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NATIONAL ACADEMIES Sciences Engineering Medicine

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AGNI-NAR: AN ASYNCHRONOUS GRAPH MODEL FOR SIMULATING BUILT ENVIRONMENT DAMAGE IN THE WILDLAND URBAN INTERFACE

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OUTLINE OF THE PRESENTATION

- Motivations
- Vulnerability
- Damage Assessment
- Communicating Risk
- Discussion and Future Work
- Questions

1

Motivation

Large Losses and Probabilistic Risk Assessment

Wildfires as a Global Issue

- Yearly expenditures on managing wildfires exceed US$1 billion
- Current fire suppression tactics of wildland fires have led to a rise in the frequency of high-intensity fires

Wildfires are a part of nature, and we simply need to co-exist with fires

2025 Palisades Fire in LA (photo credit: David

How fires propagate in communities is largely unknown

Mahmoud (2023), ***Nature***

Motivation

Increase in frequency of extreme fire events and population living in the Wildland Urban Interface (WUI) regions

- Every community has specific characteristics – *‘One size fits all solution is probably not the most optimal approach’*
- Need tools/models to better understand fire behavior in extreme events and its impact on communities
- Developing effective fire mitigation strategies for communities require appropriate modeling frameworks

The developed tools need to computational friendly such that they can be utilized with minimal data and in real-time

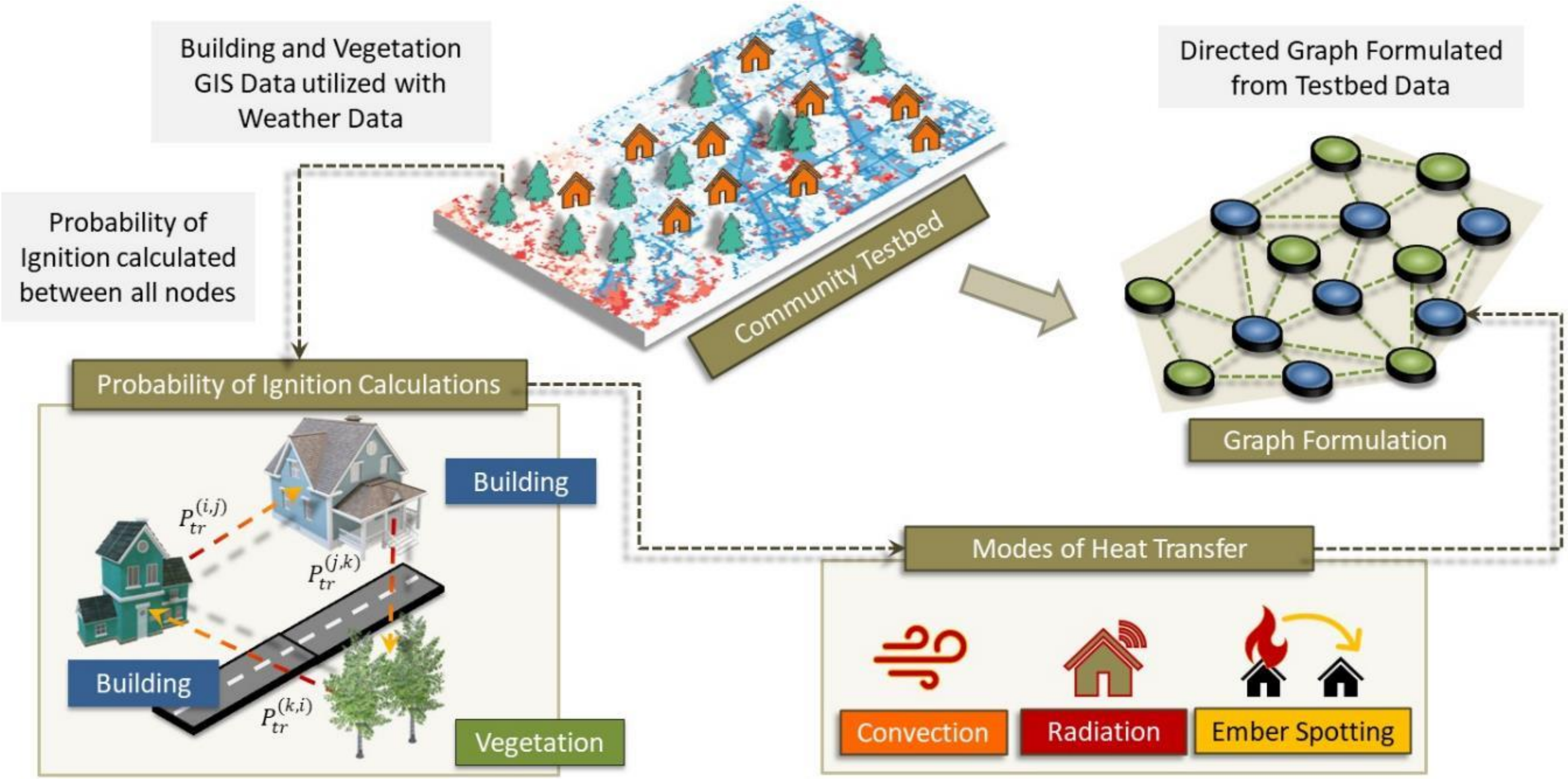
The pressing need lies in exploring alternative directions to quantify WUI risk of communities

2

Vulnerability

Wildland and Community Propagation Models

Graph Theory Application (1)

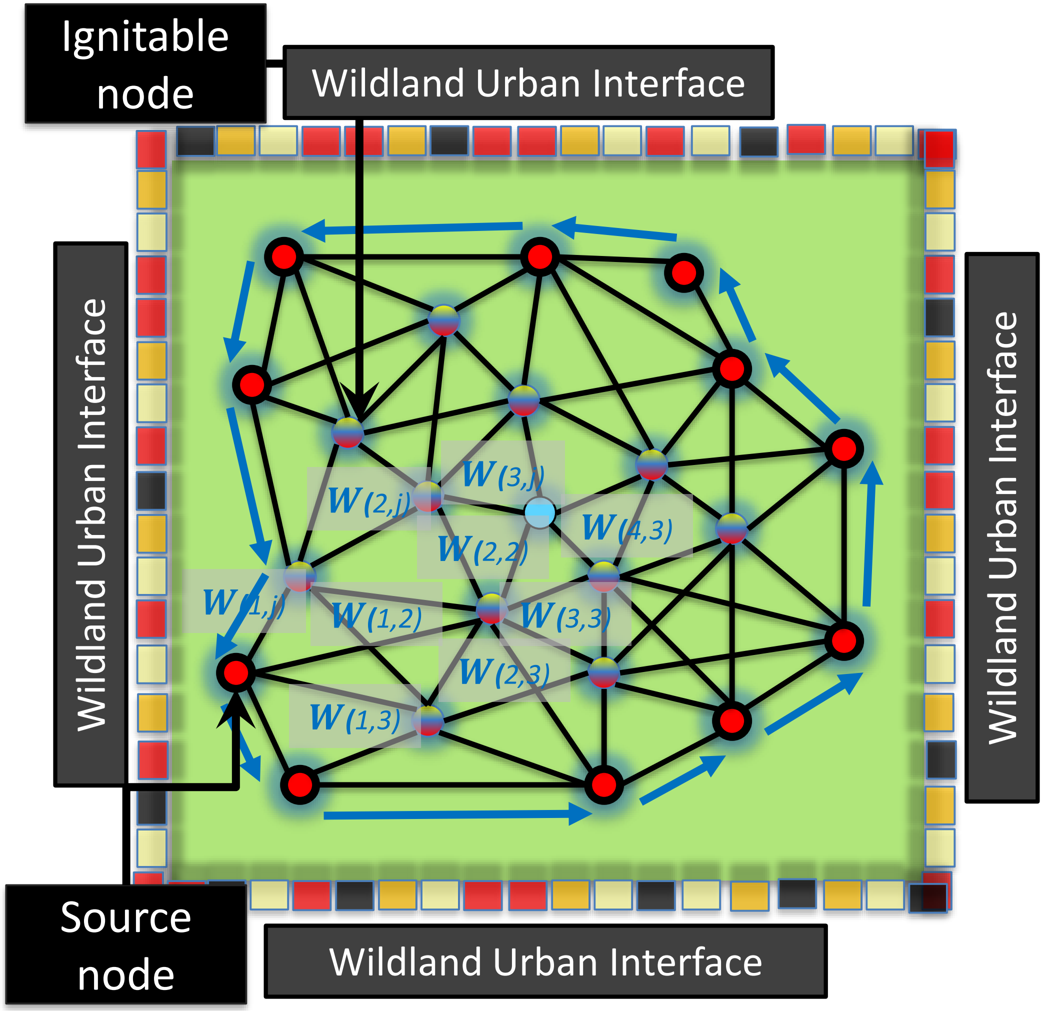


- **Two analysis can be conducted with the AGNI-NAR model**
    - Most probable path to calculate the fire boundary.
    - Relative venerability to determine likelihood of damage for a given fire boundary.

Graph Theory Application (2)

Discontinuous Fuels inside Communities !

Discontinuous Propagation inside Communities !



Step 1

Identify ignitable objects and boundary nodes to develop corresponding graph

Step 2

Calculate weights (*W(a,b)*) for each edge

Step 3

Identify most probable paths

Step 4

Calculate probability of ignition (P_i) from most probable paths for each boundary node

Probability of Ignition

- Each node classified into **’Ignitable’** or **‘Non-Ignitable’**
- Probability of ignition between 2 nodes defined as

$$P_{tr}^{(i,j)} = \begin{cases} \min\left(\boxed{P_{total}^{(i,j)}}, 1\right) & if\{j \neq W_{(m)}: i = W_{(m)}\}_{m\in\mathbb{R}} \\ P_{cond}^{(i,j)} & if\{j = W_{(m)}: i = W_{(m)}\}_{m\in\mathbb{R}} \end{cases}$$

$$\boxed{P_{total}^{(i,j)} = \left(P_{conv}^{(i,j)} \cup P_{rad}^{(i,j)} \cup P_{ember}^{(i,j)}\right)}$$

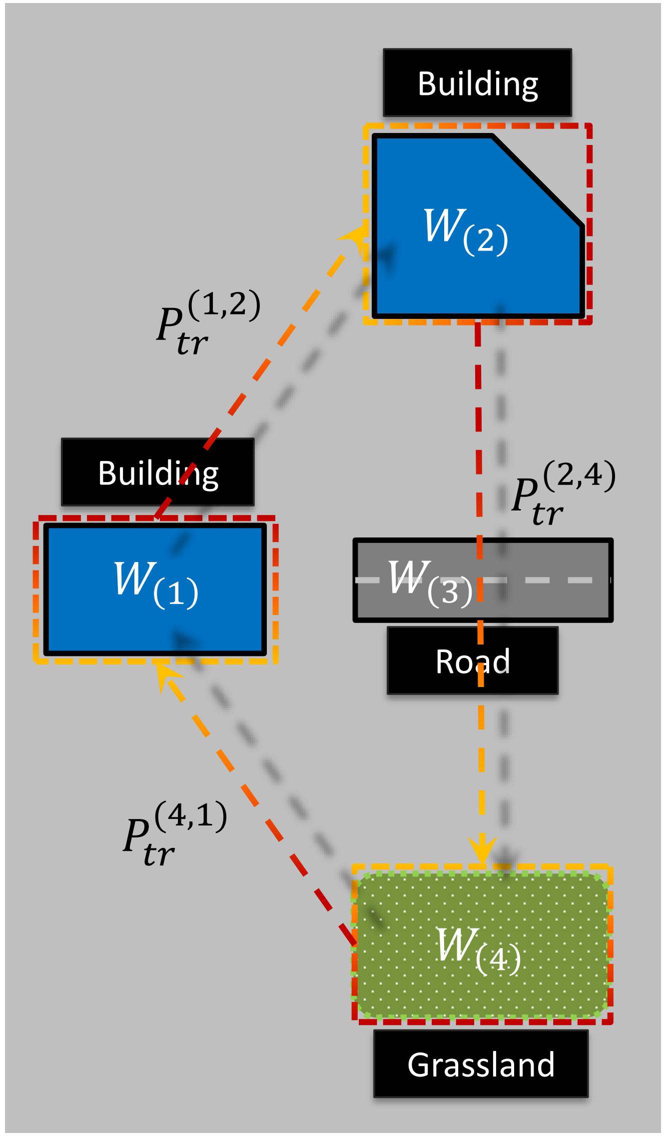
$P_{conv}^{(i,j)}$ = Probability of ignition due to **Convection**

$P_{rad}^{(i,j)}$ = Probability of ignition due to **Radiation**

$P_{ember}^{(i,j)}$ = Probability of ignition due to **Ember Spotting**

$P_{cond}^{(i,j)}$ = Probability of ignition due to **Conduction**

$W_{(m)}$ = Node set for Way *m*



Convection and Ember Model

Convection Model

$$P_{conv}^{(i,j)} = f\left(d^{(i,j)}, F_{cc}^{(i,j)}, h_f^{(i)}, \theta_f\right)$$

Distance between nodes

Effect of wind direction

Flame height

Flame angle

Ember Model

$$P_{ember}^{(i,j)} = h\left(P_{acc}^{(i,j)}, F_{cc}^{(i,j)}, g^{(i,j)}\right)$$

Access probability

Effect of wind direction

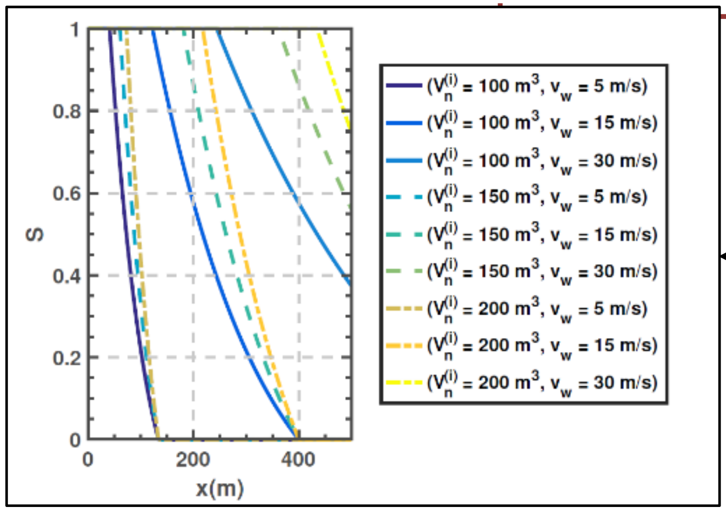
Ember distribution

$$g^{(i,j)} = S\left(V_n^{(i)}, d^{(i,j)}, v_w\right)$$

Volume of node

Distance between nodes

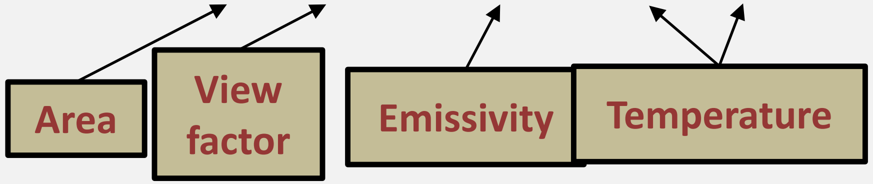
Wind velocity



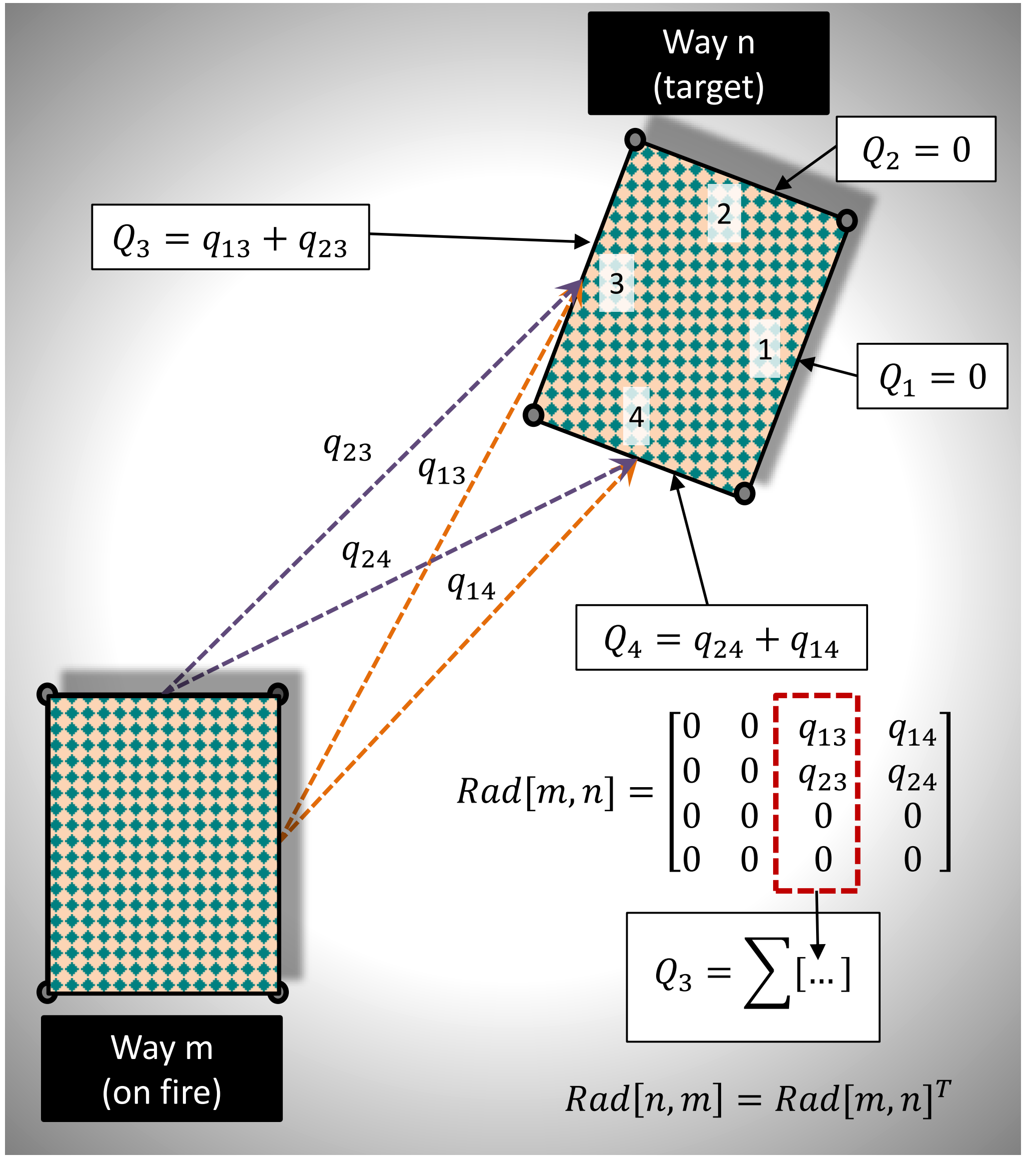
Radiation Model

- Stefan-Boltzmann law used to calculate radiation flux

$$q_{(k,l)}^{(m,n)} = \left(A_{(k)}^{(m)}\, vf_{(k,l)}^{(m,n)}\, \epsilon_{(k)}^{(m)}\, \sigma\left(T_f^4 - T_a^4\right)\right)$$



- Interaction between each possible source-target surface pair evaluated
- Independent view factors found due to varying relative surface inclination & size
- Net flux on each surface obtained as sum of flux from all surfaces of source way



$$Rad[m,n] = \begin{bmatrix} 0 & 0 & q_{13} & q_{14} \\ 0 & 0 & q_{23} & q_{24} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Q_3 = \sum[\dots]$$

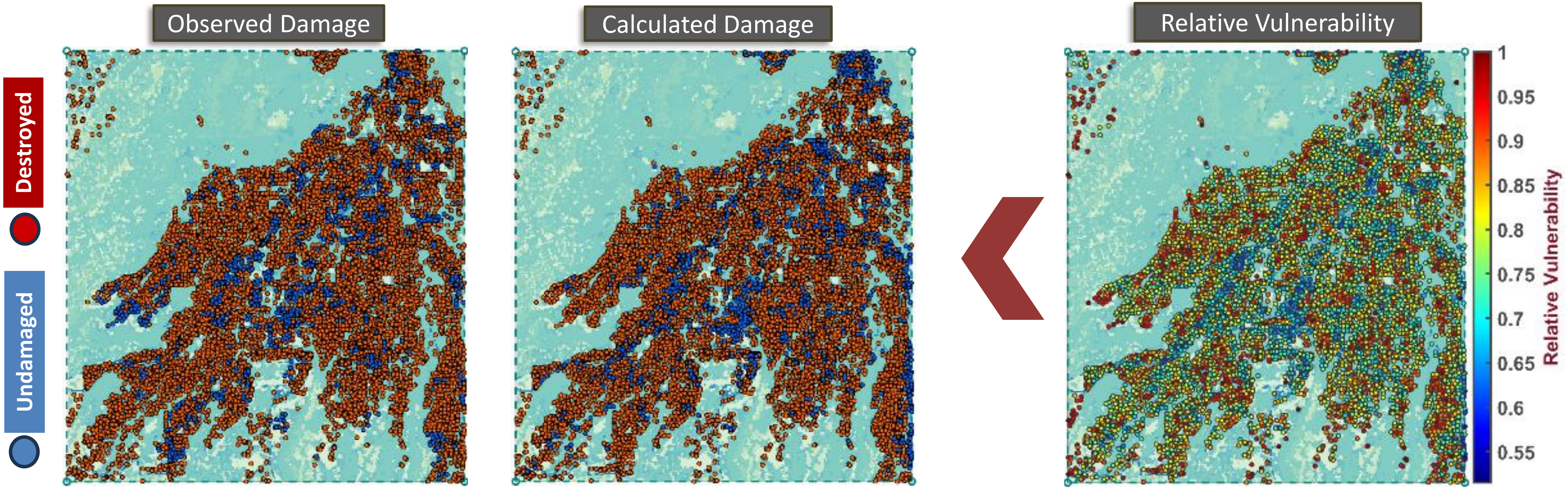
$$Rad[n,m] = Rad[m,n]^T$$

3

Damage Assessment

Survivability Likelihood

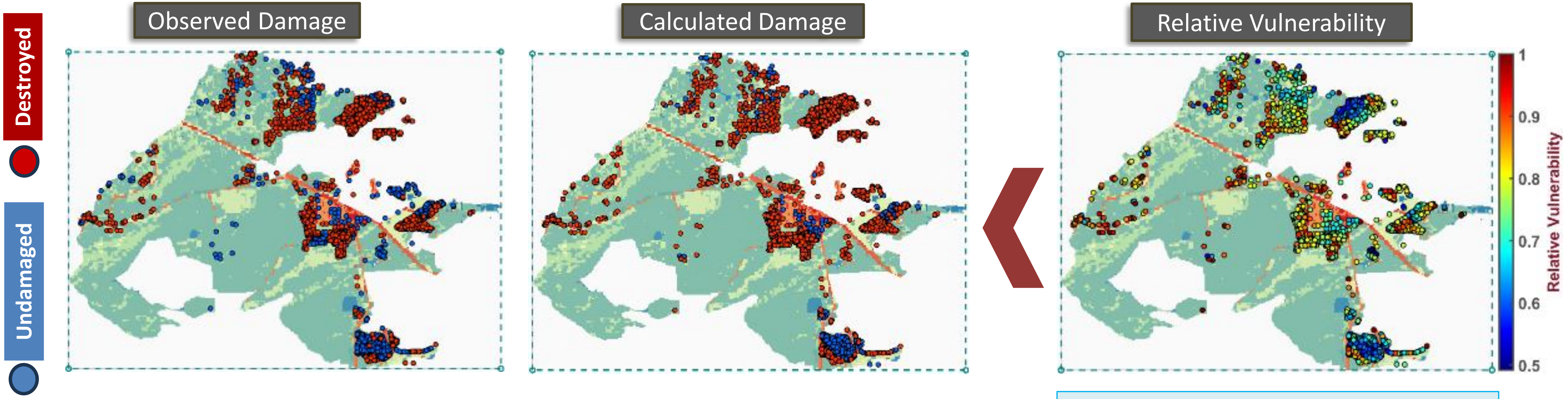
Damage Prediction for Camp Fire



Chulahwat et al. (2022) ***Sci. Rep.***

85% accuracy between observed and predicted damage

Damage Prediction for Marshall Fire

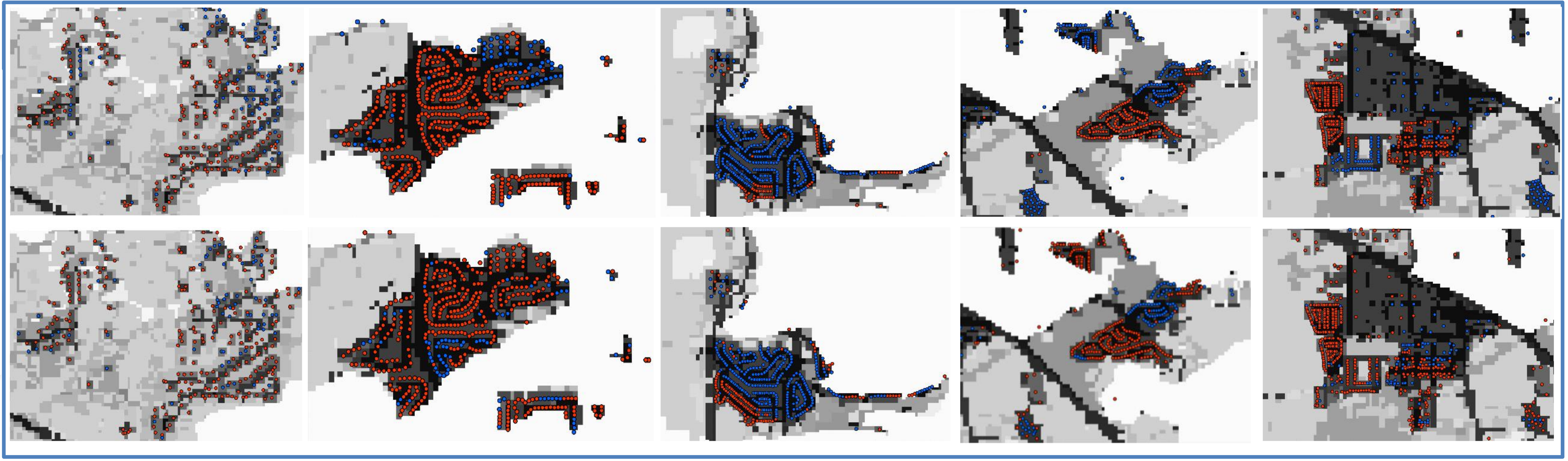


Chulahwat and Mahmoud (2023) ***Nat. Haz. Rev.***

72% accuracy between observed and predicted damage

Damage Prediction for Marshall Fire (1)

Zoomed-In Areas of the Affected Region

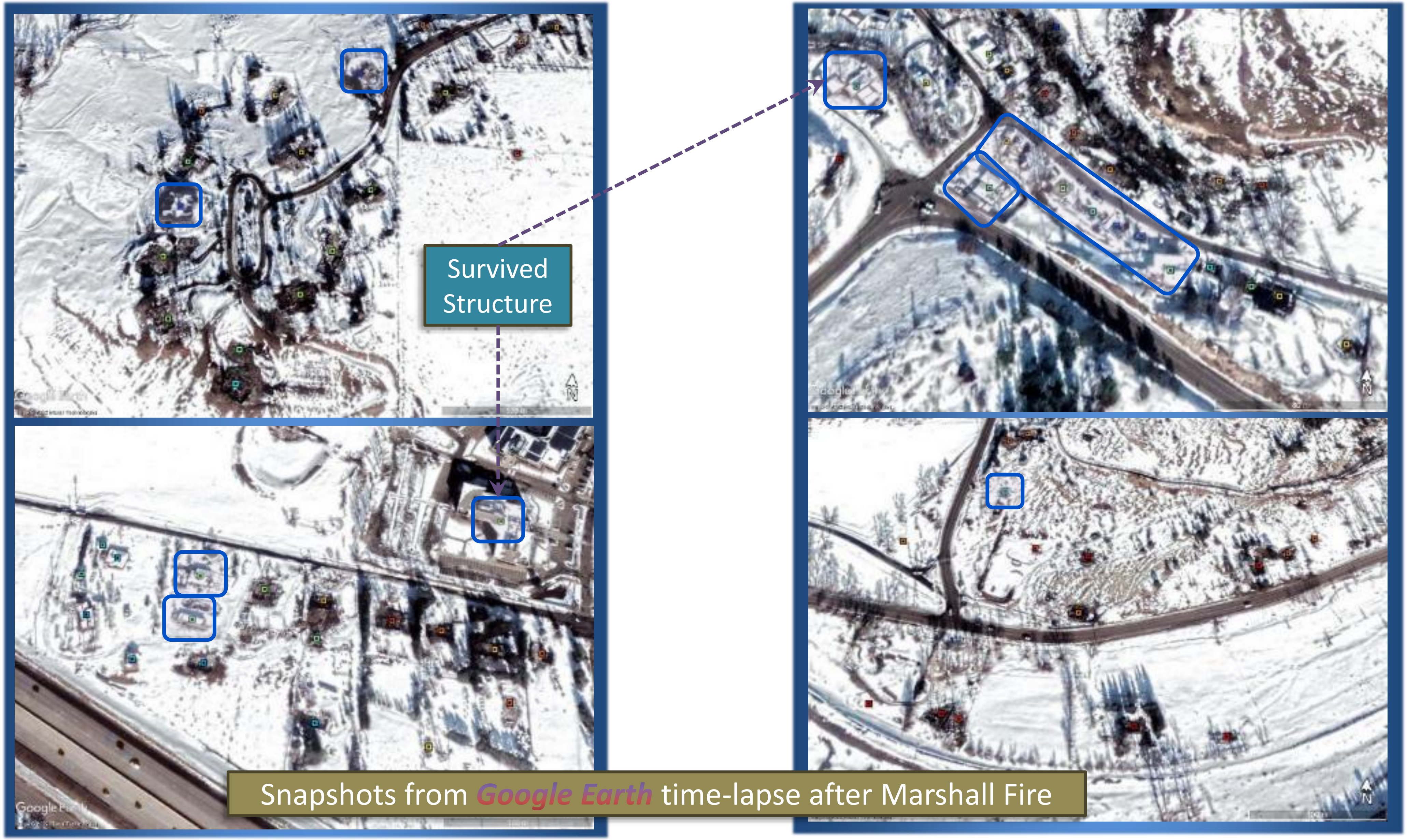


Observed Damage

Calculated Damage

Zoomed-in comparisons are good although some local behavior is not captured such as firefighting efforts and the impact of defensible space fuel due to lack of data

Damage Prediction for Marshall Fire (2)



Snapshots from *Google Earth* time-lapse after Marshall Fire

4

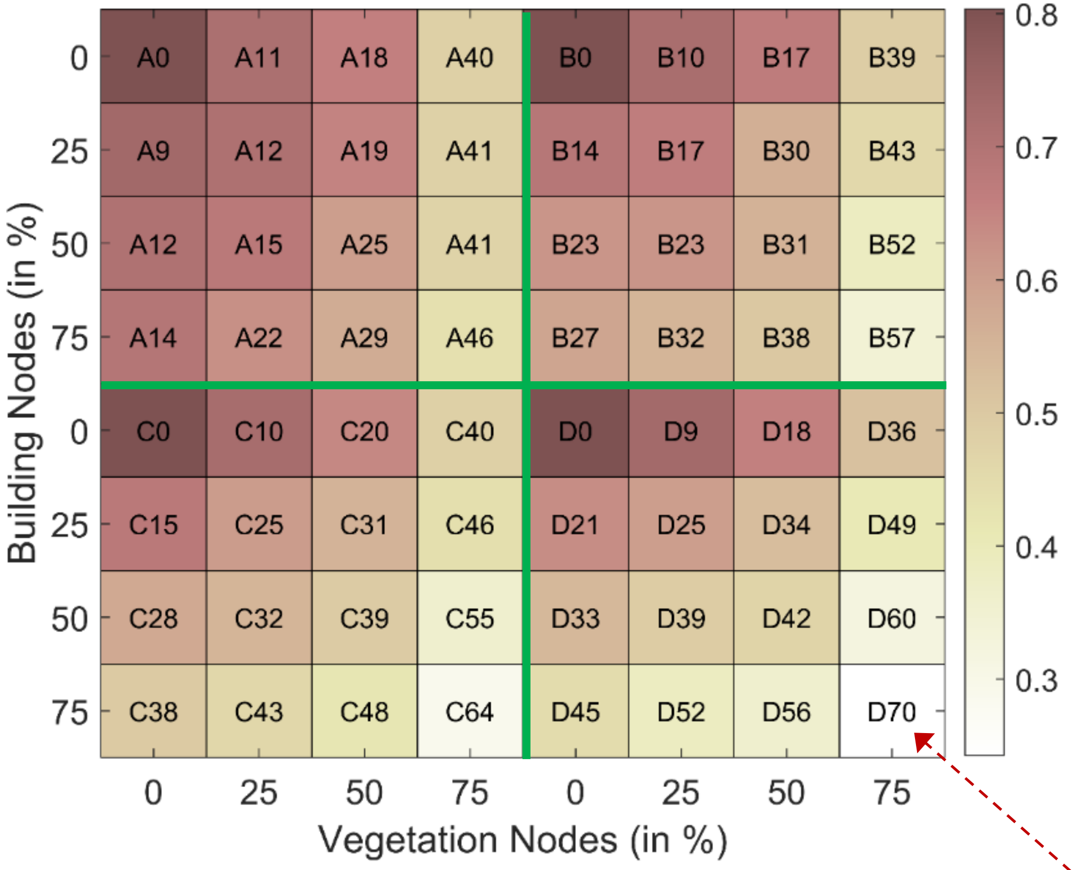
Vulnerability and Risk Reduction

Targeted Mitigation

Sensitivity Analysis Results

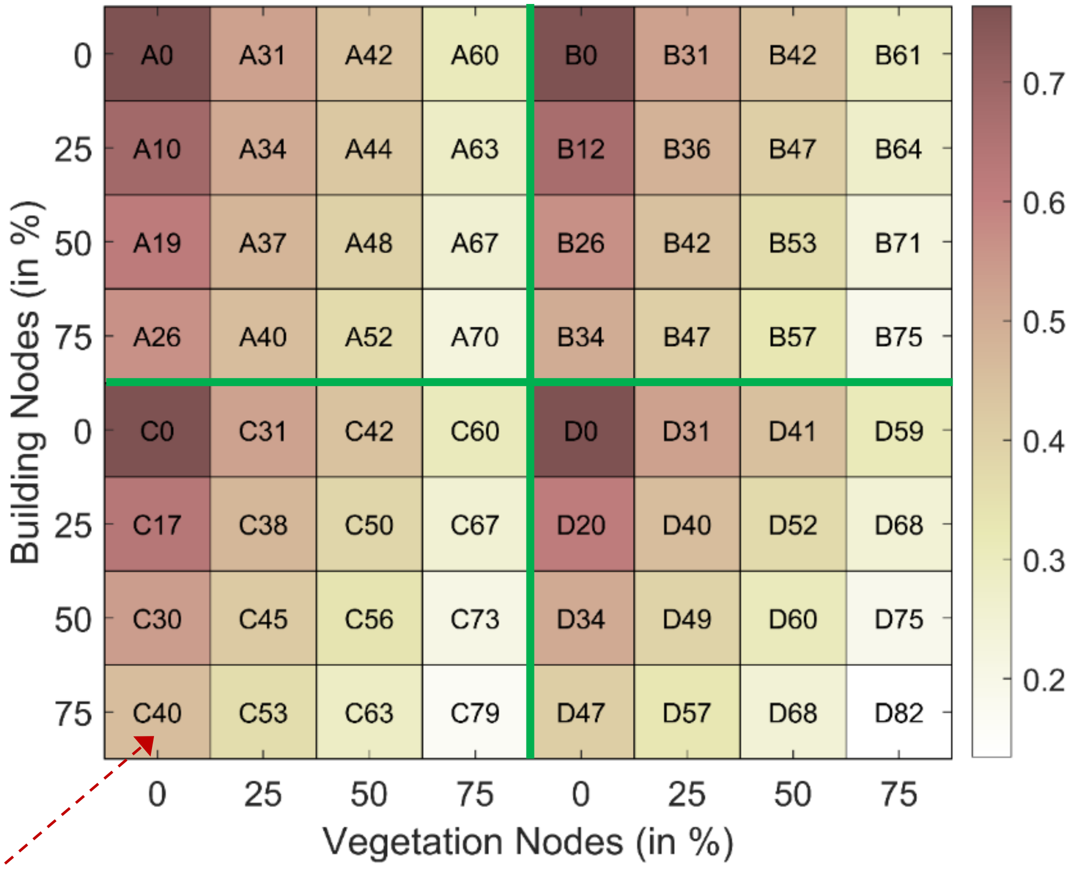
Building Hardening Strength **A = 25% B = 50% C = 75% D = 100%**

2018 Camp Wildfire



	0	25	50	75	0	25	50	75
0	A0	A11	A18	A40	B0	B10	B17	B39
25	A9	A12	A19	A41	B14	B17	B30	B43
50	A12	A15	A25	A41	B23	B23	B31	B52
75	A14	A22	A29	A46	B27	B32	B38	B57
0	C0	C10	C20	C40	D0	D9	D18	D36
25	C15	C25	C31	C46	D21	D25	D34	D49
50	C28	C32	C39	C55	D33	D39	D42	D60
75	C38	C43	C48	C64	D45	D52	D56	D70

2020 Marshall Wildfire



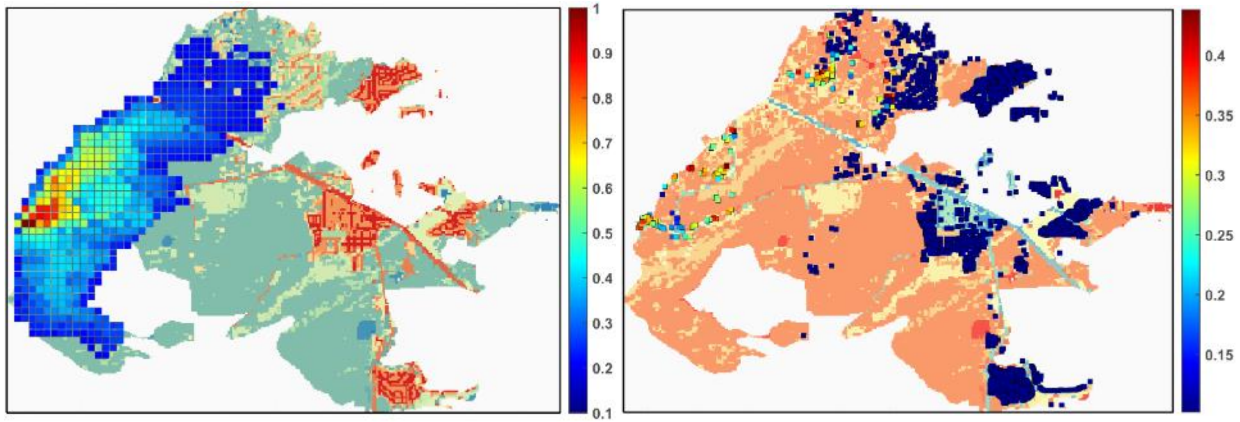
	0	25	50	75	0	25	50	75
0	A0	A31	A42	A60	B0	B31	B42	B61
25	A10	A34	A44	A63	B12	B36	B47	B64
50	A19	A37	A48	A67	B26	B42	B53	B71
75	A26	A40	A52	A70	B34	B47	B57	B75
0	C0	C31	C42	C60	D0	D31	D41	D59
25	C17	C38	C50	C67	D20	D40	D52	D68
50	C30	C45	C56	C73	D34	D49	D60	D75
75	C40	C53	C63	C79	D47	D57	D68	D82

Percentage Reduction in Mean Vulnerability from the case when no mitigations are applied

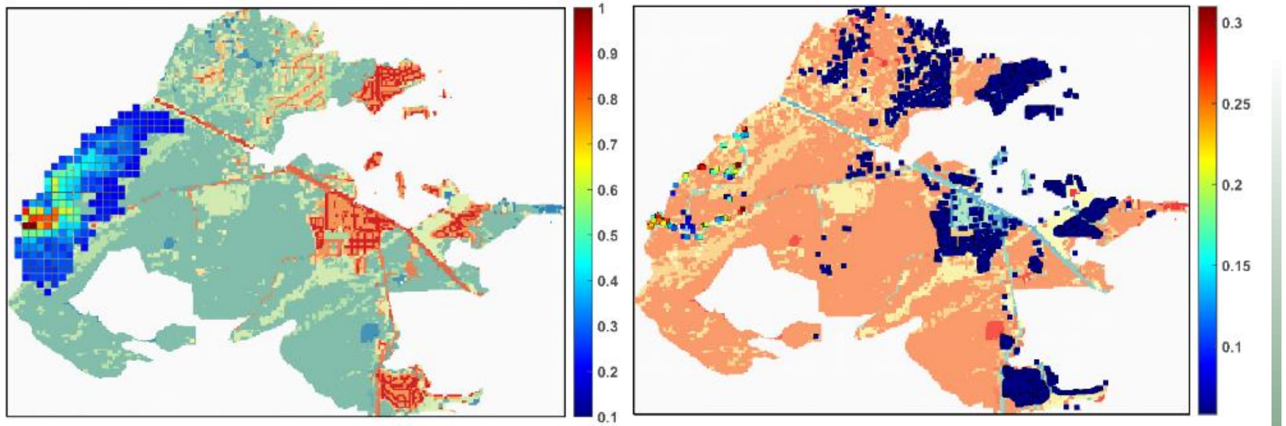
Wildfire Mitigation (Marshall Fire)

Wind Speed considered **10 m/s** with wind direction the same as Marshall fire

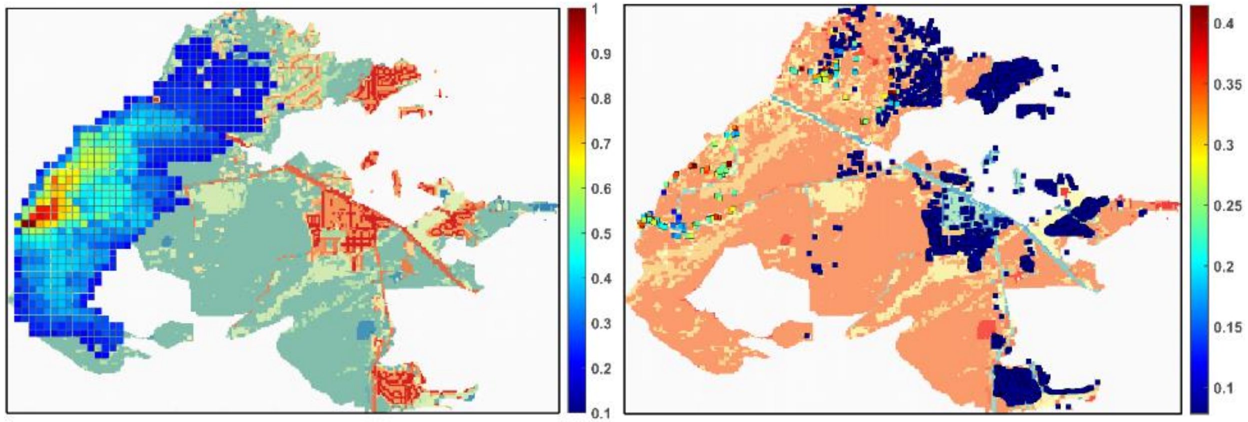
Building Mitigation = 0 % Vegetation Mitigation = 0 %



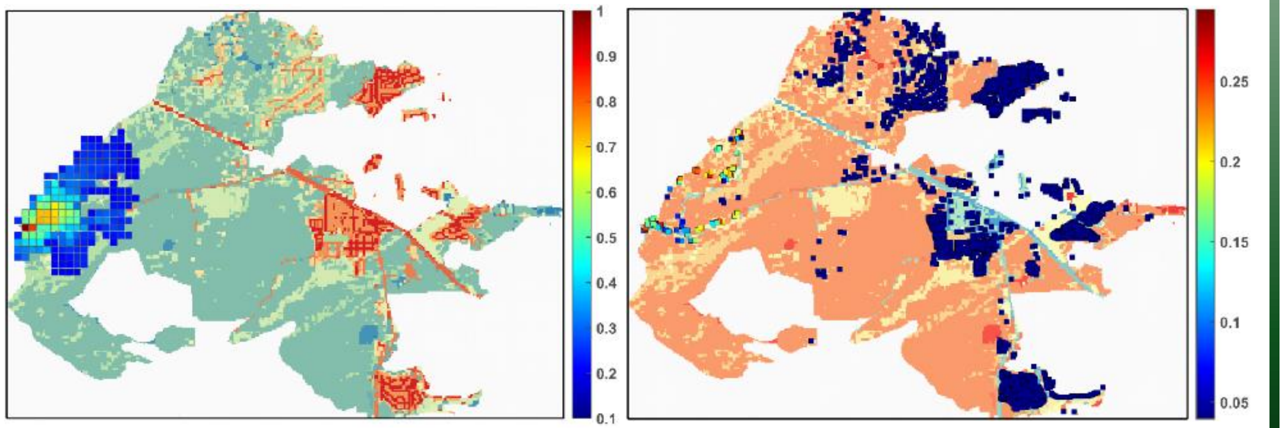
Building Mitigation = 0 % Vegetation Mitigation = 50 %



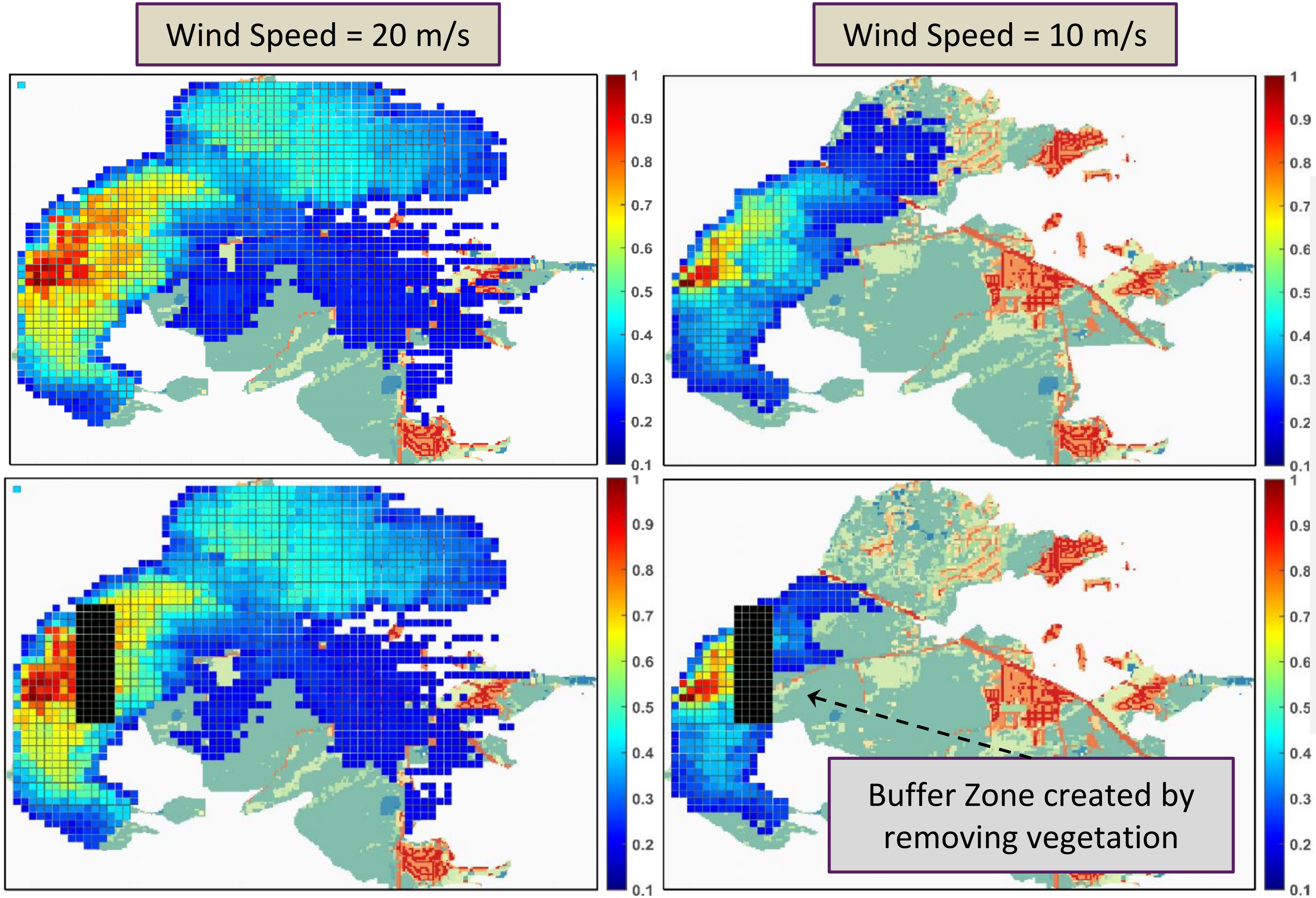
Building Mitigation = 50 % Vegetation Mitigation = 0 %



Building Mitigation = 50 % Vegetation Mitigation = 50 %



Vegetation Mitigation



Wind Speed = 20 m/s

Wind Speed = 10 m/s

Buffer Zone created by removing vegetation

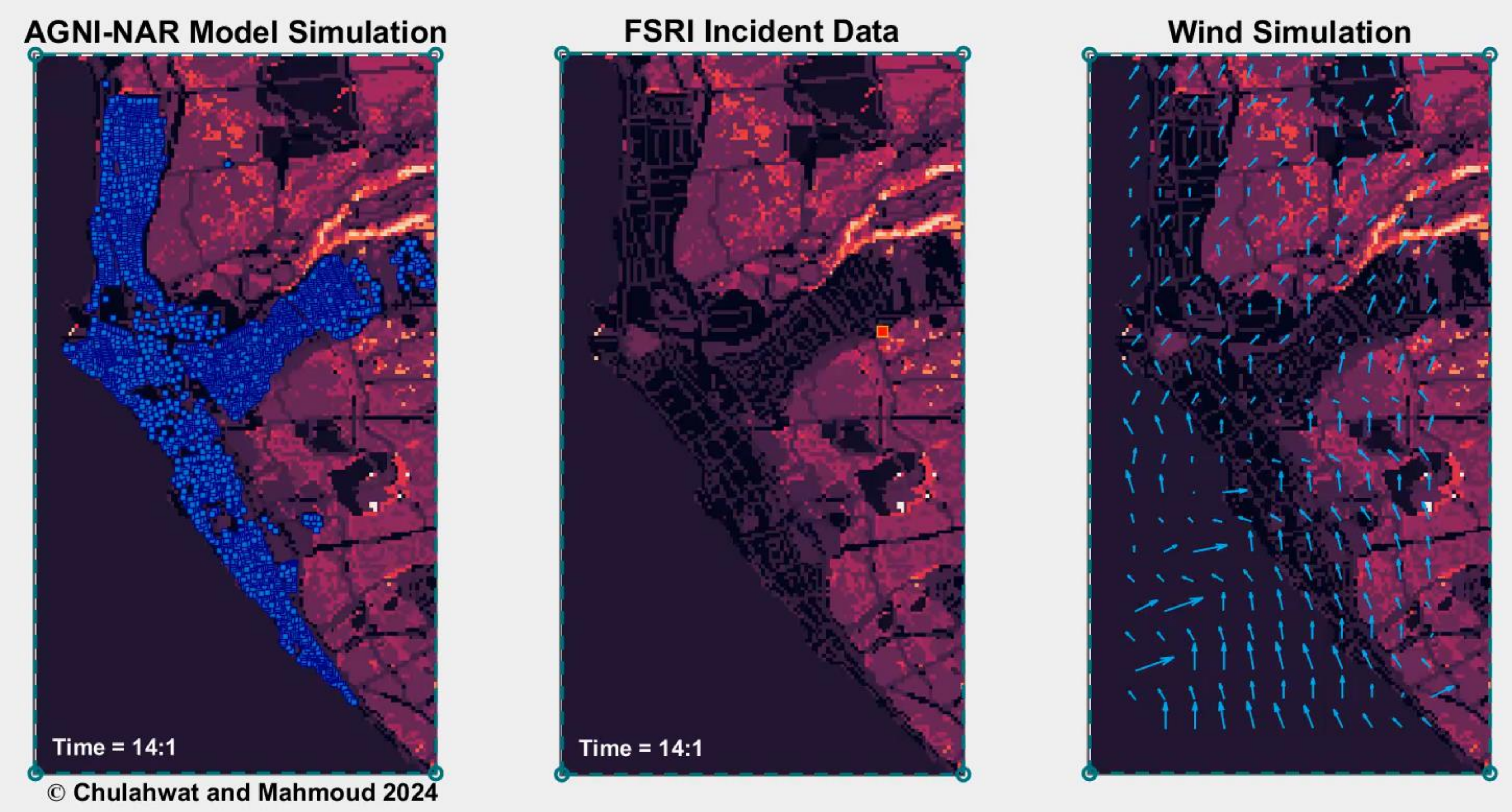
- Wildfire propagation shown after introduction of a buffer zone (750 x 2500 m) created by removing vegetation areas
- The results demonstrate that the effectiveness of the buffer zone reduces significantly at higher wind speeds

6

Future Work

Fire Mitigation Policies

Time-Dependent Propagation – Lahaina 2023



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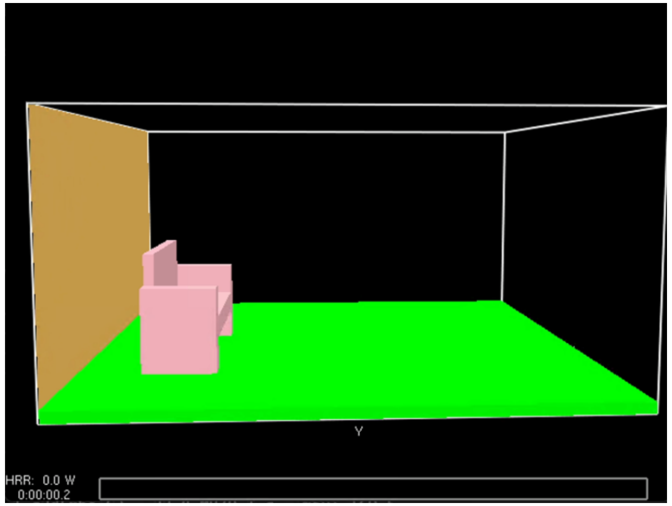
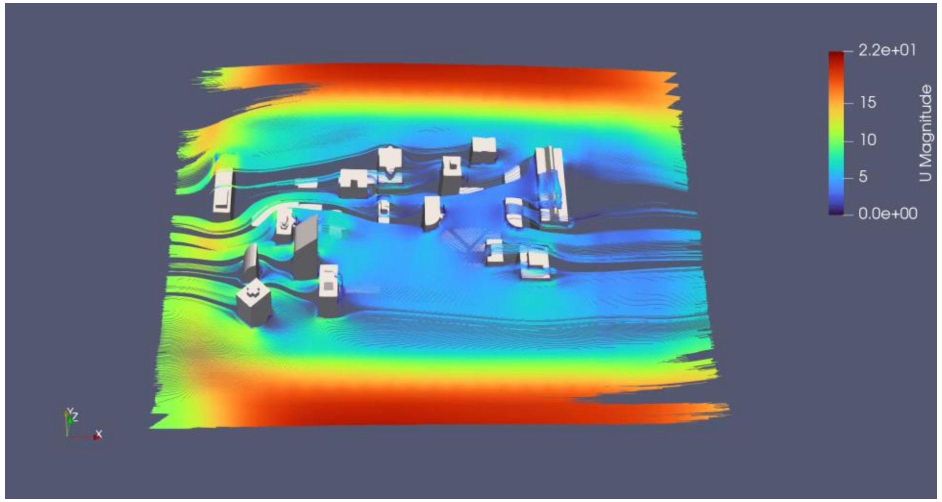
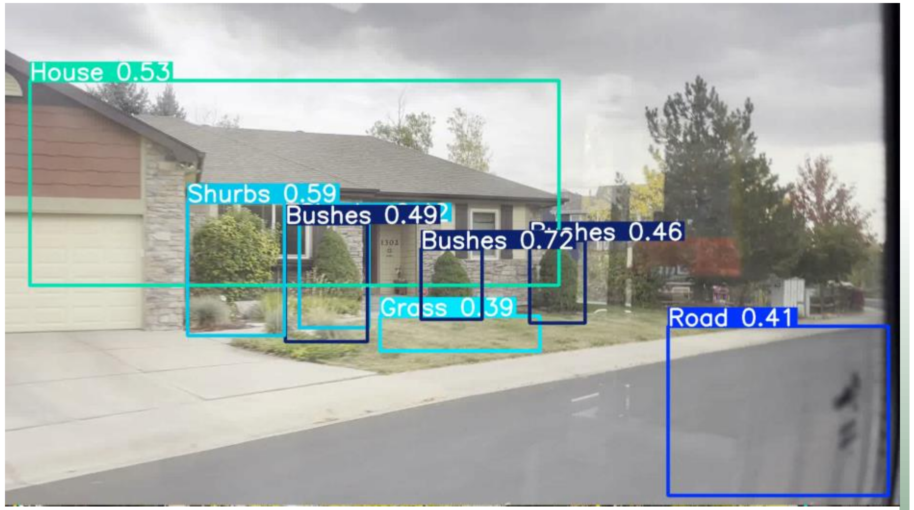
Fuel Interaction, Refined Wind, and Automated Data



Need to capture local interaction and modify the graph accordingly



Need more detailed wind field at the community level



Need to automate data collection and include people in the process

- Vulnerability versus risk.
- The role of urban growth and climate change.
- Balancing acceptable structural losses and ecological health.
- The social dilemma of enforcing mitigations.

THANK YOU!

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QUESTIONS?

For more information
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Or visit us at
http://www.engr.colostate.edu/~hmahmoud

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RAPID NHERI Natural Hazards Reconnaissance

NSF