



# Analyzing the Vulnerability of Landscapes to Pyro-terrorism

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# Presentation Outline

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A stylized graphic of a flame, rendered in shades of yellow, orange, and red, with a glowing effect. The flame is composed of several pointed, overlapping shapes that create a sense of movement and heat. The word "Introduction" is centered over the flame.

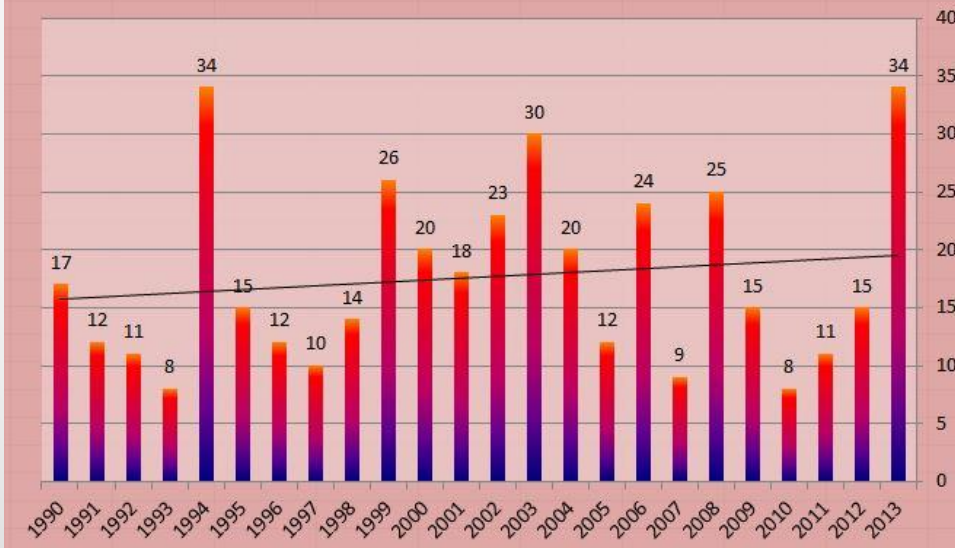
# Introduction

# Wildfires

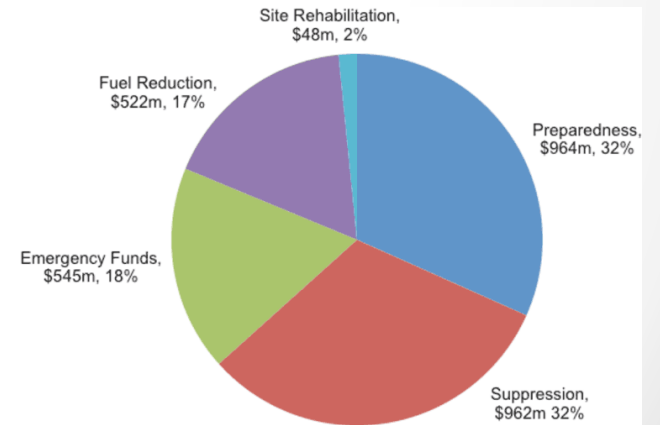


### Wildland Fire Fatalities in United States, 1990 - 2013

Data from NIFC



### Wildfire protection fundings on federal lands, FY 2002-2012



# Pyro-terrorism

- Pyro-terrorism is defined as the use of large-scale arson attacks by non-state organizations to terrorize, intimidate or coerce a government, the civilian population, or any segment in order to advance, political or social objectives (Bendele 2009).
- Pyro-terrorism events have been documented in Israel, France, Spain, and Greece (Baird, 2006; Deshpande, 2009).



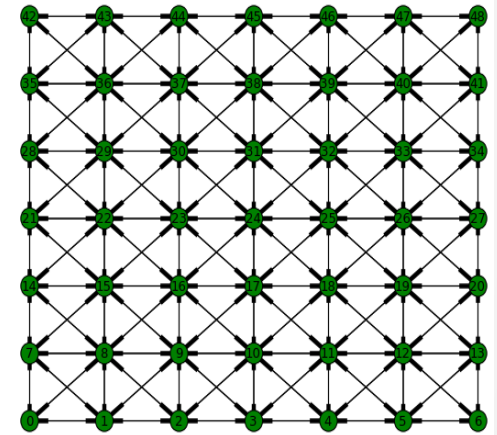
A stylized graphic of a flame, rendered in shades of yellow, orange, and red, with a soft glow. The flame is composed of several pointed, overlapping shapes that create a sense of movement and heat. The colors transition from bright yellow at the base to deep red at the tips.

# Problem Description

# Modeling Fire Spread



43	44	45	46	47	48	49
36	37	38	39	40	41	42
29	30	31	32	33	34	35
22	23	24	25	26	27	28
15	16	17	18	19	20	21
8	9	10	11	12	13	14
1	2	3	4	5	6	7

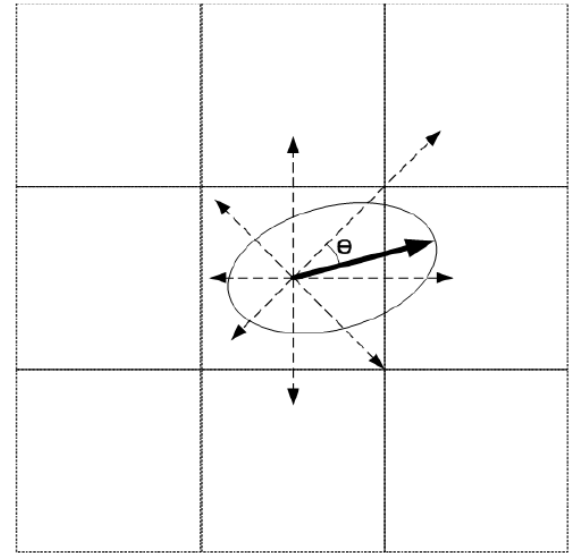


Graph  $G(V,E)$

# Rate of Spread of Fire

$$[A1] \quad R = \frac{b^2 - c^2}{b - c \times \cos(\theta)} \quad (0 \leq \theta < \pi/2)$$

$$[A2] \quad R = \frac{b^2 - c^2}{b + c \times \cos(\pi - \theta)} \quad (\pi/2 \leq \theta < \pi)$$



Retrieved from (Wei 2012)

- $b$  and  $c$  are standard parameters describing an ellipse.
- $c$  denotes half of the distance between two foci.
- $b$  denotes half of the length of the major axis.



# Assumptions

- It is assumed that fire spreads through the network using paths with the minimum travel time.
- In case of multiple fires, the interactions between fires are ignored.
- It is assumed that all fires can be controlled within duration  $d$ .
- Cell  $r$  is assumed burnt when the first fire reaches its center.
- Fire is assumed to spread in an elliptical shape within each cell.
- Areas outside the boundary of the landscape are assumed unburnable.
- The fire intensity for every cell is assumed high.
- To consider the worst case scenario, it is assumed that Pyro-terrorists know the geographical characteristics of the landscape, the wind direction, and major fire spread in each cell.



# Mixed Integer Programming Model

# Notations

- Sets and indexes:

$D$  and  $d$ : the set and index of expected fire durations.

e.g.:  $D = \{12, 18, 24, 30, 36, 42, 48\}$

$C$ : the set of raster cells in a landscape;  $r$ ,  $i$  and  $j$  are the index of raster cells in a landscape.

$C'$ : the set of raster cells with high fire intensity in a landscape.

$N_r$ : the set of raster cells in the neighborhood of cell  $r$

# Notations

- Parameters:

$L_{i,j}$ : The distance between the center of cell  $i$  and the center of cell  $j$

$t_{i,j} = \frac{L_{i,j}}{R_{i,j}}$ : the fire spread time from cell  $i$  to  $j$

$B$ : the budget denotes a limit on the number of ignition points

$p_d$ : the probability of a fire lasting for a duration  $d$

$v_r$ : the value of cell  $r$  to be protected from fire

# Notations

- Variables:

$x_{r,i,j}$ : 1 if the shortest path to cell  $r$  from an ignition point passes cell  $i$  and  $j$  (link  $(i, j)$  is in the shortest path), 0 otherwise.

$z_j$ : 1 if a fire starts at cell  $j$ , 0 otherwise.

$y_{d,r}$ : 1 if cell  $r$  is reached and therefore burnt by a fire within duration  $d$ , 0 otherwise.

# Mixed Integer Programming (I)

$$\text{Max } f = \sum_d \sum_r P_d \times V_r \times y_{d,r} \quad (1)$$

s. t.:

$$x_{r,0,j} \leq z_j \quad \forall j, r \quad (2)$$

$$\sum_{j \in N(i)} x_{r,i,j} - \sum_{j \in N(i)} x_{r,j,i} = \begin{cases} 1 & i = 0 \\ 0 & i \neq 0, r \\ -1 & i = r \end{cases} \quad \forall i, d, r \quad (3)$$

$$y_{d,r} \leq \frac{d}{\sum_{(i,j)} x_{r,i,j} t_{i,j}} \quad \forall d, r \quad (4)$$

$$\sum_j z_j \leq B \quad (5)$$



## When is a Cell Burnt?

$$y_{d,r} \leq \frac{d}{\sum_{(i,j)} x_{r,i,j} t_{i,j}} \quad \forall d, r \quad (4)$$

- $\sum_{(i,j)} x_{r,i,j} t_{i,j} \leq d \quad \Rightarrow \quad \frac{d}{\sum_{(i,j)} x_{r,i,j} t_{i,j}} \geq 1$

$y_{d,r}$  can take a value of 1  $\Rightarrow$  cell r is burnt with fires lasting d.

- $\sum_{(i,j)} x_{r,i,j} t_{i,j} > d \quad \Rightarrow \quad \frac{d}{\sum_{(i,j)} x_{r,i,j} t_{i,j}} < 1$

$y_{d,r}$  cannot take a value of 1  $\Rightarrow$  cell r is Not burnt with fires lasting d.

## Mixed Integer Programming (II)

$$\text{Max } f = \sum_{d \in D} \sum_{r \in C} P_d \times V_r \times y_{d,r} \quad (1)$$

s. t.:

$$y_{d,r} \leq \sum_{j \in C} \varphi_{d,r,j} z_j \quad \forall d, r \quad (2)$$

$$\sum_{j \in C} z_j \leq B \quad (3)$$

$\varphi_{d,r,j}$

1 if the length of the shortest path from  $j$  to  $r$  is less than  $d$ , 0 otherwise

## When is a Cell Burnt?

$$y_{d,r} \leq \sum_j \varphi_{d,r,j} z_j \quad \forall d, r \quad (2)$$

If there is at least one ignition point which can cover cell  $r$ , (its fire can reach cell  $r$  within  $d$ ), then cell  $r$  is considered as burnt.

$$\exists j \quad z_j = 1 \quad \& \quad \varphi_{d,r,j} = 1 \quad \Rightarrow \quad y_{d,r} = 1.$$

A stylized graphic of a flame, rendered in shades of yellow, orange, and red, with a white outline. The flame is positioned centrally on the page, behind the text.

# Experimentation

# Artificial Landscapes

Type 1

45	45	45	45	45	45	45
45	45	45	45	45	45	45
45	45	45	45	45	45	45
45	45	45	45	45	45	45
45	45	45	45	45	45	45
45	45	45	45	45	45	45
45	45	45	45	45	45	45

Type 2

225	225	225	225	225	225	225
45	225	225	225	225	225	225
45	45	225	225	225	225	225
45	45	45	225	225	225	225
45	45	45	45	225	225	225
45	45	45	45	45	225	225
45	45	45	45	45	45	225

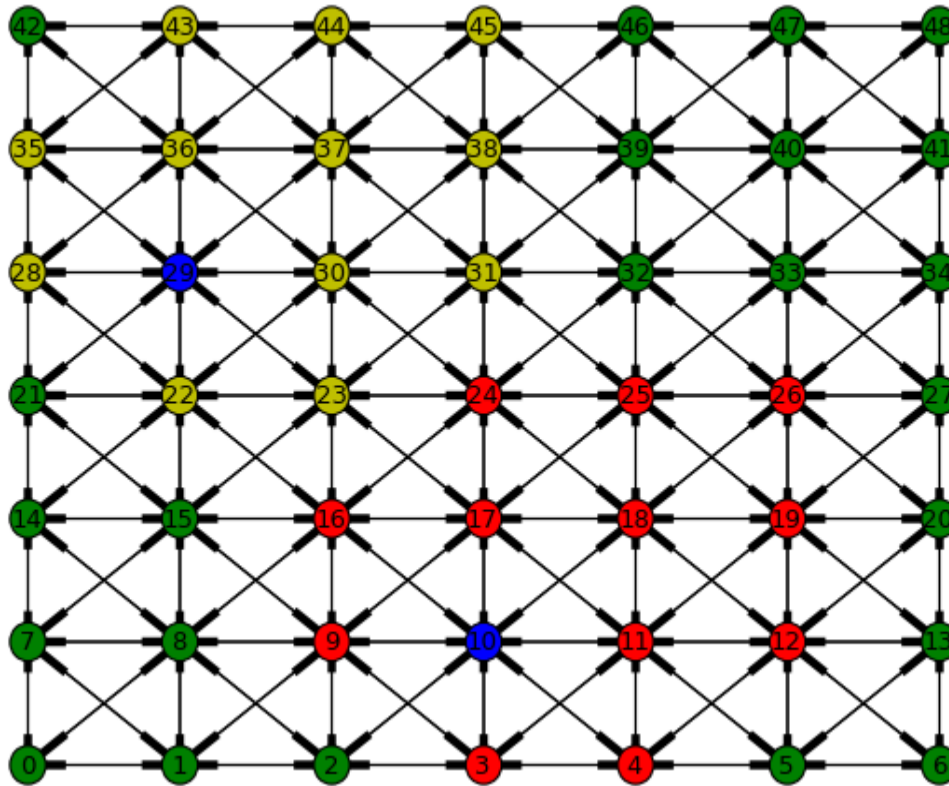
Type 3

315	315	315	0	45	45	45
315	315	315	0	45	45	45
315	315	315	0	45	45	45
270	270	270	0	90	90	90
225	225	225	180	135	135	135
225	225	225	180	135	135	135
225	225	225	180	135	135	135

Type 4

124	108	278	91	336	60	11
93	161	128	116	280	344	25
3	198	307	199	292	356	196
107	158	228	278	262	176	15
30	73	166	155	193	96	21
0	291	119	278	311	9	52
172	183	245	314	205	152	185

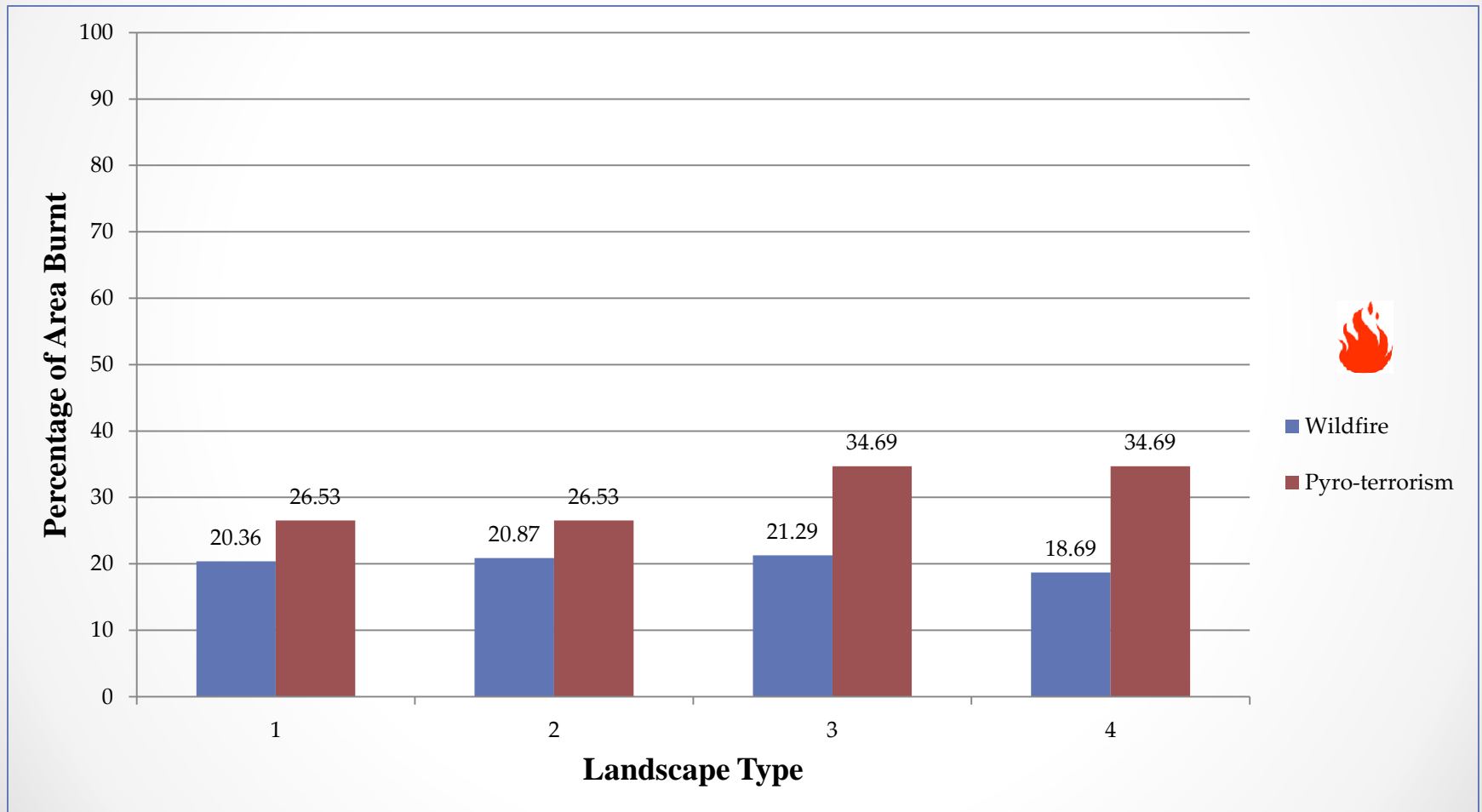
# Example: Pyro-terrorism with 2 ignition points



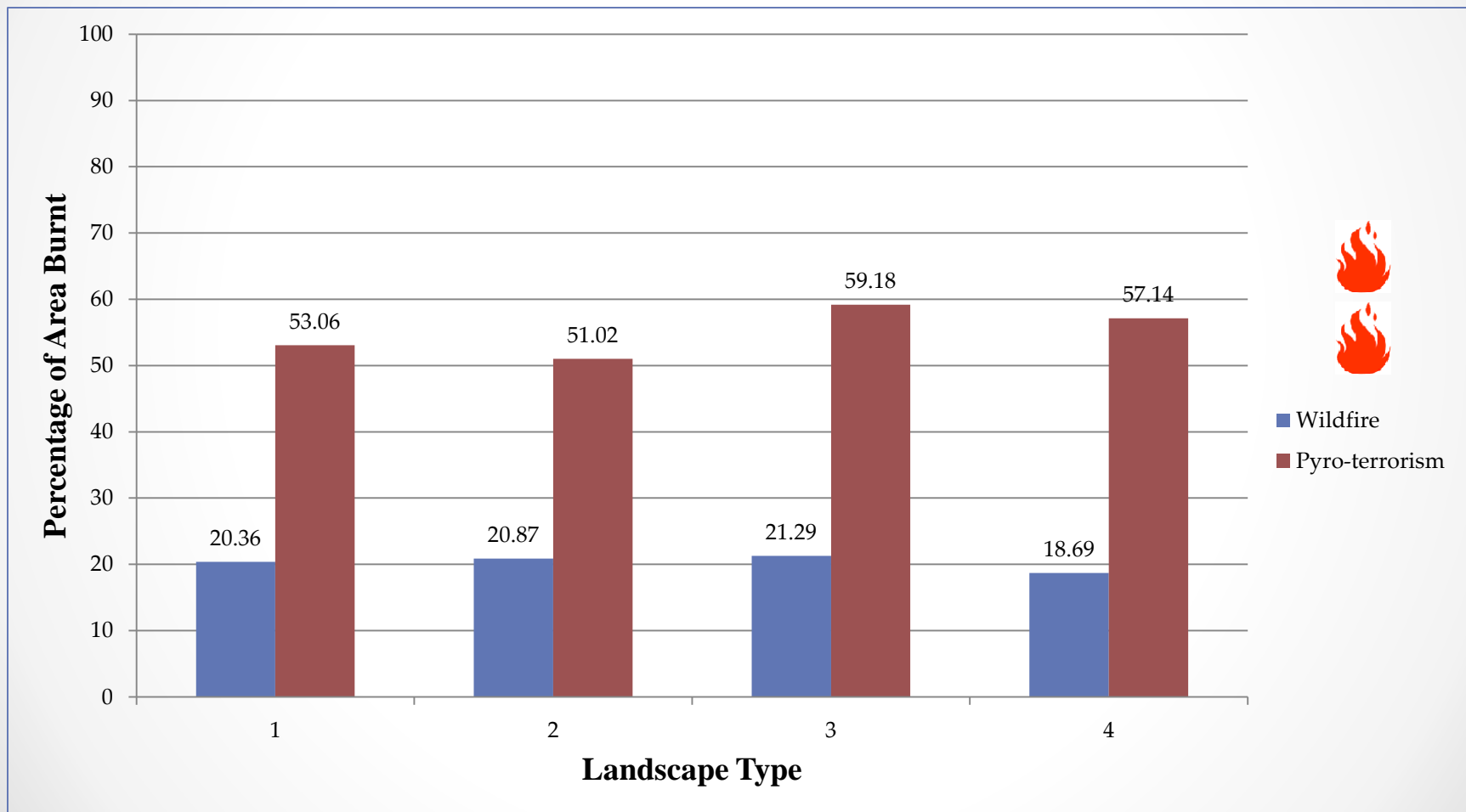
Type 1



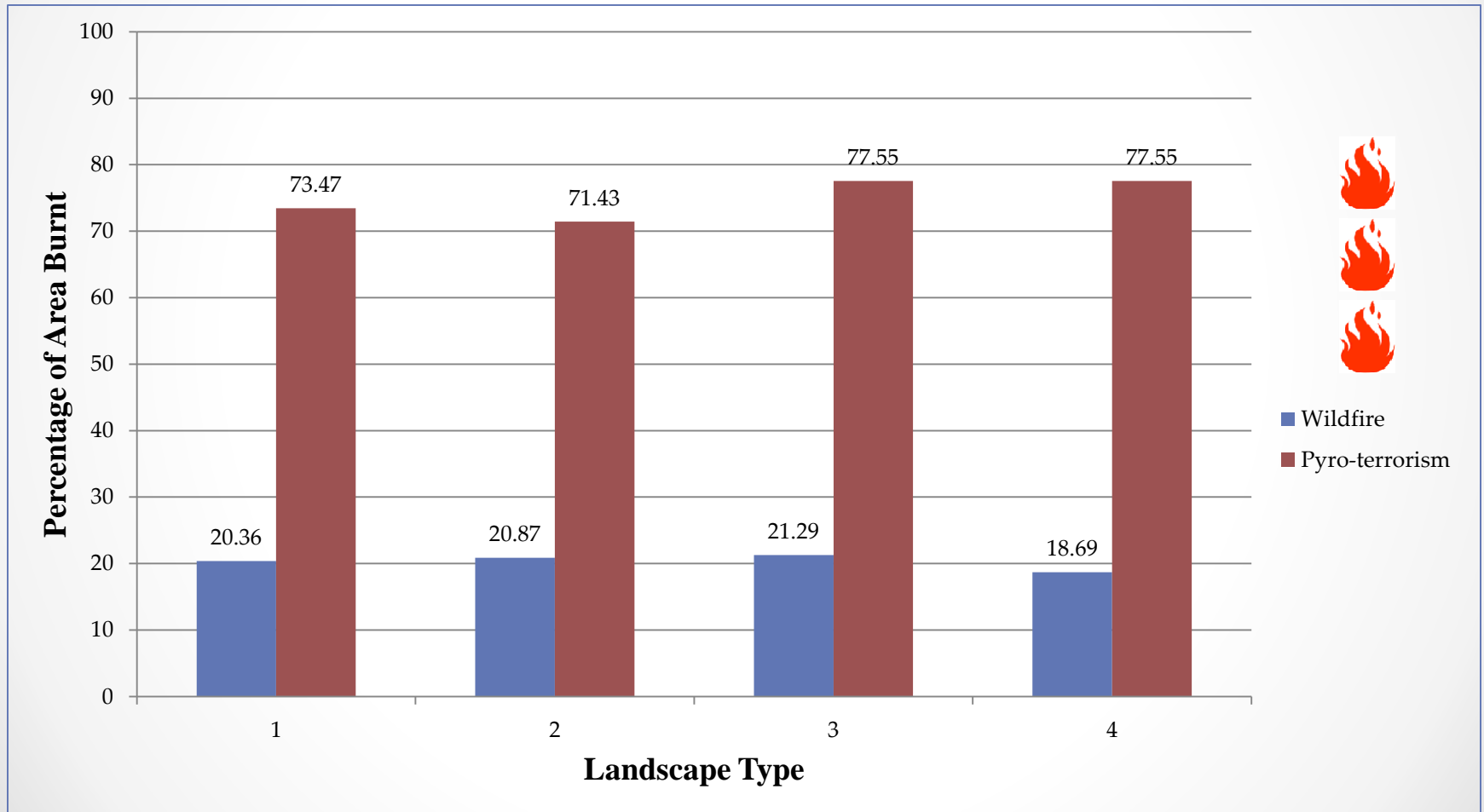
# Wildfire V.S. Pyro-terrorism with 1 ignition points



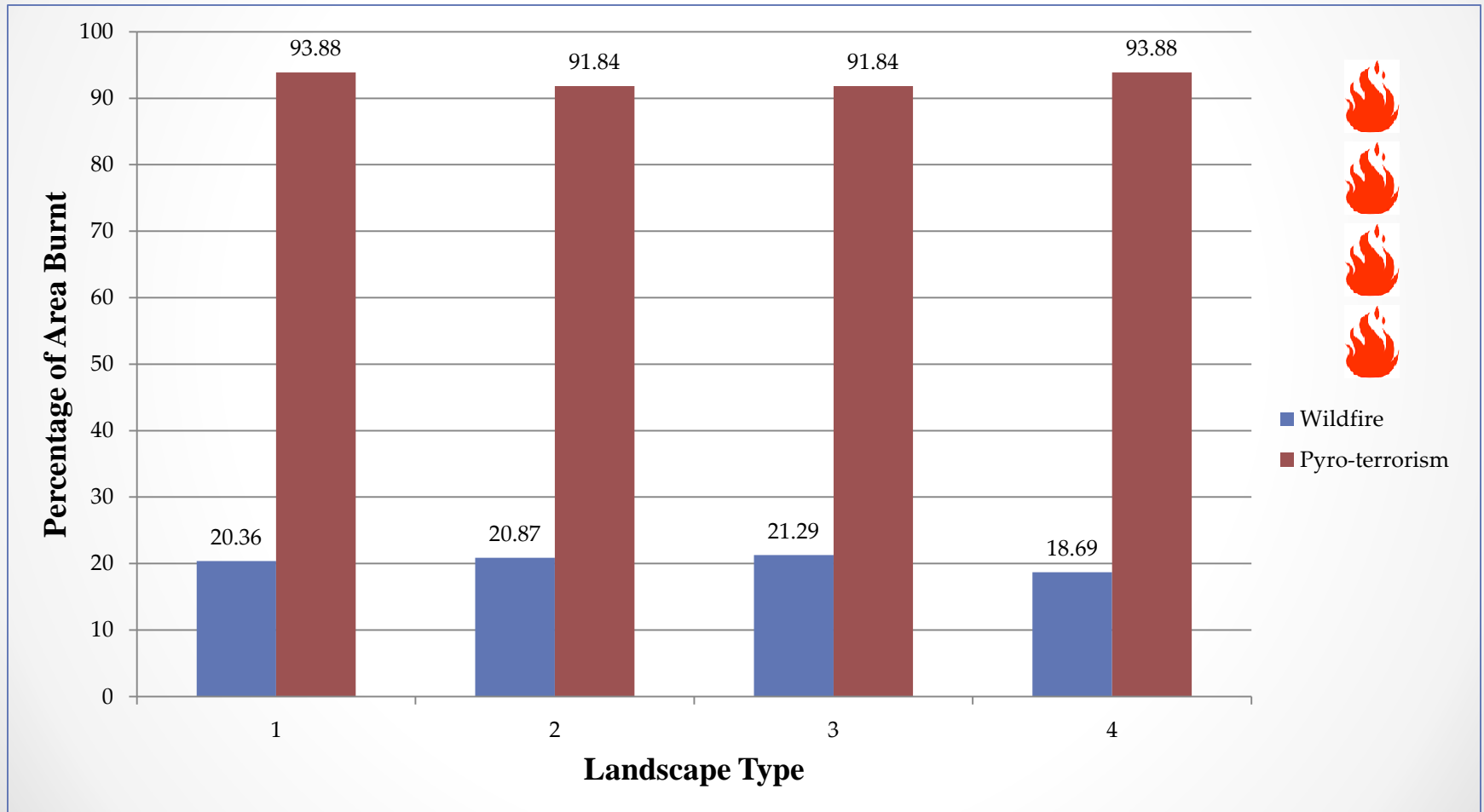
# Wildfire V.S. Pyro-terrorism with 2 ignition points



# Wildfire V.S. Pyro-terrorism with 3 ignition points



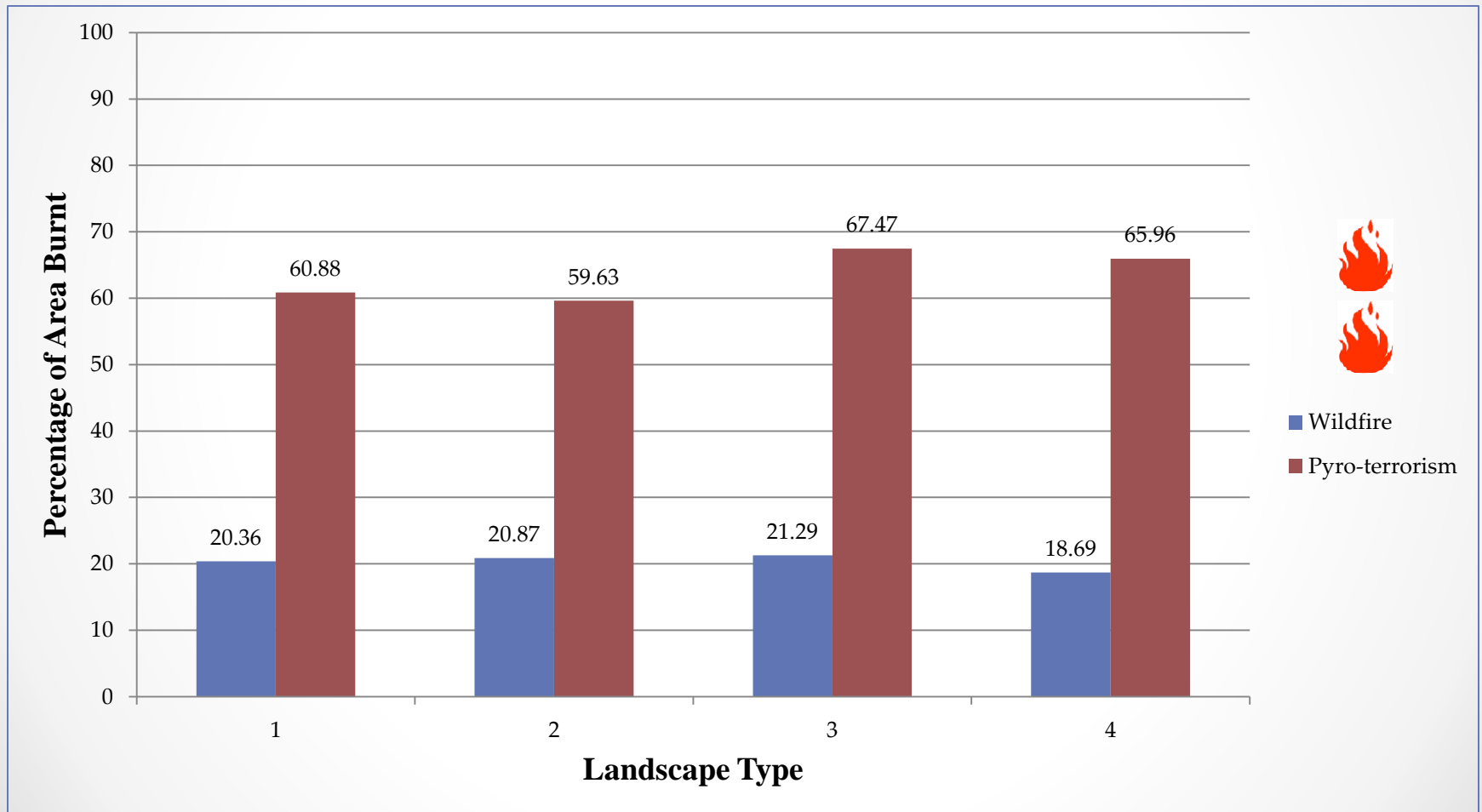
# Wildfire V.S. Pyro-terrorism with 4 ignition points



# Longer Fire Duration: Multiple Fire Effect

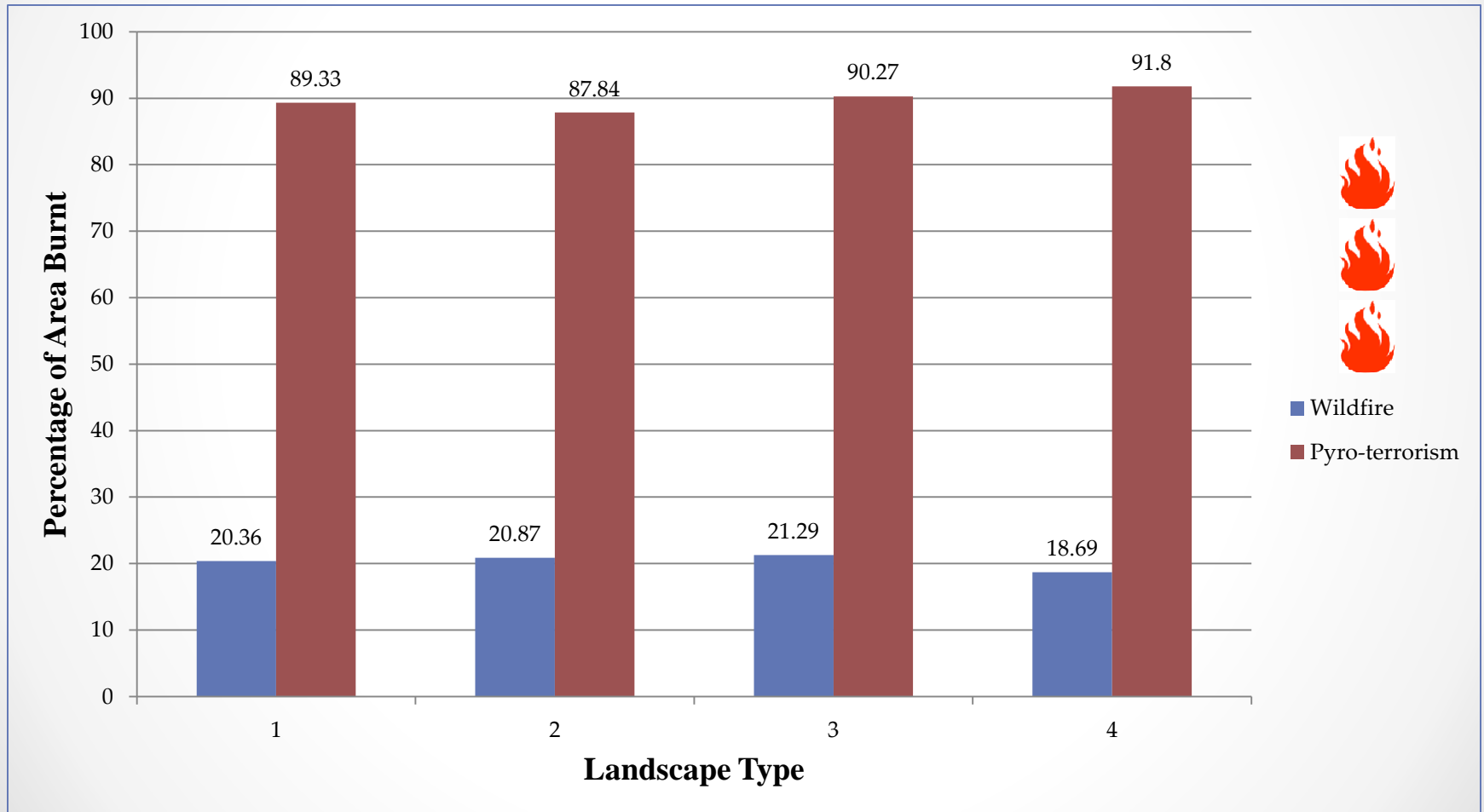
Fire Duration	Number of Ignition Points		
	2	3	4
12	0.09	0.01	0.0
18	<b>0.13</b>	0.04	0.0
24	<b>0.22</b>	<b>0.14</b>	0.01
30	<b>0.34</b>	<b>0.28</b>	0.09
36	0.16	<b>0.36</b>	<b>0.21</b>
42	0.05	0.13	<b>0.34</b>
48	0.01	0.04	<b>0.36</b>

# Wildfire V.S. Pyro-terrorism with 2 ignition points

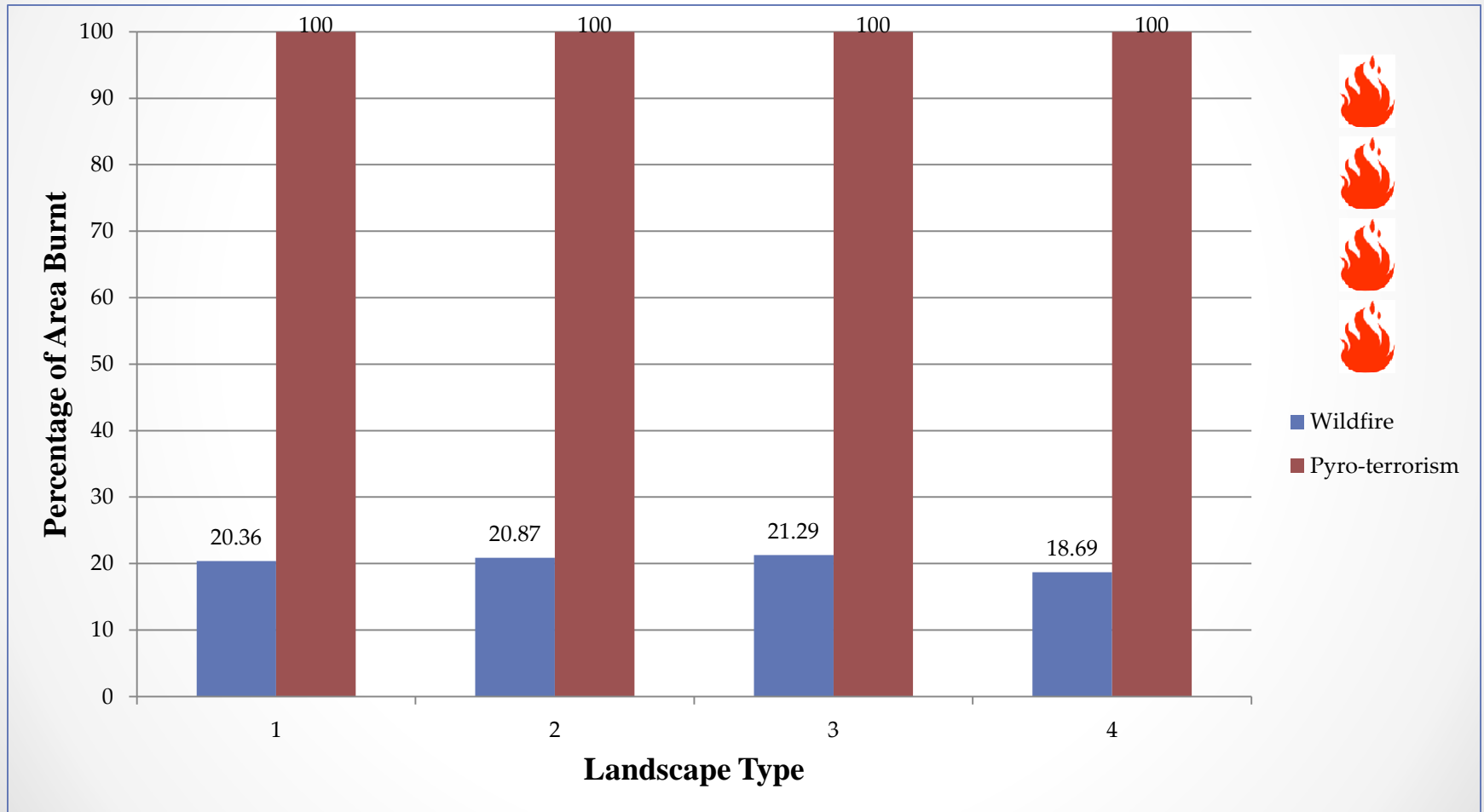




# Wildfire V.S. Pyro-terrorism with 3 ignition points



# Wildfire V.S. Pyro-terrorism with 4 ignition points



A stylized graphic of a flame, rendered in shades of yellow, orange, and red, positioned centrally behind the text.

# Summary & Conclusions

# Summary & Conclusion

- Pyro-terrorism with carefully selected ignition points can be more destructive than wildfires with random ignition point.
- In our experiments with four artificial landscapes, in average, a wildfire can burn 20.30% of the landscapes, while Pyro-terrorism fires with two, three and four ignition points burn 55.1%, 75%, and 92.86% of the landscape respectively.
- Given that the fire interactions between multiple fires intensifies the fire and makes it harder to be put out. They can last longer and do more damage.

# Summary & Conclusion

- In all the cases we have assumed that each cell in the landscape has the same value = 1, however in reality each cell can have different value based on vegetation type, the existence of wildland-urban interface (WUI) in some cells, and that makes these cells the targets for Pyro-terrorism to burn.
- Next we want to develop a network interdiction model to mitigate the Pyro-terrorism using fuel management as the interdiction strategy.

Thanks for your attention

Question?

# References

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- Bendle, Mervyn F., "Australia's nightmare: bushfire jihad and pyroterrorism", *National Observer* (Council for the National Interest, Melbourne) 79 (2009), pp. 8--22.
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