Toward actionable wildland fire prediction enabled by high performance computing

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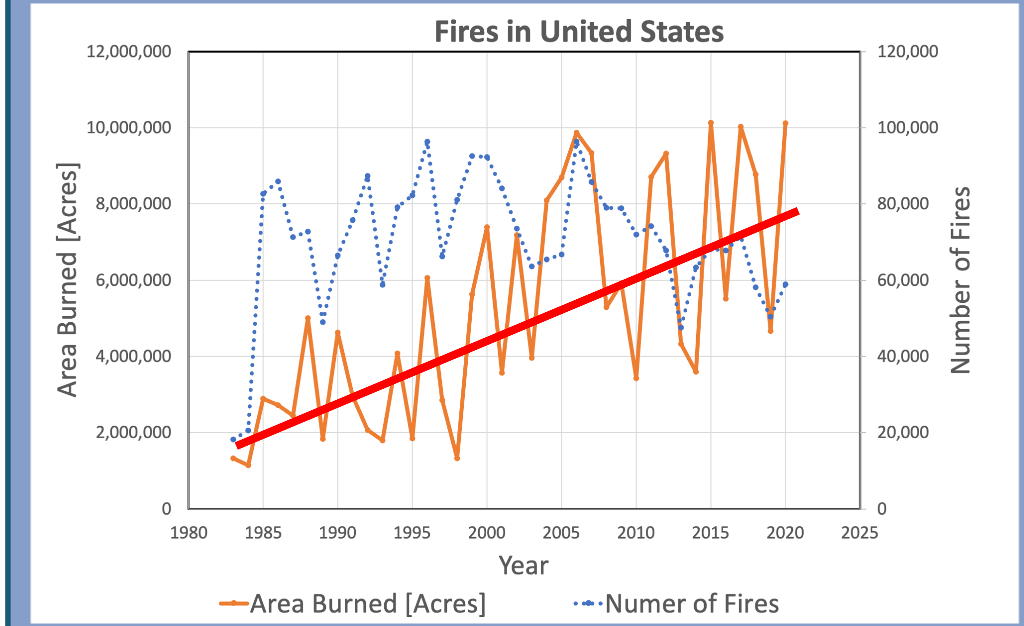
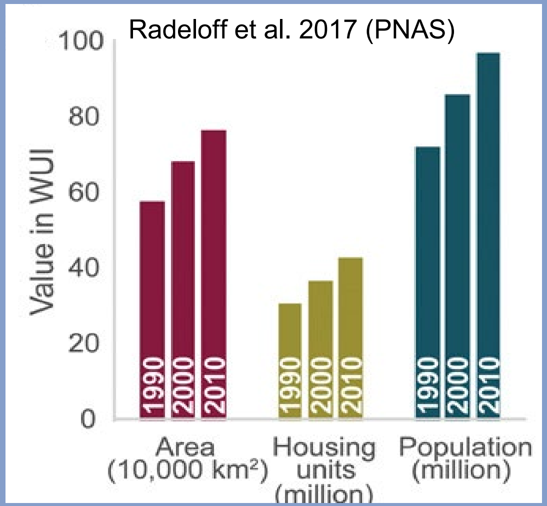
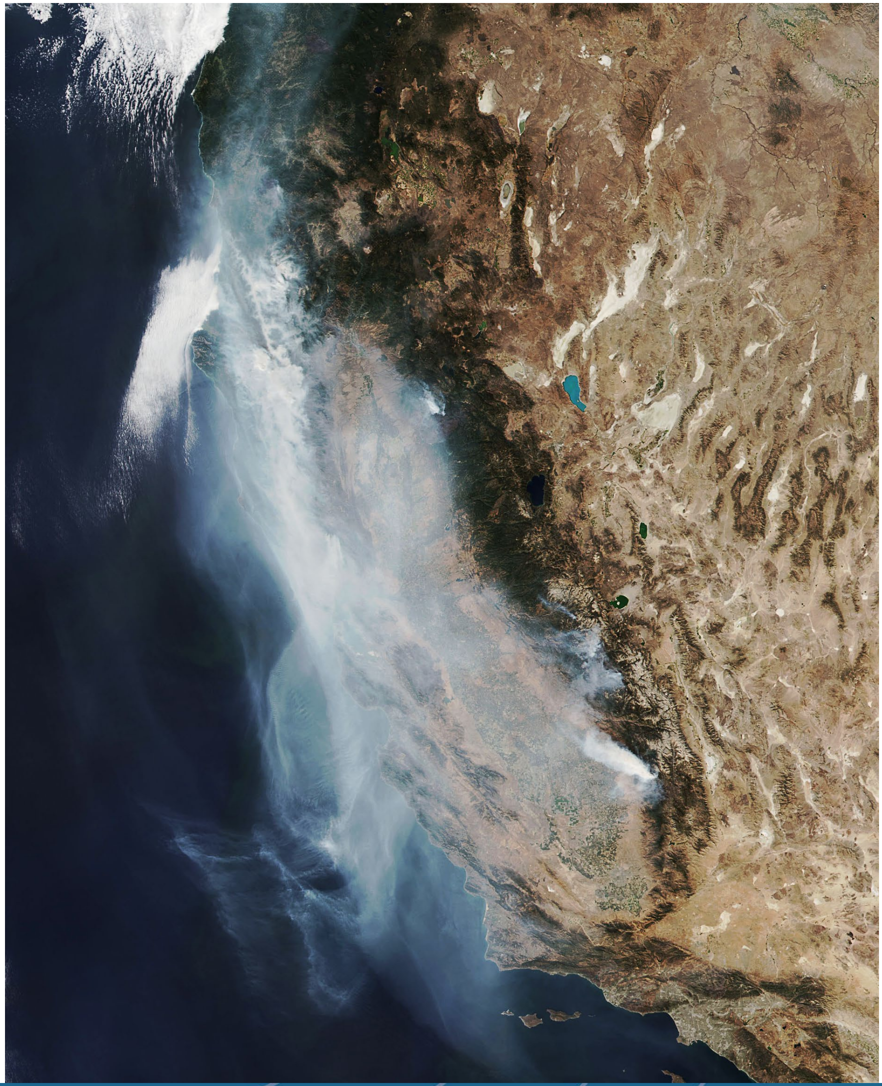
Impact of wildland fires is increasing in the United States and throughout the world

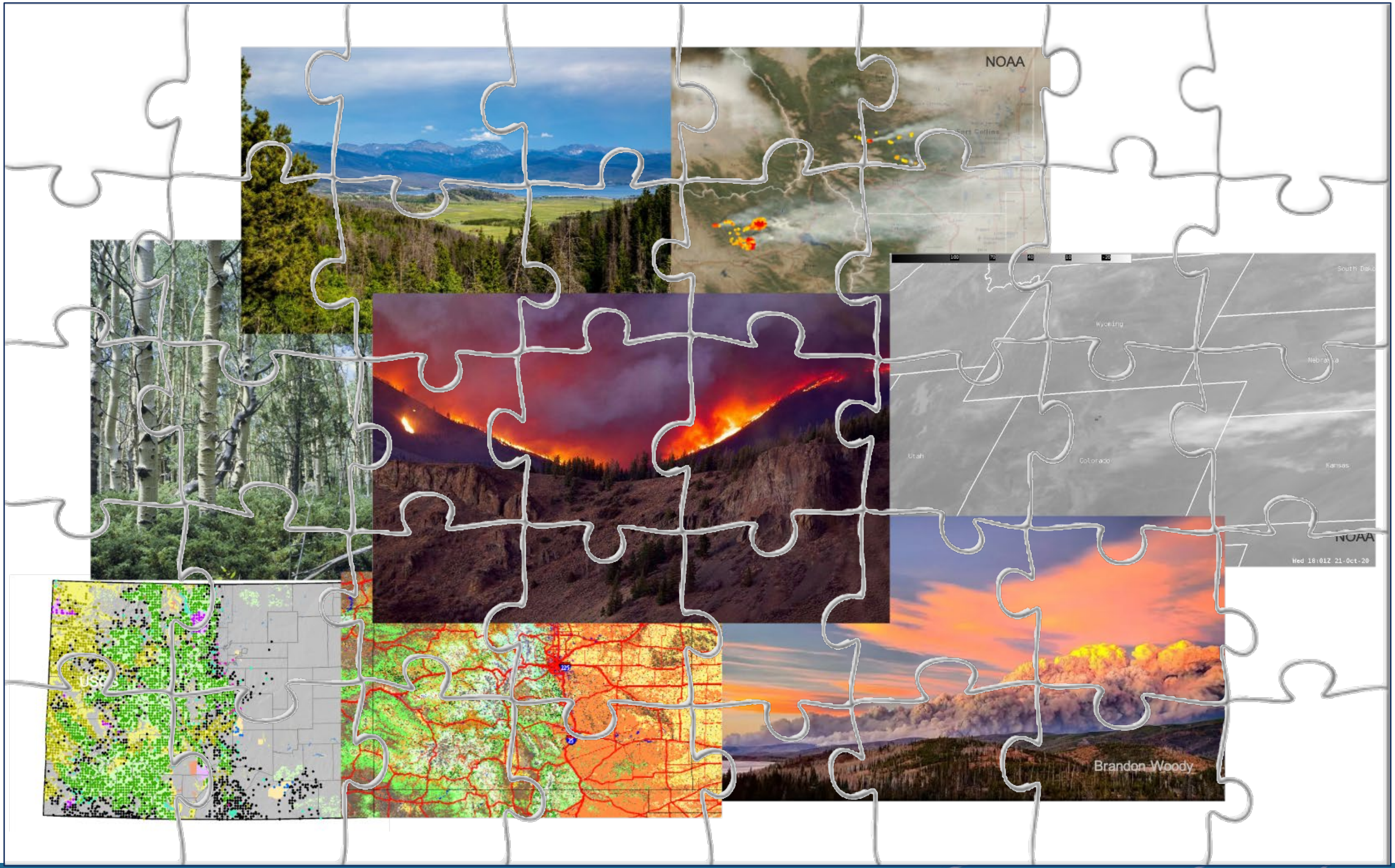
- The area burned due to wildland fires shows clear upward trend over last thirty years
- Population and number of housing units in wildland urban interface are increasing
- In 2020 we have seen some of the largest and most devastating wildland fires on record



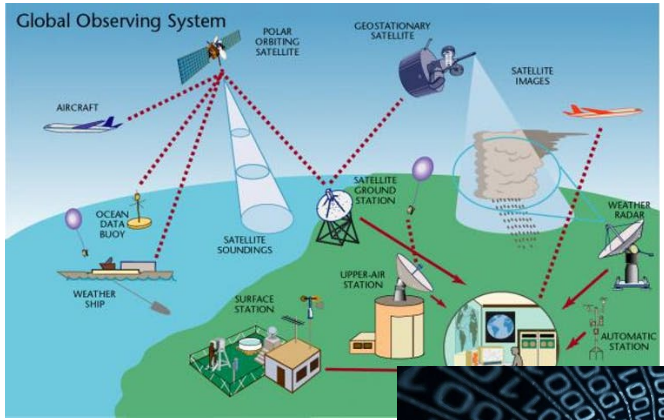


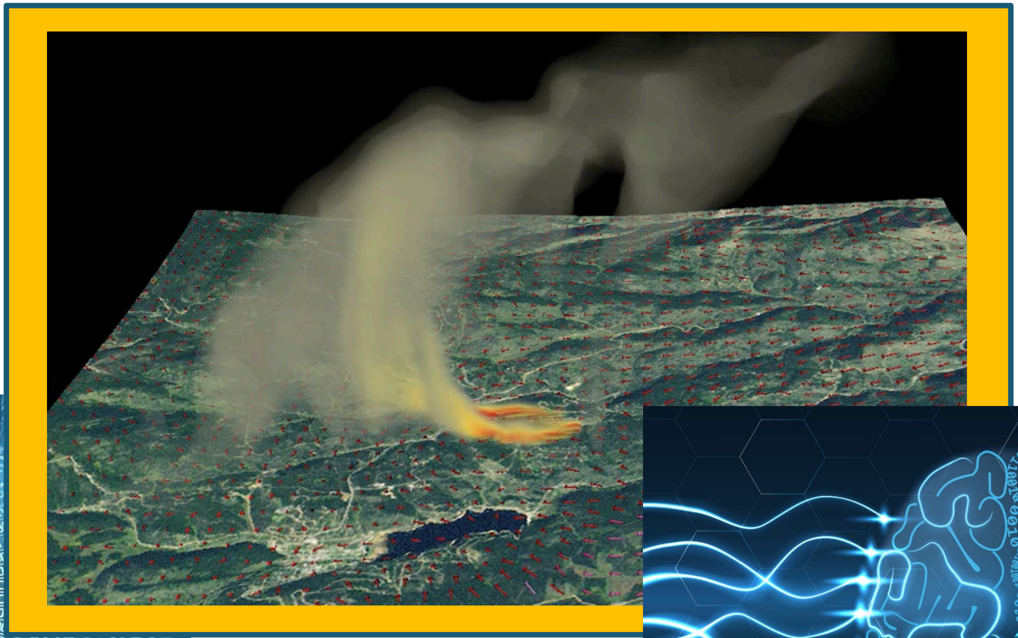


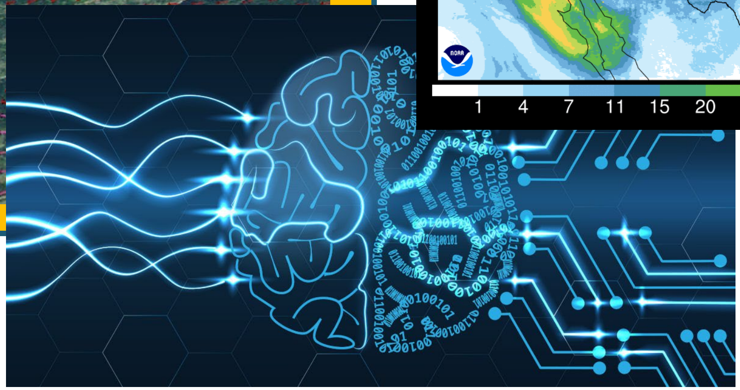
Wildland fire is a complex natural phenomenon

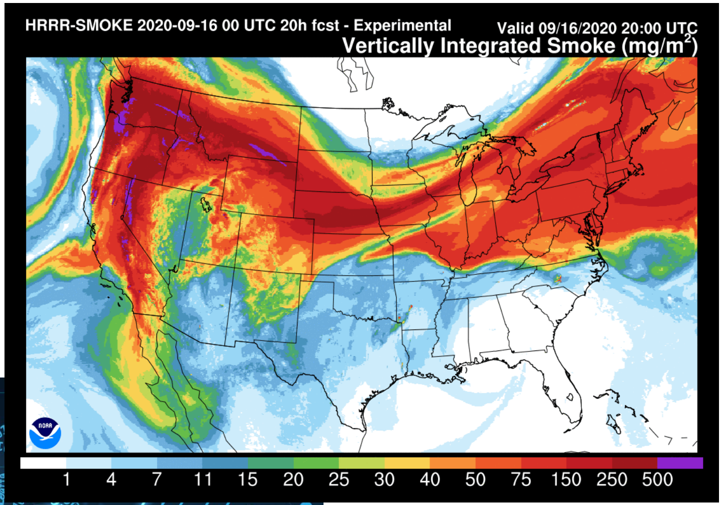


Models and simulations are one link in a wildland fire prediction chain…









…and each step in the chain depends on HPC technology and big data analytics.

The goal is not only to understand how wildland fire spreads but to be able to predict its spread faster than real time.

Coupled model enables simulation of fire weather phenomena

The wind (i.e. atmosphere) and fuel moisture affect the rate of spread of fire. Wind also affect the direction of fire spread.

Burning fuel and releases heat and water vapor into the atmosphere, causing updrafts and changing the winds.

Weather prediction model Weather Research and Forecasting model is coupled with a fire behavior model

Level set method tracks fire perimeter

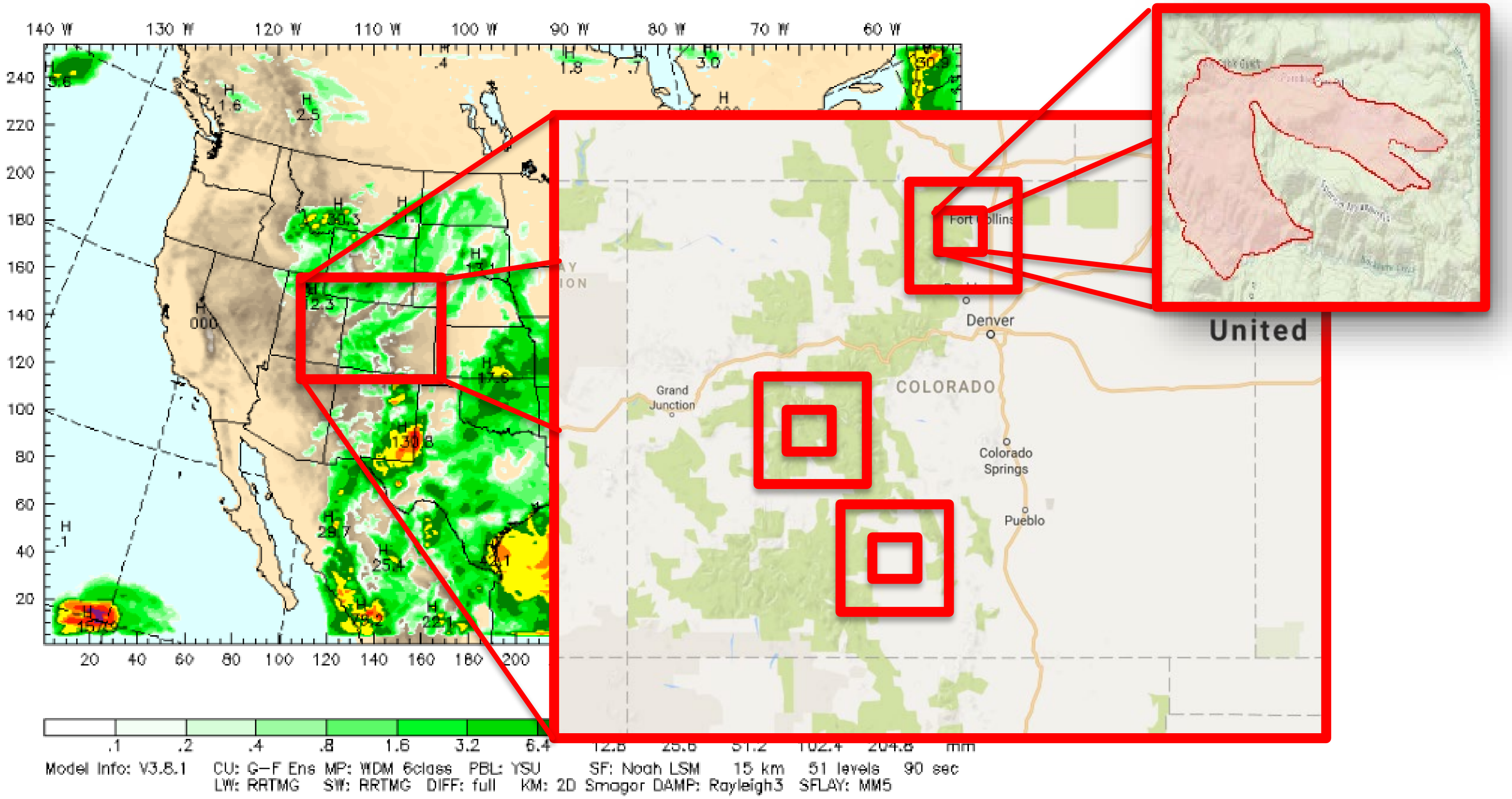
Rate of spread of flaming front is computed as function of fire-affected fuel, wind, and slope using a semiempirical Rothermel (1972) model.

Surface fire heats and dries the canopy.
If the surface fire heat flux exceeds the empirical threshold, fire transitions into the canopy.

Flow in atmosphere is affected by fire through heat, water vapor, and smoke released by burning of the fuel.

The coupled atmosphere – wildland fire behavior model is based on Weather Research and Forecasting (WRF) model

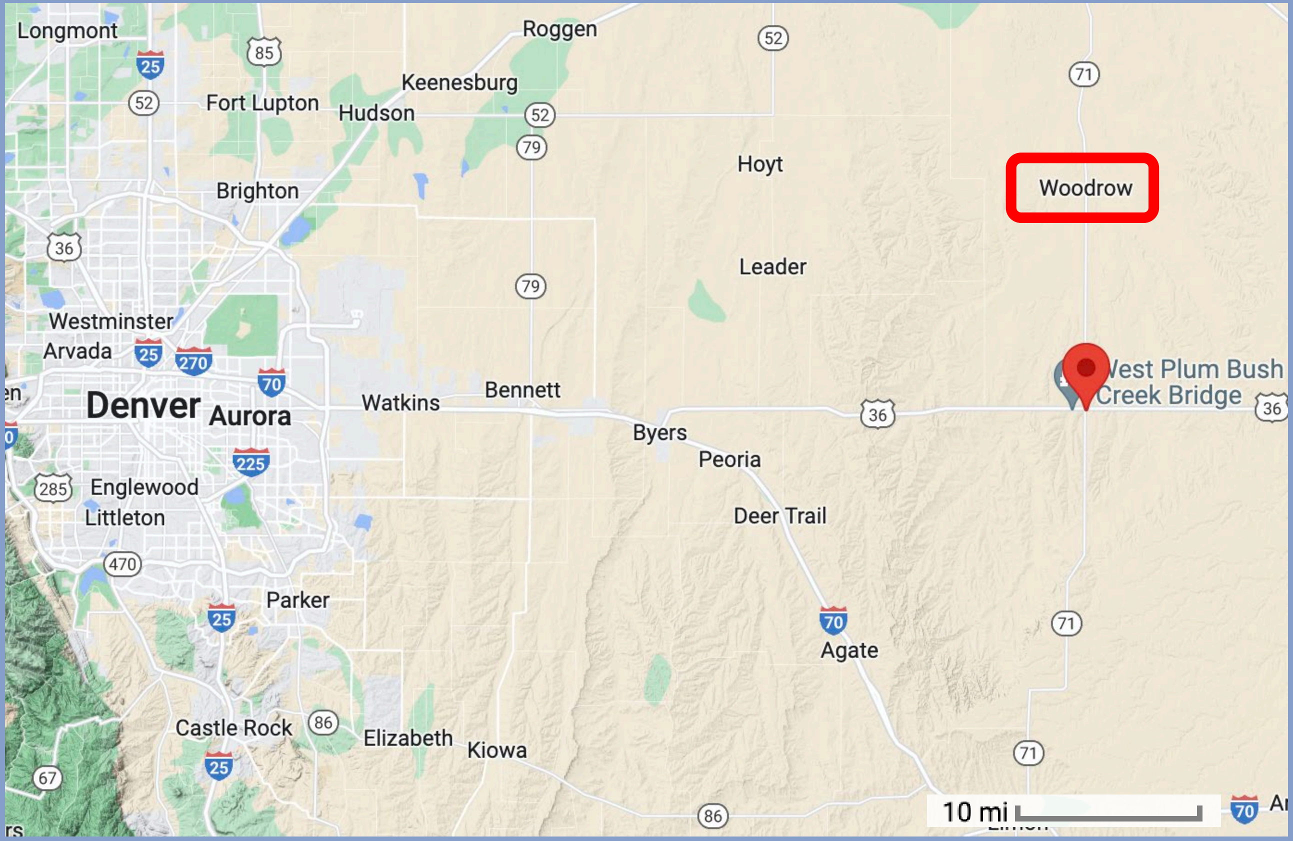
For real time prediction, initial and boundary conditions are derived from a global or a regional weather forecasting systems: High Resolution Rapid Refresh (HRRR, 3 km resolution over CONUS), or Global Forecasting System (GFS) provided by the National Center for Environmental Prediction (NCEP).



- Atmospheric flow is downscaled using multiple nested domains to a large-eddy simulation
- Fire behavior model is used on the innermost nest
- Wildland fire prediction in complex terrain requires high resolution
- Fuel maps for US are available at 30 m resolution, therefore this is the highest commonly used resolution
- At 100 m resolution, simulations execute 6x faster than real time for actionable, operational prediction

Last Chance, Colorado, fire in 2012 was successfully simulated using WRF-Fire

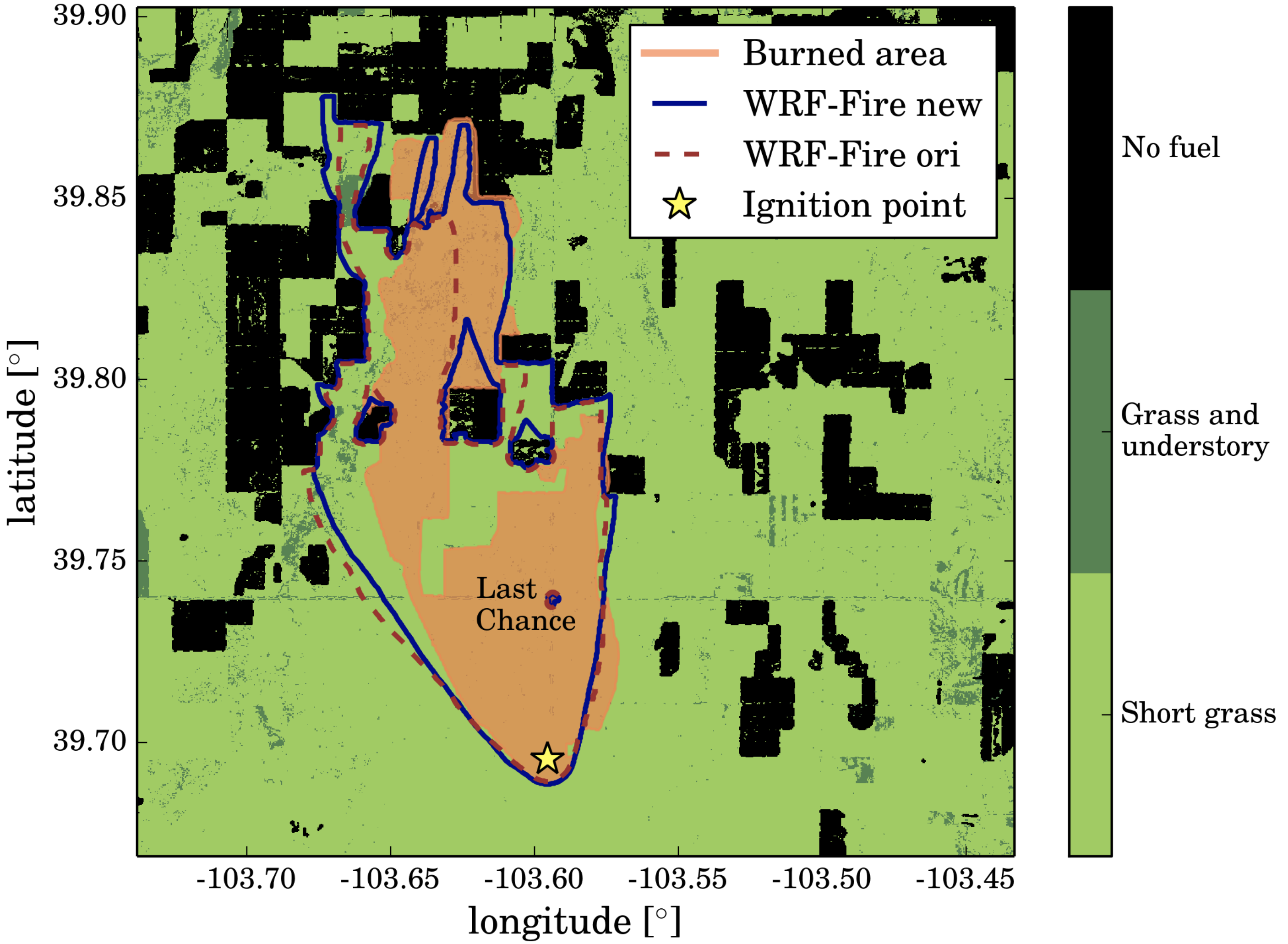
- Grass fire
- Fire spread 17 km north of the ignition in less than 24 hours
- Reached Woodrow the next morning



Last Chance, Colorado, fire in 2012 was successfully simulated using WRF-Fire

Excellent prediction

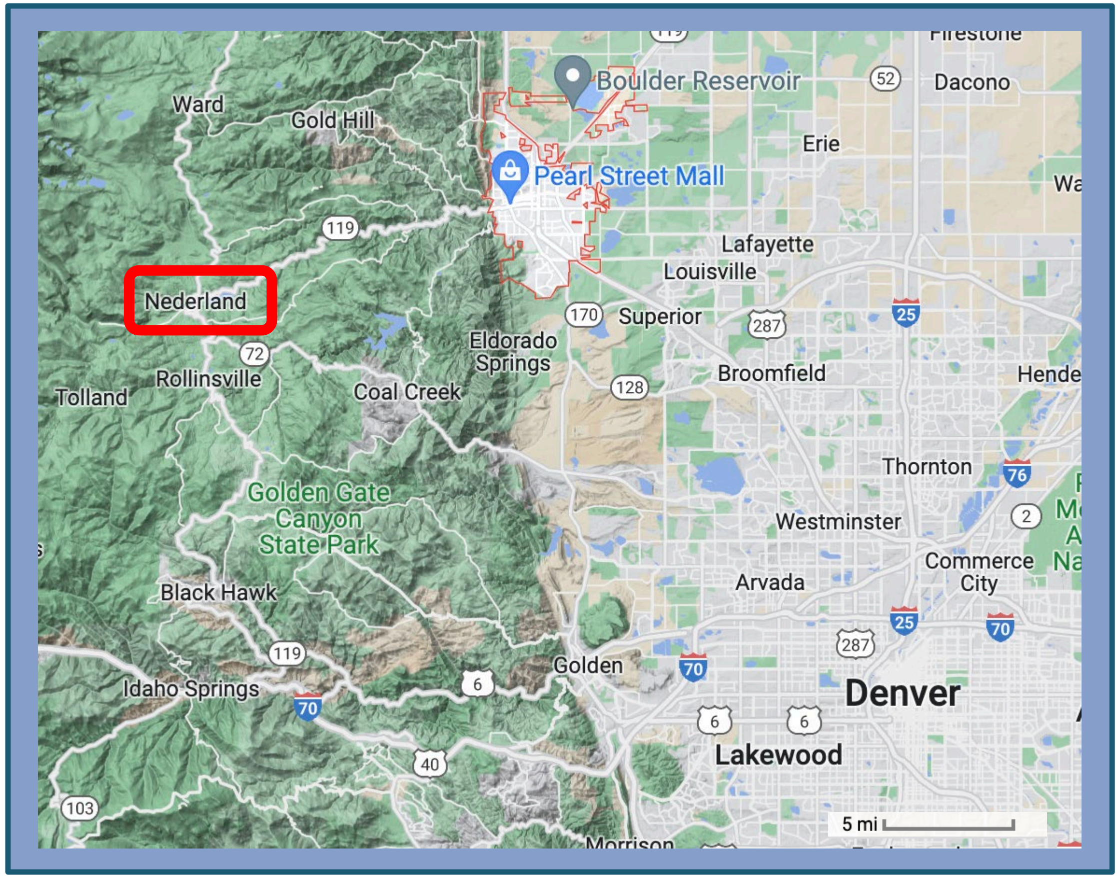
- Accurate weather information
- Strong southerly wind
- Single fuel type
- Accurate fuel moisture

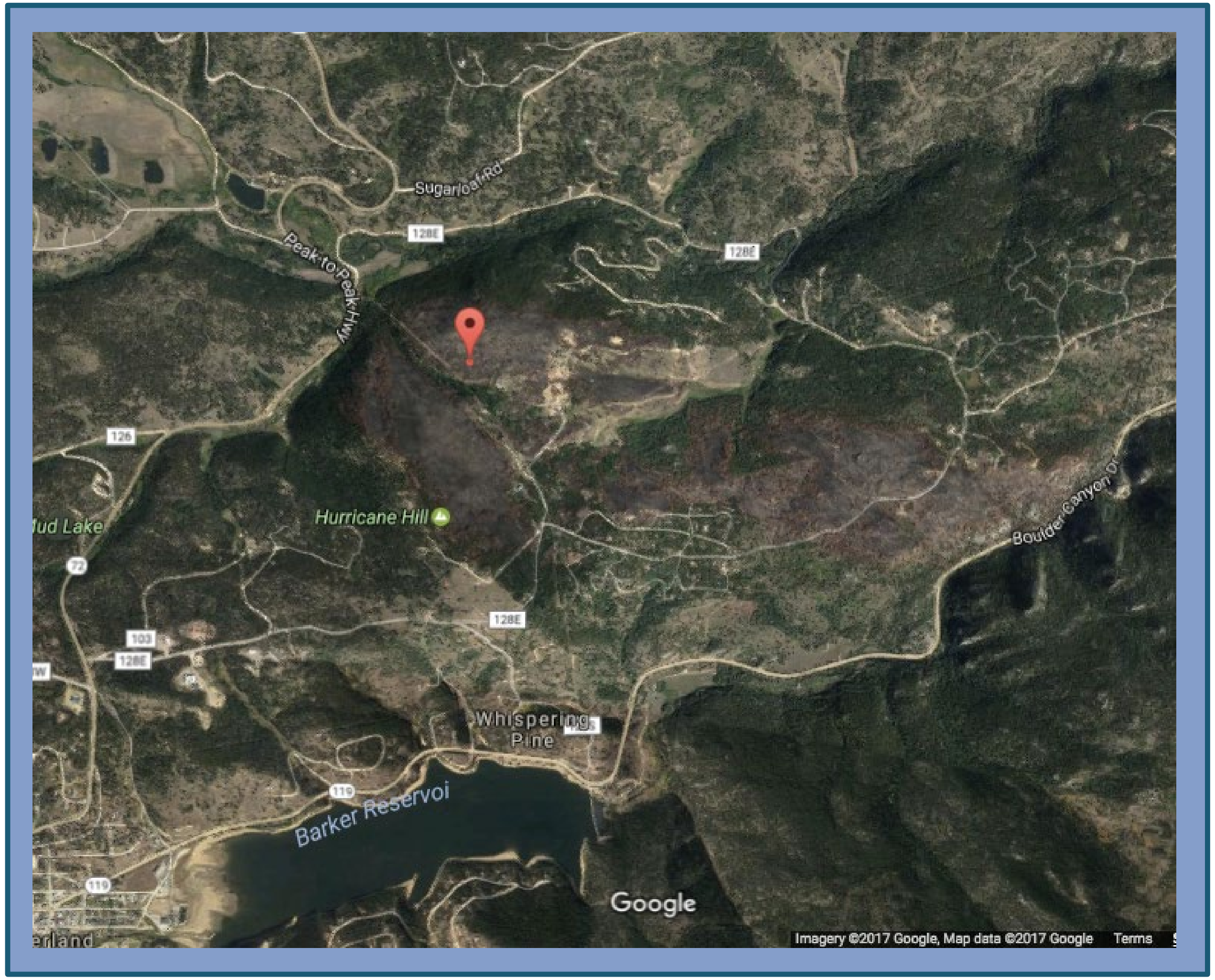


Muñoz-Esparza, Kosovic, and Jimenez, 2018

Cold Springs fire near Nederland, Colorado, was simulated using WRF-Fire

- Human-caused fire ignited on July 9, 2016 at ~ 01:45 PM local time
- 528 acres and 8 homes burned



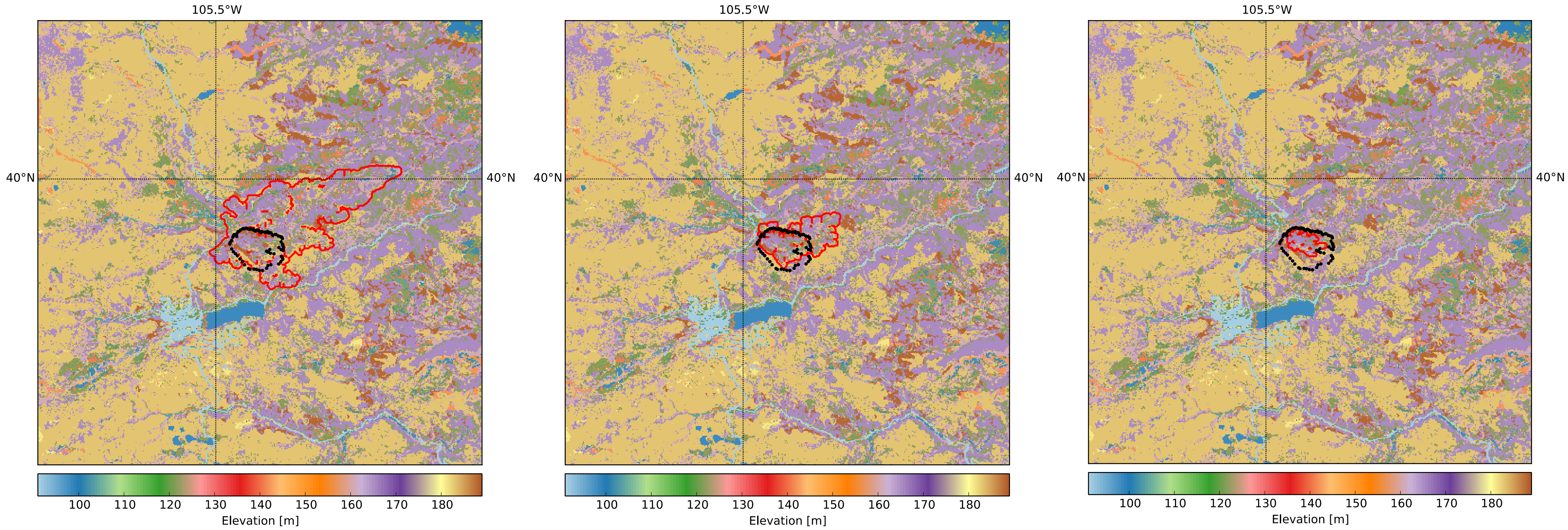


We have studied model sensitivity to fuel moisture content

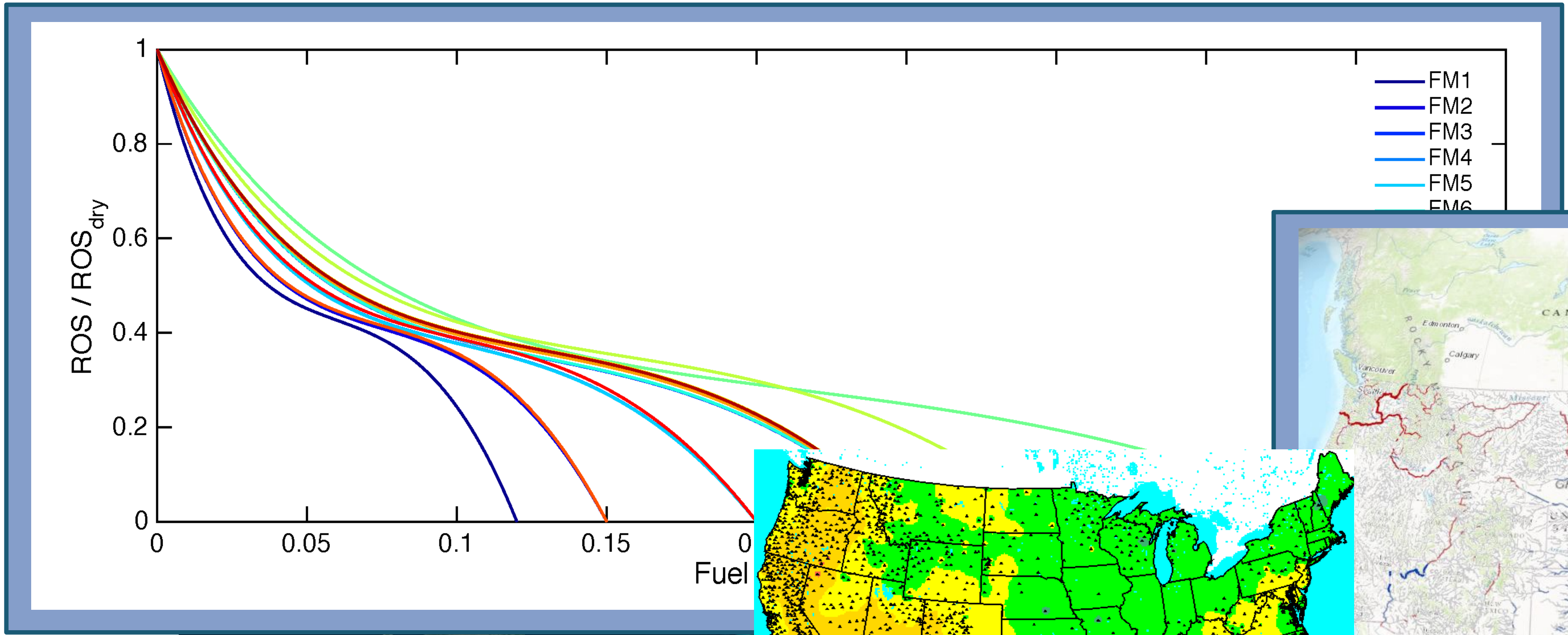
High sensitivity to the fuel moisture content (FMC) requires accurate estimate of FMC

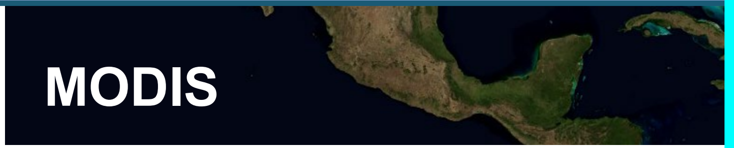
Cold Springs Fire

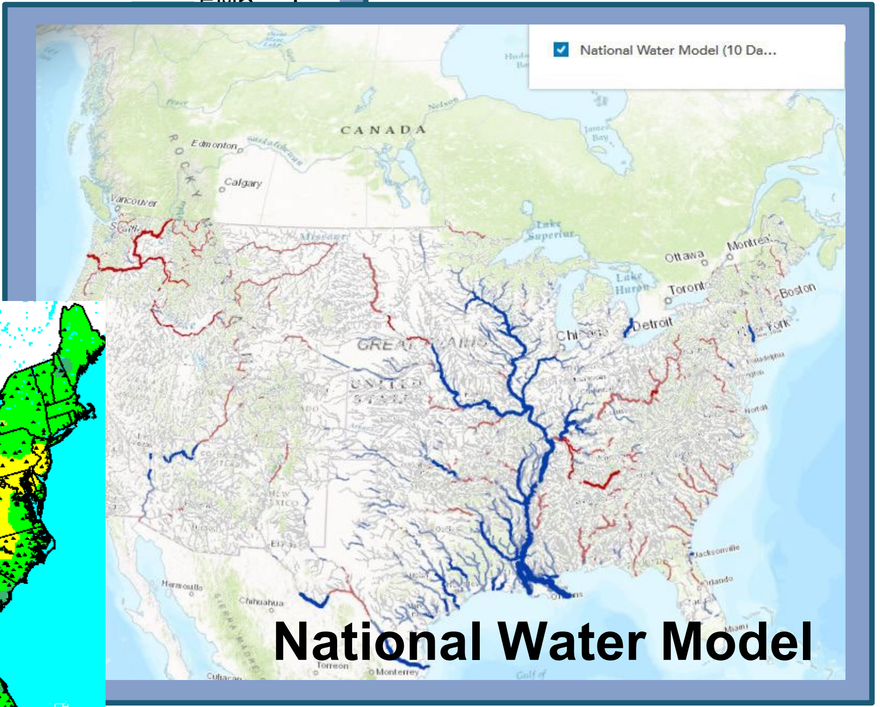
FMC = 0.02 **FMC = 0.08** **FMC = 0.16**

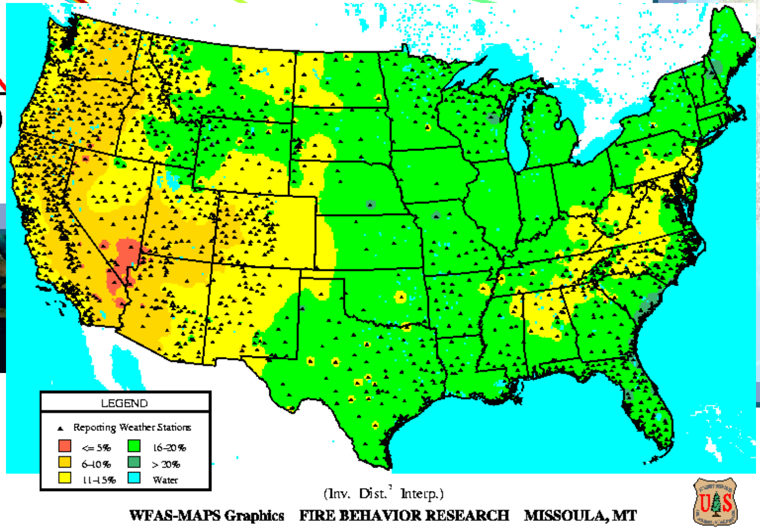


Topography, MODIS data, and National Water Model output are combined using a machine learning model trained on surface observations of FMC









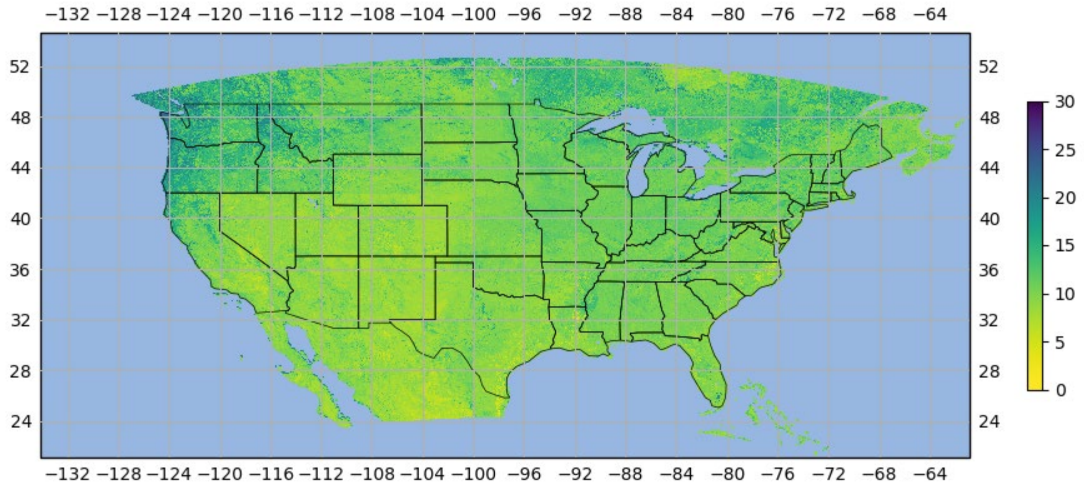
National Fuel Moisture Database

We produce daily CONUS 1 km gridded fuel moisture content maps

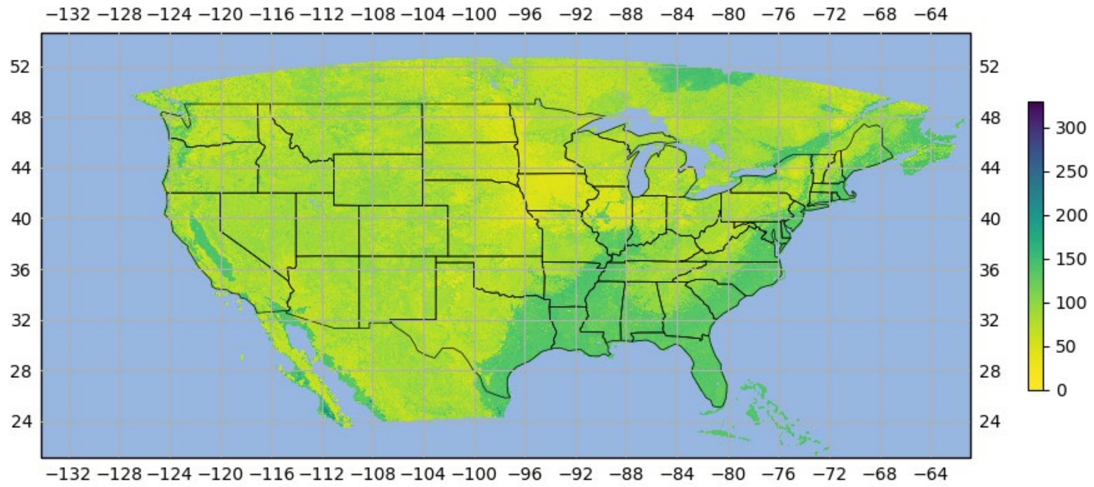
We use machine learning methodology to combine MODIS Aqua and Terra satellite observations, National Water Model output, and terrain data with surface observations and estimate dead and live fuel moisture content (FMC) over CONUS and produce daily a gridded, 1 km resolution, FMC maps.

Fuel Moisture Content over CONUS on 2022-03-09

Dead Fuel Moisture Content



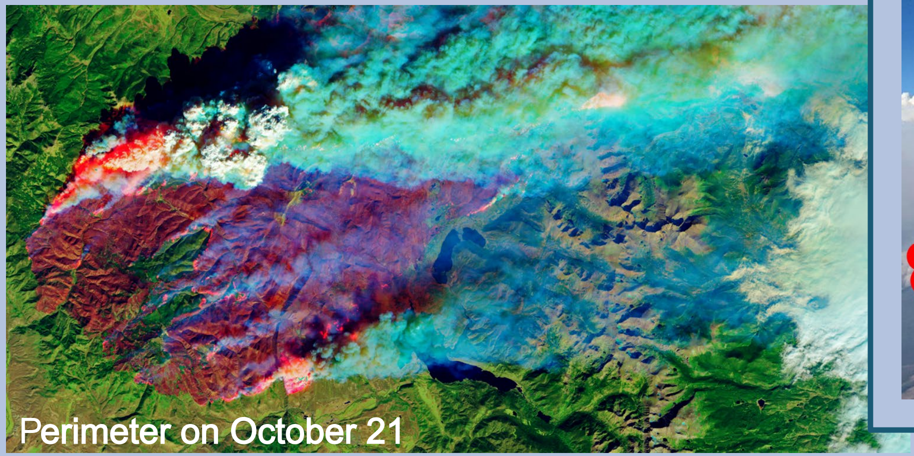
Live Fuel Moisture Content

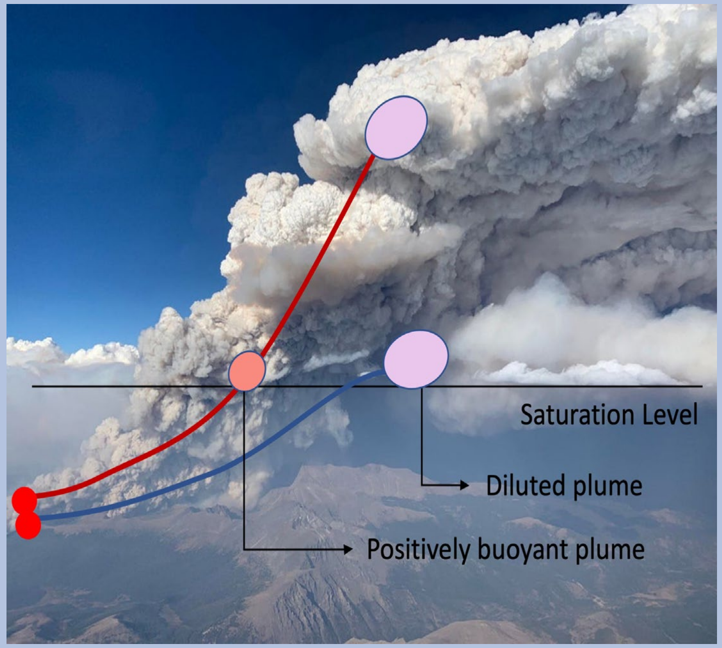


Daily dead and live FMC data are served through:
https://ral.ucar.edu/solution/products/improved -wildland-fire-spread-prediction
Data are archived at NCAR's DASH:
https://data.ucar.edu/dataset/fuel -moisture-content-live-and-dead-over-the-conterminous-united-states

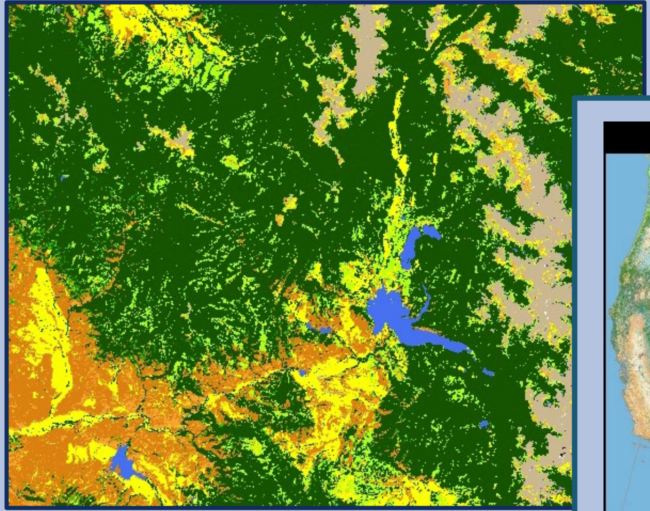
East Troublesome Fire - the second -largest recorded fire in Colorado

- Ignited on October 14, 2020
- Underwent an explosive growth on October 21
- 2 fatalities, 580 structures destroyed
- 87,000 acres burned between October 21 and 22
- Created a pyrocumulonimbus that rose to ~12,000 m
- Fuel described as “jackstraw”
- Crossed continental divide
- Unknown cause



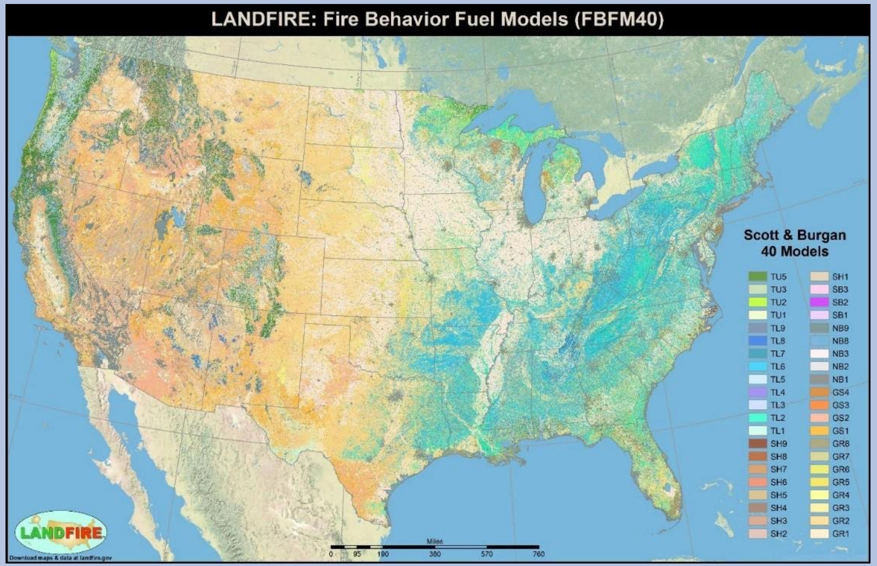


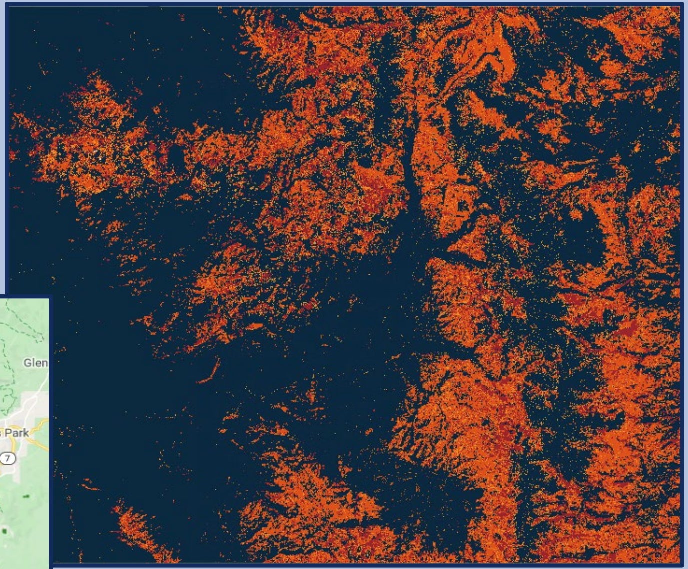
We use LANDFIRE, landscape change (USGS), and satellite (ESA) data and train a machine learning model using Insect Disease data (USFS)

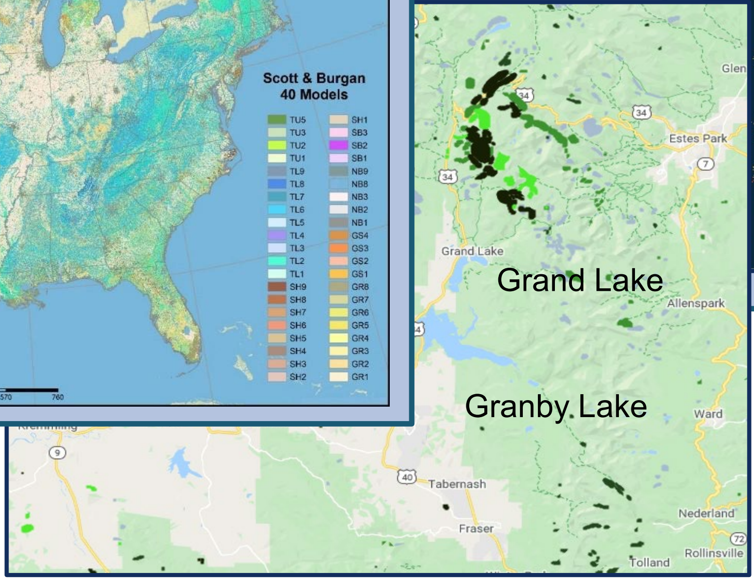


land cover classes over the study area from 2019

LANDFIRE - fuel models used as input in WRF-Fire







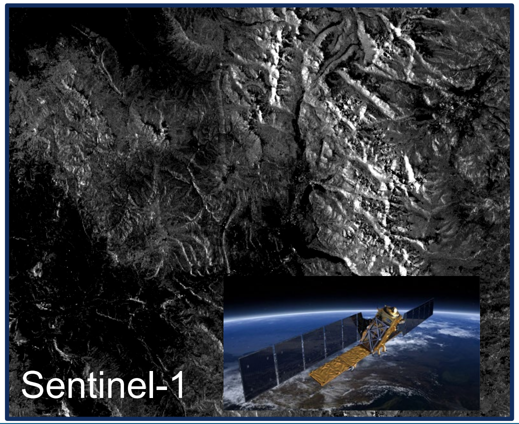
Insect Disease Survey locations within the study area from July 2019, Dataset includes polygons labelled with levels of tree mortality

85% of test data is classified correctly, mortality:

Low: 6.4%;

High: 8.2%

Chlorophyll Red-edge Index is the most important feature

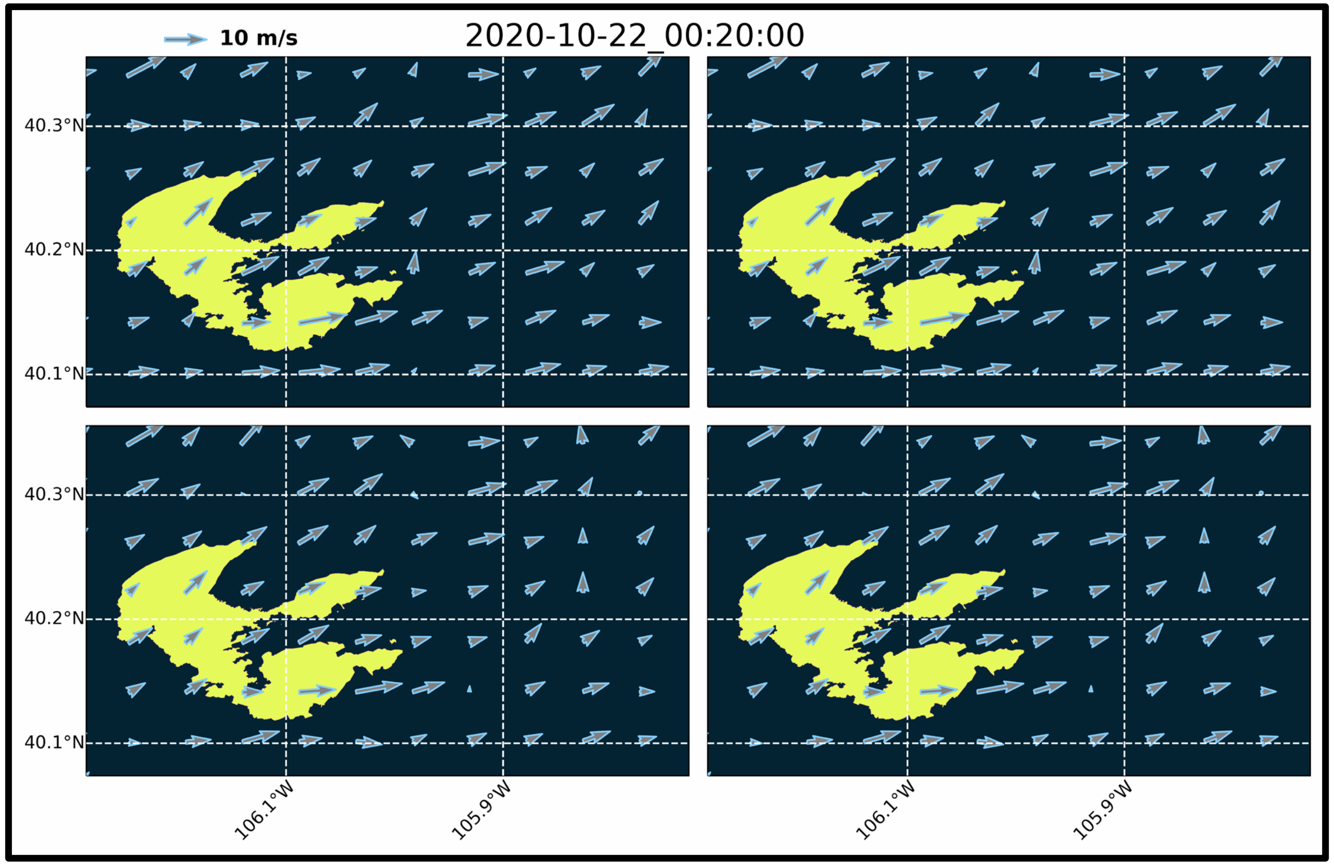


DeCastro et al. (2022)

Time evolution of modeled burn area

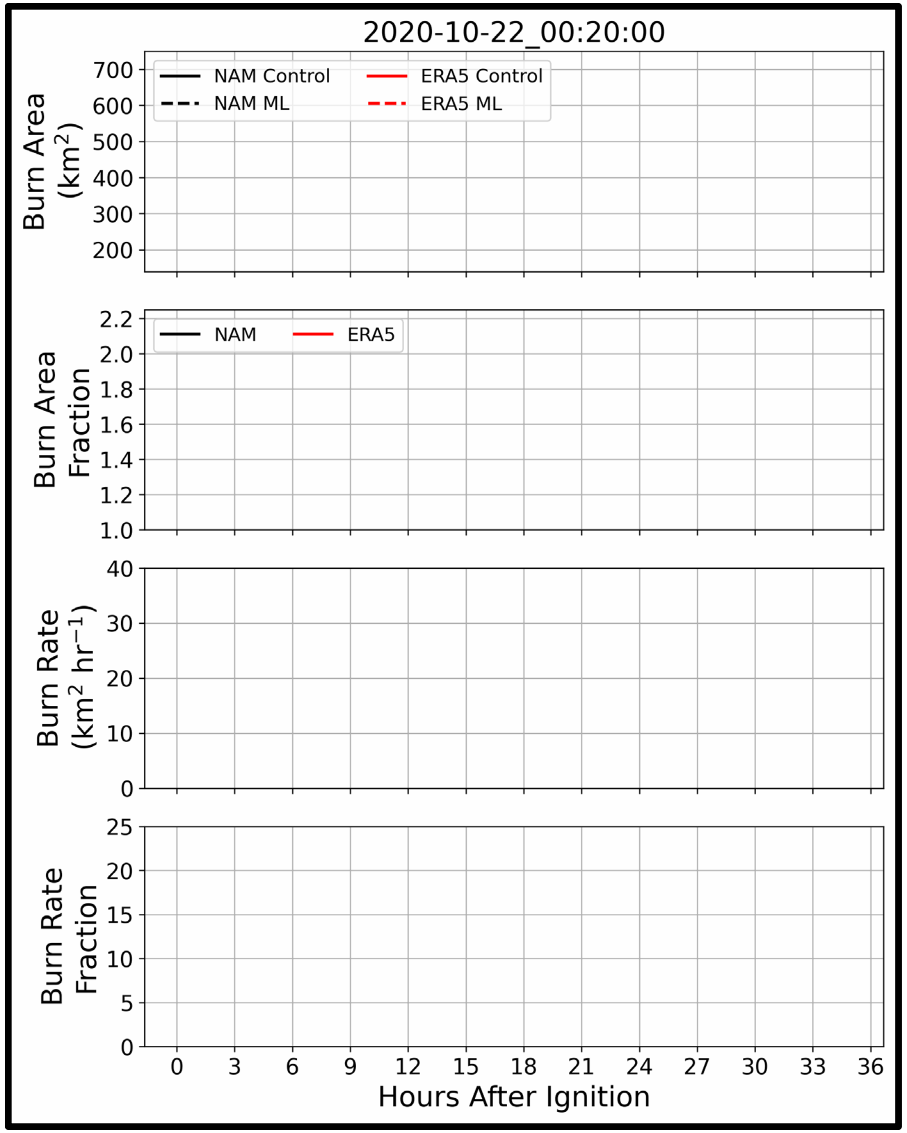
NAM IC/BC

ERA5 IC/BC



Default Fuel Map

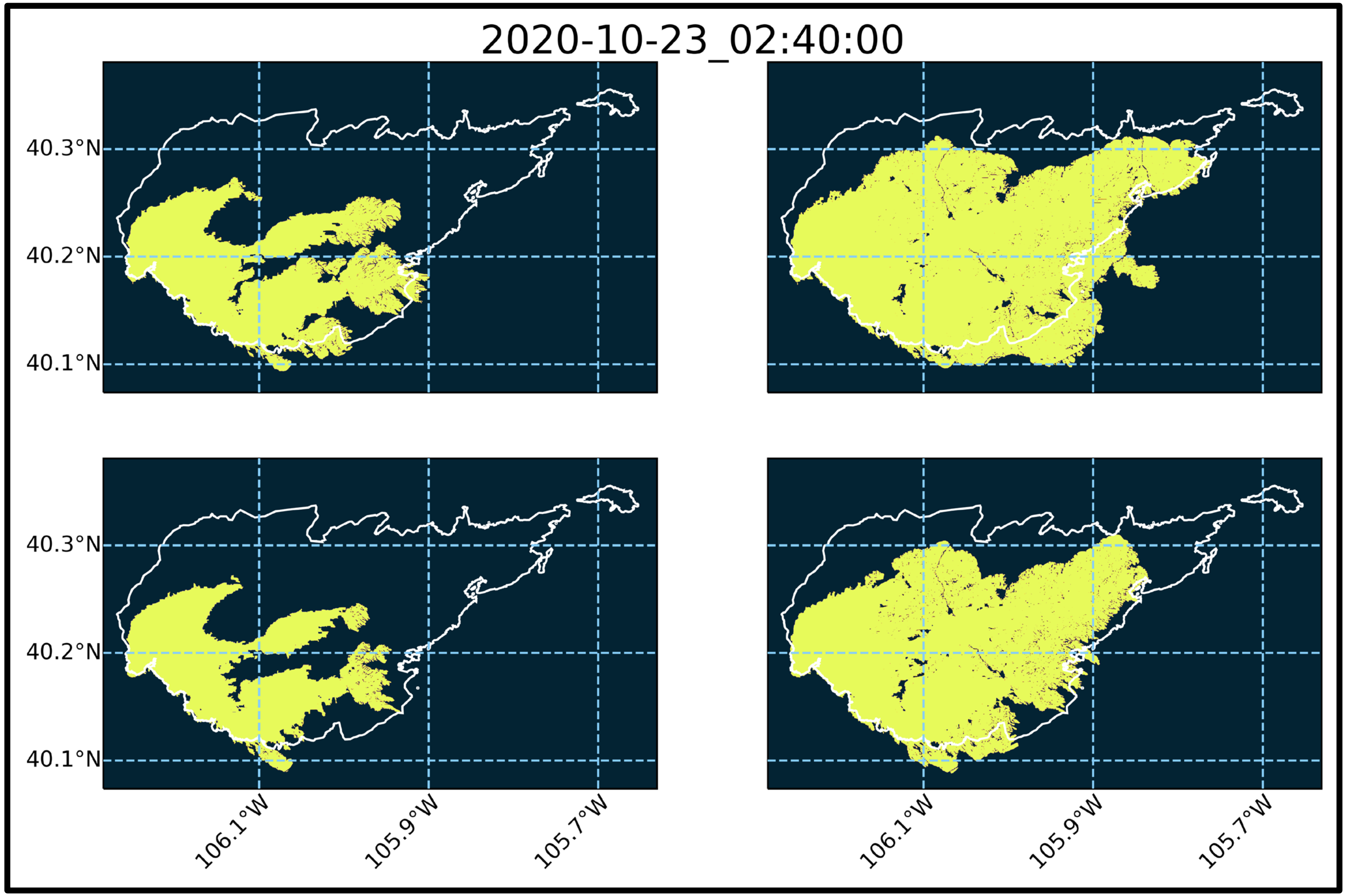
Modified Fuel Map



Fire perimeters: WRF-Fire compared to observations

NAM IC/BC

ERA5 IC/BC



Default Fuel Map

Modified Fuel Map

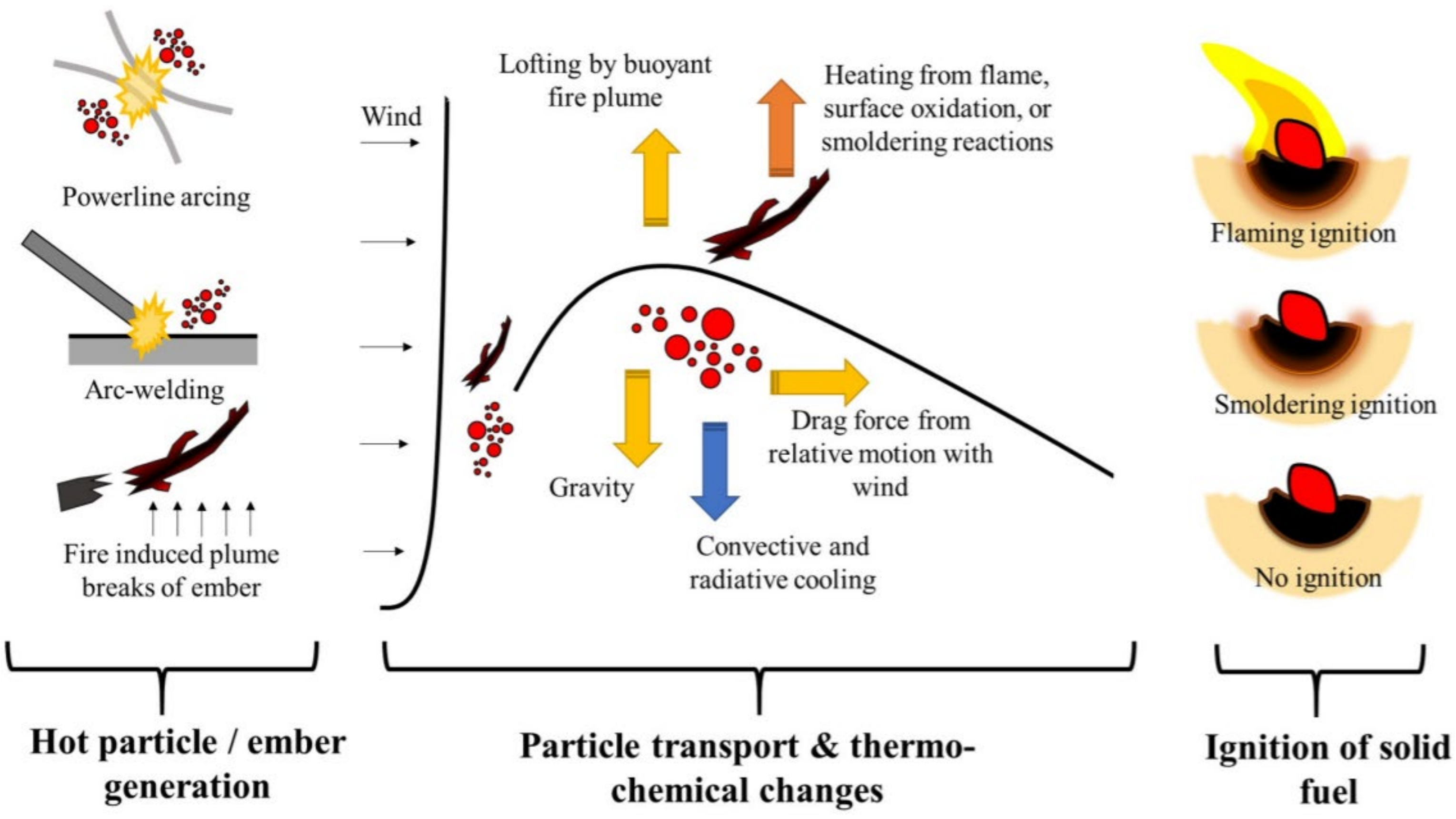
A Lagrangian particle model was implemented in WRF to estimate the likelihood of spot fires

Large, crown fires can spread fast through spotting.

Spotting is inherently a stochastic process that can be divided in three phases:

- Firebrand generation
- Firebrand transport and burning
- Firebrand deposition and spot ignition

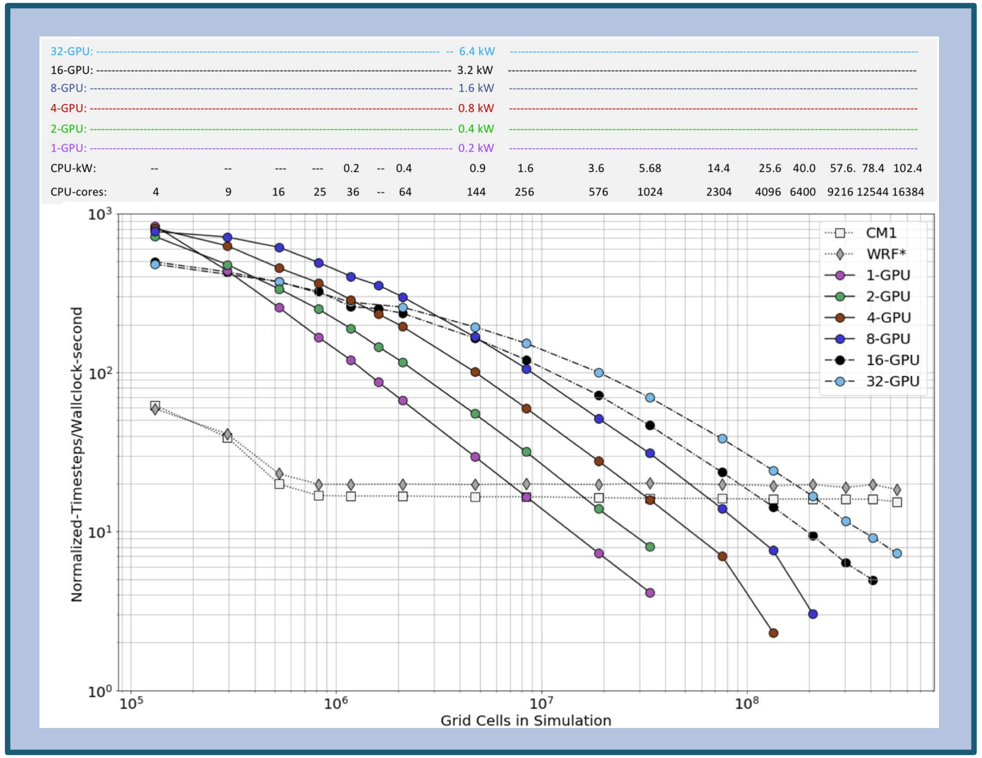
The challenge in developing an effective spotting model is lack of data



Urban (2017)

Coupled models are computationally complex and expensive - speedup can be achieved using GPUs

- NCAR/RAL has developed a GPU-resident LES model, FastEddy, capable of high-resolution, turbulence resolving simulations faster than real time (it is not yet coupled with a fire behavior model)
- Computational performance is more than an order of magnitude faster and power consumption is almost an order of magnitude lower compared to CPU-based models
- This capability makes ensemble, turbulence resolving simulations possible



For actionable wildland fire prediction it is essential to engage experts and stakeholders in all the stages of the process