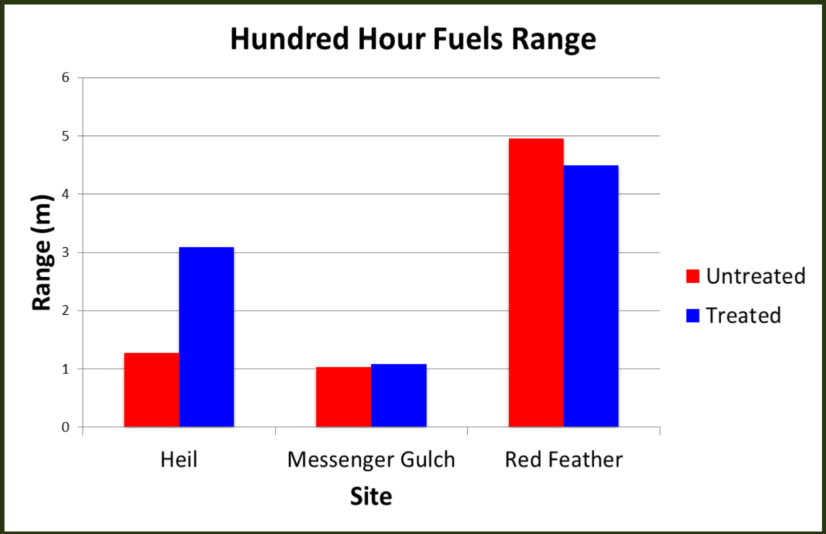
Surface Fuels: Methods

- Spatial variability (sill) and fuel patch size (range) was analyzed for the 1, 10, 100-hr and fine fuels (litter+1-hr fuels) classes using variograms



Surface Fuel Results





- Surface fuel patch sizes < 14 m
- Sills are highly variable
- No consistent effect of restoration on surface fuel variability

Canopy Fuel and Fire Behavior Methods

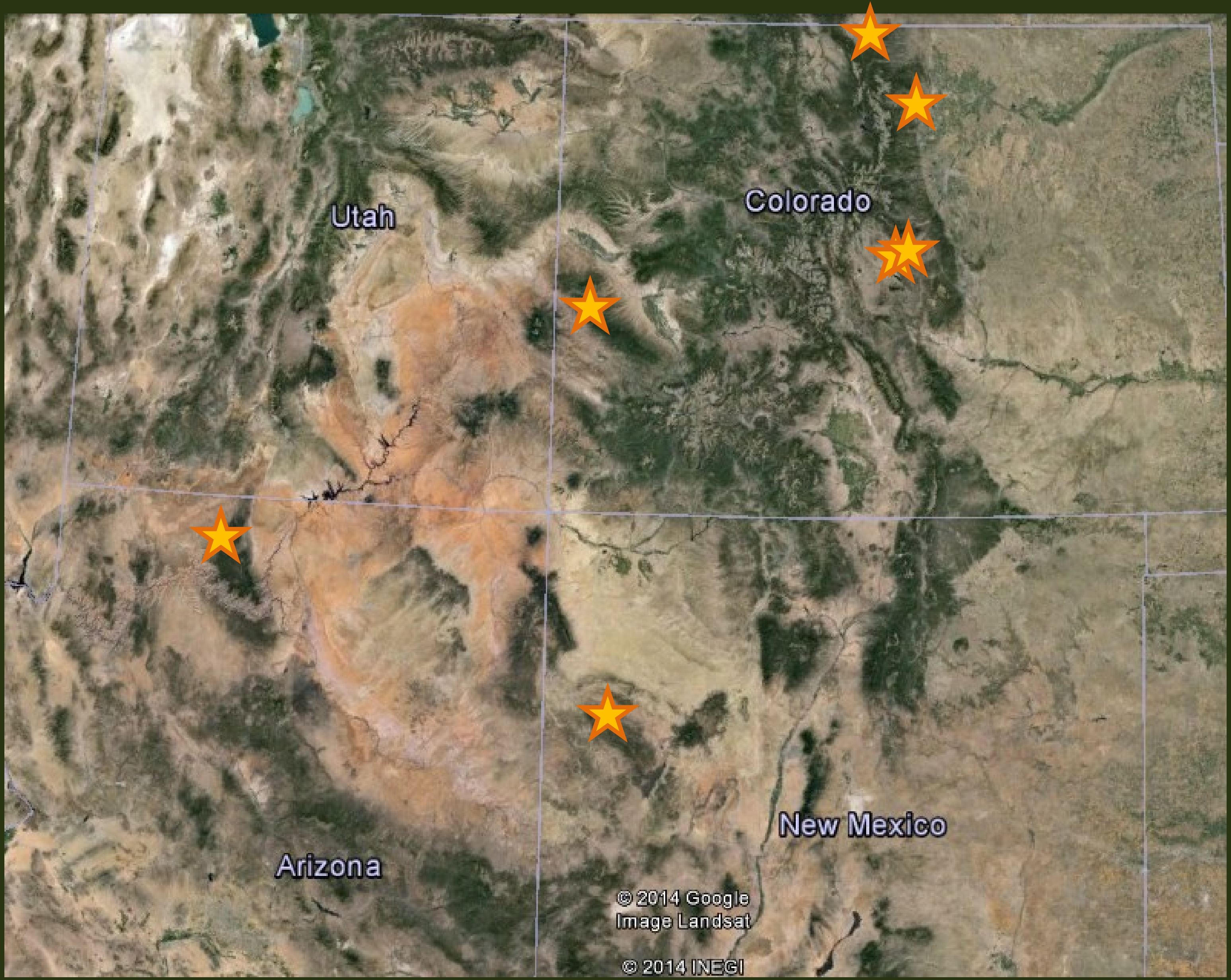
Study site selection

- 7 restoration thinnings across southern Rockies and the Colorado Plateau
- Ponderosa pine dominated
- Silvicultural ℞ emphasized:

  - enhancing structural complexity (create openings, retain patches, increase aggregation, etc.)

  - fire hazard reduction

Site map



Utah
Colorado
Arizona
New Mexico
© 2014 Google
Image Landsat
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Example sampled stands

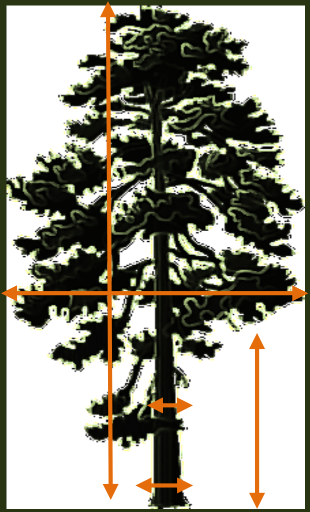
LC – Kaibab NF

PC– Pike NF

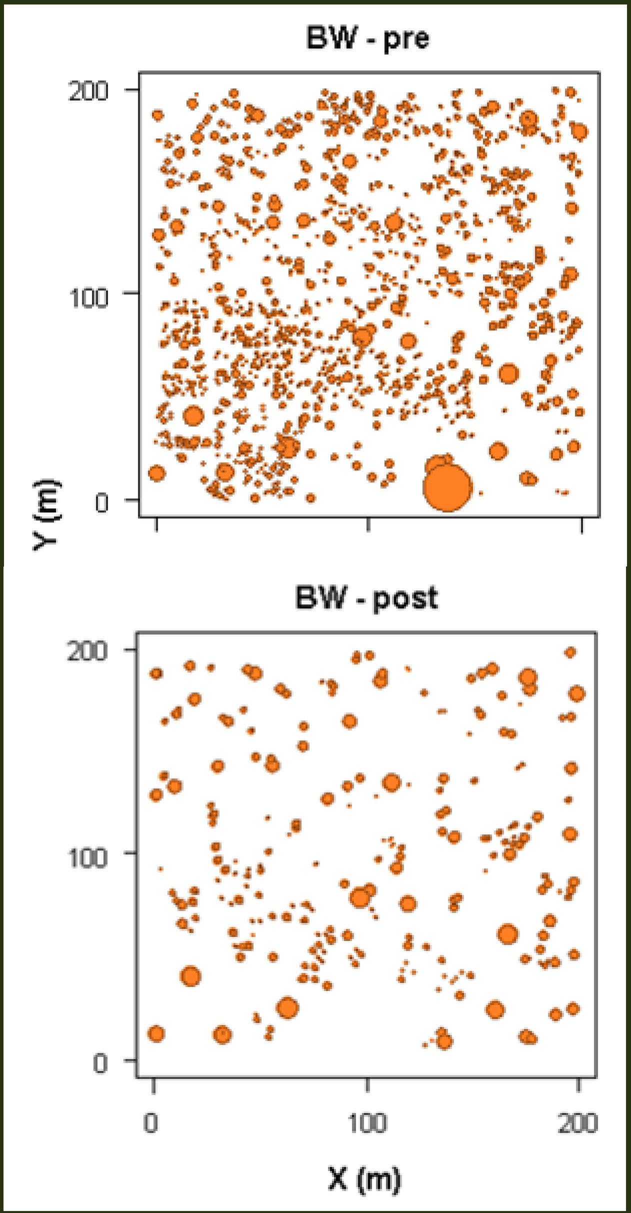
HB - Boulder County Open Space

Structure/Fuels Inventory

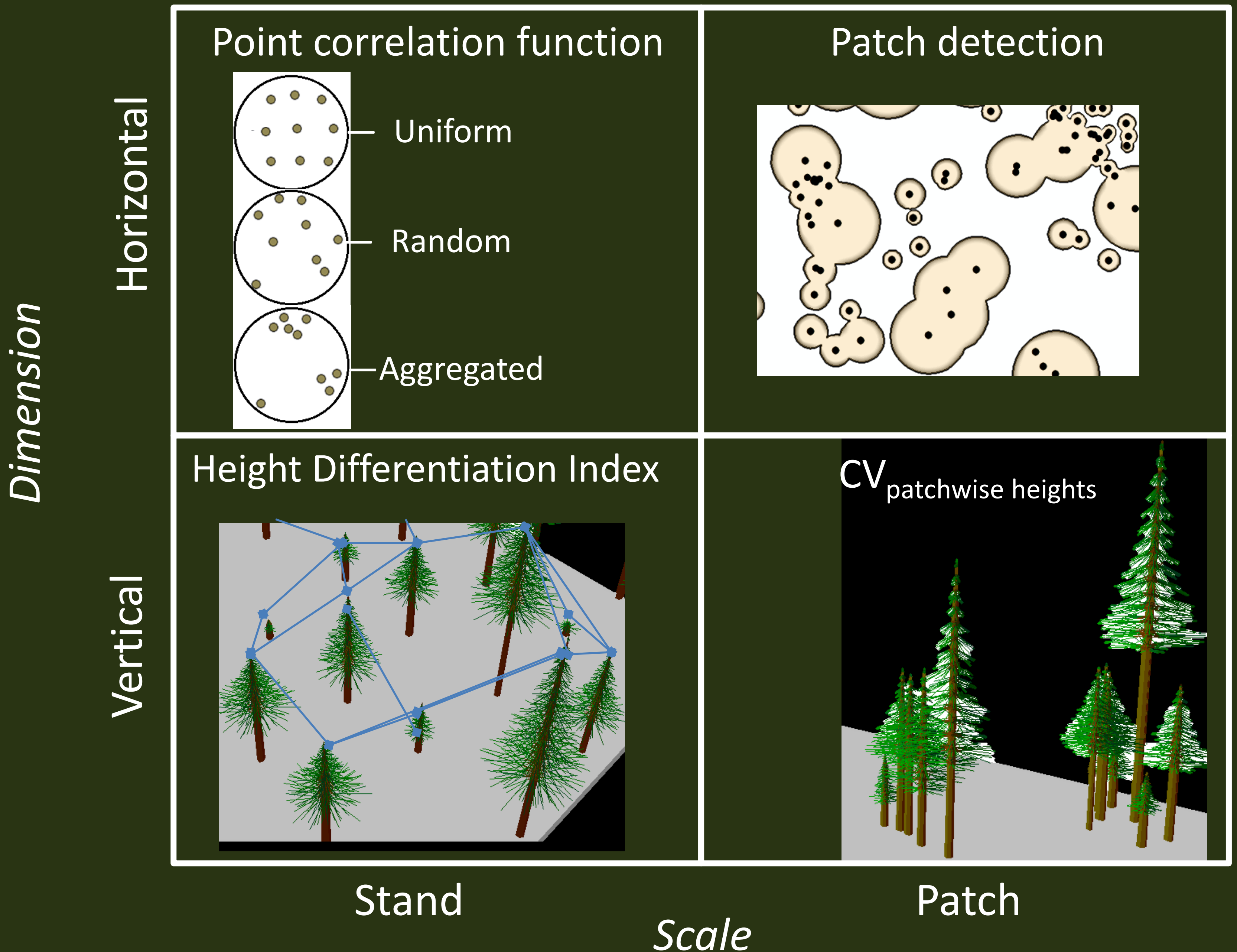
- A single 200-m x 200-m plot per site
- All trees > 1.4 m height mapped
- Measured: height
  crown width
  crown base ht.
  DBH
  DSH



- All stumps mapped and DSH measured
- Regressions built to reconstruct stumps
- Surface fuels were systematically sampled across each unit and in an adjacent unthinned stand

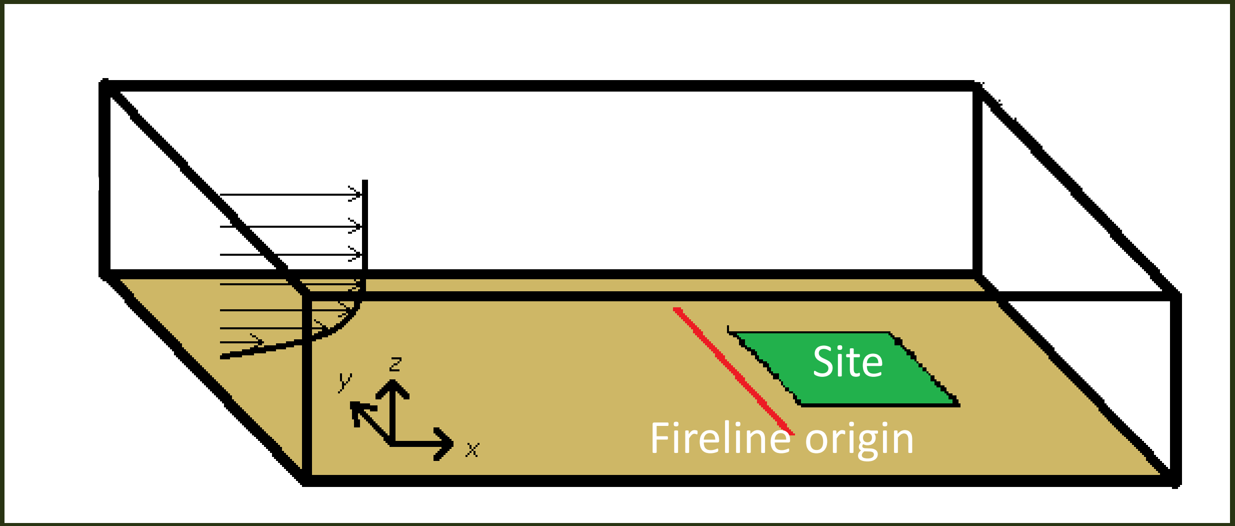


Structural complexity analytical framework



WFDS simulation framework

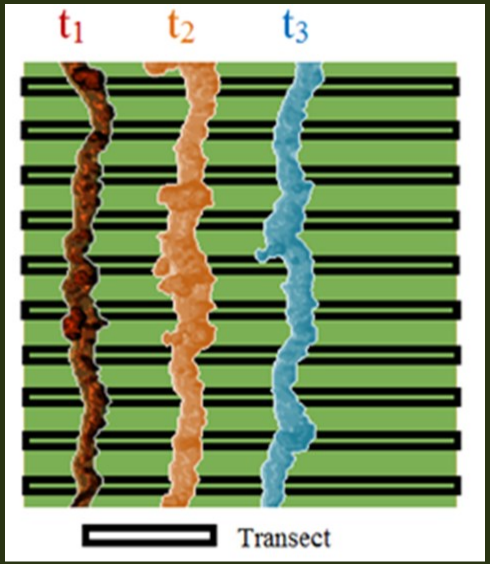
- 7 field-measured sites simulated
- Pre- and post-thinning
  - Populated tree locations with measured crowns
  - Surface fuels – mean load & depth (shrub, herb, litter, 1-hr)
- 4 inflow, open (20 m) wind speeds
  - V. low (2.2 m s^{-1}), low (4 m s^{-1}), mod. (9 m s^{-1}), high (13.4 m s^{-1})
- 100% crown and 5% surface fuel moisture
- Line fire ignition



Evaluating changes in fire behavior

Wind
- Examined mean wind profiles across each simulation

Fire behavior
- Rate of spread, and
- Fireline intensity
- Percent of canopy consumed



Driving factors of restoration impacts

fixed-fx ANOVAs

Response:
- Mean rate of spread
- Mean fireline intensity
- % canopy consumed

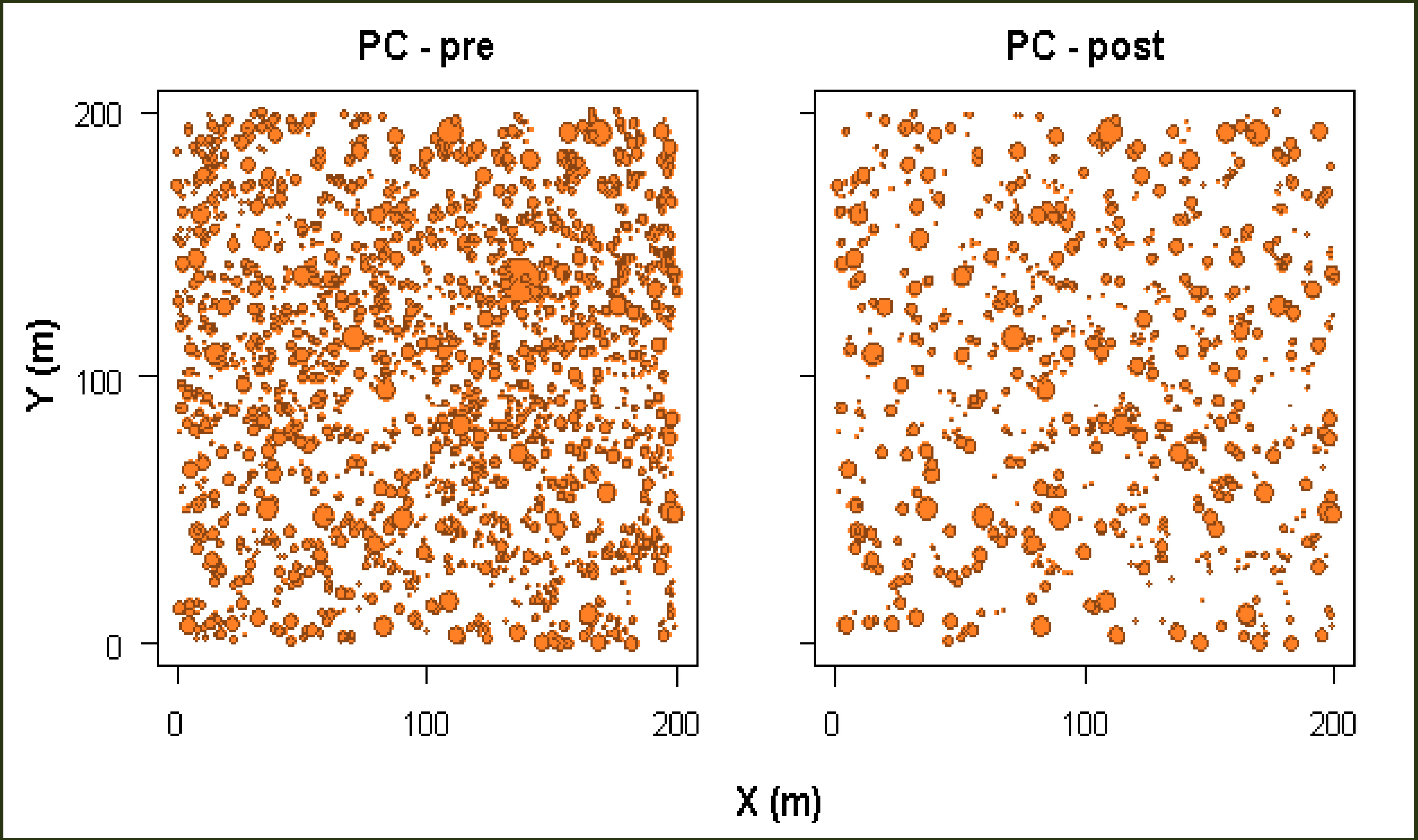
Factors:
- Open wind speed
- Surface fuel load
- Canopy bulk density
- Canopy base height

Results – Non-spatial structure

Stand-averaged structure

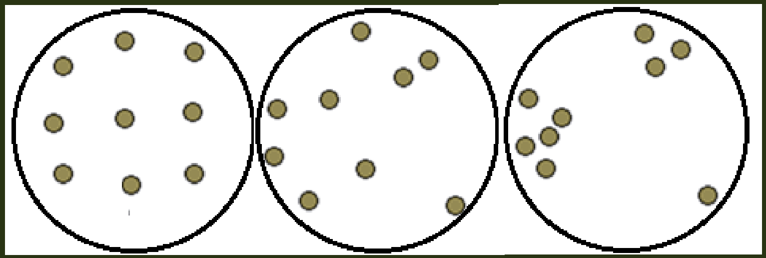
Measure	Pre	Post	Change
Basal area (kg m^{-2})	14—26	8—20	23—62% decrease
Canopy height (m)	10—22	10—26	3—27% increase
Surface load (kg m^{-2})	0.25—1.30	0.25—1.30	50% decrease—50% increase*

Implications of current restoration treatments for spatial heterogeneity

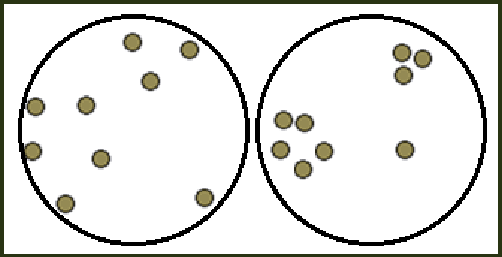


Restoration impacts on horizontal complexity

At the stand level



uniform random aggregated



less more

Site	Pattern, pre-thin	Pattern, post-thin	Δ degree of aggregation
LC	Agg	Agg	Less
PC	Agg	Agg	**More**
UM	Agg	Agg	Less

Restoration impacts on horizontal complexity

At the patch level all thinnings

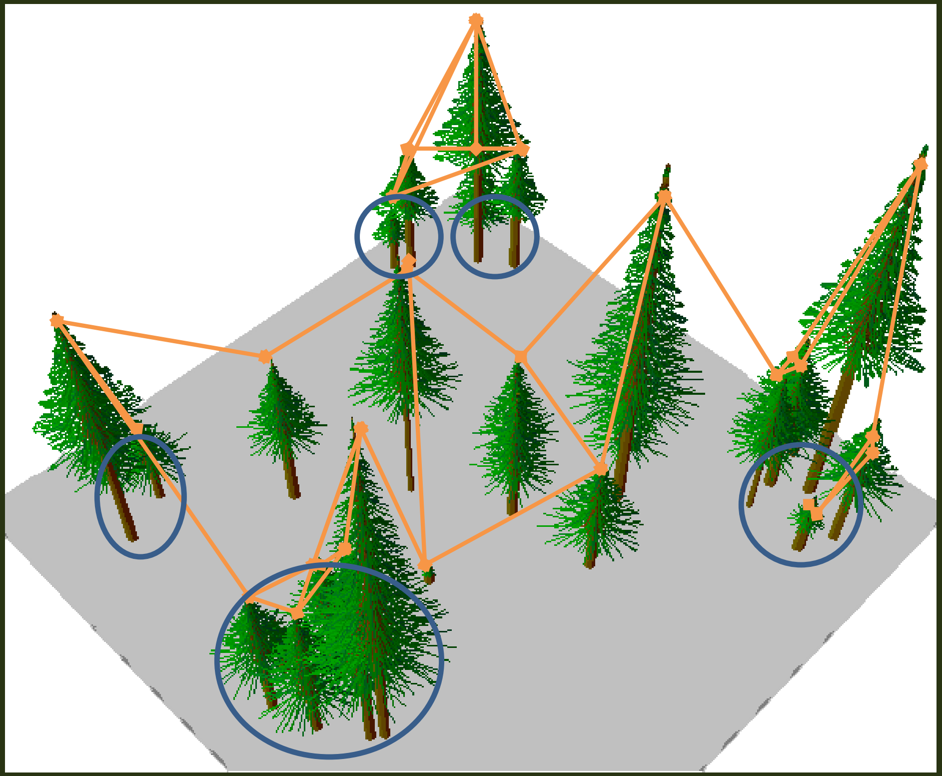
- Decreased frequency of larger patches (11-20 and 21+ trees)

- Increased frequency of small patches (2-5 trees)

Patch size (# trees/ patch) distribution.

Restoration impacts on vertical complexity

Site	Stand Δ	Patch Δ
LC	Less	Less
PC	**More**	None
UM	Less	None



Bottom line

- Thinnings commonly decreased vertical complexity

Did restoration thinnings increase structural complexity?

Dimension	Stand	Patch
Horizontal	*Point correlation function* Aggregated pattern **YES (pre 6/7, post 7/7)** More aggregated following thinning **Mixed (4/7) at least in the short term**	*Patch detection algorithm* Decrease in cover of largest patch sizes **YES (7/7)**
Vertical	*Height Differentiation Index* Higher median value following thinning **Mixed (3/7) at least in the short term**	*$CV_{patch\text{-}wise\ heights}$* Higher median value following thinning **Rare (1/7) at least in the short term**

Scale

Beyond pattern: connections to process

- Stands are heterogeneous – treatments are retaining heterogeneity

BUT

What does this mean for the process we are interested in within our forests?

Can fuel treatments restore more natural fire behavior?

- Over 139 publications identified, only 54 had quantitative data for inclusion in the review. (Rocky Mnts. Not well represented in literature)

- The answer: a strong “but qualified” yes
  - Little experimental work, none in high intensity fires
  - mostly modeling studies

Fule et al. (2012)

Principles of fire resistance for dry forests

Principles of fire resistance for dry forests (adapted from Agee, 2002 and Hessburg and Agee, 2003)

Principle	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Control easier; less torching[a]	Surface disturbance less with fire than other techniques
Increase height to live crown	Requires longer flame length to begin torching	Less torching	Opens understory; may allow surface wind to increase
Decrease crown density	Makes tree-to-tree crown fire less probable	Reduces crown fire potential	Surface wind may increase and surface fuels may be drier
Keep big trees of resistant species	Less mortality for same fire intensity	Generally restores historic structure	Less economical; may keep trees at risk of insect attack

[a] Torching is the initiation of crown fire.

Agee and Skinner (2005)

Did restoration treatment meet the principles of fire resistance?

Photo by: P. Brown

- YES - TPA reduced by 50%
- YES - CBD reduced by 44%
- YES - Surface fuels reduced by 15%
- YES - QMD increased by 8%
- YES - CBH increased by 15%

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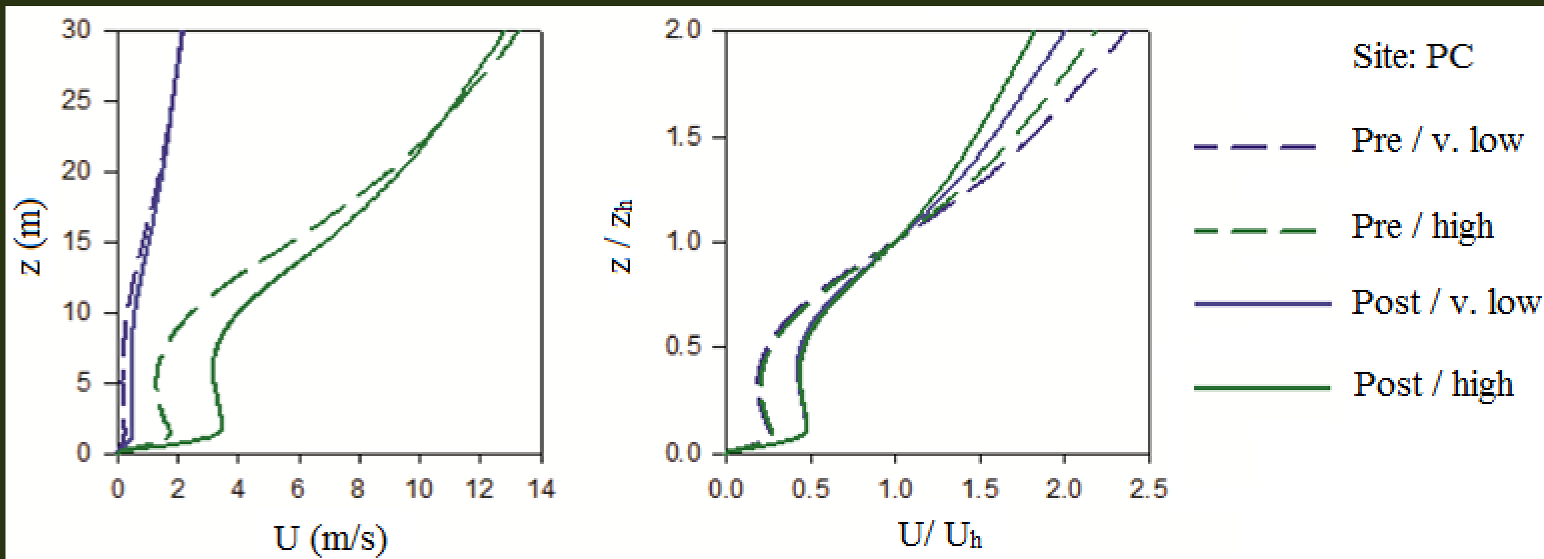
Increase height to live crown	Requires longer flame length to begin torching	Less torching	[illegible]
Decrease crown density	Makes tree-to-tree crown fire less probable	Reduces crown fire potential	[illegible]
Keep big trees of resistant species	Less mortality for same fire intensity	Generally restores historic structure	Less [illegible] may keep trees at risk of insect attack

[a] Torching is the initiation of crown fire.

Agee and Skinner (2005)

- These concerns suggest that there is a tradeoff between reduced fuel loadings and increased wind speed
  - If altered wind environment results in greater heat flux exposure we could have increased crown fire activity

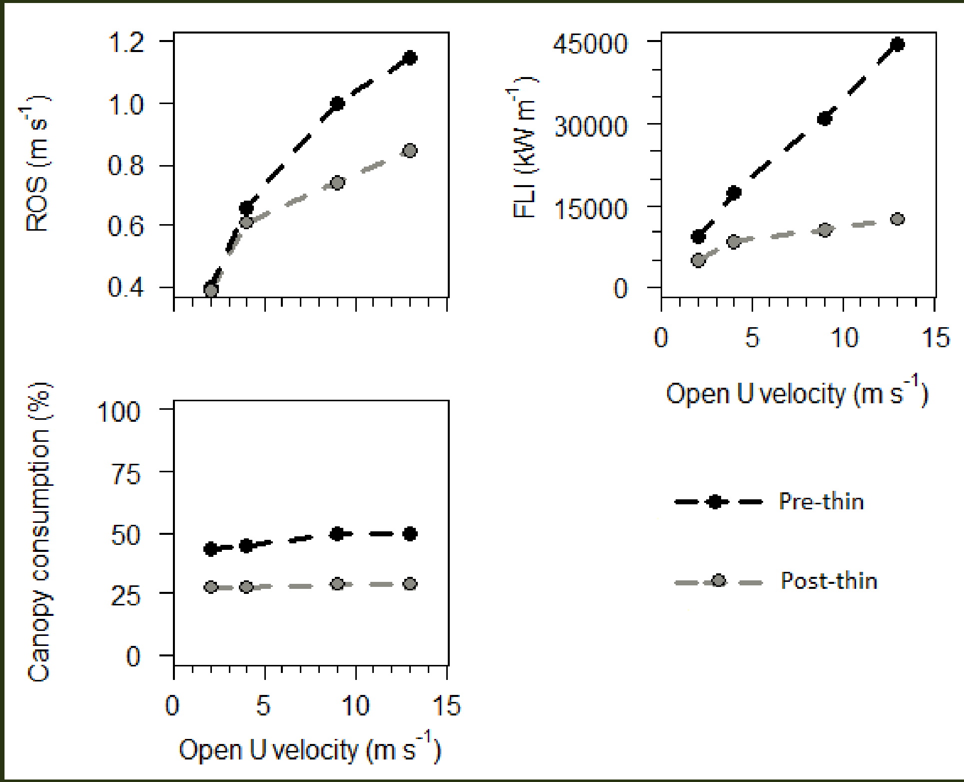
WFDS simulation results-wind



- Within canopy wind velocity (*U*) increased after thinning
- ↑within canopy wind velocity positively related to thinning intensity
- Shape of wind profile is altered throughout the canopy

WFDS simulation results

- All metrics of fire behavior were reduced following thinning
- Greater reductions at higher wind speeds

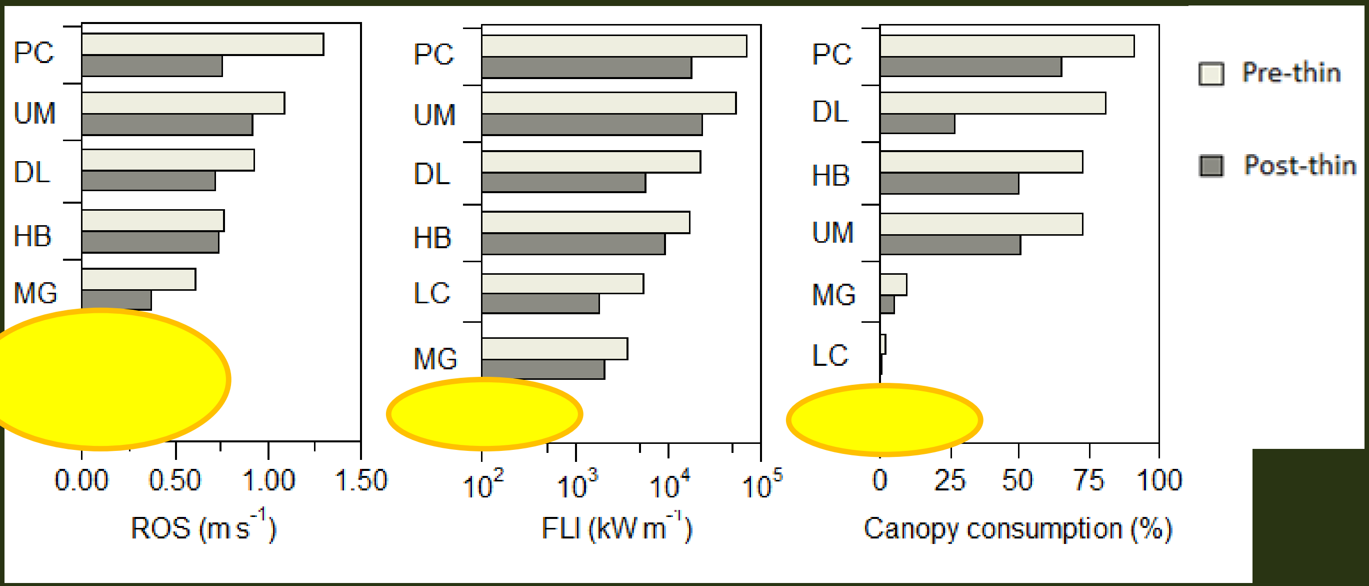


Fire behavior by open wind speed, averaged across sites

WFDS simulation results

However,

- Fire behavior reduction is not consistent across all sites



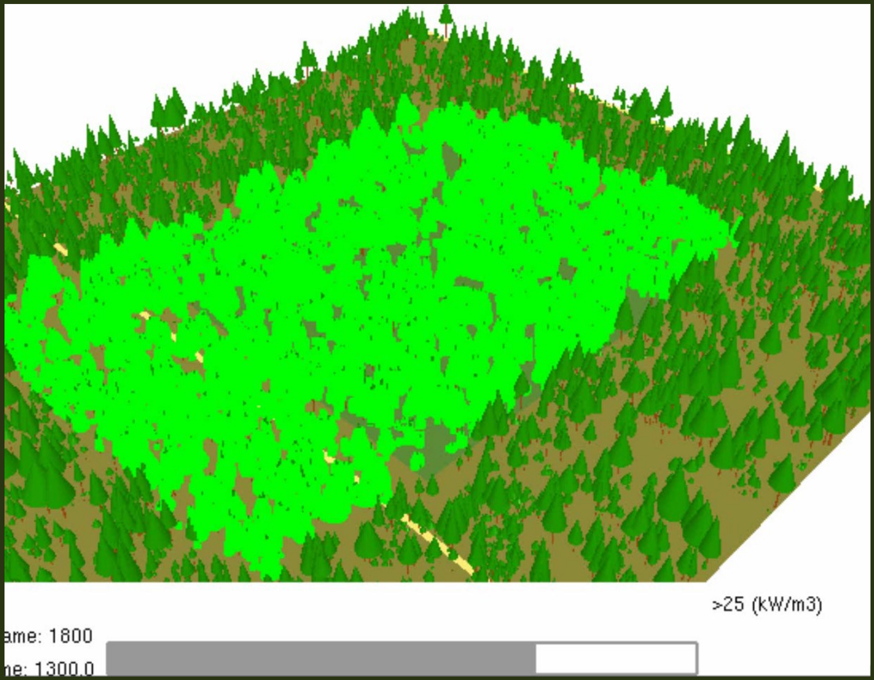
Fire behavior by site, averaged over open wind speed

- Treatments may not reduce fire behavior in all cases....
  - Especially when surface fire is the dominate type of fire behavior

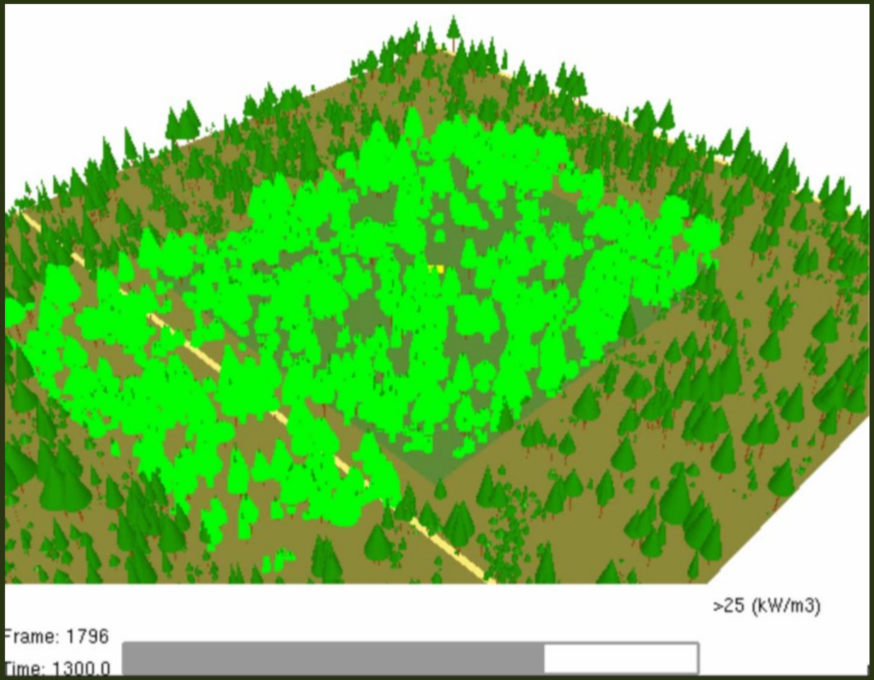
WFDS simulation results

Site: UM
Wind scenario: High

Pre-thinning



Post-thinning



Rate of Spread: 1.8 m s^{-1}
Fireline intensity: ~100,000 kW/m
% Canopy consumed: 80%

Rate of Spread: 1.4 m s^{-1}
Fireline intensity: ~35,000 kW/m
% Canopy consumed: 50%

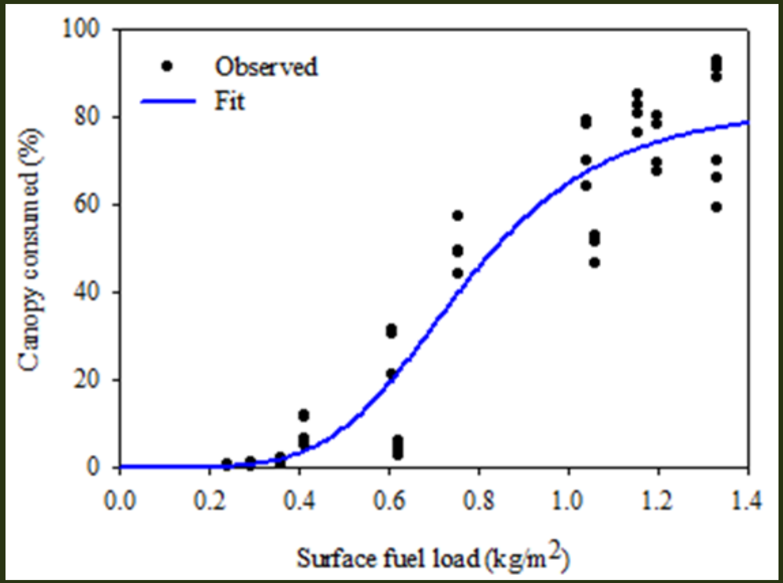
WFDS simulation results

Driving factors of effectiveness

- Fire behavior varied greatly across sites
- Site variability is largely explained by wind velocity and surface fuels

Source of variation	ω^2 (%)		
Open wind speed	28*	10*	0
CBD	4*	8*	1*

* Significant ($p<0.05$)



Implications of current restoration treatments for spatial heterogeneity

Treatments did…

- Reduced stand density, canopy bulk density and surface fuel loadings,
- Increased CBH
- Decrease large continuous patches of fuels

Treatments did not necessarily

- increase the level of horizontal aggregation or create aggregation
  - Stands were already heterogeneous pre-treatment (both the surface fuels and canopy fuels)
- Increase the level of vertical heterogeneity
- Alter the spatial variance of surface fuels

Implications of current restoration treatments for fire behavior

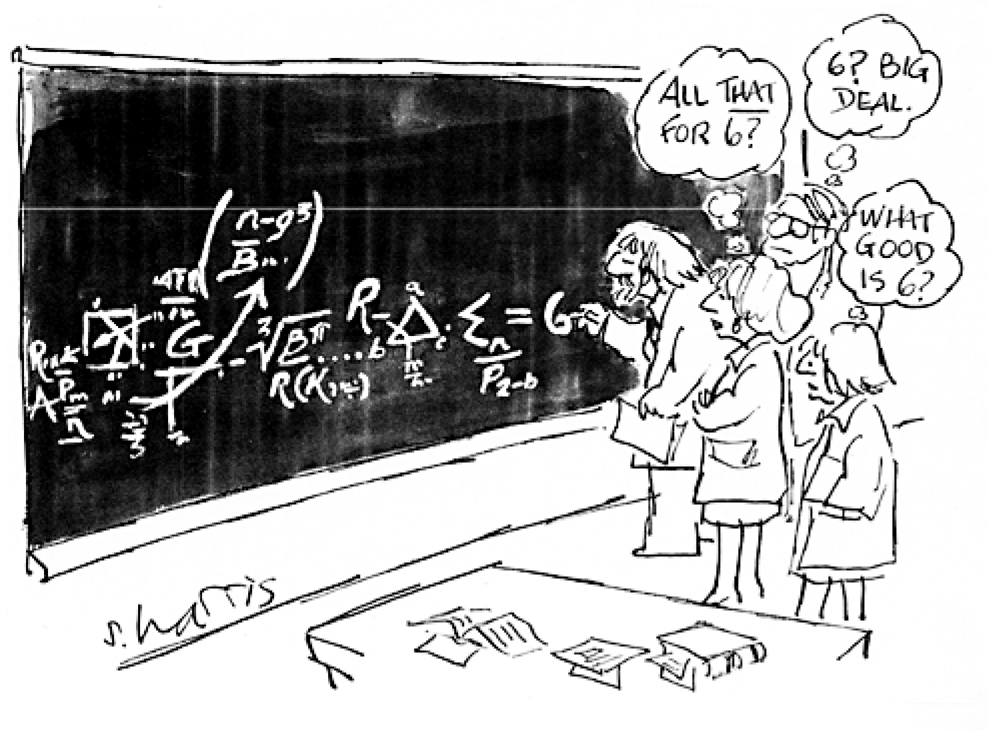
- Restoration treatments:
  - Generally reduce common fire behavior metrics
    - Effect of reduced fuels was greater than effect of increased wind velocity
  - However not in all situations are the same…
    - Careful consideration of changes in wind velocity and surface fuels should be considered
    - In some cases increased fire behavior may occur….
      - Could limit the effectiveness of fuels treatments for fire operations?

Final thoughts and ideas

- Given paucity of information, use an adaptive, management approach
  - Set clear objectives, monitor, analyze, adapt

After the meeting they realized the new manager suffered from some adaptive difficulty

- Managers are ahead of the science…
  - We are just now starting to understand the effect of heterogeneity on many process
    - wildlife, understory species diversity, regeneration, growth, microclimate etc….
  - Future research will likely continue to emphasize spatial heterogeneity
    - Expect more models

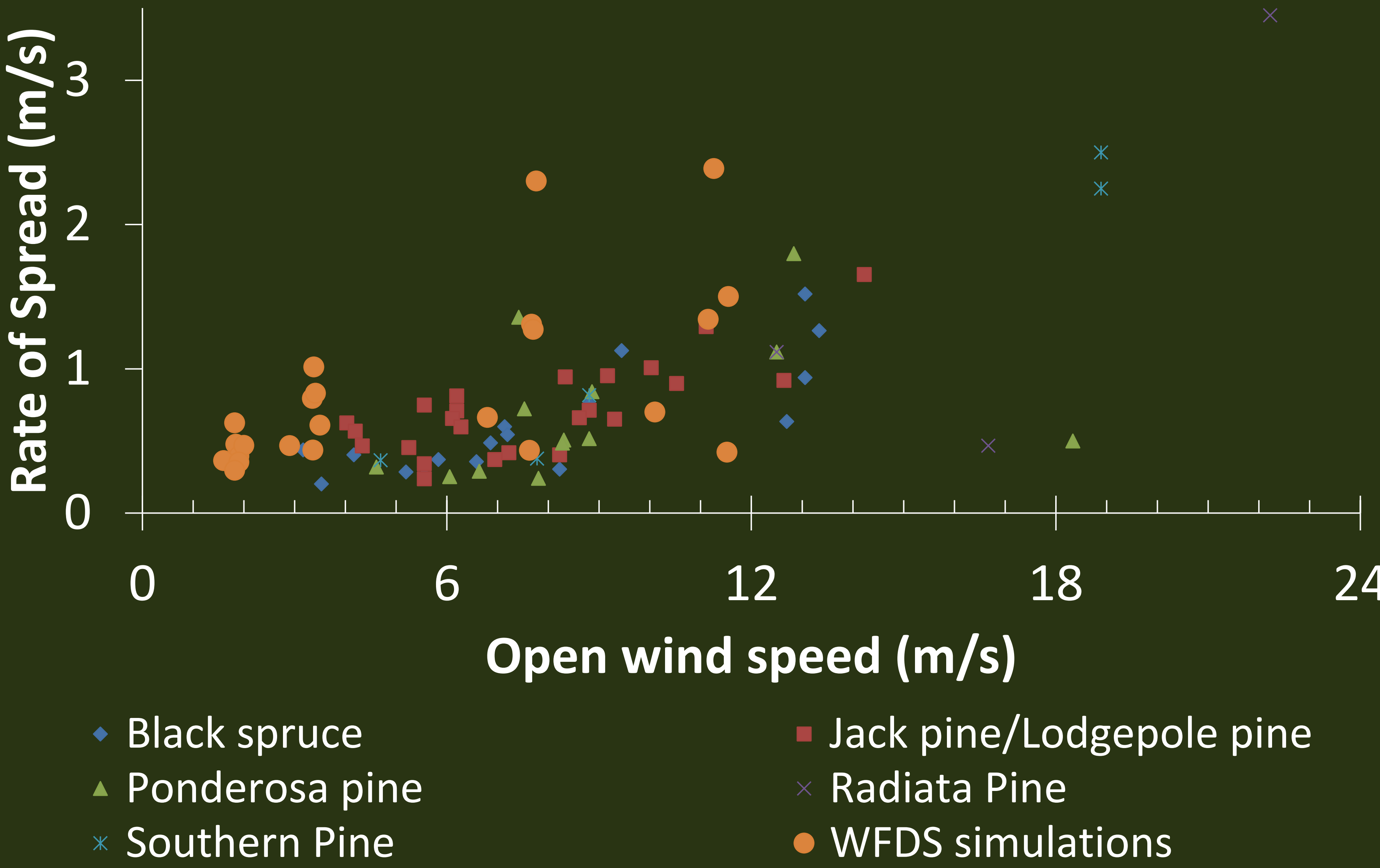


Future steps…

- What is the future of these stands? How does spatial heterogeneity influence other ecosystem services
- Increased knowledge of fuel heterogeneity influences on fire behavior
  - Across scales
  - Role of large atmospheric processes
    (e.g. Atmospheric stability, lee or gravity waves)
  - Connecting pre-active and post-fire effects

Questions?

Partners and Funding agencies for this work



Rate of Spread (m/s)
0
1
2
3
0
6
12
18
24
Open wind speed (m/s)
Black spruce
Jack pine/Lodgepole pine
Ponderosa pine
Radiata Pine
Southern Pine
WFDS simulations

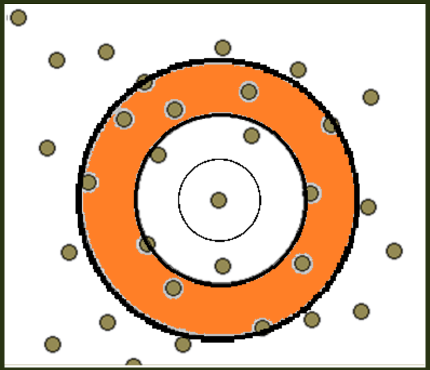
Examining the extremes

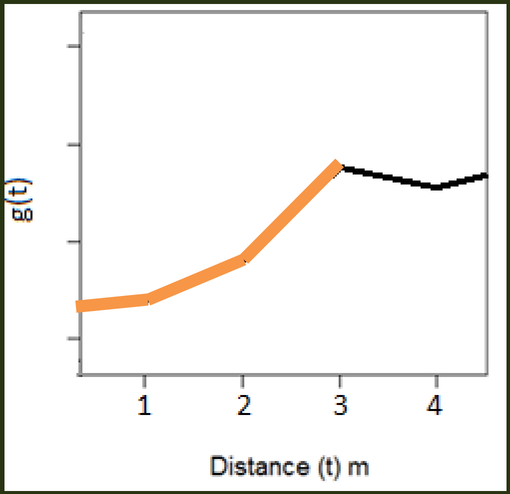
Why is rate of spread so high?

1. High canopy fuel load, > 2 kg/m^2
2. Low canopy base height
    - 25% of stems < 1 m
    - 50% of stems < 2 m
3. Highest observed surface fuel loading
    - 1.3 kg/m^2
4. Temporal sampling differences

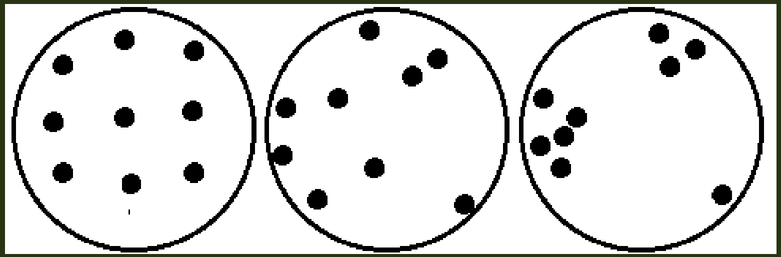
Point correlation function
(Horiz. Stand level)

- Determines degree of aggregation at multiple scales



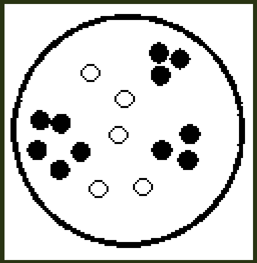


Question 1:
What spatial pattern resulted from thinning?

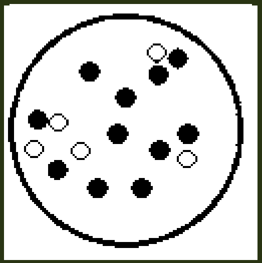


Uniform Random Aggregated

Question 2:
How do thinnings alter the degree of aggregation?



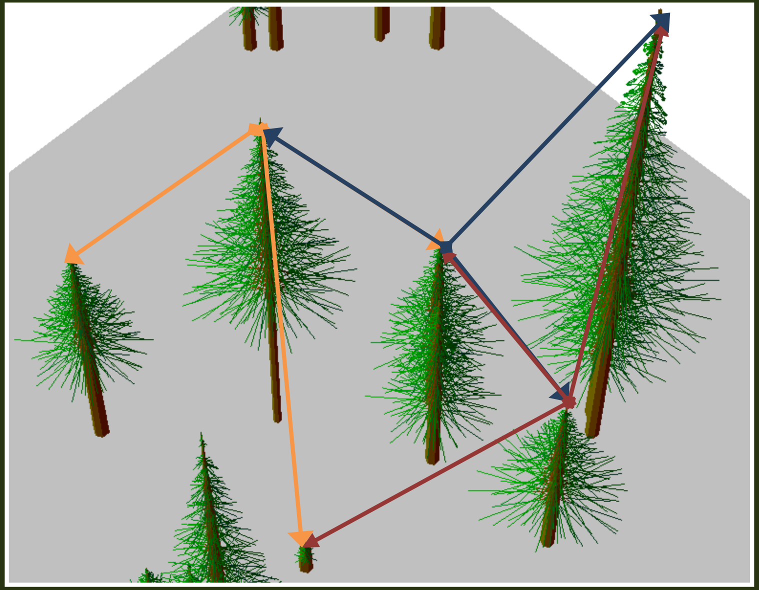
More



Less

Height Differentiation Index
(*Vert. Stand level*)

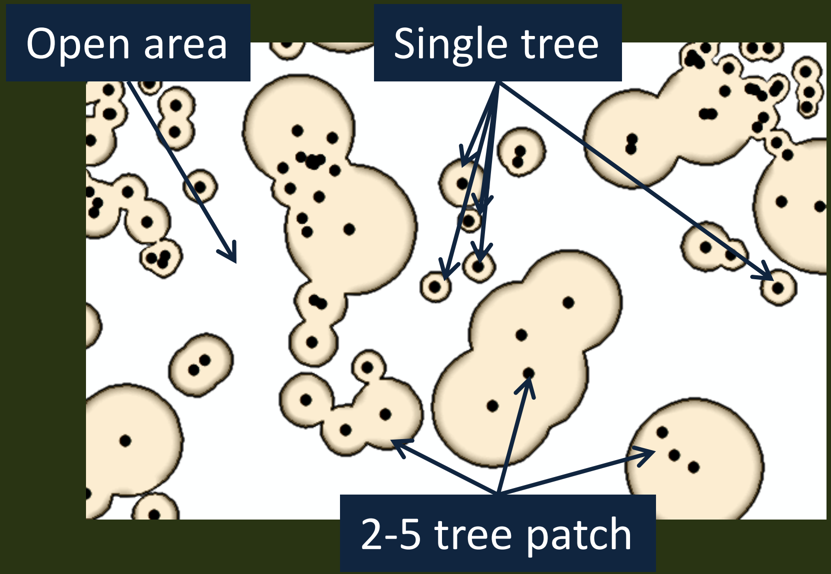
- Tree-centric index of height differences between neighboring trees



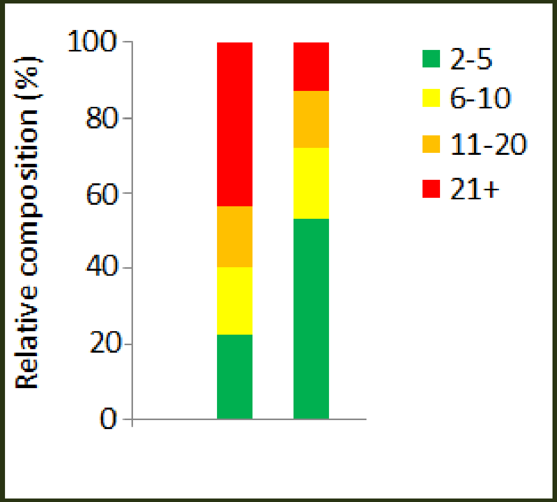
Complexity at the patch level

Patch detection

Patches—unique chains of trees with overlapping crowns.



Explored changes in patch size distribution…



And, coefficient of variation of patches' tree heights.