Measurement and Modeling of Fire Behavior in Leaves and Sparse Shrubs

Dallan R. Prince

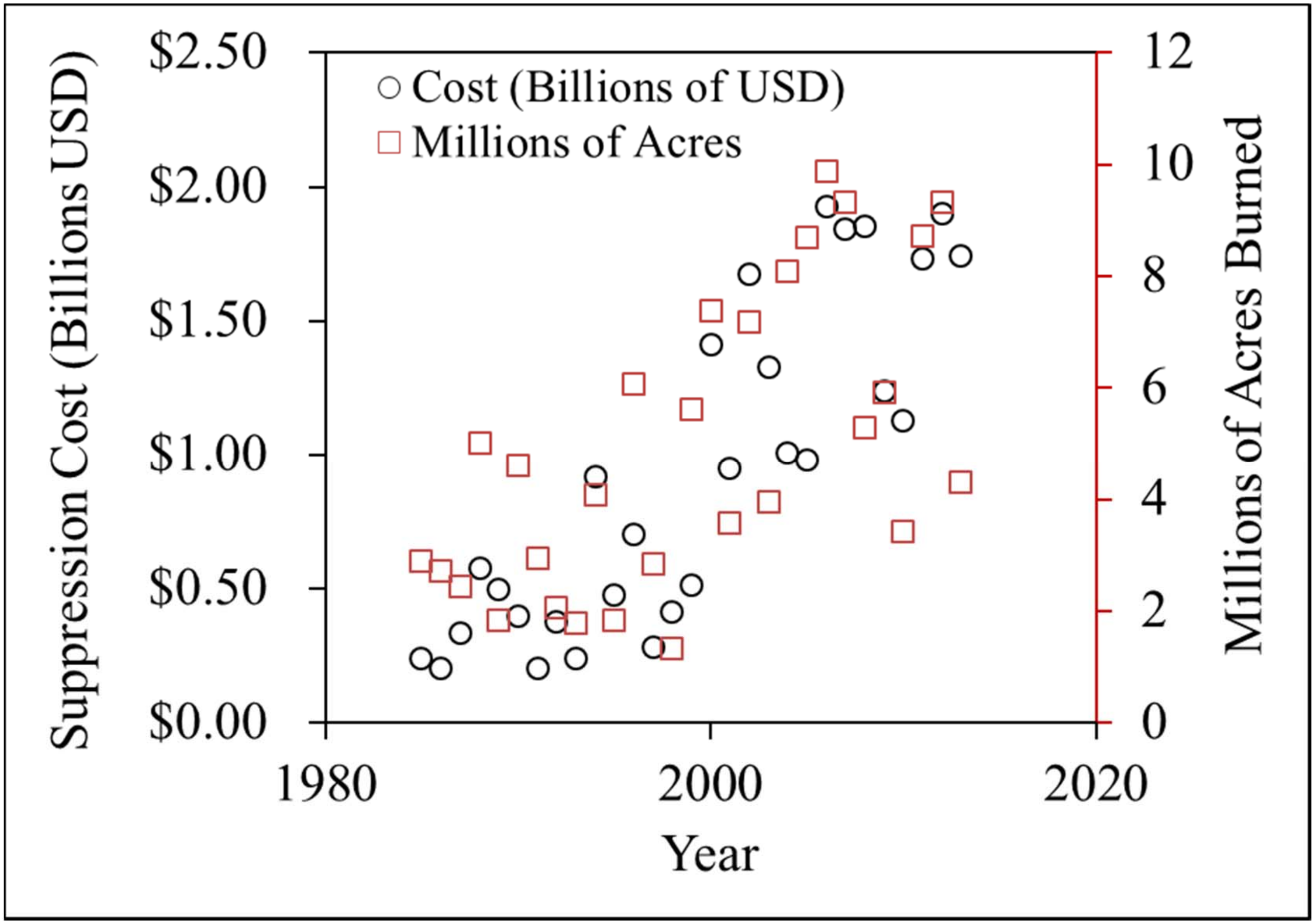
Tuesday, June 25, 2014, 2 pm

Dissertation Defense Presentation

Overview

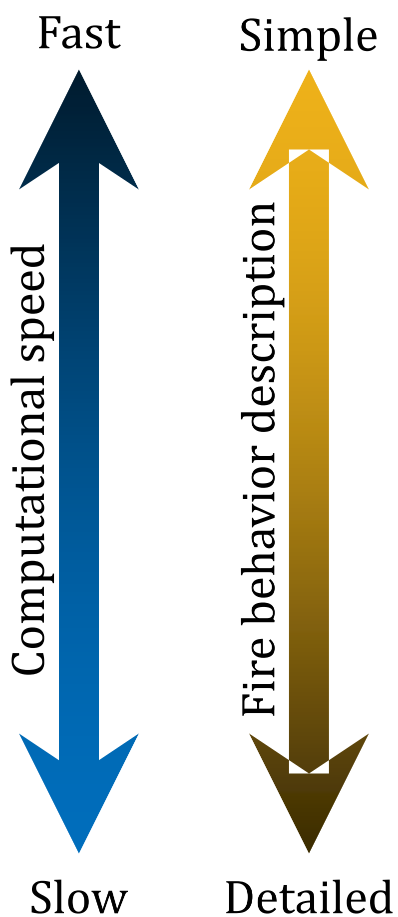
- Background
  – Wildfires and wildfire models
  – BYU's wildfire model
- Contributions to wildfire science
  – Fuel matrix modeling of shrubs
  – Study of dead and live fuels during rapid heating
  – Improved shrub fire spread model

Wildfire Impact in the U.S.



National Interagency Fire Center: http://www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf

Wildfire Models



Operational models

- Help fire managers make decisions

BYU semi-empirical fire spread model

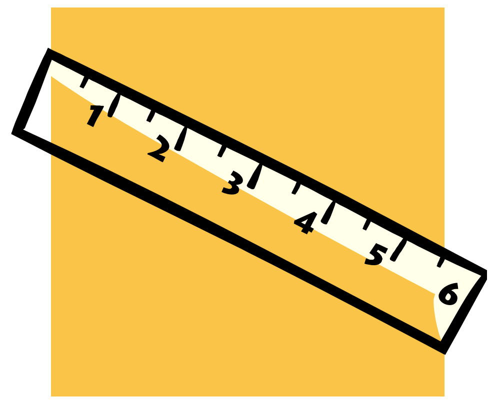
- Provide insights about fire behavior
- Some operational potential

Computational fluid dynamics (CFD) models

- Provide extensive insights about fire behavior

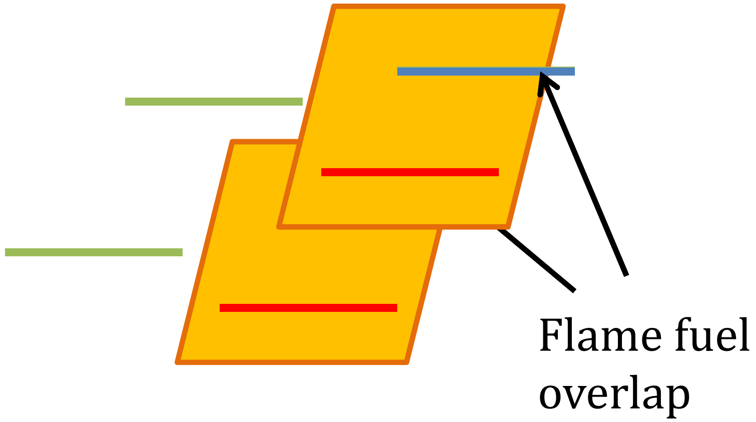
Challenges

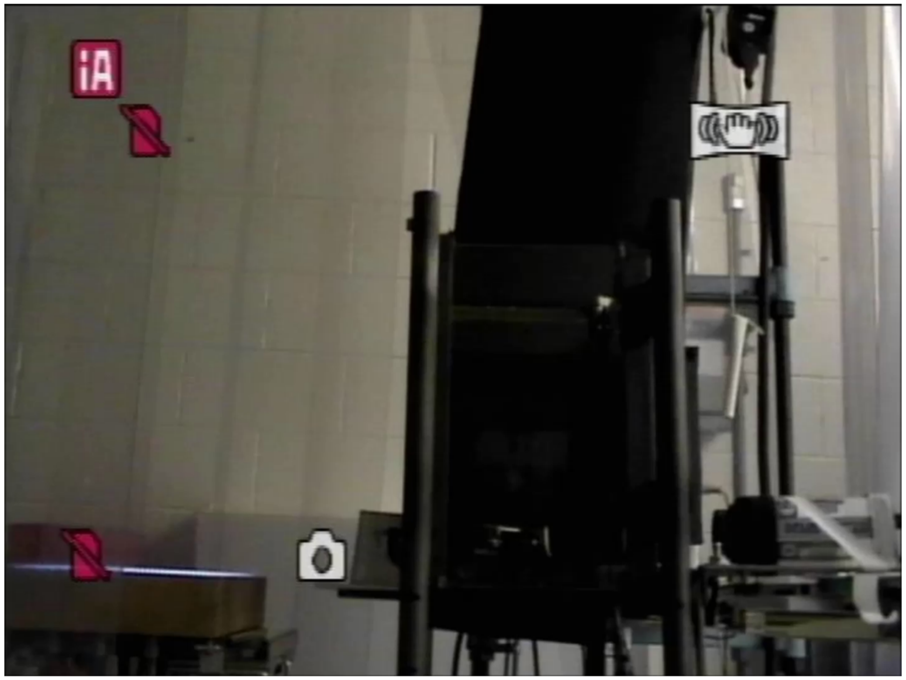
- Tremendous ranges of scale
  - Solid reactions (< 1 mm)
  - Landscape (100s of acres)
  - Vertical scales (1000s of feet)
  - Time scales from *ms* to *weeks*
- Model run time: 30 minutes



A Brief Introduction to the BYU Fire Spread Model

- Experiments measure flame behavior
- Fire spread is modeled by flame-fuel overlap





Manzanita Live Old Run 6 Video

BYU Shrub Combustion Model

Ignition

Flame height as function of tim

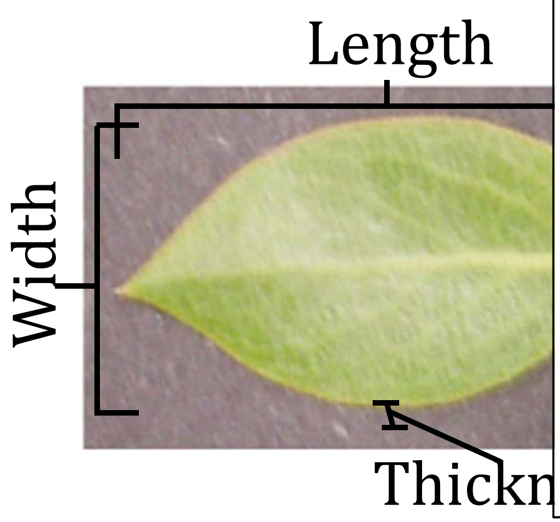
Flame-flame interactions (modify

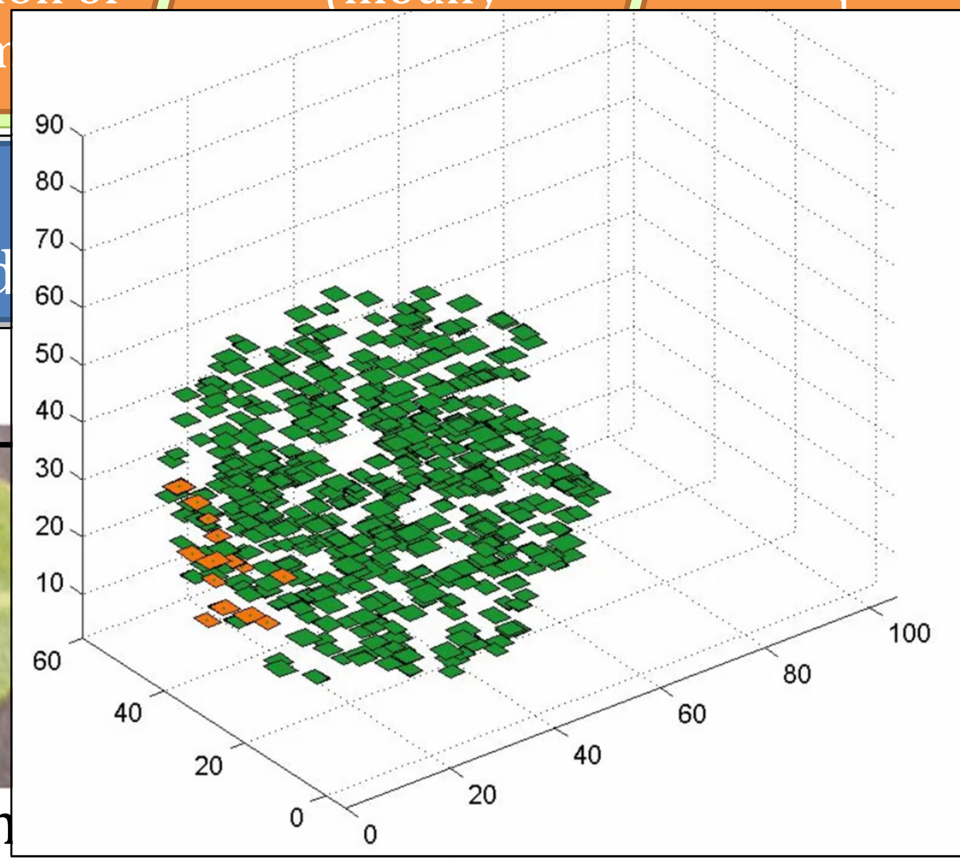
Check for flame-leaf

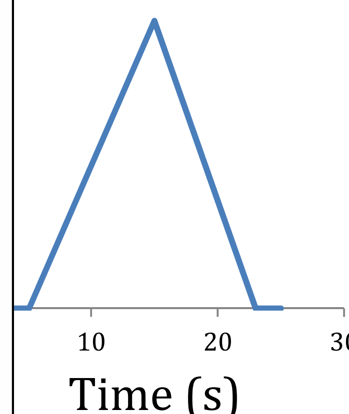
Advance time

Fuel Physical Parameters Mod

el Flame avior Model

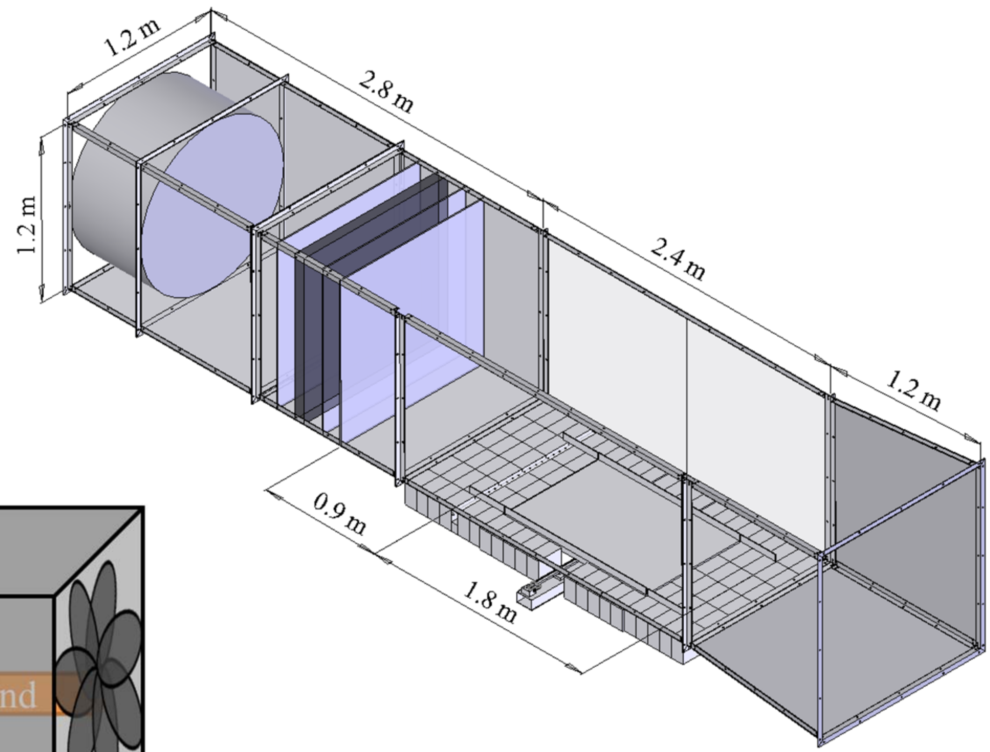


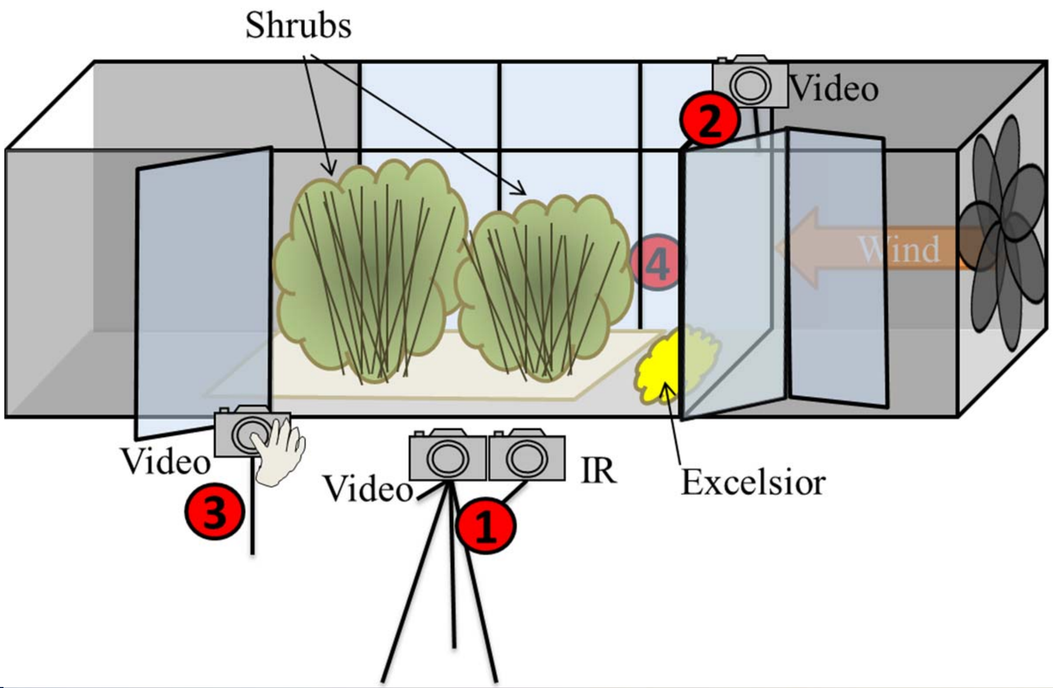




Riverside Experimental Setup
(For Validation Experiments)

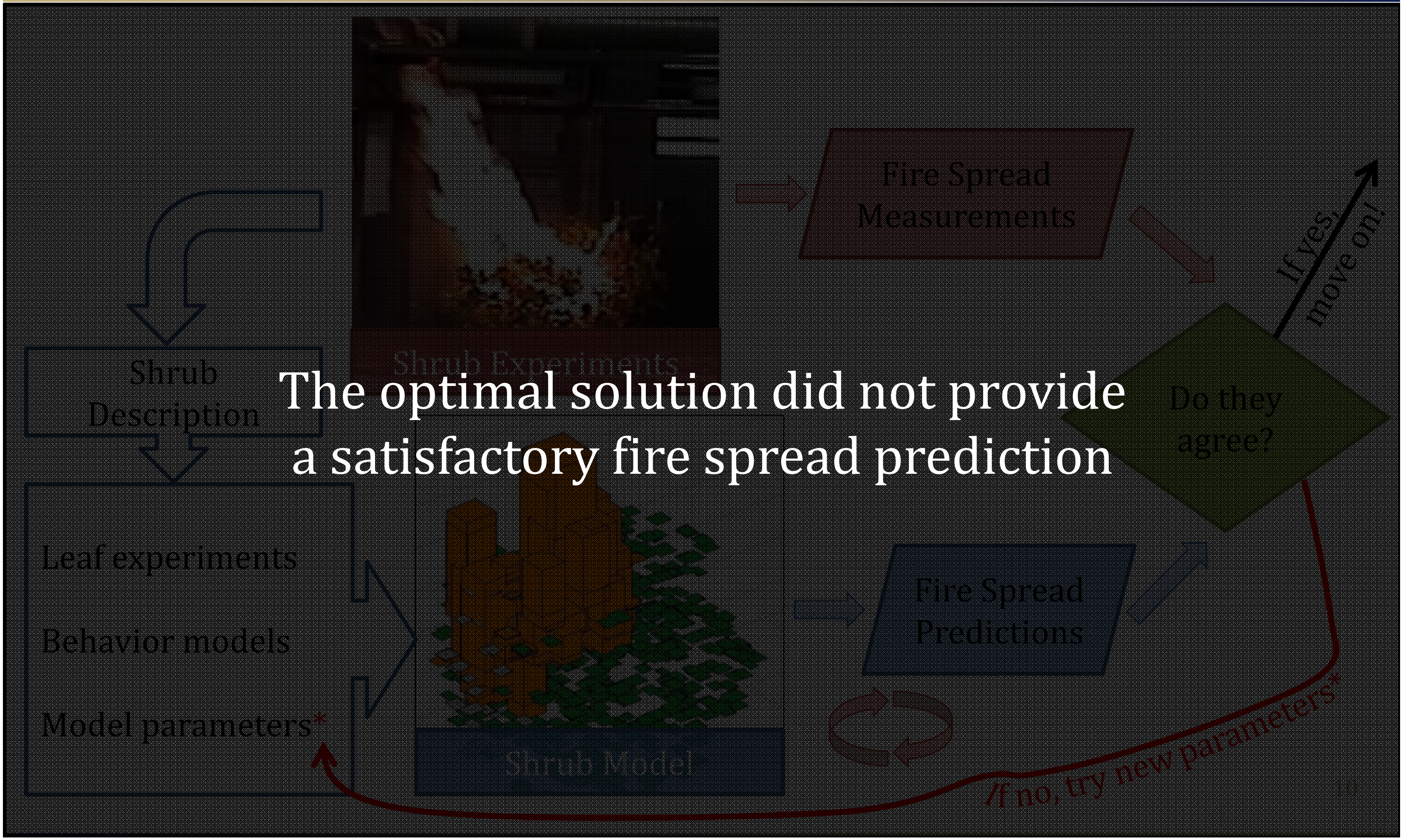
USDA Forest Service,
Riverside, CA





Wind Tunnel Burn Experiments
(Pacific Southwest Research Station, USDA FS)

First Attempt to Compare a New Model with Actual Fire Spread Data



The optimal solution did not provide a satisfactory fire spread prediction

Redirecting My Dissertation

- Find and improve main sources of error
  - Fuel placement
  - Experimental vs. actual heating conditions
  - Flame-flame interactions
  - Heat transfer mechanism
- In addition, dead vs live behavior

Outline

- Fuel location models
  - Manzanita, chamise, Utah juniper
- Developing a physical model for leaf combustion
  - Temperature and mass release measurements of live vs dead leaves
  - Mass release modeling of live and dead leaves
- Shrub fire spread modeling and comparison

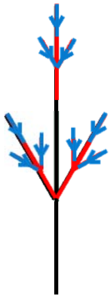
Fuel Location is Important

- Albini[1]: operational models are primarily limited by modeling vegetation as:
  - Uniform
  - Continuous
  - Homogenous
  - Single-layer
- Response: develop fuel element location model which closely follows real plants

[1] Albini, F. A., "Estimating Wildfire Behavior and Effects," General Technical Report INT-30, Ogden, UT, USDA Forest Service (1976).

Approaches to Fuel Placement

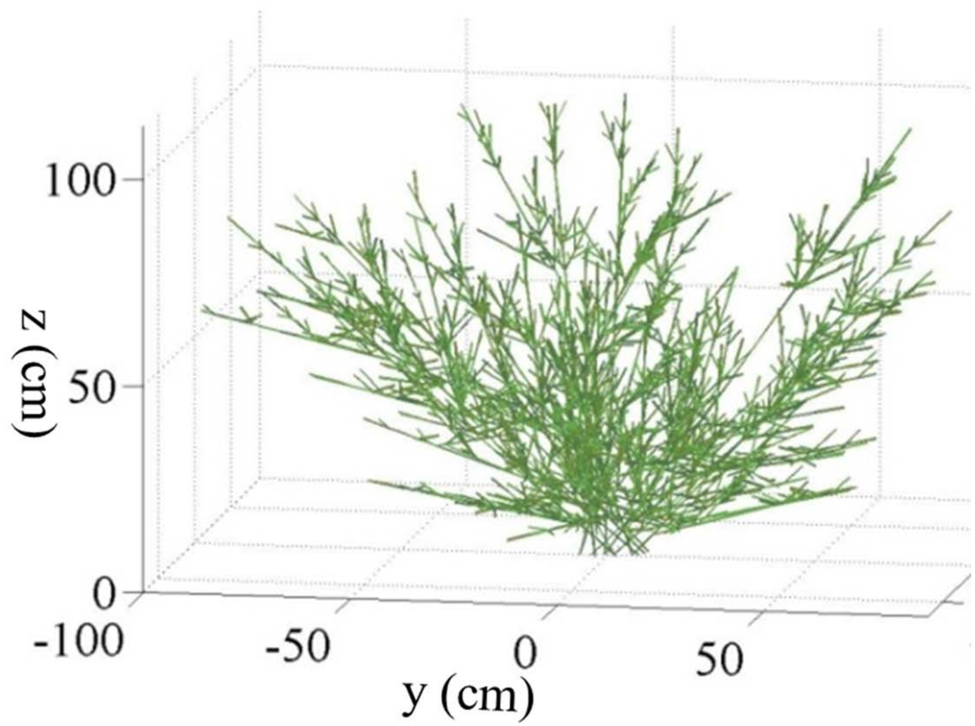
- Fuel placement methods
  - Fuel placement based on shrub images
  - L-systems models (from fractal theory)



1. Unit
2. Replace unit with pattern
3. Replace with pattern again
4. And again …

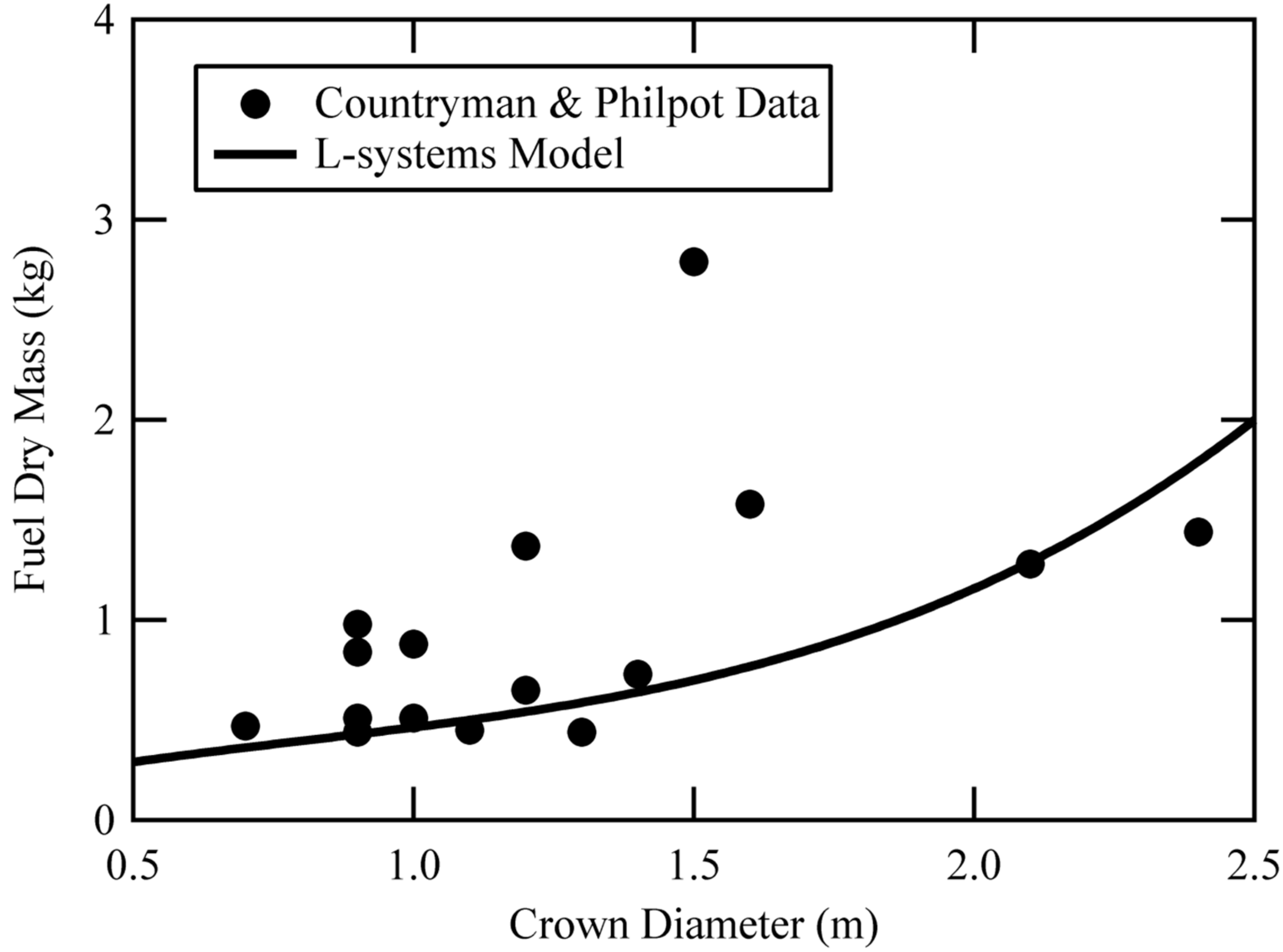
Chamise by L-systems

(a)



(b)

Chamise: Matching Fuel Mass to Crown Diameter

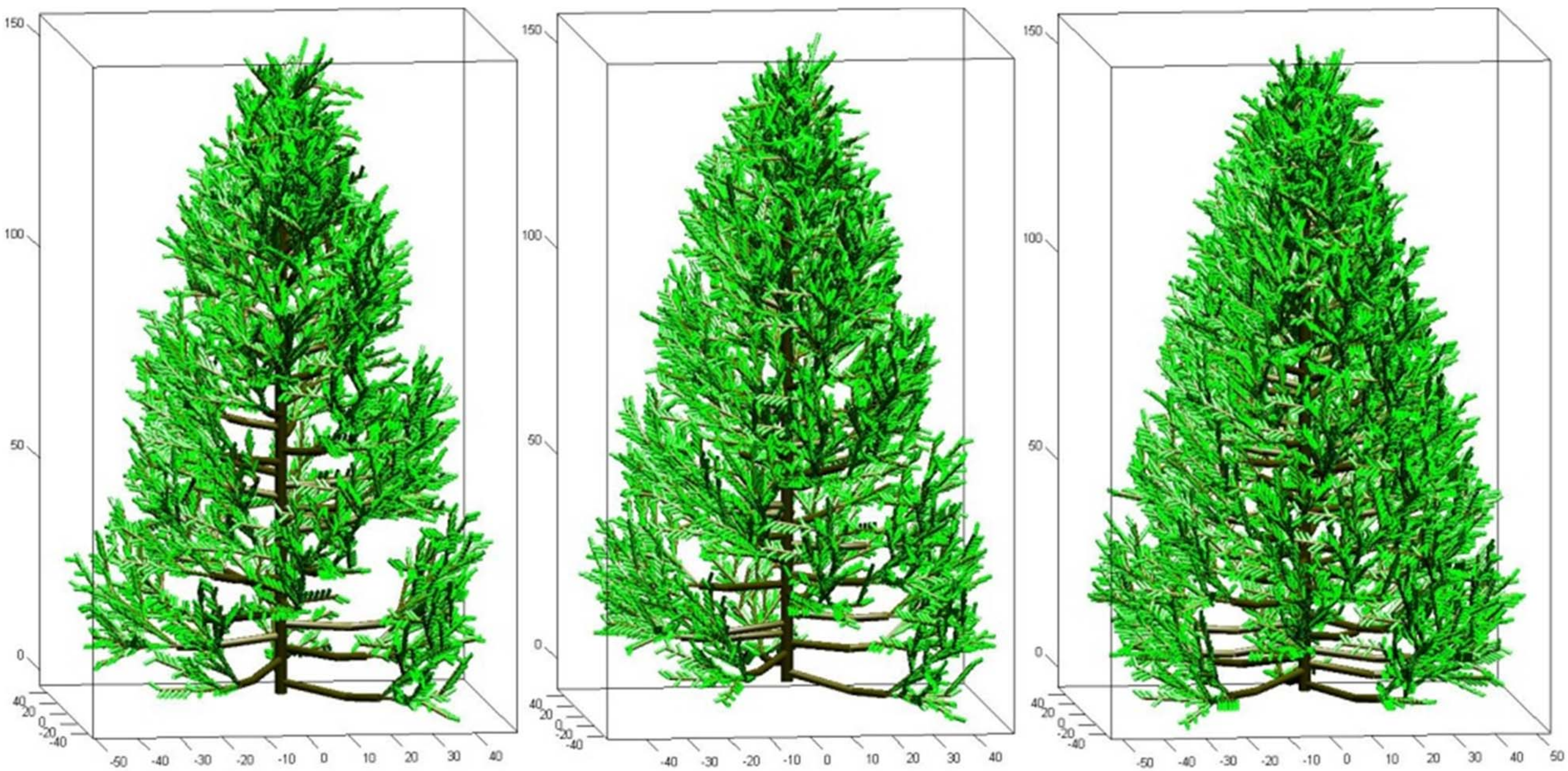


Utah juniper by L-systems

(a)

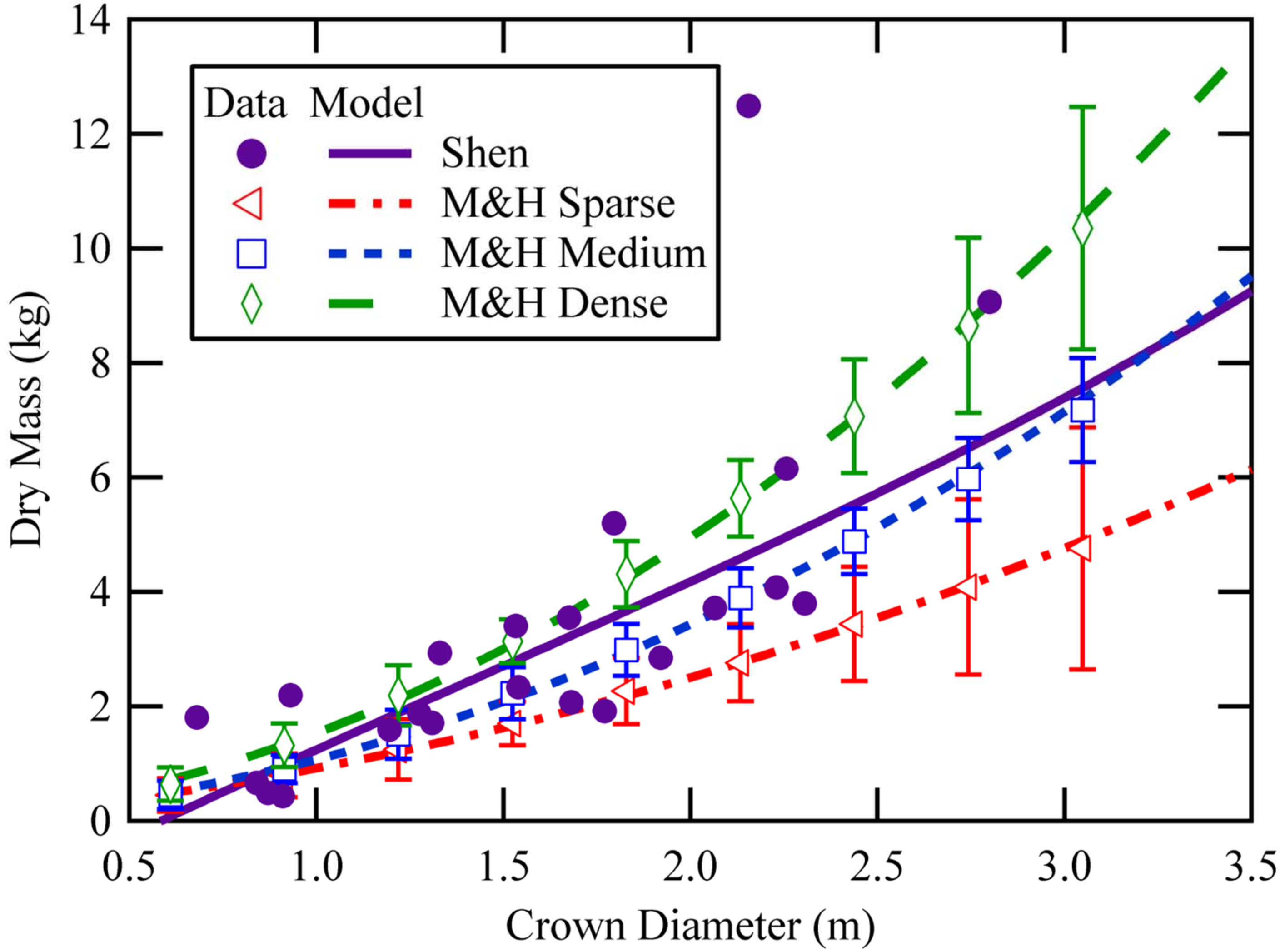
(b)

Sparse, Medium and Dense Foliage



(a) (b) (c)

Juniper: Matching Mass to Crown Diameter



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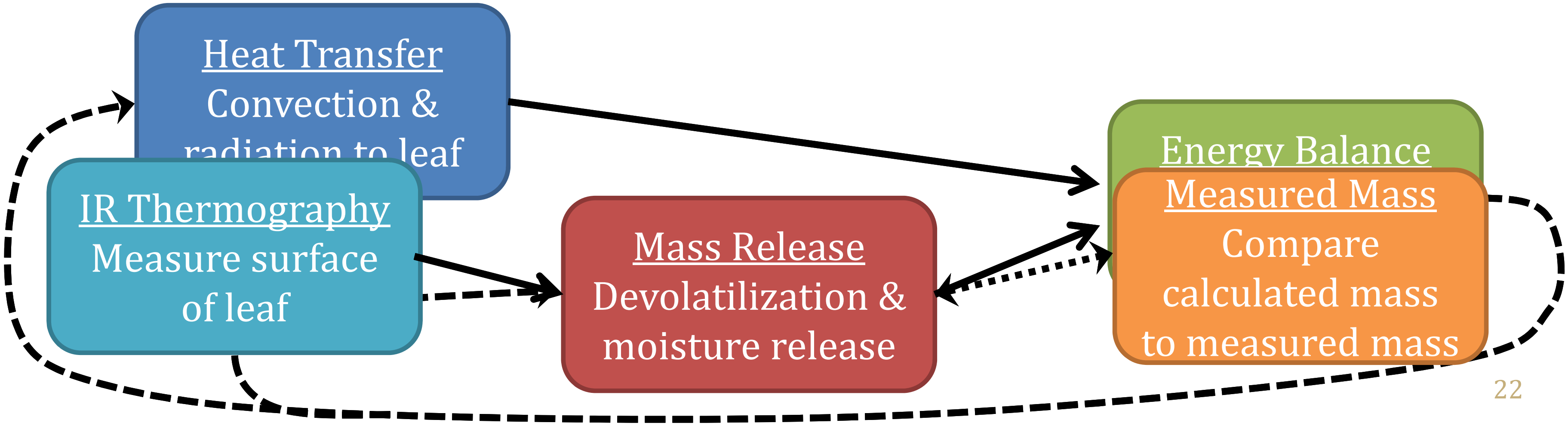
Additional Goal of Surface Temperature Study

- Develop understanding of why and how dead and live leaves burn differently
  - Live vegetation burns at a higher moisture content than does dead vegetation, but why?

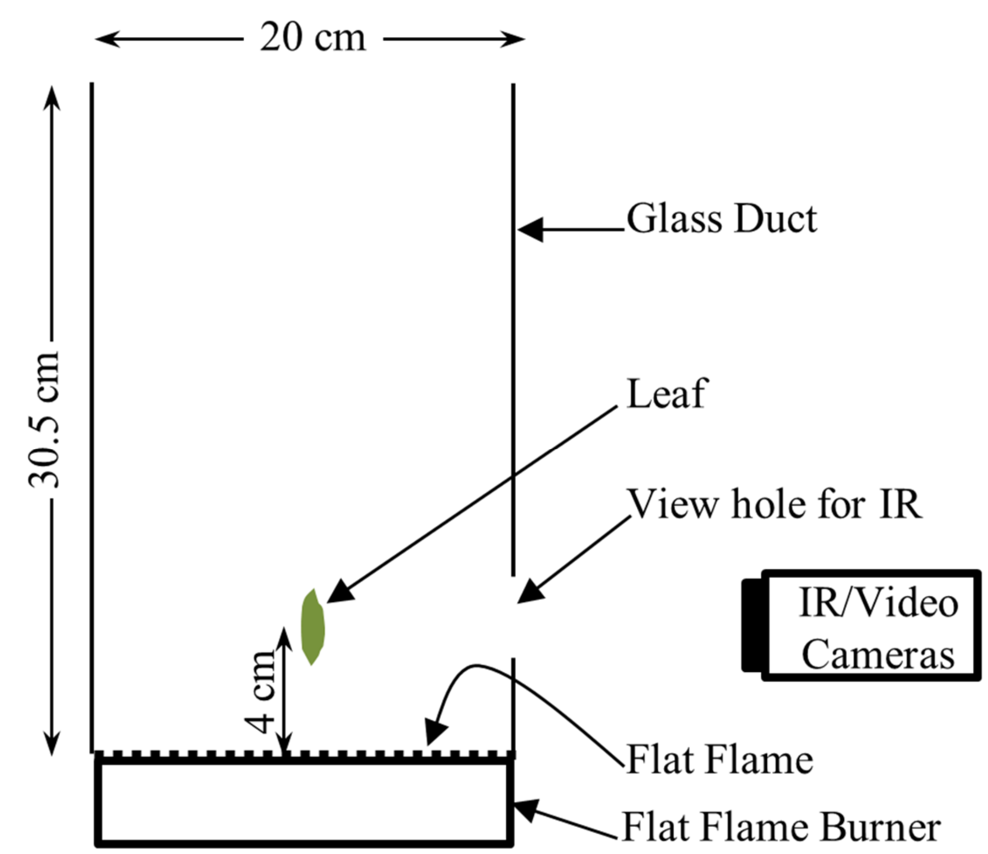
Physical Combustion Model

- Motivation: develop a model which would allow experiments to extend beyond a single condition
- Began with attempt to model leaf heating, devolatilization and moisture release
- Replaced heat transfer/energy balance calculations with experimental data



Experimental Setup

- Premixed rectangular burner
- Postflame gas
  - 1000°C
  - 10 mol% O_2
- Fuel/oxidizer
  - CH_4, H_2 / Air



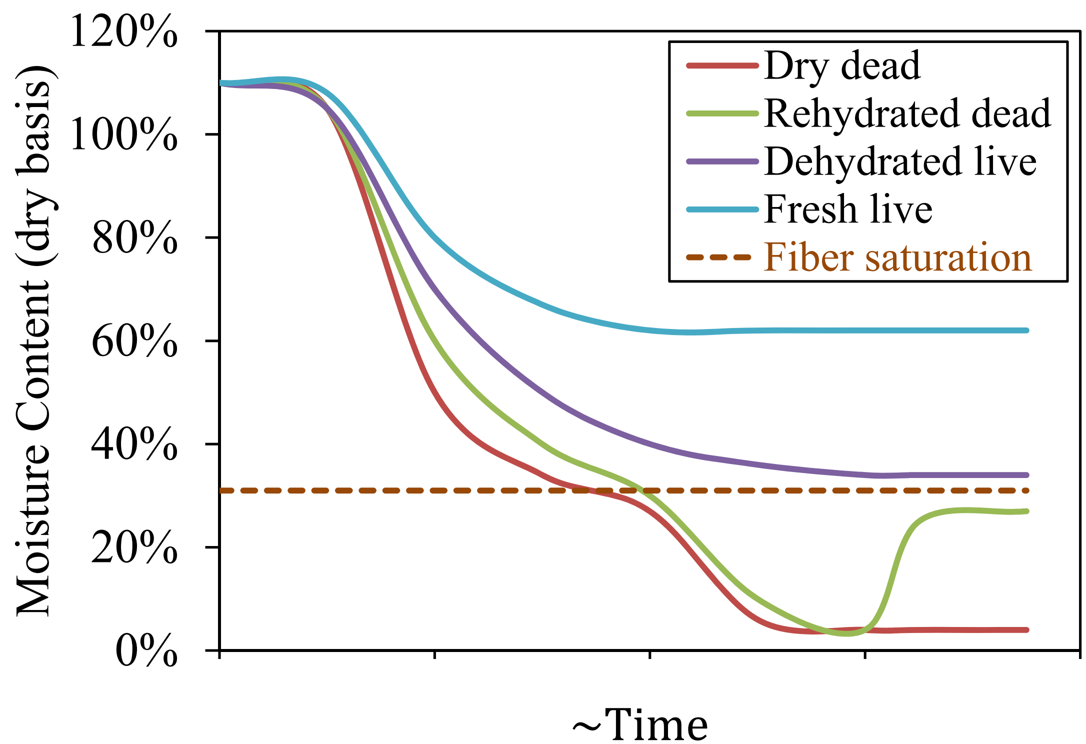
Prince, D. R., T. H. Fletcher, "Differences in Burning Behavior of Live and Dead Leaves: 1. Measurements," Combustion Science and Technology, in review (2014).

How do you compare live and dead leaves?

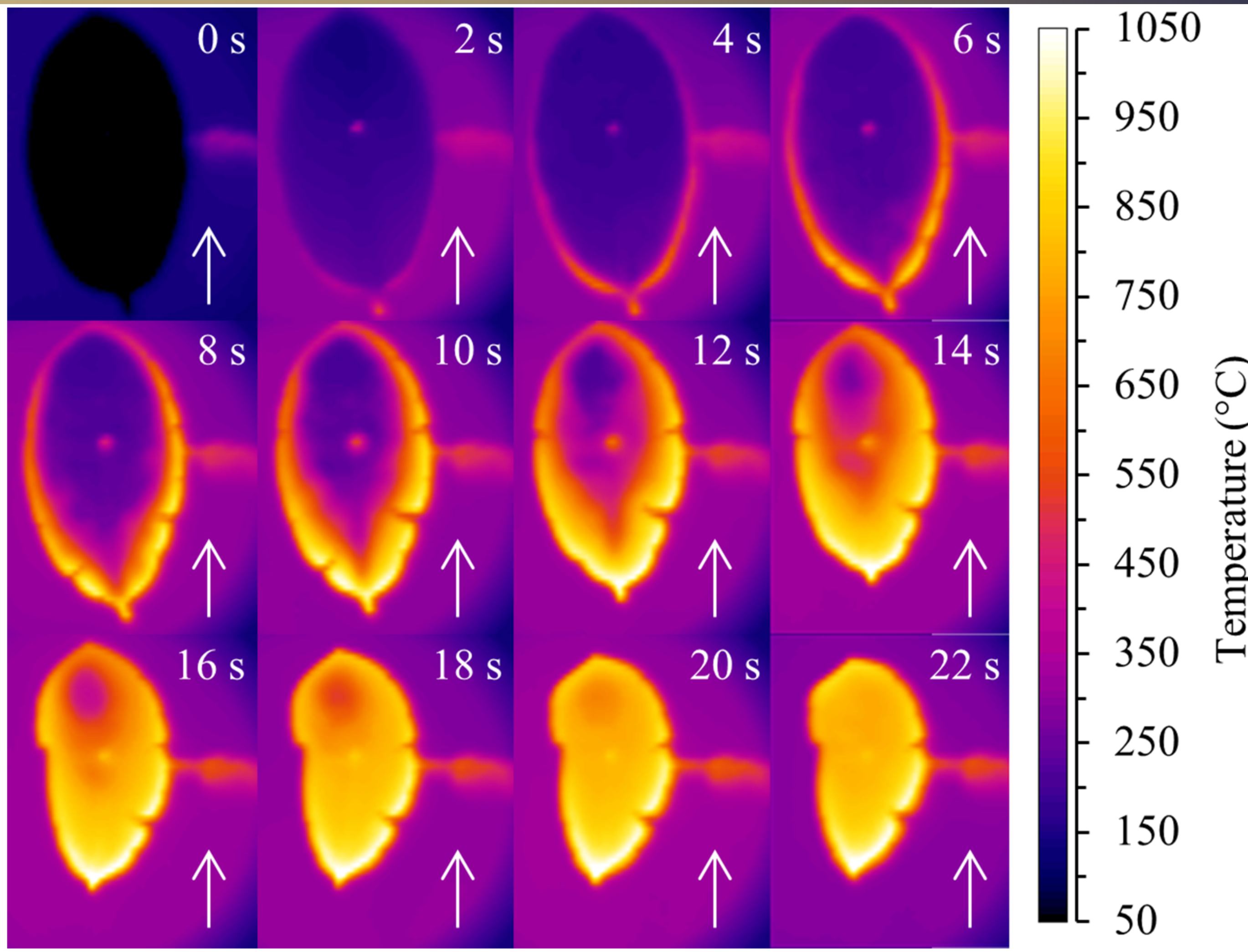
- Moisture content: live > dead
- How to evaluate effect of live vs dead?
  - Minimize difference in moisture content
  - Dehydrate live leaves
  - Rehydrate dead leaves
- But do dehydrated leaves act like live leaves?
  - Include fresh live leaves and dry dead leaves for perspective

Fuel Conditioning to Compare Dead and Live Leaves

- Four groups of manzanita leaves
- Prepared to examine effect of moisture/leaf state
- Burned at final "hydration stage"



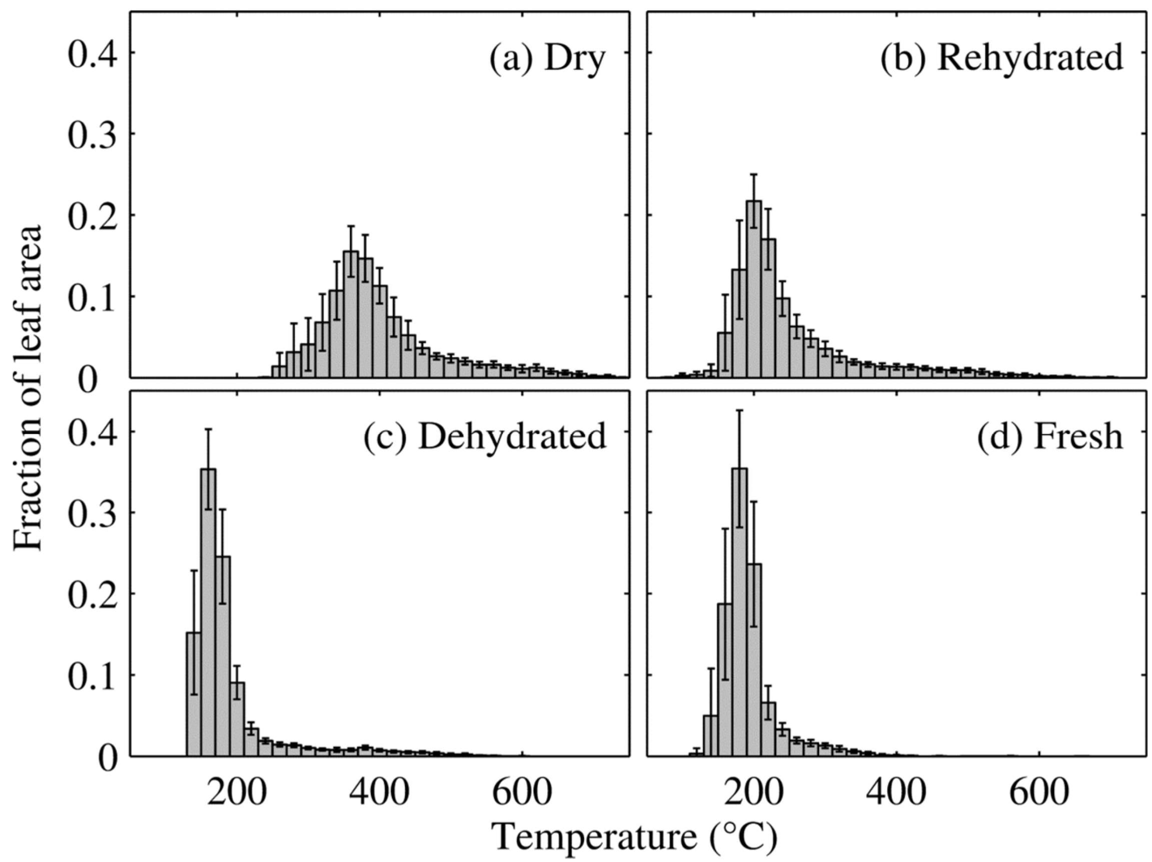
Manzanita Leaves did not Heat Isothermally



Prince, D. R., T. H. Fletcher, "Differences in Burning Behavior of Live and Dead Leaves: 1. Measurements," Combustion Science and Technology, in review (2014).

Differences in early temperature distribution (3 s residence time)

- Distinct temperature distributions
- Why the difference?

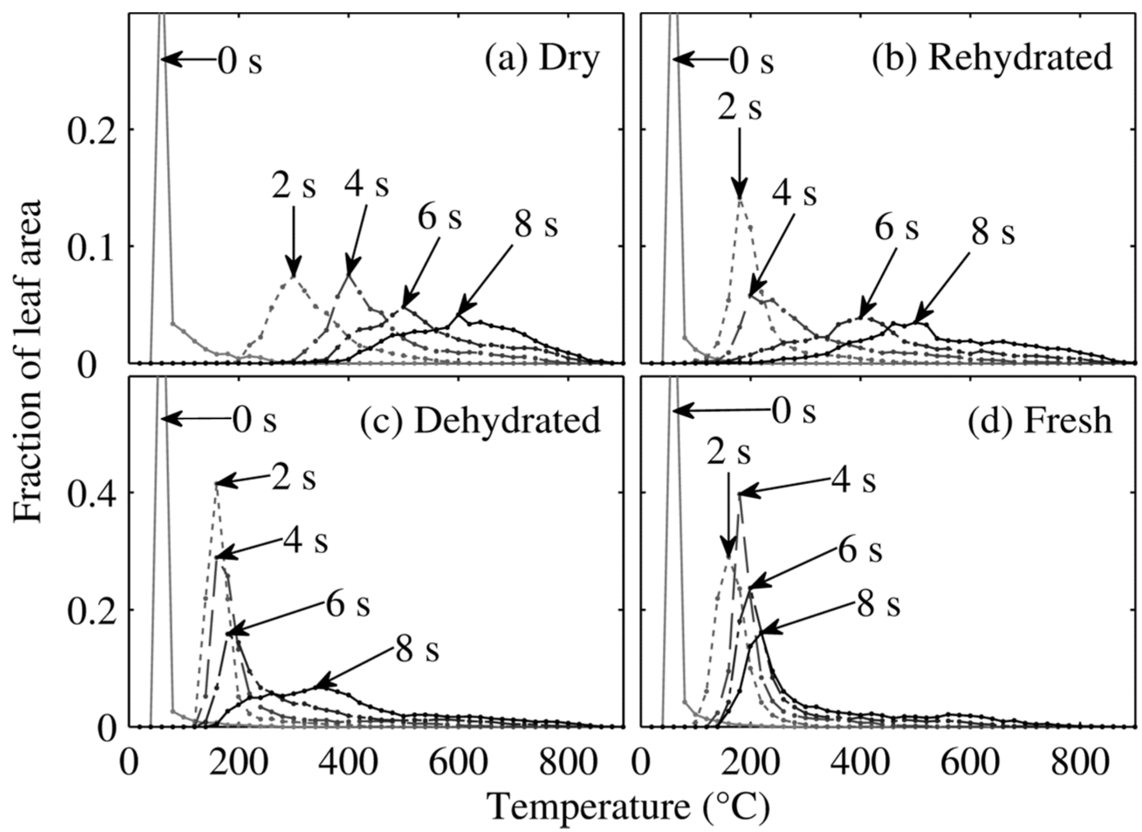


Histogram Details
- 20 K bin-widths
- 95% confidence intervals
- Fractions by pixel-counting

Prince, D. R., T. H. Fletcher, "Differences in Burning Behavior of Live and Dead Leaves: 1. Measurements," Combustion Science and Technology, in review (2014).

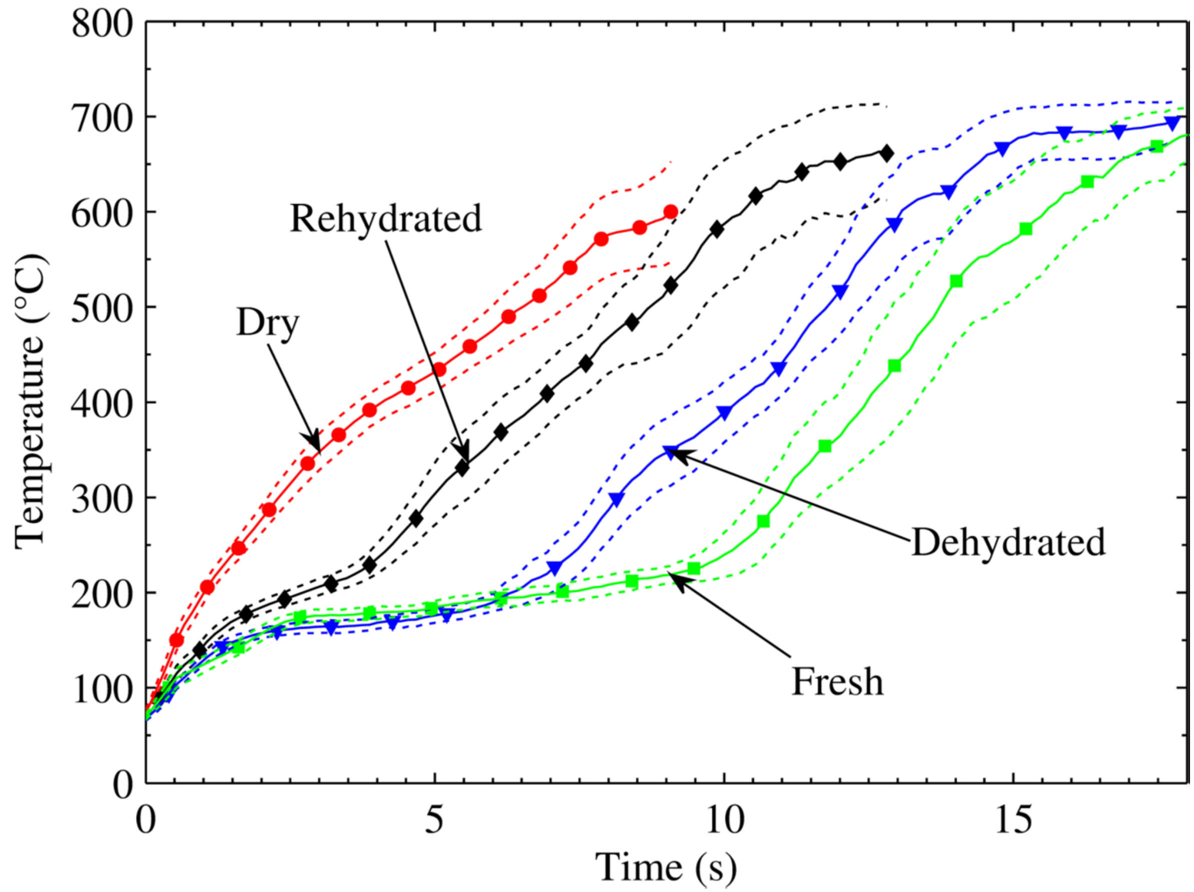
Moisture Causing Stall in Temperature

- No stall for dry
- Least pronounced for rehydrated dead
- Effect of leaf state/moisture history

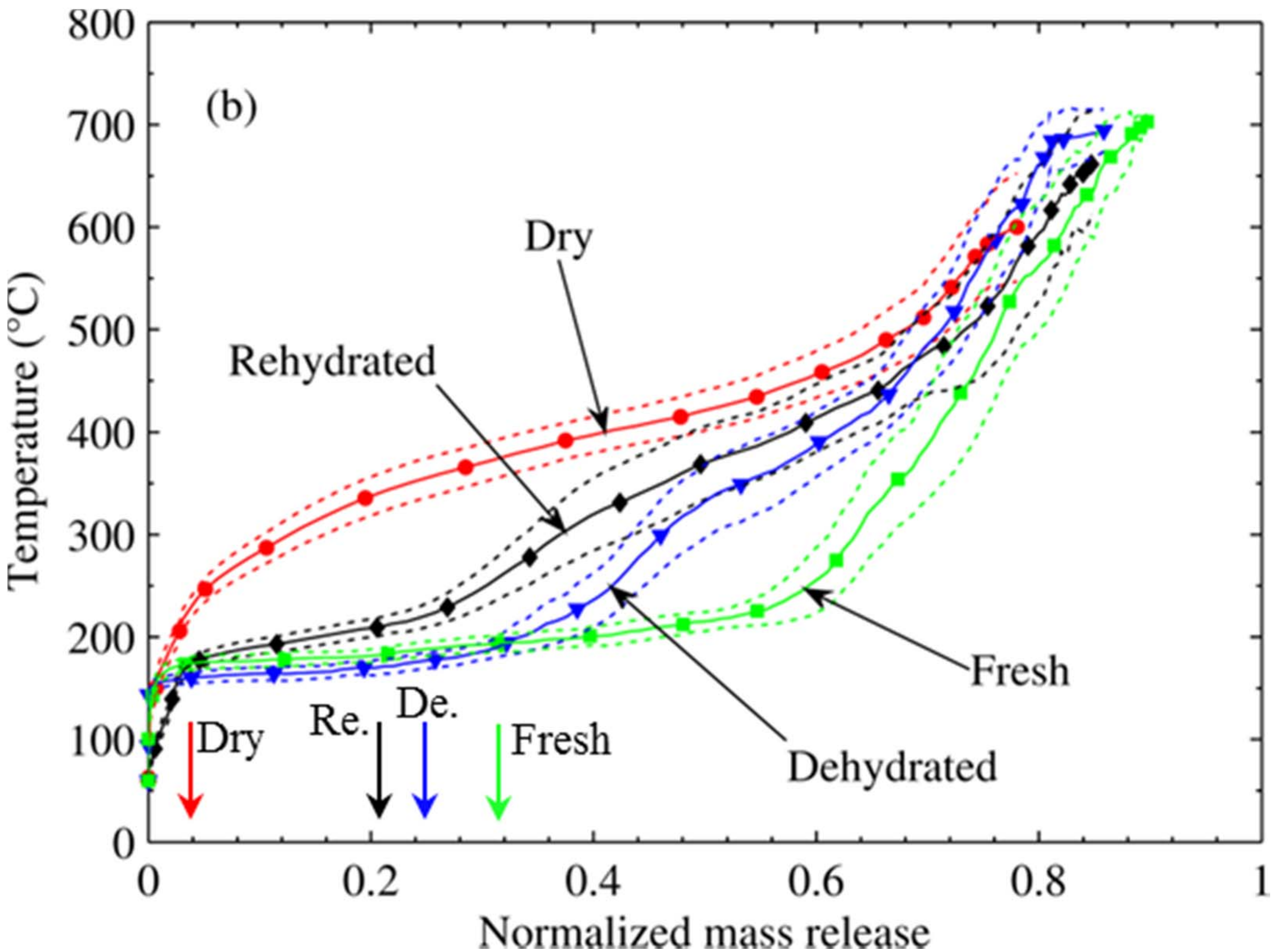


Mode Temperature with 95% CI

- Moisture has stronger effect in live than dead leaves
- Why?
  - Adsorbed water vs. liquid water



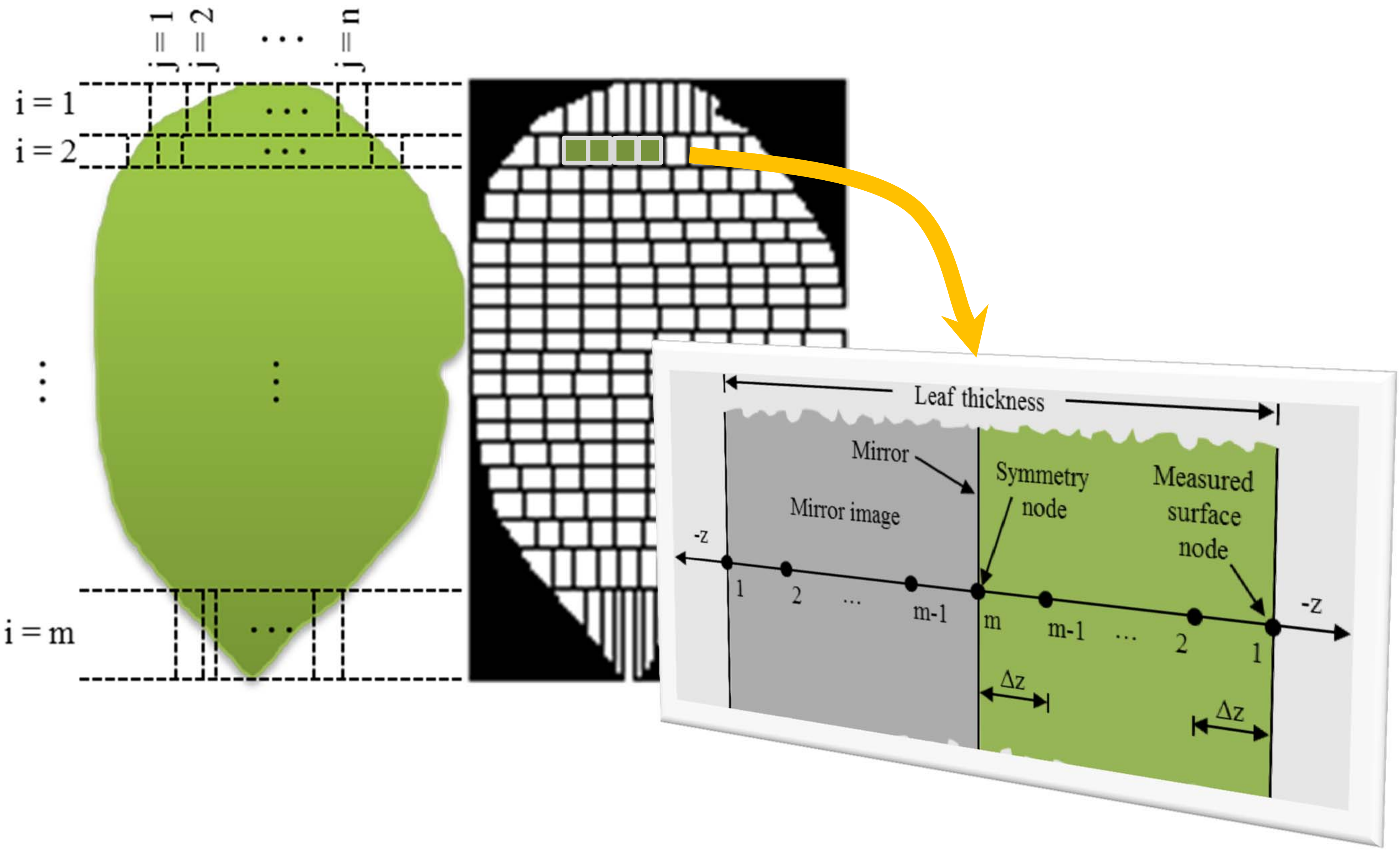
How Long Does Moisture Last?



Devolatilization and Moisture Release Modeling

- Detailed treatment of leaf temperature
- Dry mass: modeled with CPD for all biomass
- Water: modeled as pressure-driven diffusion through porous membrane

Divide Leaf into 600 Mass Release Bins
Get Temperature of Each Bin



Model Formulation

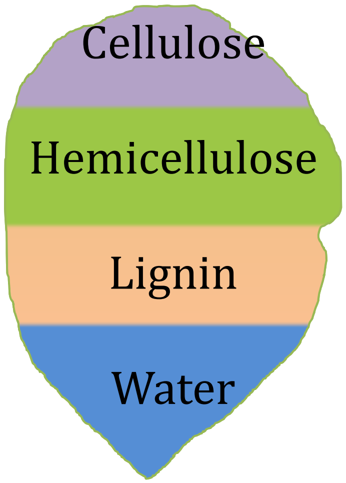
- Mass of leaf divided up
- Model mass release of each component for each local temperature
- Devolatilization
  - Approach 1: Chemical Percolation Devolatilization (CPD)
  - Approach 2: 1-step devolatilization model

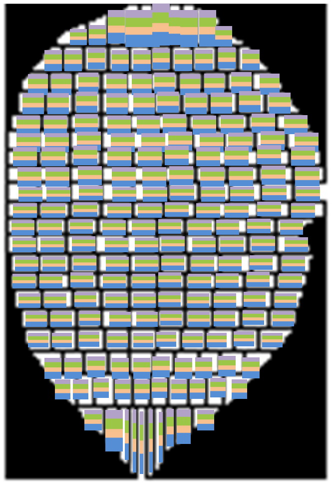
$$\frac{dV_i}{dt} = A_i \exp\left(\frac{-E_i}{RT}\right)\left(V_{\infty i} - V_i\right)$$

- Diffusive moisture release:

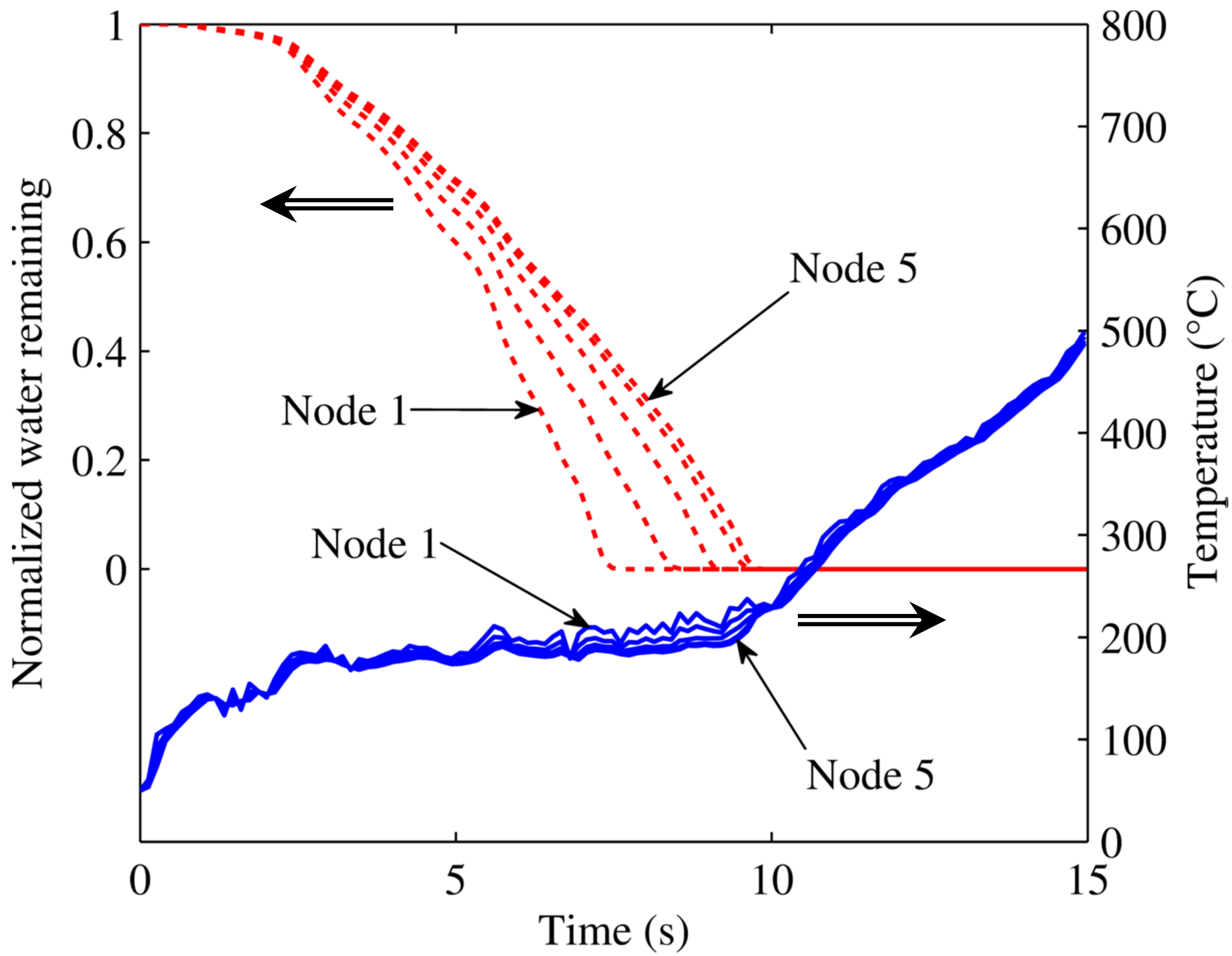
$$\mathcal{D}_S = \exp\left(3.746 - 5.12\gamma - \frac{4317}{T/K}\right)\frac{cm^2}{s}$$

$$n_w = \mathcal{D}_S A_c \left(\frac{c_{w_1} - c_{w_2}}{z_2 - z_1}\right)$$

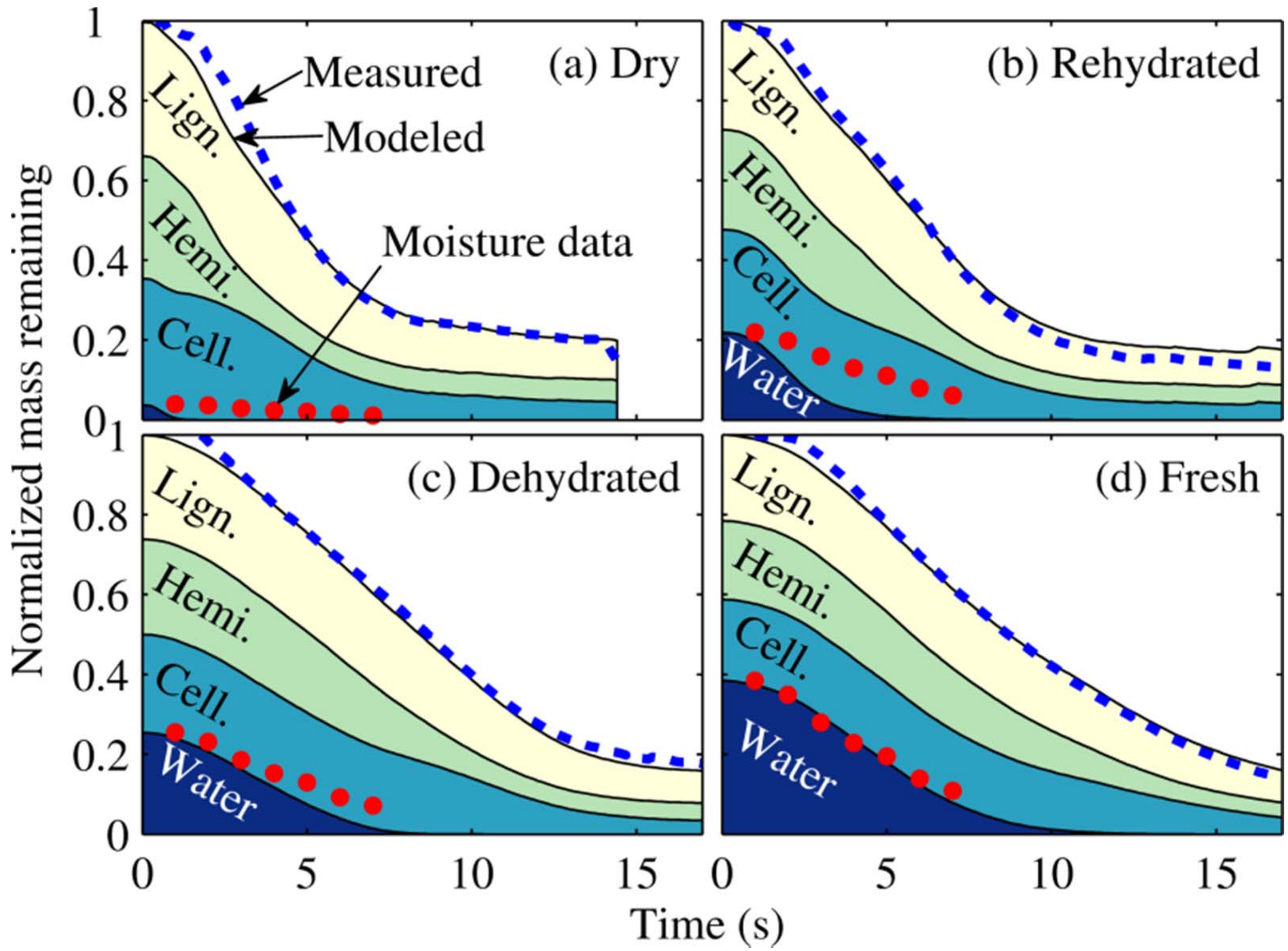




Moisture Release vs. Temperature Fresh Live Leaf #5



Mass Release Model vs. Mass Measurements with Moisture Points



Prince, D. R., T. H. Fletcher, "Differences in Burning Behavior of Live and Dead Leaves: 2. Mass Release Modeling," Combustion Science and Technology, in preparation (2014).

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Major Changes to Bush Model

- Flame merging:

$$\hat{S}_{i,j} = \sqrt{\left(\frac{S_{i,j}}{r_{f,i} + r_{f,j}}\right)^2 + \left(\frac{z_i - z_j}{L_{f,j}}\right)^2}$$

$$\frac{L_{f,i}}{L_{1,i}} = \frac{h_{f,i}}{h_{1,i}} = \left(\frac{v}{v_0}\right)^{c_3} \sum_{j=2}^{N^*} \left(\frac{c_1 \ln\left(\frac{j}{j-1}\right)}{1 + c_2 \hat{S}_{i,j}}\right) + 1$$

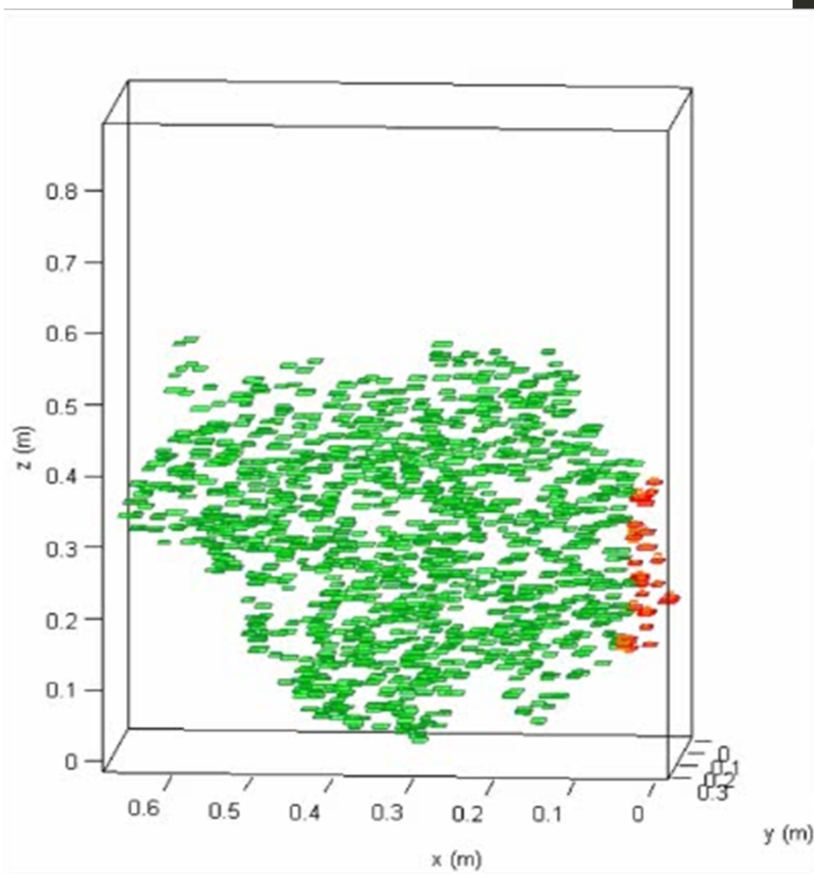
- Flame radius/downward flame extension:

$$r_f = \frac{h_1 / c_4}{\left(\frac{h_f}{h_1}\right)^{c_5}}$$

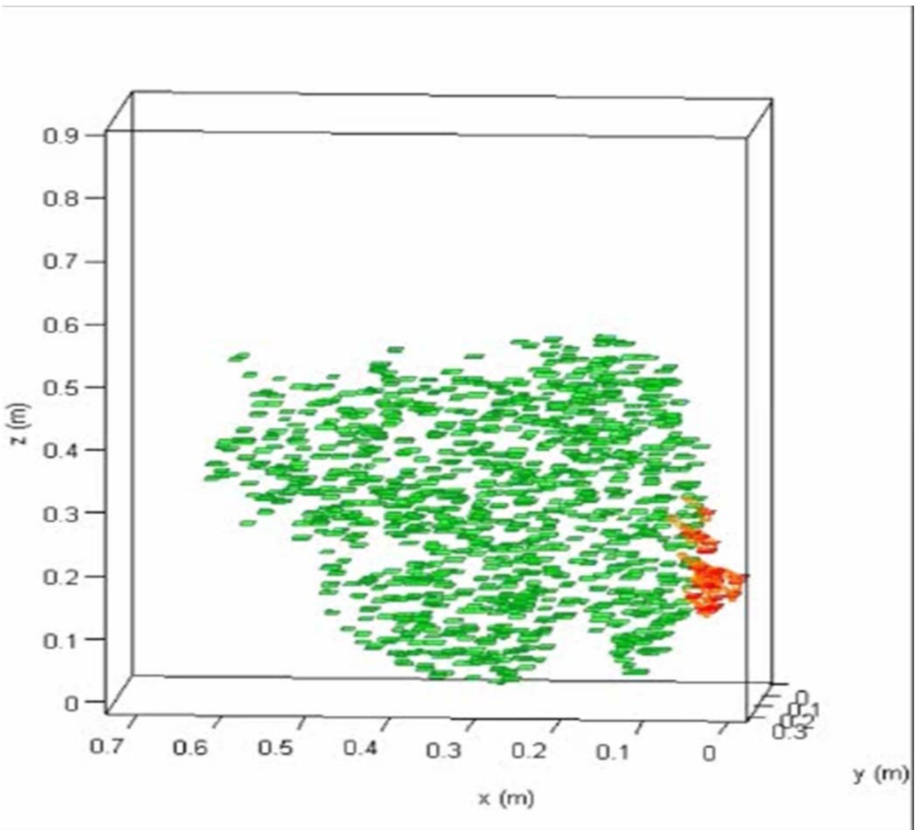
- Flame angles based on collective flame of local clusters
- Flame parameter scaling based on a physics-based combustion model
  - The temperature-dependent mass release
  - A mechanistic description of heat transfer to the leaf
  - The energy balance of the leaf

} Based on ratios

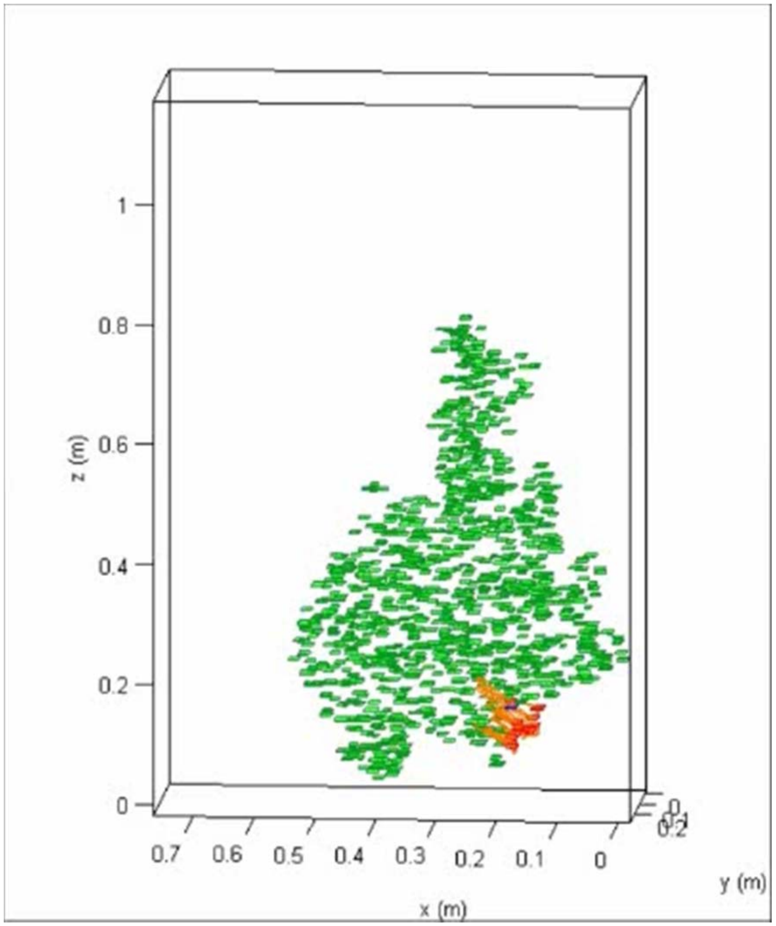
Riverside (2009) Run 1: 3x speed
Improved Bush Model vs. Experiment
Wind: 0 m/s, Mass: 780 g



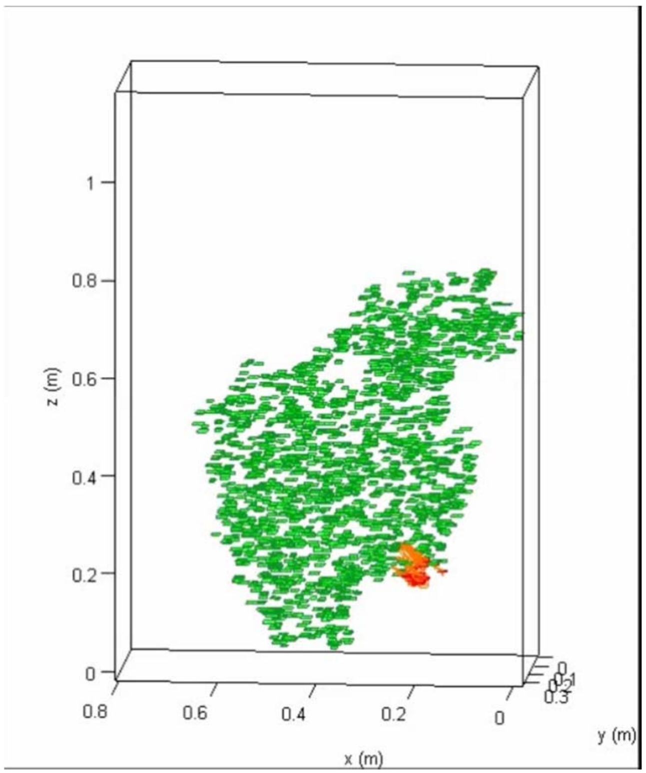
Riverside (2009) Run 2: 3x speed
Improved Bush Model vs. Experiment
Wind: 0.45 m/s → 0 m/s (141 s), Mass: ~780 g



Riverside (2009) Run 3: 3x speed
Improved Bush Model vs. Experiment
Wind: 1.1 m/s, Mass: 2098 g



Riverside (2009) Run 4: 3x speed
Improved Bush Model vs. Experiment
Wind: 0.7 m/s, Mass: 3239 g



Conclusions

- Improvement to bush model (fuel placement, heating effects, flame merging) permitted semi-quantitative agreement with data from wind tunnel
- A diffusion model provided the best representation of moisture release from live and dead leaves
- Moisture has a stronger cooling effect in live leaves than dead leaves

Technical Contributions

- Differences between dead vs live leaves are quantified for the first time ever
- Identified high-pressure water retention in manzanita leaves
- Highly representative fuel location models
- Flame merging expression including vertical offset and non-equal flames

Journal Papers

Prince, D. R., M. E. Fletcher, C. Shen and T. H. Fletcher, "Application of L-Systems to Geometrical Construction of Chamise and Juniper Shrubs," *Ecological Modelling,* **273**, 86-95 (2014).

Prince, D. R., Fletcher, T. H., "Differences in Burning Behavior of Live and Dead Leaves: 1. Measurements," *Combustion Science and Technology,* **Accepted for publication** (2014).

Prince, D. R., Fletcher, T. H., "Differences in Burning Behavior of Live and Dead Leaves: 2. Modeling," *Combustion Science and Technology,* **In preparation** (2014).

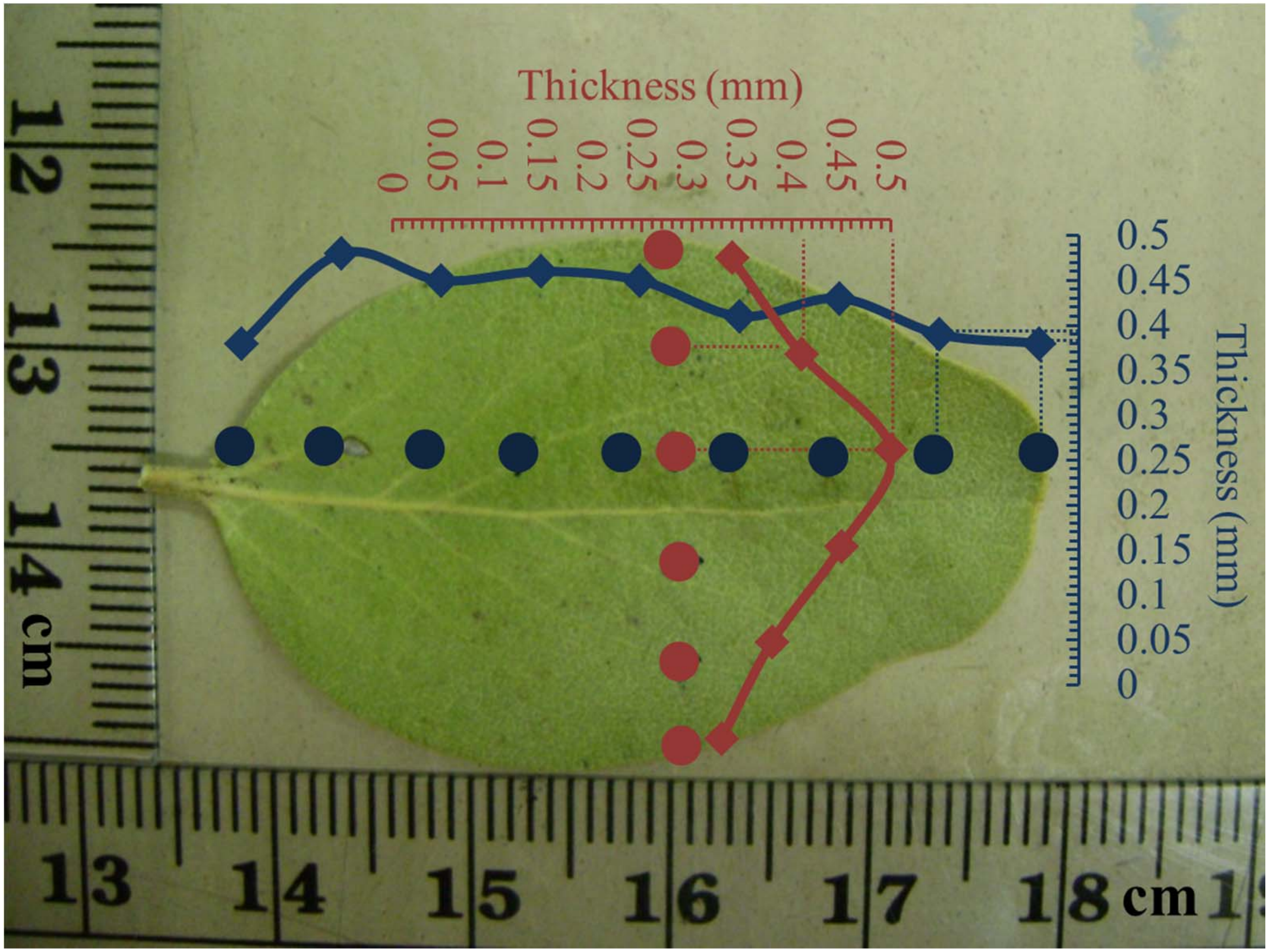
Prince, D.R., B. T. Andersen, W. J. Cole, B. M. Pickett, T. H. Fletcher, and D. R. Weise, "Semi-empirical multi-leaf fire spread simulator for manzanita shrubs," **In preparation** (2014).

Thank you

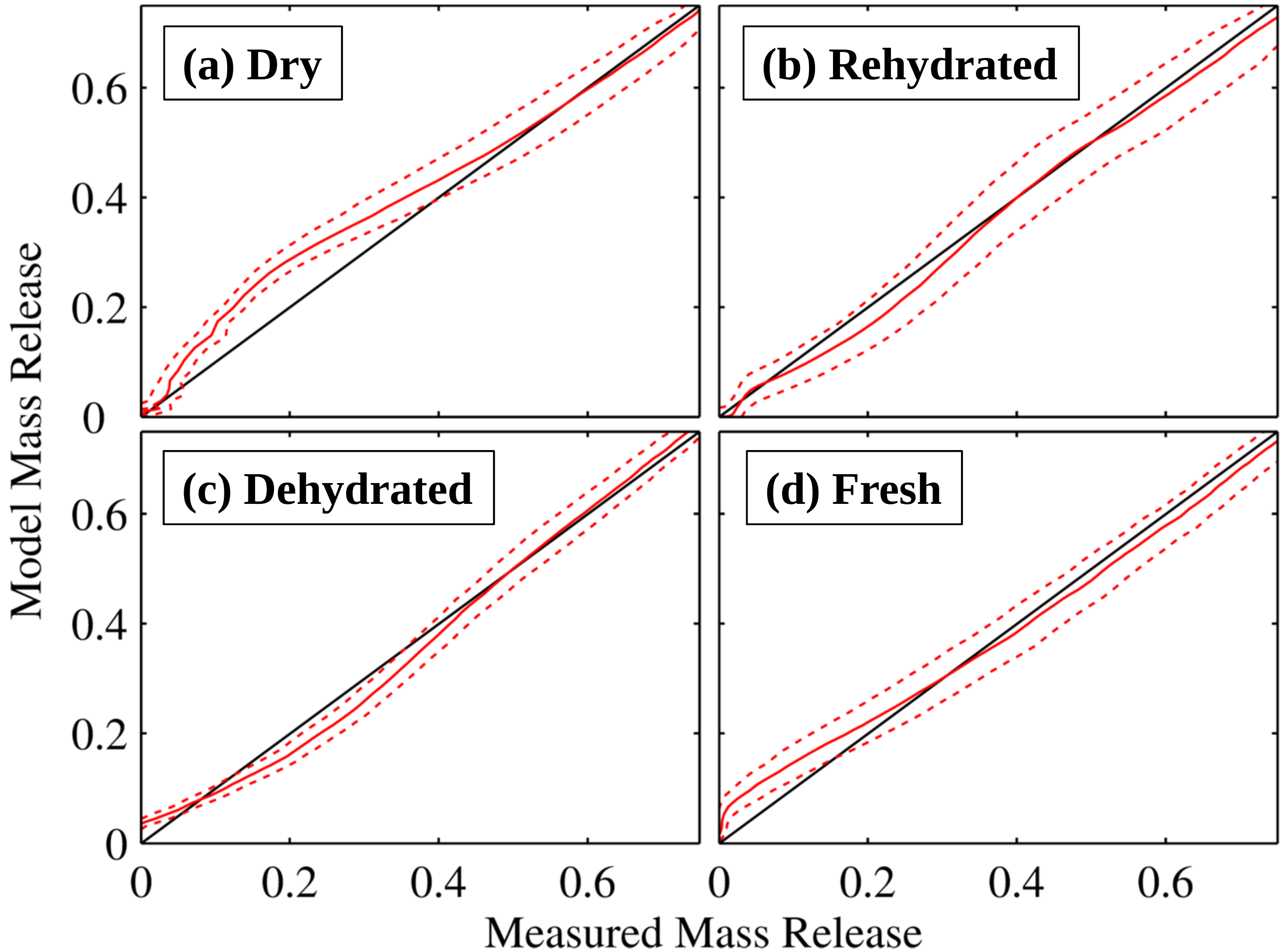
- Graduate committee
  - Advisor: Thomas Fletcher
  - David Weise (USDA Forest Service)
  - David Lignell
  - William Pitt
  - Brad Bundy
- USDA Forest Service
  - Joey Chong, Gloria Burke
- Undergrad Research Assistants:
  - Wesley Cole, Brandon Anderson, McKaye Dennis, Corinne Olsen, Mitch Withers, Kelsey Wooley, Ganesh Bhattari, Jay Liu, Kenneth Alford, Eddie Overy, Amelia Rapp, Merete Capener, Kellen Rowberry, Jared Little, Cory Bowen, Victoria Lansinger, Marianne Fletcher, Kristen Nicholes, Sydney Hansen, and Jenalyn Clegg
- Others
  - Chen Shen, Jonathan Gallacher, Aaron Lewis
  - John Prince
- Funding:
  - National Science Foundation, Joint Fire Science Project

End of slide show, click to exit.

Supplemental Slides



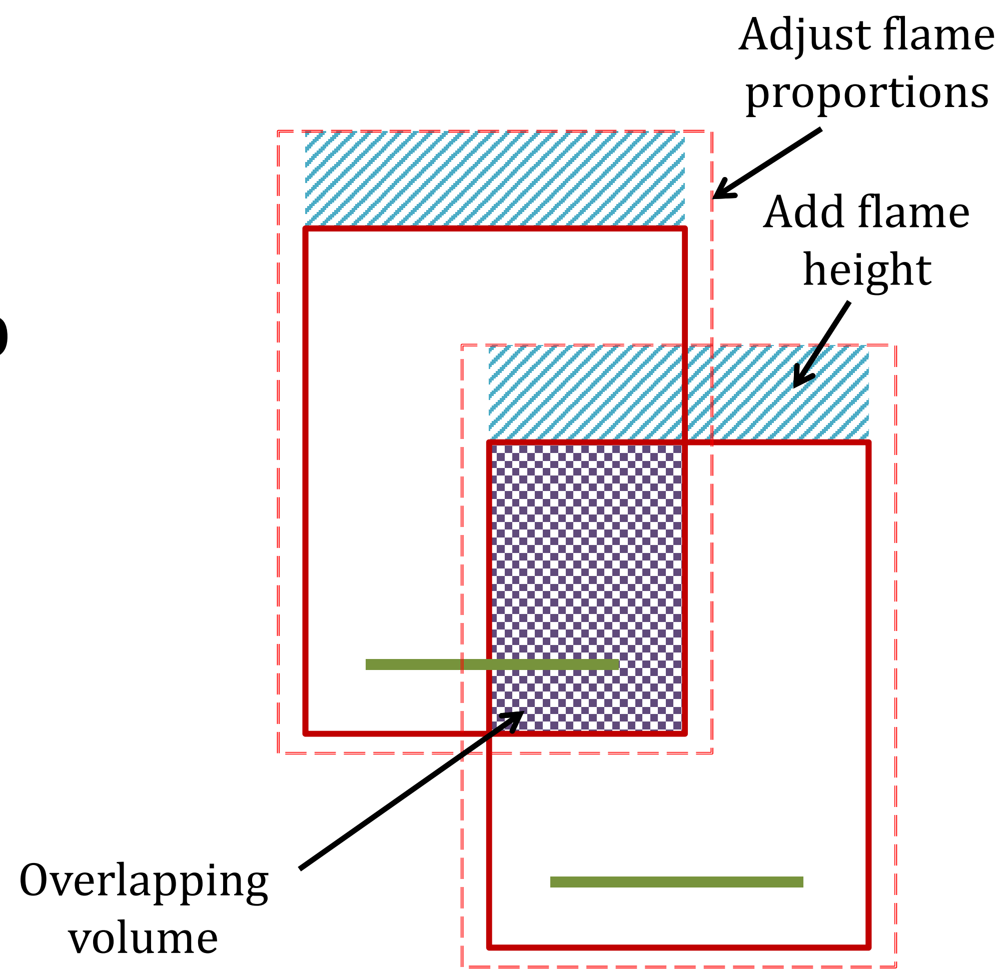
Measured vs. Model Mass
(with 95% CI on mean)



Prince, D. R., T. H. Fletcher, "Differences in Burning Behavior of Live and Dead Leaves: 2. Mass Release Modeling," Combustion Science and Technology, in preparation (2014).

Flame-flame Interactions

- Flames interact synergistically
- Volumetric overlap
  - – Flames enlarged proportional to overlap with other flames



Flame-flame Interactions

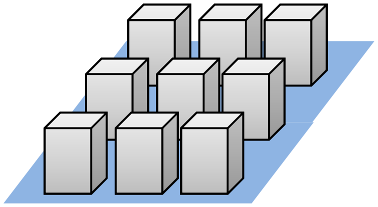
- Experiments using porous burners (literature)
- Correlation for 2-D flame merging[1]

$$\frac{L_f}{L_m} = \left(\frac{2\sqrt{N}\left(\sqrt{N}-1\right)S^2 + \lambda D^2}{\lambda\left(2\sqrt{N}\left(\sqrt{N}-1\right)S^2 + D^2\right)}\right)^B$$

- Developed expression for 3-D-spaced flame:

$$\widehat{S_{3D}} = \frac{S}{2 \cdot r_f} + \frac{|\Delta z|}{L_f}$$

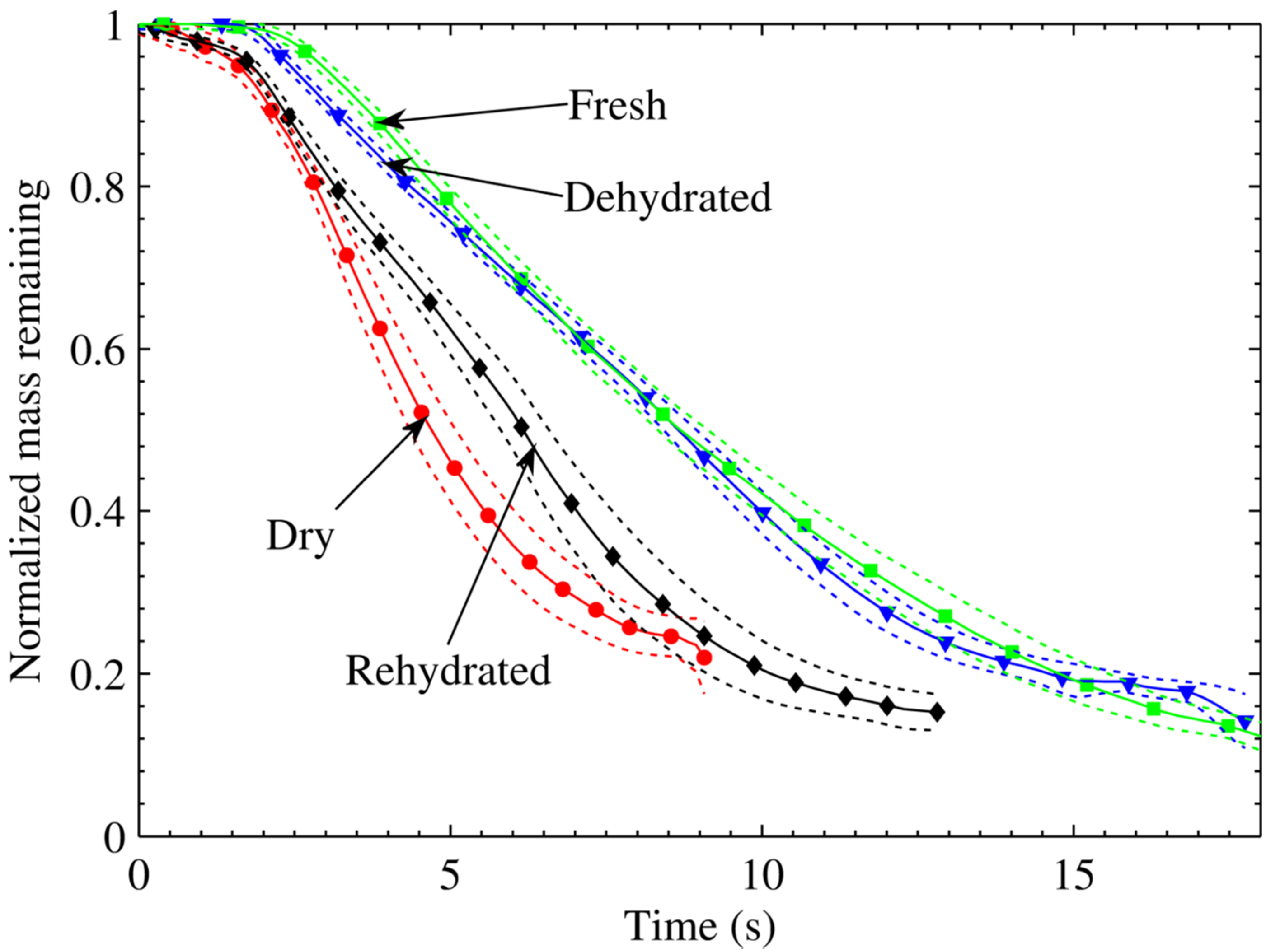
- Adapted equation for *any* number
- Now subject of a new PhD thesis



2-D burner grid

L_f – merged flame length at S
L_m – merged flame length at S=0
N – number of burners in square arrangement
S – horizontal burner spacing
D – side dimension of burner
λ – coefficient
S_{3D} – equivalent horizontal spacing
r_f – flame radius
Δz – vertical spacing

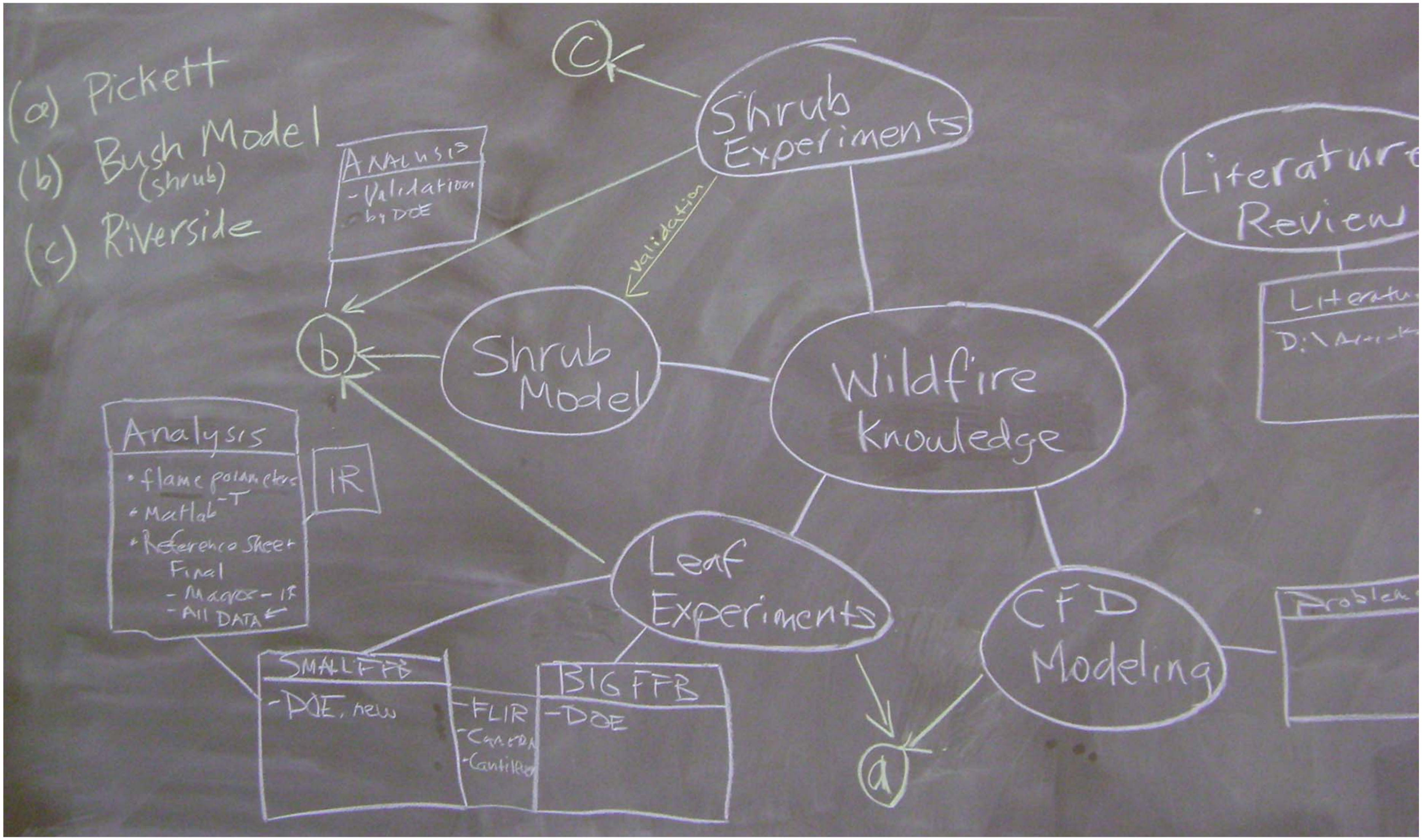
[1]Weng, W. G., D. Kamikawa, Y. Fukuda, Y. Hasemi and K. Kagiya, "Study on Flame Height of Merged Flame from Multiple Fire Sources," *Combustion Science and Technology*, **176**(12), 2105-2123 (2004).


Fresh
Dehydrated
Dry
Rehydrated
Normalized mass remaining
Time (s)
0
0.2
0.4
0.6
0.8
1
0
5
10
15

Overview

- Background
  - Wildfires
  - Wildfire models
  - Shrub fire spread model (my group)
- Advancing the shrub model
- Developing a kinetic basis for flame growth
  - Temperature measurements
  - Pyrolysis and water release

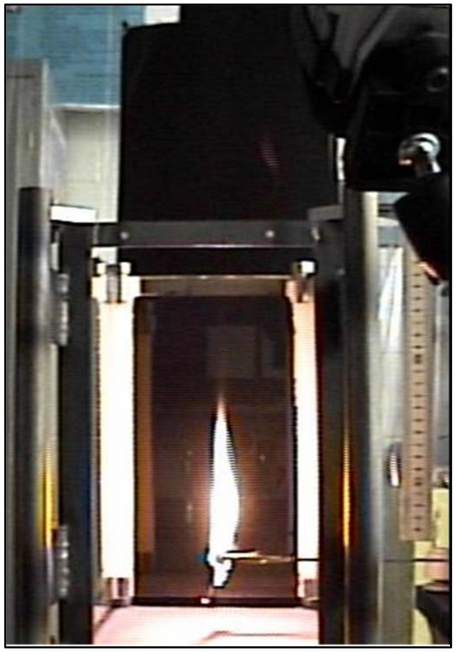
Project Transfer Day

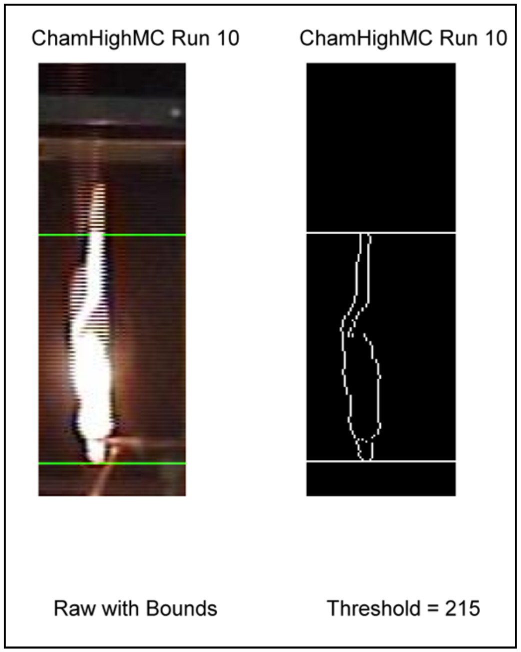


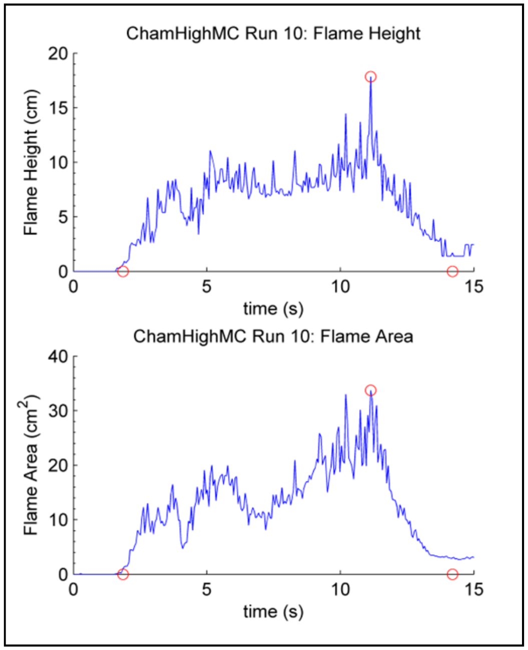
Specific Challenges

- Changing landscape
  - "Suicide neighborhoods"
  - Invasive species
  - Drier/hotter weather
- Firefighter safety vs. protecting property
- Prescribed (planned) burns

Automating Image and Data Analysis



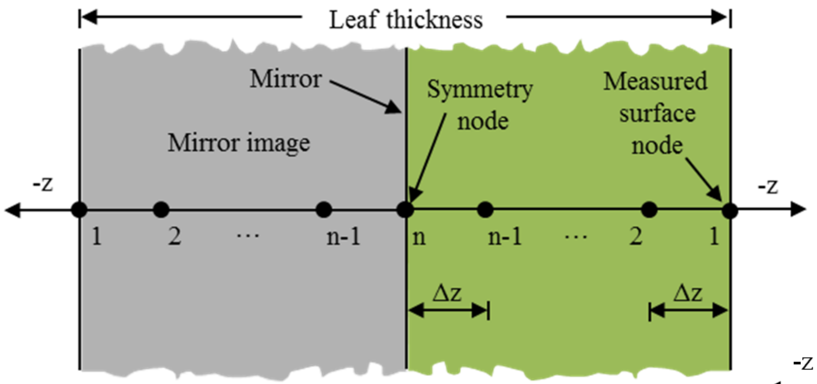


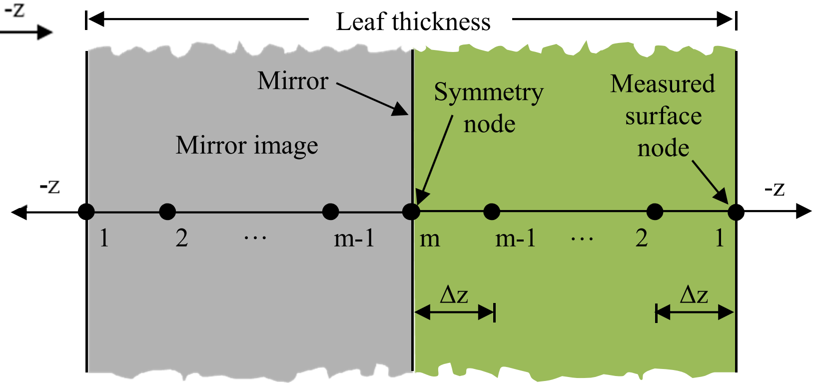


Code for flame interactions

```
% Modular shrub fire sperad model BETA
% Started 9/5/2012 by Dallan Prince
% FUEL ELEMENT FLAME UPDATE script
% for Manzanita

% flame height (singular flame height)
x_centroid = sum((Dm_solid/dt)*x_fuels)/sum(Dm_solid/dt);
y_centroid = sum((Dm_solid/dt)*y_fuels)/sum(Dm_solid/dt);
z_centroid = sum((Dm_solid/dt)*z_fuels)/sum(Dm_solid/dt);
sig_x = ((1/sum(Dm_solid/dt))*sum(((x_fuels-x_centroid).^2).*Dm_solid/dt))^0.5;
sig_y = ((1/sum(Dm_solid/dt))*sum(((y_fuels-y_centroid).^2).*Dm_solid/dt))^0.5;

D_eff = l;

Q_W = (20000*Dm_solid - Dm_water*DH_vap)/dt;
h_f_s = 0.235*((Q_W)./1000).^(2/5) - D_eff;
% h_f_s = (burn_stage==3).*...
%    ((t_rxn<=t_h).*h_max./(t_h - t_ig).*(t_rxn - t_ig) ...
%     + (t_rxn>t_h).*h_max./(t_fd - t_h).*(t_fd - t_rxn)); % single/unmerged flame
stage3 = find(h_f_s>.01);
n_stage3 = length(stage3);

% flame radius (h_scale currently based on previous time step or initialization)
rF = h_f_s.*((h_scale-1)/1.1 + 1)/2/4.5;

% flame down (h_scale currently based on previous time step or initialization)
dF = h_f_s.*(h_scale)/2/2.5;

% flame base location
% x_shift % shift base of flame based on wind
x_sh = zeros(n_fuels,1);
x1 = x_fuels(stage3) + x_sh(stage3); % flame ends WITH wind shift
y1 = y_fuels(stage3);
z1 = z_fuels(stage3); % used as flame source, below
```

```
% FLAME INTERACTION SIZE UPDATE, based on Weng, adapted by Dallan Prince
Lm_Ls = ones(n_stage3,1);
ln_inc = (log((2:n_stage3)./(1:n_stage3-1)));
for i3 = 1:n_stage3
  % Coalescence (see Weng)
  % dist^2 -- to make this more 'ideal' consider rotating to make average
  % flame angle "vertical". But, also consider role of buoyancy
  D2 = (x1-x1(i3)).^2 + (y1-y1(i3)).^2;
  rr2 = (rF(stage3(i3)) + rF(stage3)).^2;
  xy_sep2 = (rr2 < D2).*(D2 - rr2).^2;
  dist2_DH = ((xy_sep2.^(1/2))./(2*rF(stage3)) + (((z1-
z1(i3)).^2).^(1/2))./h_f_s(stage3))';
  [dist2_DHs ind_dist] = sort(dist2_DH);
  Lm_Ls(i3) = 1*sum( ln_inc ./(1 + .8*dist2_DHs(2:end))) + 1;

  jlist = stage3(dist2_DH < .5); % this is a criteria for "being merged," may need
refining (a little generous probably)
  % GROUP FLAME HEIGHT
% this section groups all touching flames together into rows in the
  % globs matrix
  ij_list = [stage3(i3) jlist']; % this puts all the j's i touches and i in a list
  for ij = 1:length(ij_list)
  [r_glob,~,~] = find(globs==ij_list(ij)); % find all rows that the member of ij_list is
a member
     if ~isempty(r_glob) % if i/j is already in a globule, add the others into the list
        for j2 = 1:length(r_glob)
           Rnew = unique([globs(r_glob(j2),:),ij_list]); % make a combined list
           Rnew = Rnew(Rnew>0); % eliminate zero entries (this will remove 0 from
beginning)
           globs(r_glob(j2),:) = 0; % clear duplicate/partial duplicate rows from
matrix
           globs(r_glob(1),1:length(Rnew)) = Rnew; % write merged group to matrix
        end
     elseif ~isempty(jlist) % if there is at least a pair i/j, but they are not members
of an existing globule, start a new globule (row)
        [r_g,~] = size(globs);
        globs(r_g+1,1:length(ij_list)) = ij_list;
     else % if the i had no j-buddies, then it is not yet in a globule
        'no flame interactions for i';
     end
  end
  globs = globs(any(globs,2),:); % this clears the empty rows
end
Lm_Ls(isnan(Lm_Ls)) = 1;
```


Leaf thickness
Mirror
Mirror image
Symmetry node
Measured surface node
-z
-z
1
2
···
n-1
n
n-1
···
2
1
Δz
Δz


Leaf thickness
Mirror
Mirror image
Symmetry node
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m-1
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m-1
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2
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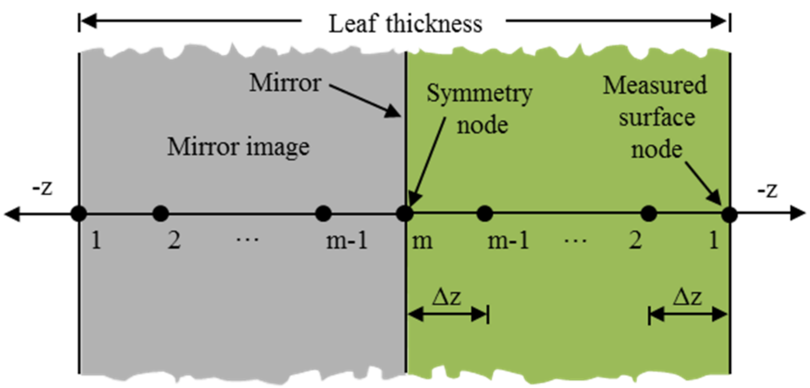
Δz
Δz


Leaf thickness
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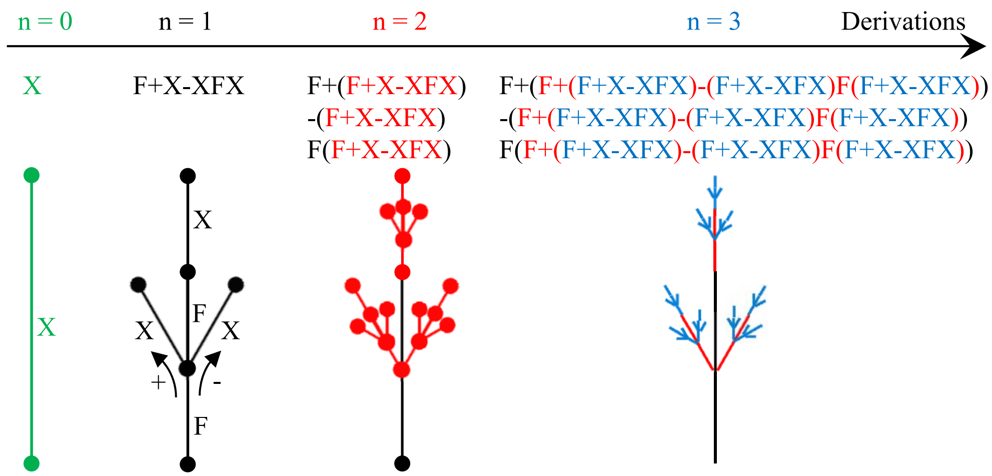
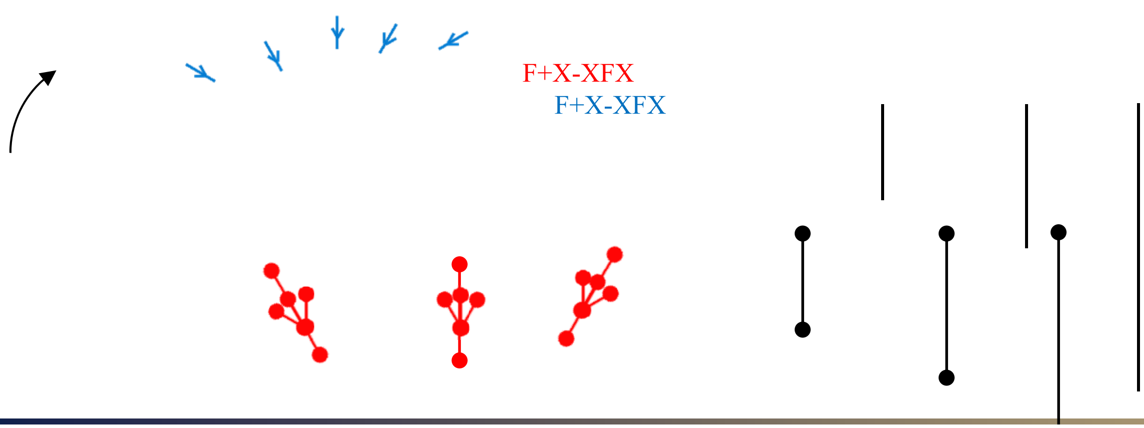
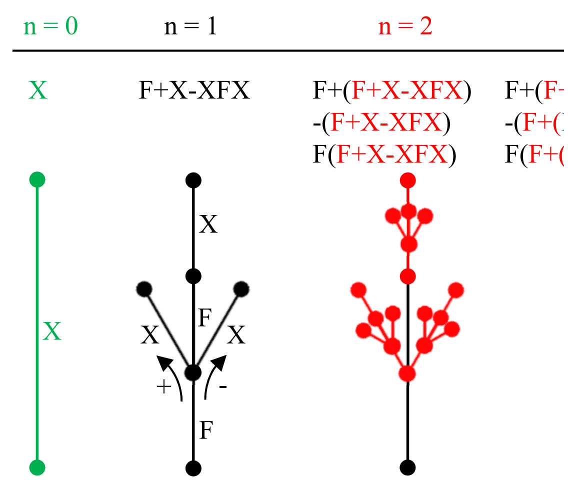
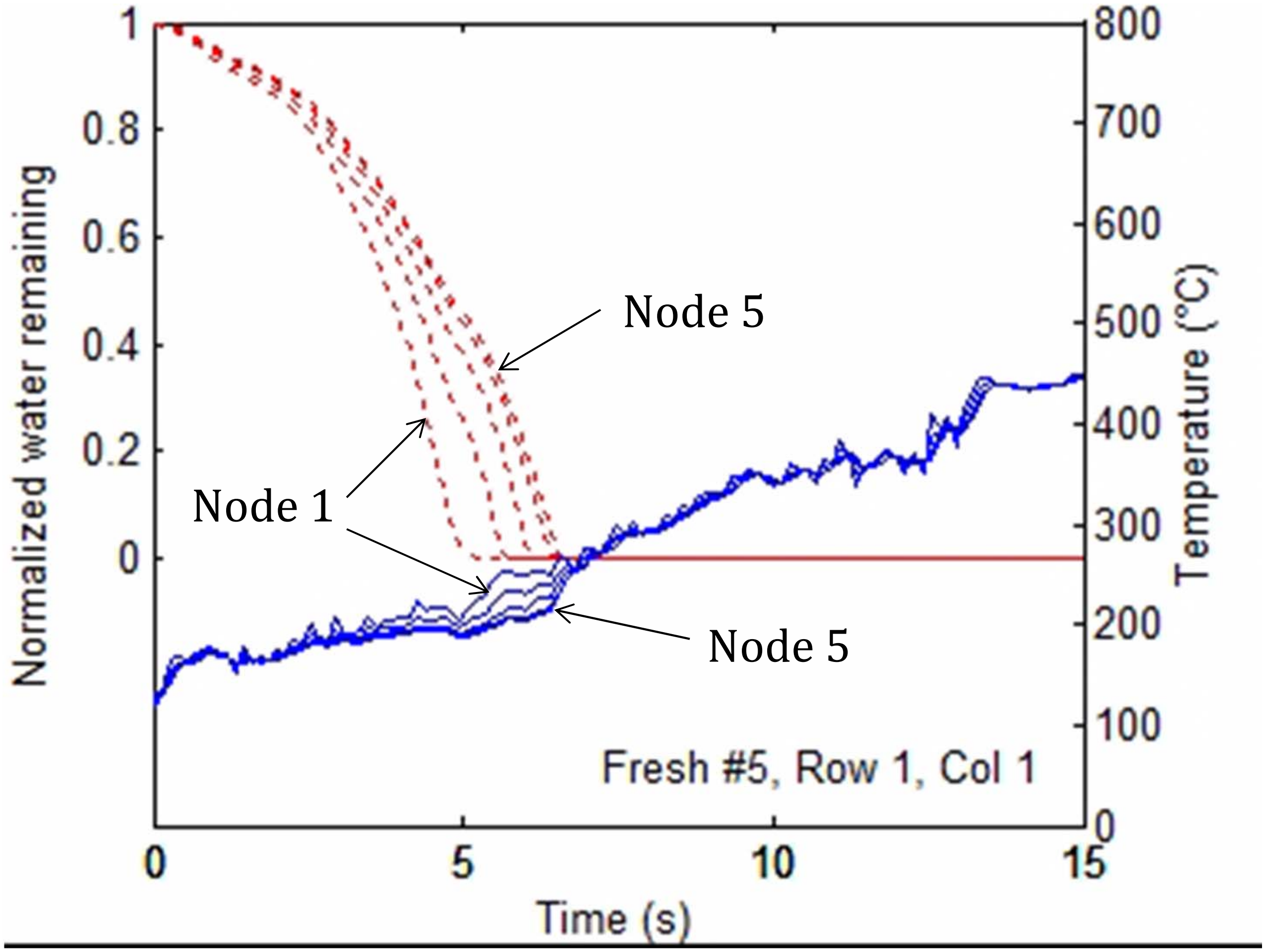
Δz


n = 0
n = 1
n = 2
n = 3
Derivations
X
F+X-XFX
F+(F+X-XFX)
-(F+X-XFX)
F(F+X-XFX)
F+(F+(F+X-XFX)-(F+X-XFX)F(F+X-XFX))
-(F+(F+X-XFX)-(F+X-XFX)F(F+X-XFX))
F(F+(F+X-XFX)-(F+X-XFX)F(F+X-XFX))
X
X
F
X
X
+
-
F

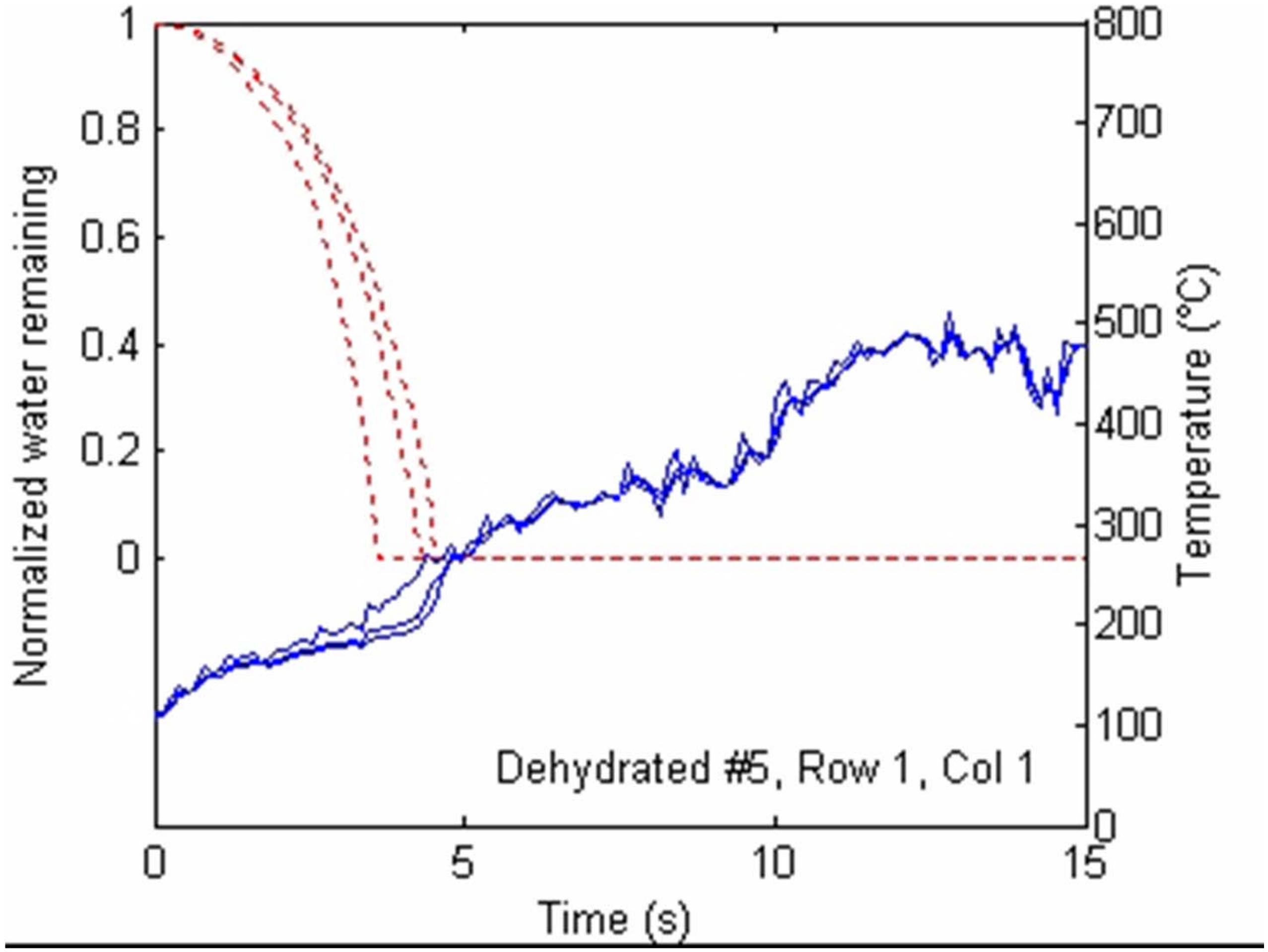

F+X-XFX
F+X-XFX


n = 0
n = 1
n = 2
X
F+X-XFX
F+(F+X-XFX)
-(F+X-XFX)
F(F+X-XFX)
X
X
F
X
X
+
-
F

Moisture Release vs. Temperature
Fresh Live Leaf #5



Moisture Release vs. Temperature Dehydrated Live Leaf #5



Moisture Release vs. Temperature Rehydrated Dead Leaf #5