Firecracker

Wildfire Modeling and Leveraging AI for Strategic Wildfire Suppression

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Photo credit: rawpixel.com
The Harris Fire

Stage 1: a small fire

Photo credit: rawpixel.com

Photo credit: Hagerty Ryan, USFWS

Stage 2: ground fuel burns quickly

Photo credit: Josh O'Connor, USFWS

Photo credit: rawpixel.com,
Thomas Mountain
Wildfire in the San Jacinto Mountains

Stage 3: fire slowly climbs up tree trunks

Photo credit: Jean Beaufort

Photo credit: Mike McMillan, USDA
The Rim Fire in the Stanislaus National Forest

Stage 4: fire ignites tree canopies

Photo credit: Kari Greer, USFS
White Water Baldy Fire in the Gila National Forest

Photo credit: rawpixel.com, USDA

Stage 5: fire quickly grows into a wildfire

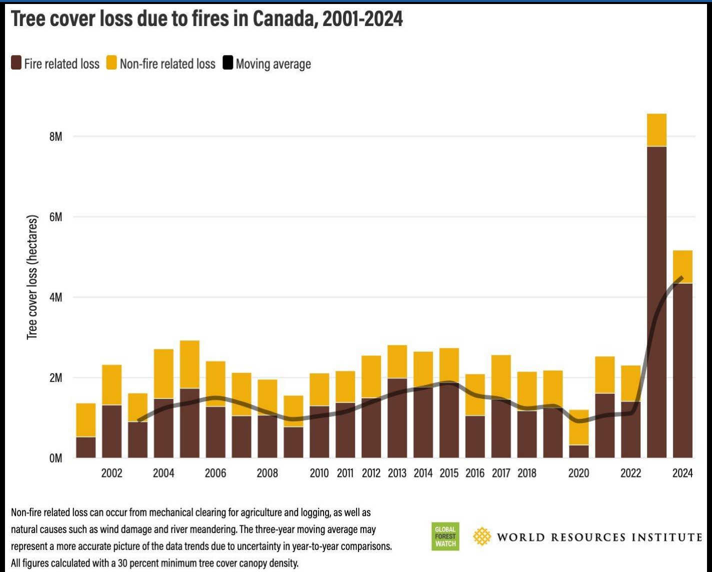
Photo credit: Stockvault, Pixabay

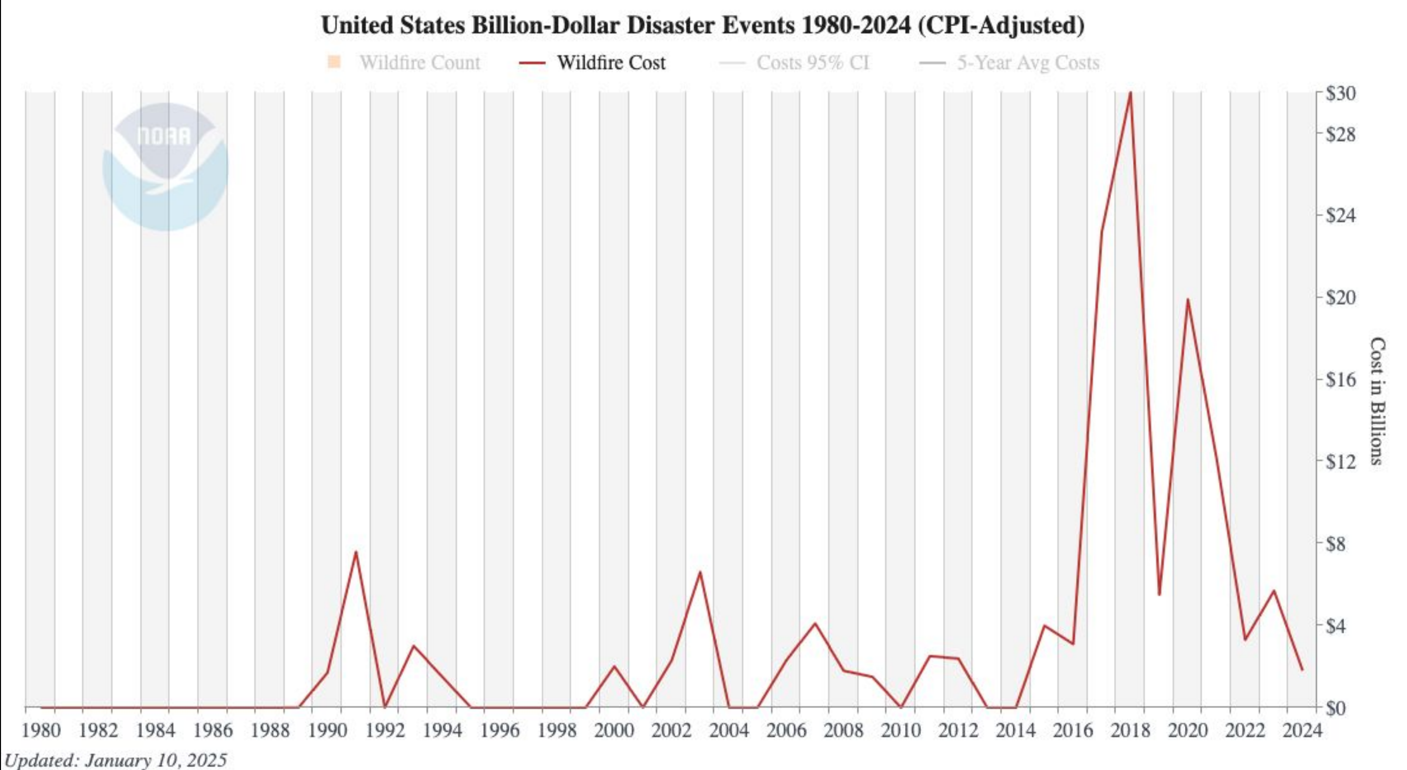
Photo credit: Flickr, Project LM

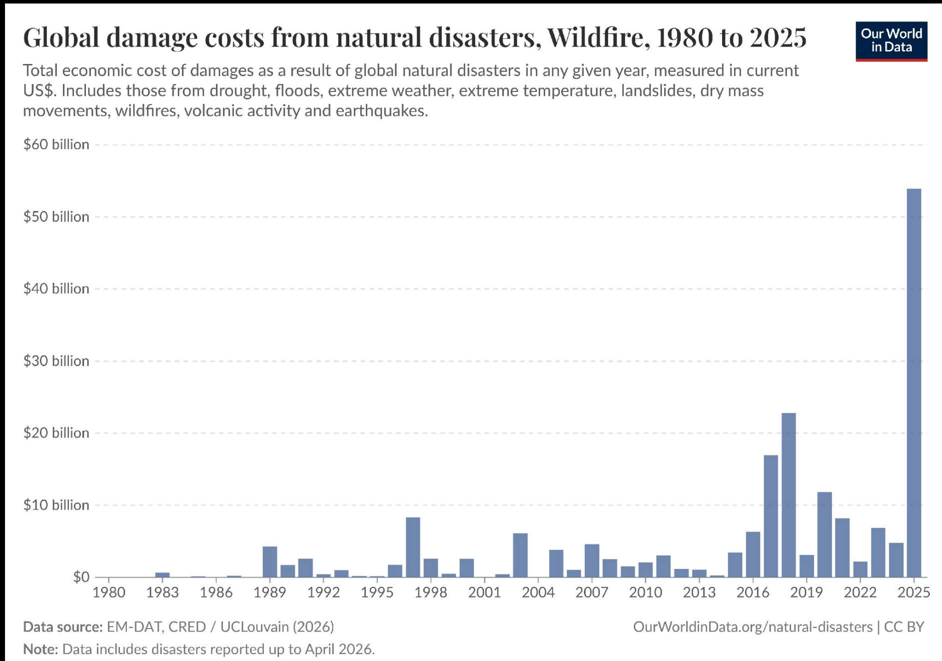
Why Wildfire Research?

Due to climate change and other factors, the annual cost of wildfires has been increasing.

Research is needed to more effectively fight these fires.







Recent Examples

Video credit: @Boldmethod, Twitter/X

Marshall Fire
30 Dec 2021 – 1 Jan 2022
Boulder Country, Co
>6,000 acres burned
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Photo credit: Ethan Swope, AP

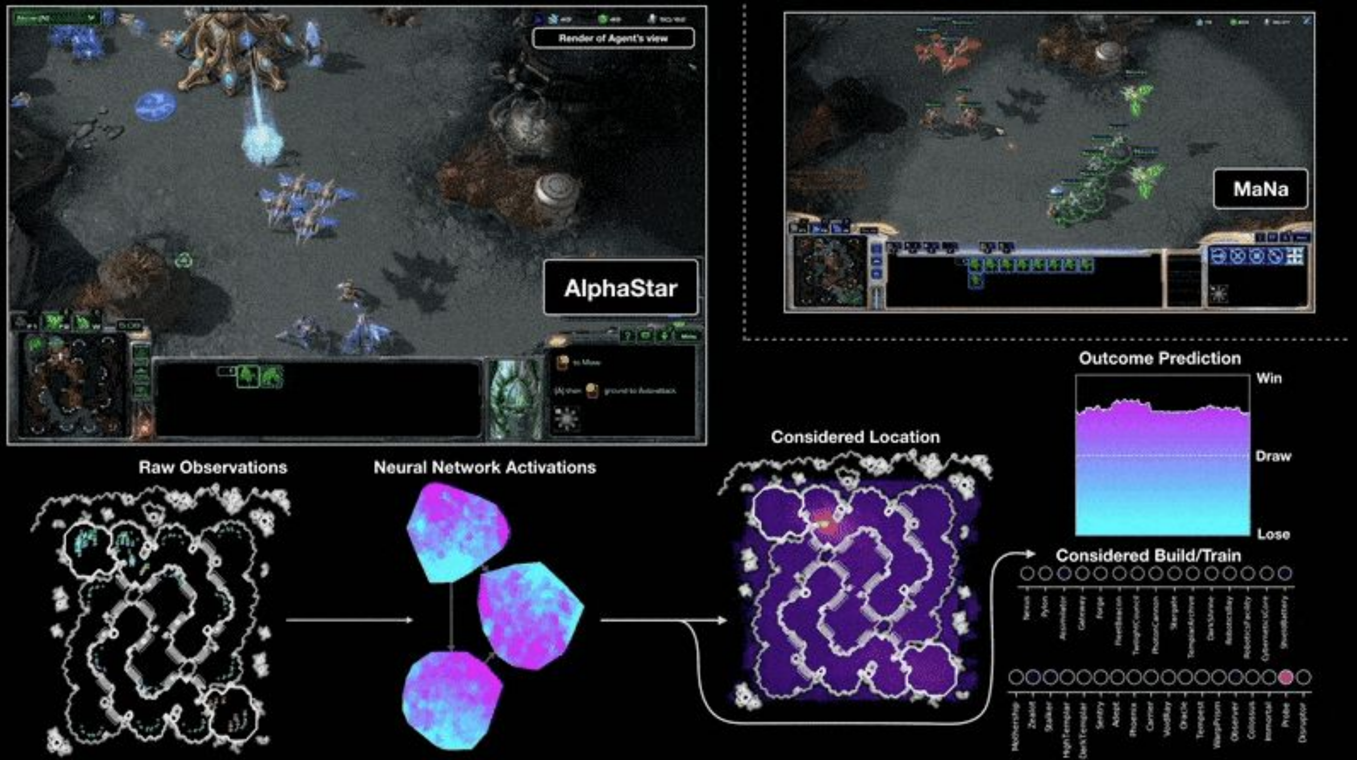
Eaton Fire
7 Jan 2025 – 31 Jan 2025
LA County, Ca
>14,000 acres burned
19 deaths
>9000 structures destroyed
>$27B USD

Motivation: Successes in AI

AI has shown to have successes in:

- Board games (DeepBlue, AlphaGo, TD-Gammon)
- RTS/MOBA Games (AlphaStar, OpenAI Five)
- Algorithm Discovery (AlphaTensor, AlphaEvolve)
- Scientific Breakthroughs (AlphaFold)
- Weather Modeling

Can AI be used to discover new strategies to combat wildfires?



Computational Fire Models

Models allow for both research and forecasting (and they are necessary for training AI agents)
There are a wide variety of models out there, each with their own advantages and disadvantages

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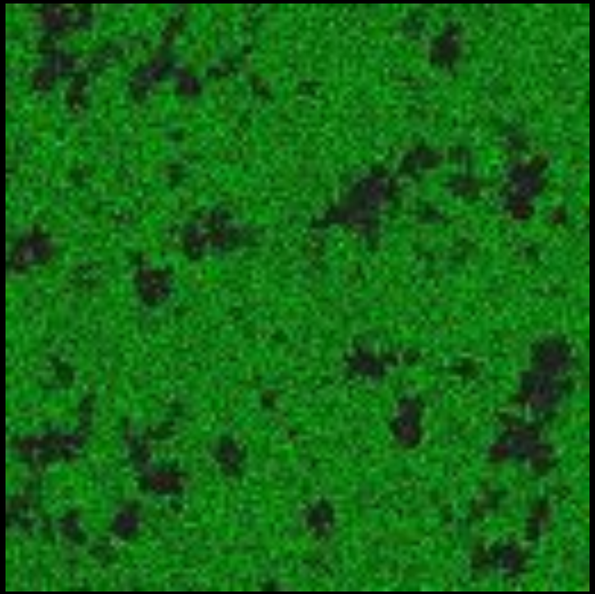

Image source: Claudio Rocchini https://commons.wikimedia.org/w/index.php?curid=1969299

Classic Cellular Automata

- Come in a wide range of flavors from simple to complex
- Often used for research where quick feedback is needed
- Can be easier to modularize/configure
- Often course resolution and don't model complex atmospheric dynamics

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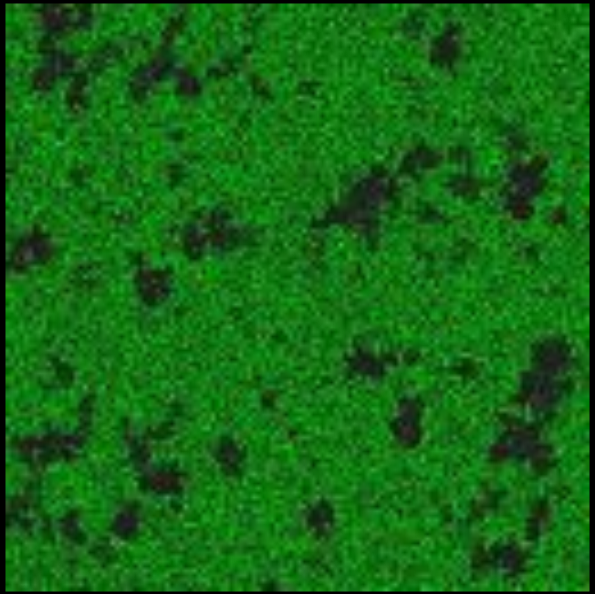

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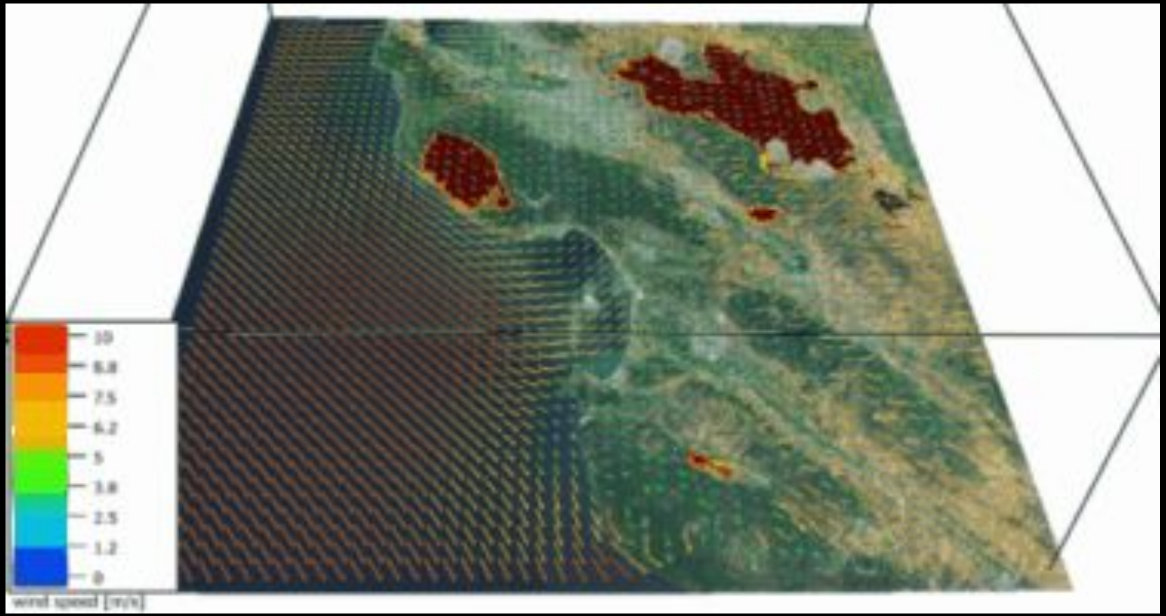
Image Source: https://www.wildfirecenter.org/research



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WRF-Fire

- The go-to community fire model for realism
- Simulates atmospheric coupling
- Too slow for use in real-time forecasting

Building Another Model

"All models are wrong, but some are useful"

-George E.P. Box, British statistician

The effectiveness of research often depends on the "usefulness" of the model

What does that mean?

A model's "usefulness" is context dependent. Most are useful in the right context

In this case, the "right context" would be what's best for training AI models

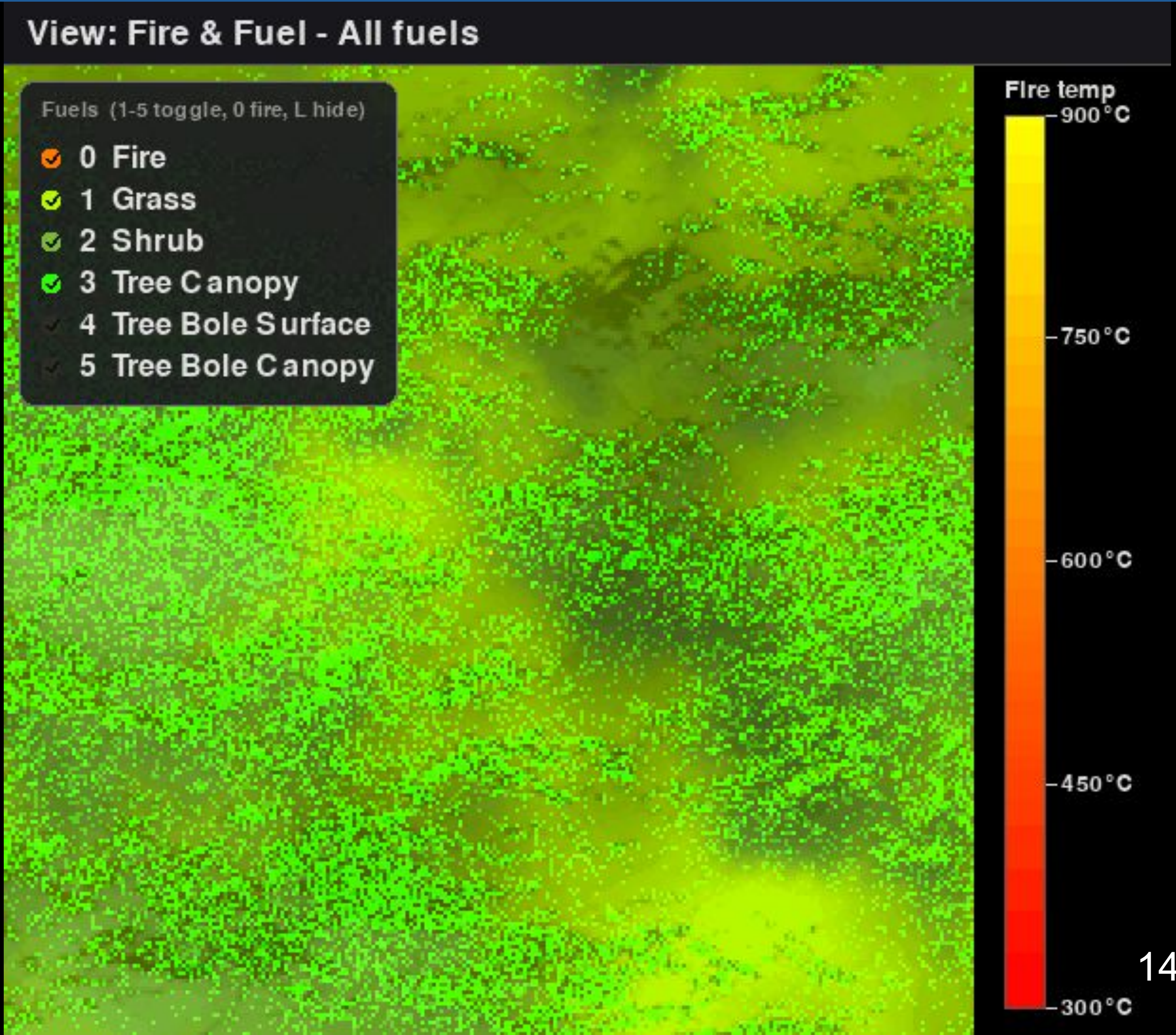
Firecracker Objective

Objective:

- Provide a fast, configurable wildfire simulator that still captures some key real-world complexities
- Provide a suite of ML tools, in-depth documentation, and an intuitive UI for making use and research easier

To be "useful" for this objective, it must be:

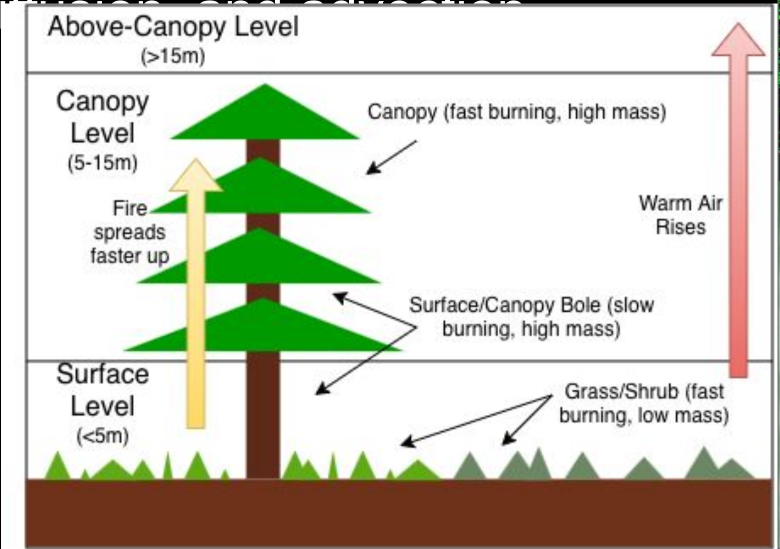
- Fast (GPU accelerated)
- Modular / configurable
- Complex (while still maintaining speed)
- Easy-to-use / well-documented
- Applicable to agentic training and use

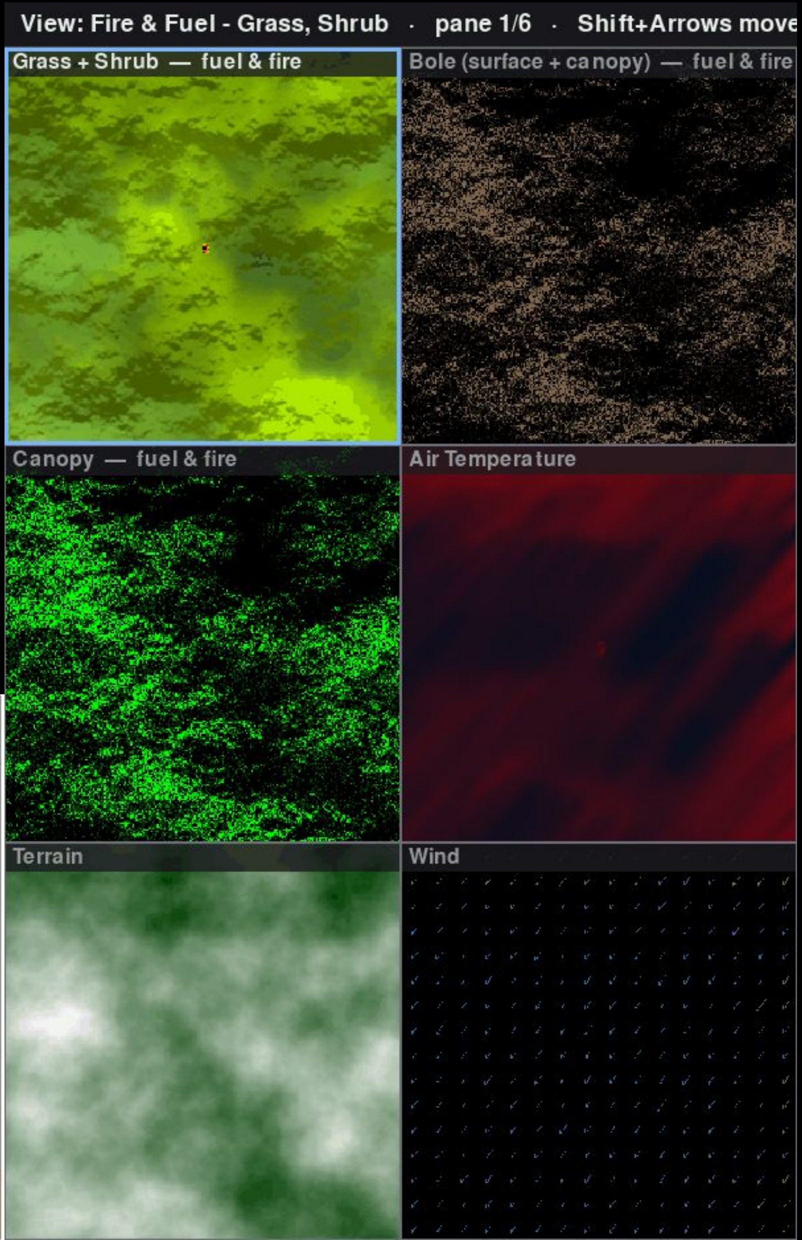


Firecracker Simulation

Firecracker simulates:

- Simplified atmospheric coupling between two surface layers and one upper-level layer
- Heat exchange between fuel and the surrounding air, along with fuel-to-fuel heat exchange
- Different fuel types and their interactions
- Dynamic winds impacted by the fire front and terrain
- Rothermel fire dynamics on sloped surfaces
- Oxygen consumption, diffusion, and advection





Firecracker & Machine Learning

Firecracker is built as a Gymnasium environment, allowing for the training of agentic systems

The observation is a 256x256 grid with 17 channels:

- 0: air temperature (K)
- 1-5: fuel temperatures (per type) (K)
- 6-10: fuel amounts (per type) (kg)
- 11-12: slope (x and y) (degrees)
- 13-14: wind velocity (x and y) (m/s)
- 15: ignited cells (0 is not burning, 1 if burning)
- 16: moisture

All observations are min-max normalized to be 0-1 during dataset generation

The action space is a masked 32x32 grid where only grid cells close to the fire front can be selected for dropping water.

Firecracker provides tools/scripts for generating/loading datasets, and training/loading neural networks

Results

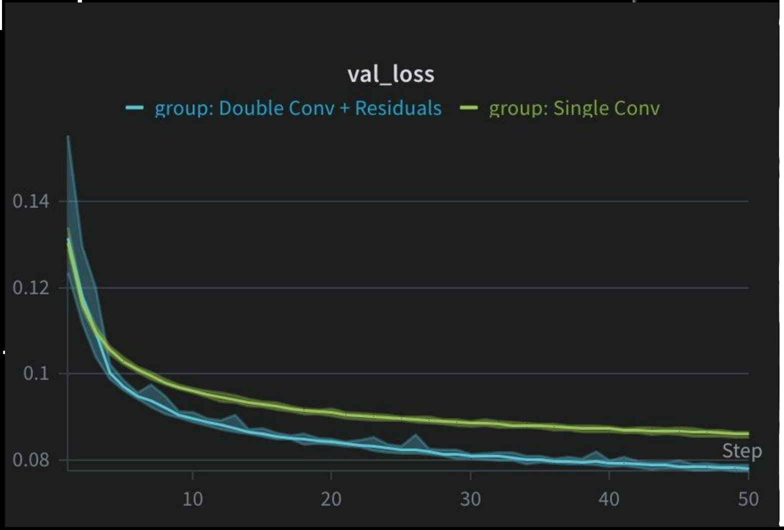
Objective: train a machine learning model to predict the evolution of the fire front for use in planning

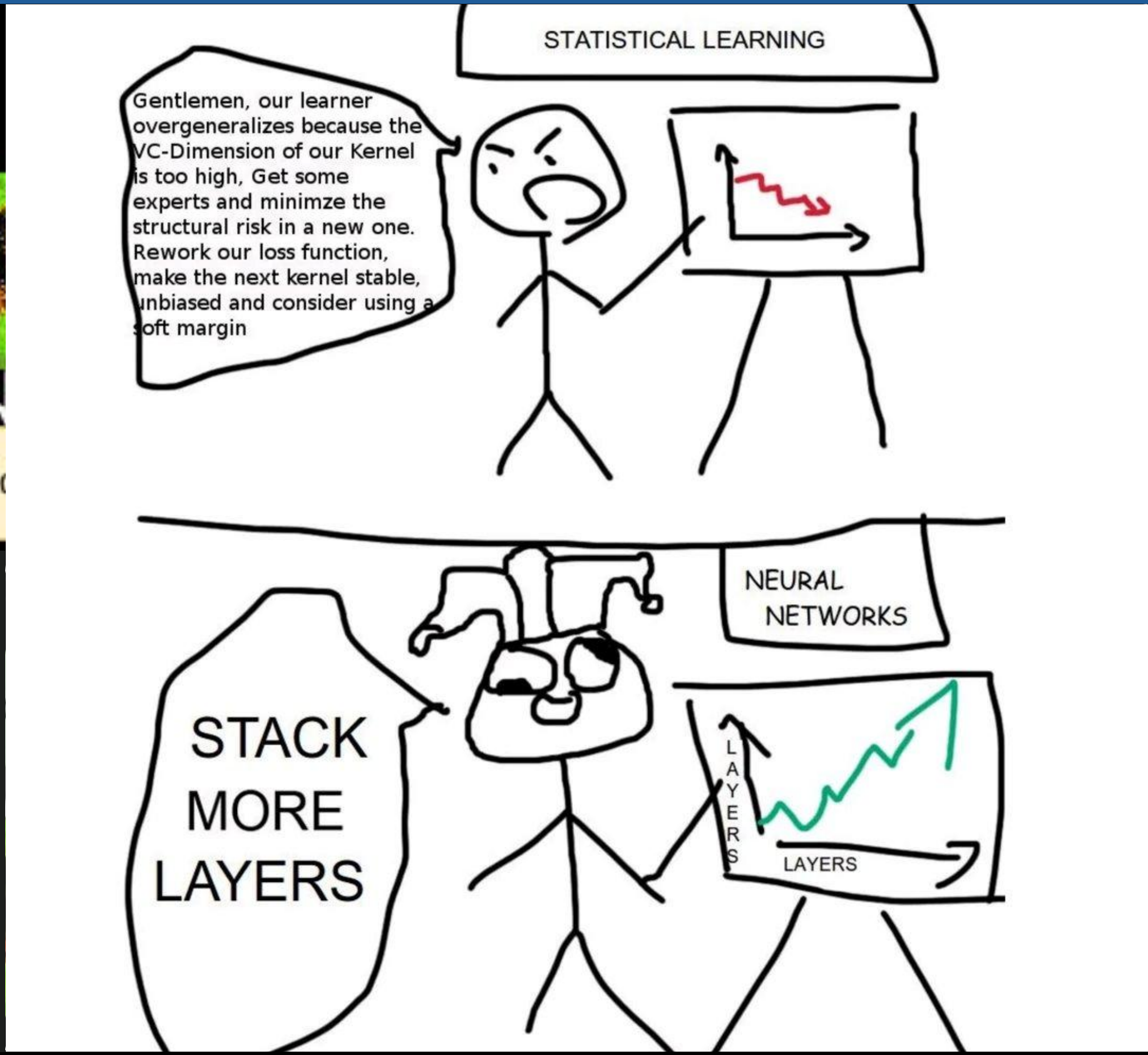
What worked:

- Representation learning with an auto-encoder
- Adding more layers
- Pre-training the encoder helped
- Multi-step training hel

What didn't work:

- Accurately predicting front
- Training end-to-end
- Up-weighting the fire changes)





Future Work & Next Steps

Training an agent to fight wildfires is hard. Wildfires are chaotic and unpredictable, and Firecracker inherits a lot of that complexity from real physics (this is intentional).

- More experiments are needed to build an agent that can actually forecast and contain wildfires
- Static fire barriers (roads, rivers, etc.)
- More expressive actions (controlled burns, etc.)
- Resource/time constraints for the agent
- Objective points to protect (like structures)

This is an open problem that needs time to solve

Time Traveler: *Kicks rock*
The timeline:

Photo credit: Noah Berger, AP
Beckwourth Complex Fire

Questions and Acknowledgements

Thank you everyone who has helped me with this project in some way, including (but not limited to):

- My mentor: John Schreck
- The MILES group (especially DJ Gagne, Charlie Becker, and Daniel Neamati)
- The SIParCS interns (especially LJ Dunphy, Ethan Campbell, Obin Sturm, Guan Xin, and Gabrille Forbes)
- Virginia Do and Jessica Amaya
- Pedro Jimenez Munoz
- And everyone who listened to my talk!

Questions?

Fire Lab Research

Richard C. Rothermel's Fire Spread Model:

- The most popular fire spread model
- Derived from empirical experiments conducted in the 1960s and 1970s
- Measured the impacts of fuel moisture, wind speed, slope, and fuel density

Photo credits: The Atlantic & Missoula Fire Sciences Laboratory