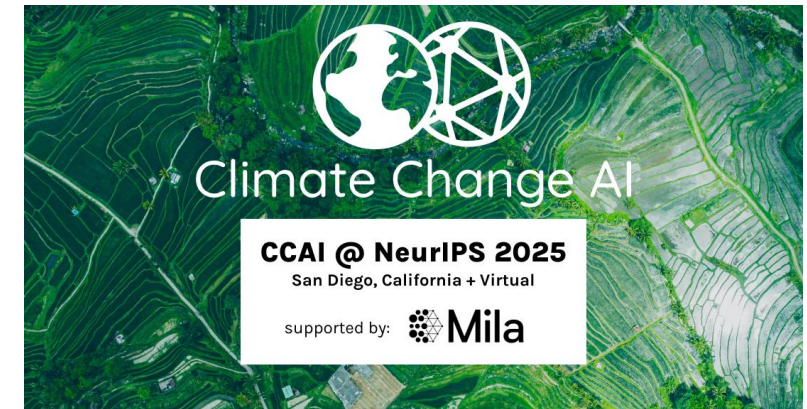




Spatial Uncertainty Quantification in Wildfire Forecasting for Climate-Resilient Emergency Planning

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Independent Research

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MOTIVATION

The Problem



The Gap

- Current ML models give deterministic predictions
- Fire managers need to know: Where might the model be wrong?
- Gap: No spatial uncertainty quantification for high-res wildfire forecasts

"Uncertainty isn't noise—it's a signal for where to focus resources"

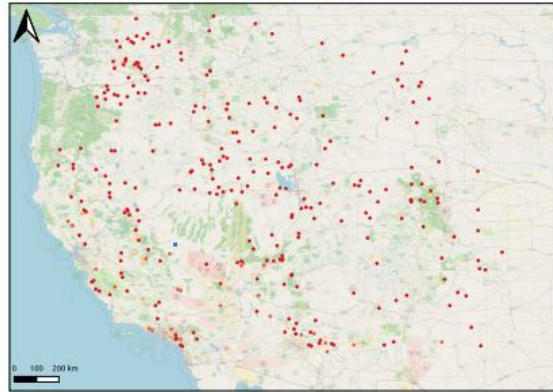
DATASET OVERVIEW

WildfireSpreadTS Dataset (Gerard et al., 2023)

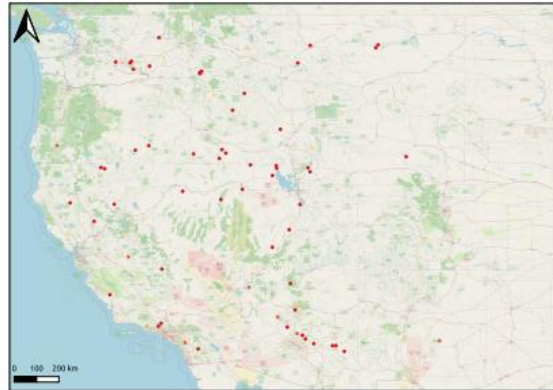
607 fire events, 2018-2021, Western US

13,607 daily images at 375m resolution

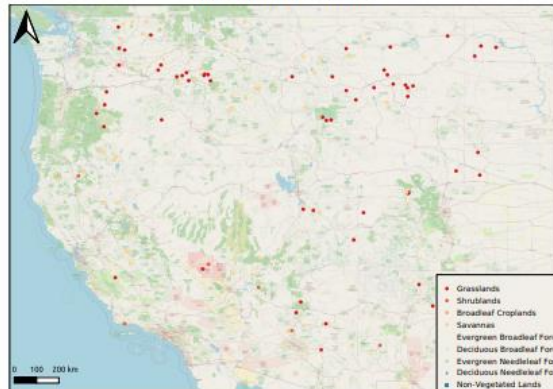
Input: 5-day sequences → Predict: Day 6 burn mask



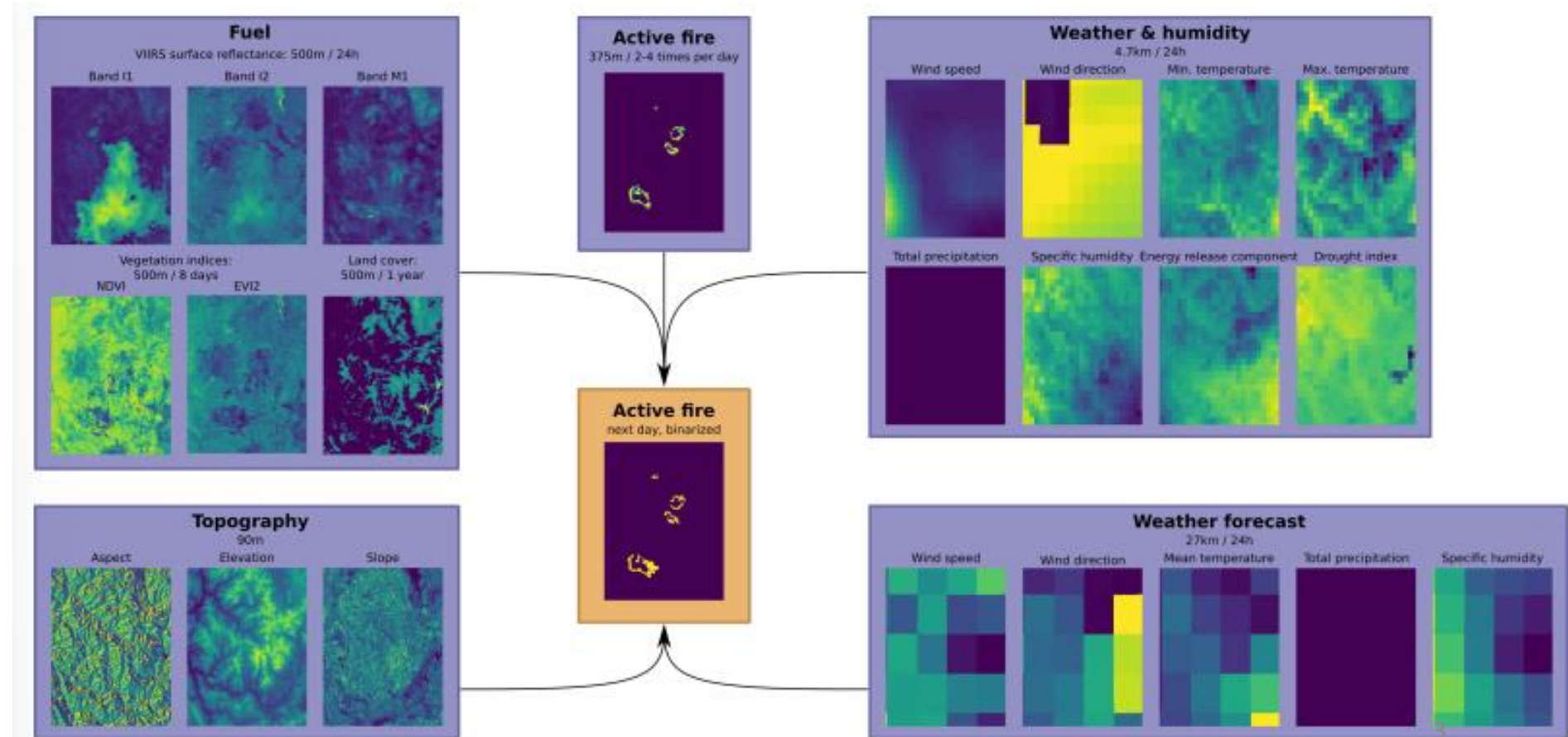
(a) Training set (2018, 2020)



(b) Validation set (2019)

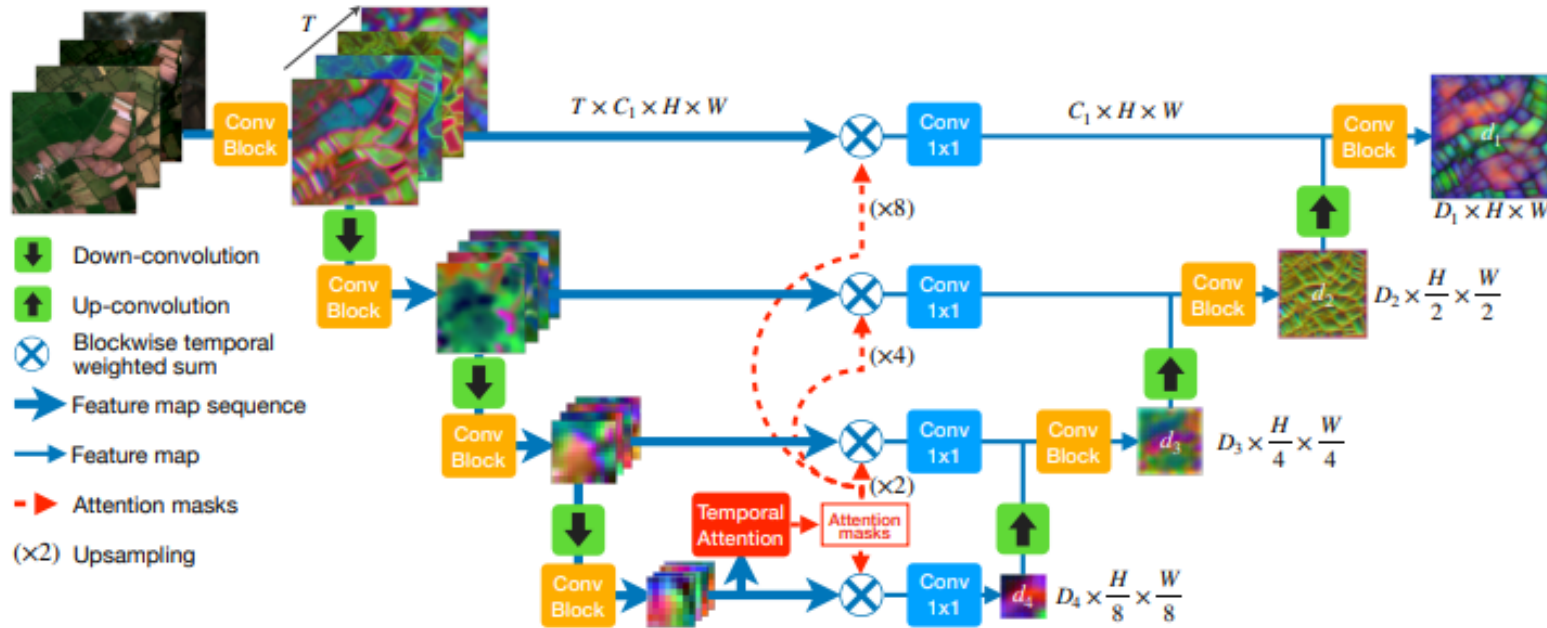


(c) Test set (2021)



METHODS AND MODEL

5-day inputs $\rightarrow$ UTAE (1M params) $\rightarrow$ Binary fire mask



UQ Approaches

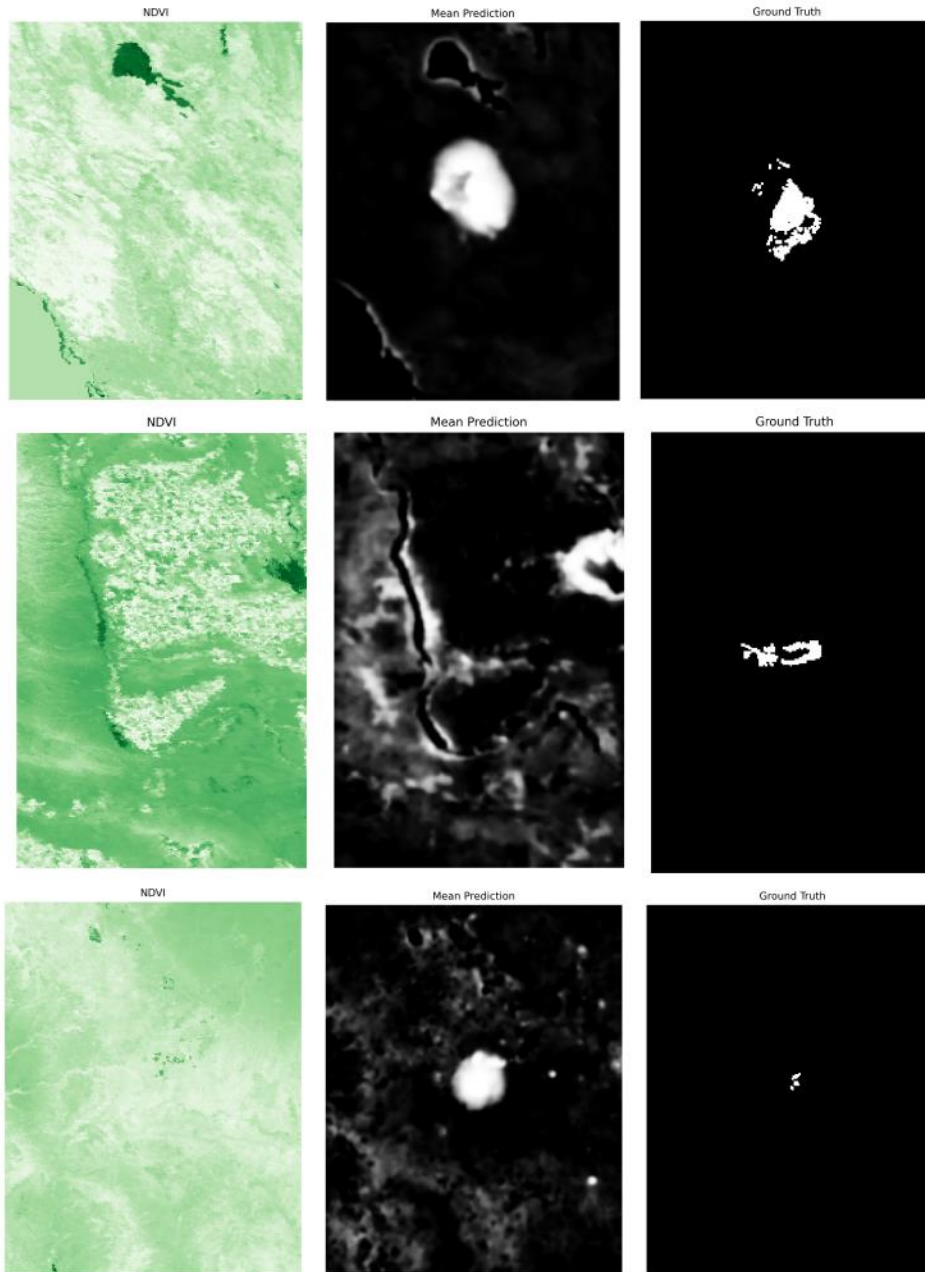
MC Dropout (20 forward passes) $\rightarrow$ Epistemic uncertainty

Deep Ensemble (5 models $\times$ 20 passes each) $\rightarrow$ More robust

Also tested BNN with variational inference—computationally expensive, marginal gains

Feature Group	Mean AP
Persistence baseline	0.191 ± 0.063
Vegetation + active fire	0.378 ± 0.083
Weather + active fire	0.323 ± 0.078
Land cover + active fire	0.319 ± 0.092
Topography + active fire	0.317 ± 0.082
All Features (veg + Weather + Land + Topo) + active fire	0.319 ± 0.077
ConvLSTM (veg. + active fire)	0.304 ± 0.093

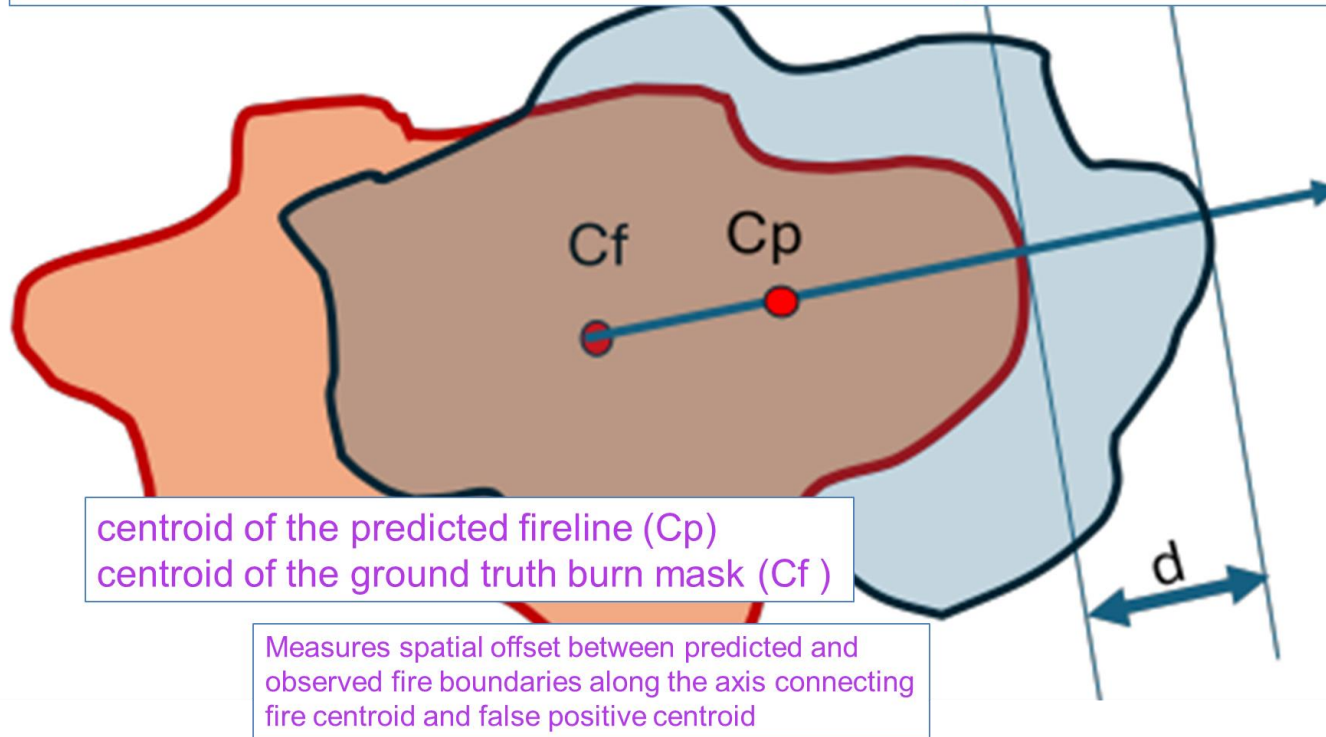
SPATIAL UNCERTAINTY IS STRUCTURED



- Uncertainty concentrates near fire perimeters
- Not random noise—spatially coherent patterns
- Modulated by vegetation gradients

BUFFER ZONES ARE QUANTIFIABLE

NOVEL METRIC: Centroid-Oriented Boundary Distance



Distance Metric	Feature Set	Peak Distance (m)
Centroid Boundary Distance	Landcover	28.14
	Topography	31.26
	Vegetation	32.19
	Weather	35.17
	All Features	33.48
Average Surface Distance (ASD)	Landcover	46.72
	Topography	52.89
	Vegetation	64.15
	Weather	57.34
	All Features	55.86
Hausdorff Distance	Landcover	148.63
	Topography	153.42
	Vegetation	165.78
	Weather	159.11
	All Features	155.67

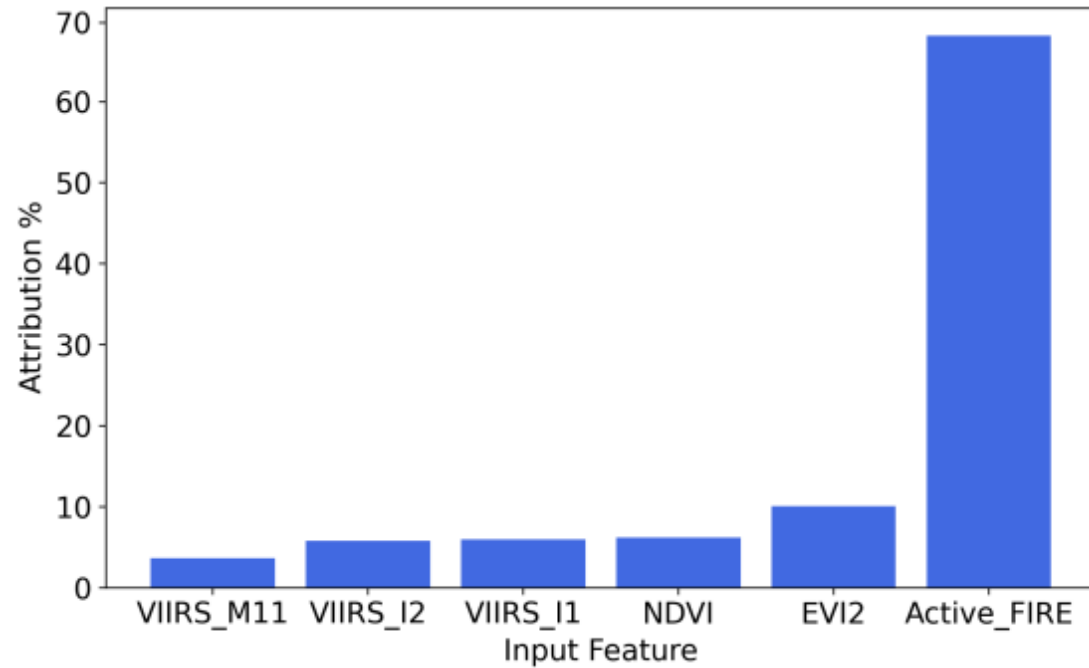
- **Centroid Boundary Distance: 28-35 meters**
- **Average Surface Distance: 47-64 meters**
- **Hausdorff Distance: 148-166 meters**

We identify the first boundary pixel $p_{gt} \in \partial M_{gt}$ along $\mathcal{L}(C_f, C_p)$ starting from C_f , and the first pixel $p_{fp} \in \partial M_{fp}$ from the opposite direction. The centroid-oriented boundary distance d is defined as:

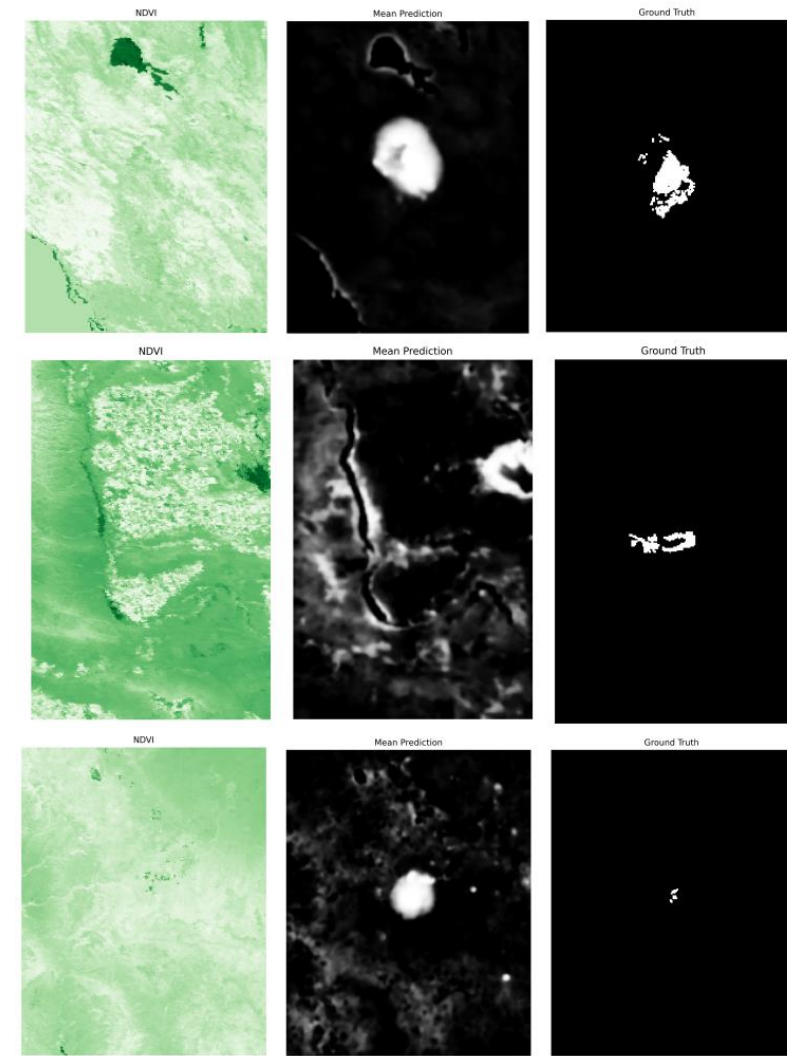
$$d = \|p_{gt} - p_{fp}\|_2 \cdot s,$$

Operational takeaway: ~30-70m buffer zones around predicted firelines capture typical model uncertainty

WHAT DRIVES UNCERTAINTY?



- Feature importance scores using Integrated Gradients on a CNN surrogate
- Active fire presence dominates attribution, followed by vegetation indices (NDVI, EVI2)
- Thermal bands are less influential in determining predictive confidence



CALIBRATION & LIMITATIONS

Table 2: Calibration metrics (12-fold averages) for the three UQ approaches. Lower values indicate better calibration. BNN shows slight improvements over MC Dropout but does not reach the performance of Deep Ensembles.

Metric	MC Dropout	BNN	Deep Ensemble
ECE	0.536 ± 0.015	0.525 ± 0.014	0.512 ± 0.018
Brier Score	0.294 ± 0.012	0.283 ± 0.019	0.265 ± 0.009
NLL	0.805 ± 0.020	0.794 ± 0.054	0.731 ± 0.023

Limitations

- US-only data (Western states)
- Epistemic uncertainty only (no aleatoric)
- Centroid metric assumes single fire focus

Next in the pipeline..

- Multi-region testing
- Fusion strategies for multi-resolution inputs

SUMMARY & IMPACT

Spatial Structure

- Uncertainty is not noise—it forms coherent 20-60m buffer zones around predicted fire boundary

Operational Utility

- Novel centroid-distance metric provides interpretable, actionable uncertainty maps for fire managers

Feature Insights

- Vegetation health + recent fire activity drive confidence
- Ambiguous fuel signatures → high uncertainty

•**Uncertainty-aware wildfire forecasting can support safer, risk-informed decision-making**

•GitHub link - <https://github.com/roloccark/wildf-UQ>

