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

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Introduction & Motivation

THE GAP

Most wildfire forecasting models are deterministic—they produce predictions without expressing WHERE or WHY the model might be wrong. This is critical for operational trust and decision-making.

OUR CONTRIBUTION

First systematic analysis of spatial uncertainty in high-resolution, Earth observation-based wildfire forecasting using:
-Monte Carlo Dropout
-Deep Ensembles
-Bayesian Neural Networks

Code Available at github.com/roloccark/wildf-UQ

Methods

MODEL: UTAE (U-Net with Temporal Attention Encoder) - Transformer-based spatiotemporal encoder-decoder - 1.1M parameters (vs 27M for Swin Transformers) - Efficient and proven for satellite time series

DATASET: WildfireSpreadTS - 607 wildfire events (2018-2021, Western U.S.) - 13,607 daily images - 64×64 patches at 375m resolution - 5-day input sequences → next-day burn prediction

INPUT FEATURES (5 channels): - VIIRS bands: M11, I2, I1 - Vegetation indices: NDVI, EVI2 - Active fire history

UNCERTAINTY QUANTIFICATION: 1. MC Dropout: 20 stochastic forward passes 2. Deep Ensembles: 5 independent models × 20 MC passes 3. Bayesian Neural Networks: Variational weight distributions

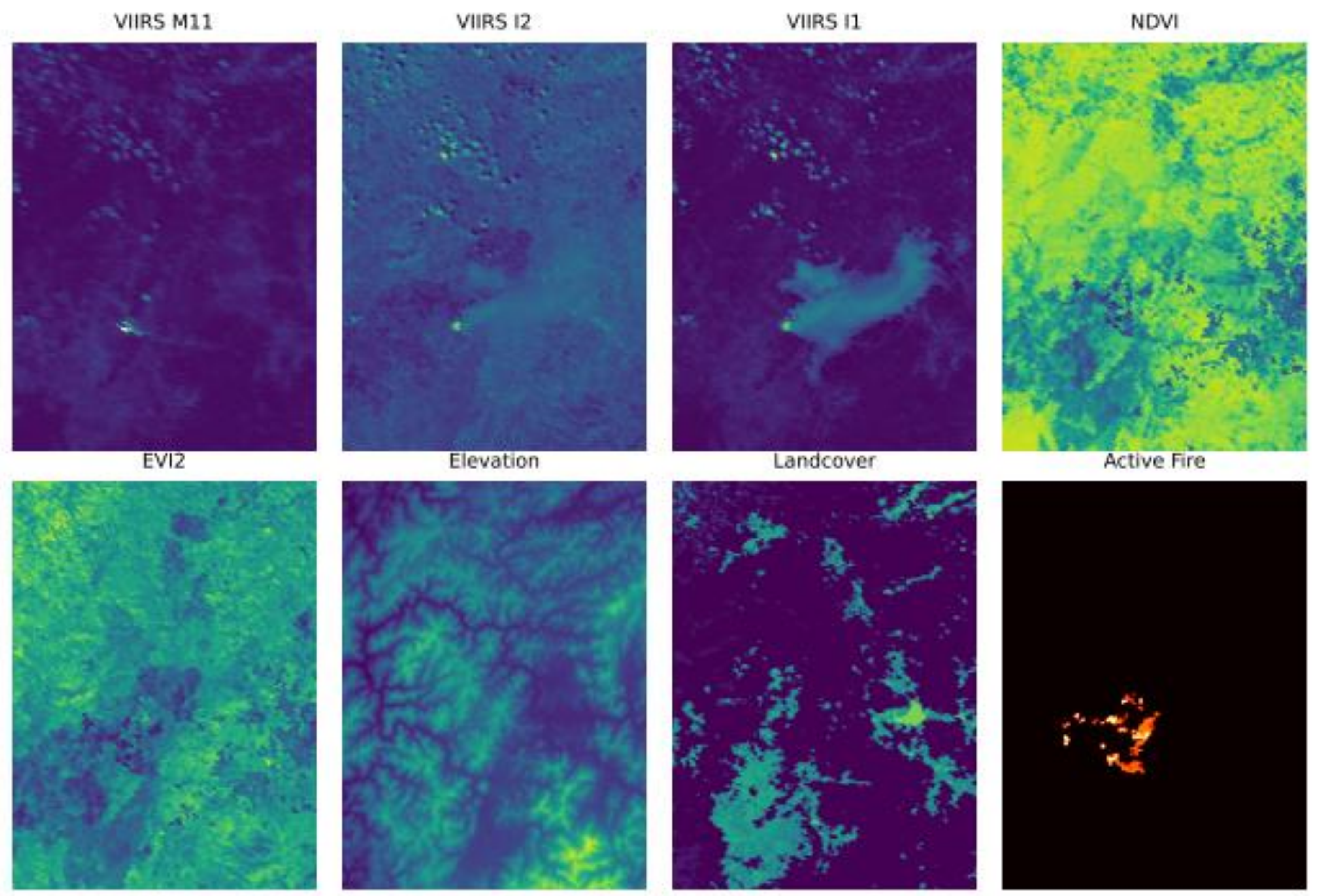
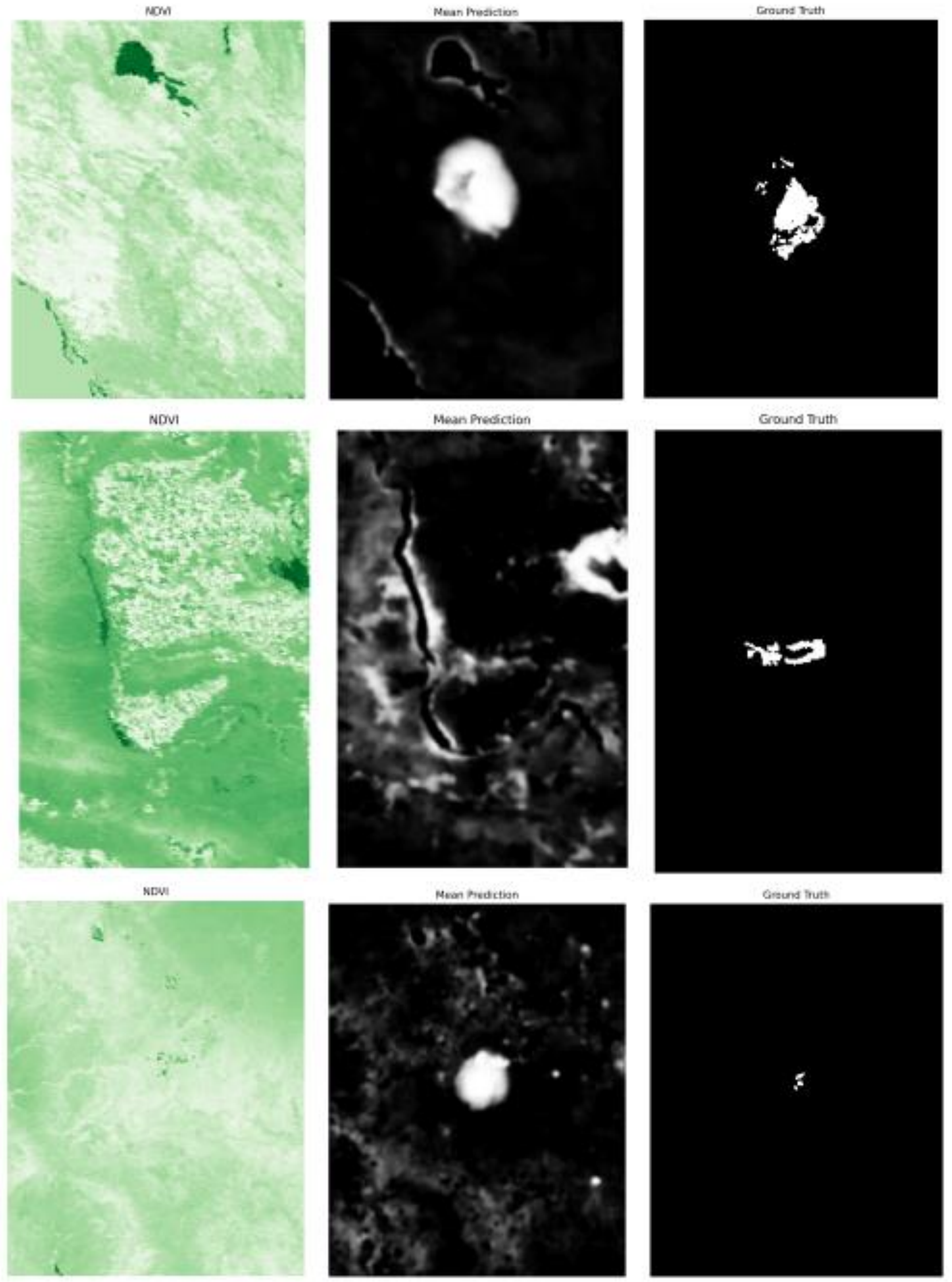


Figure 1: Example input channels from a single sample at prediction time, including Sentinel-2 bands, NDVI, EVI2, and active fire features. These inputs are provided as a 5-day sequence to the model.

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

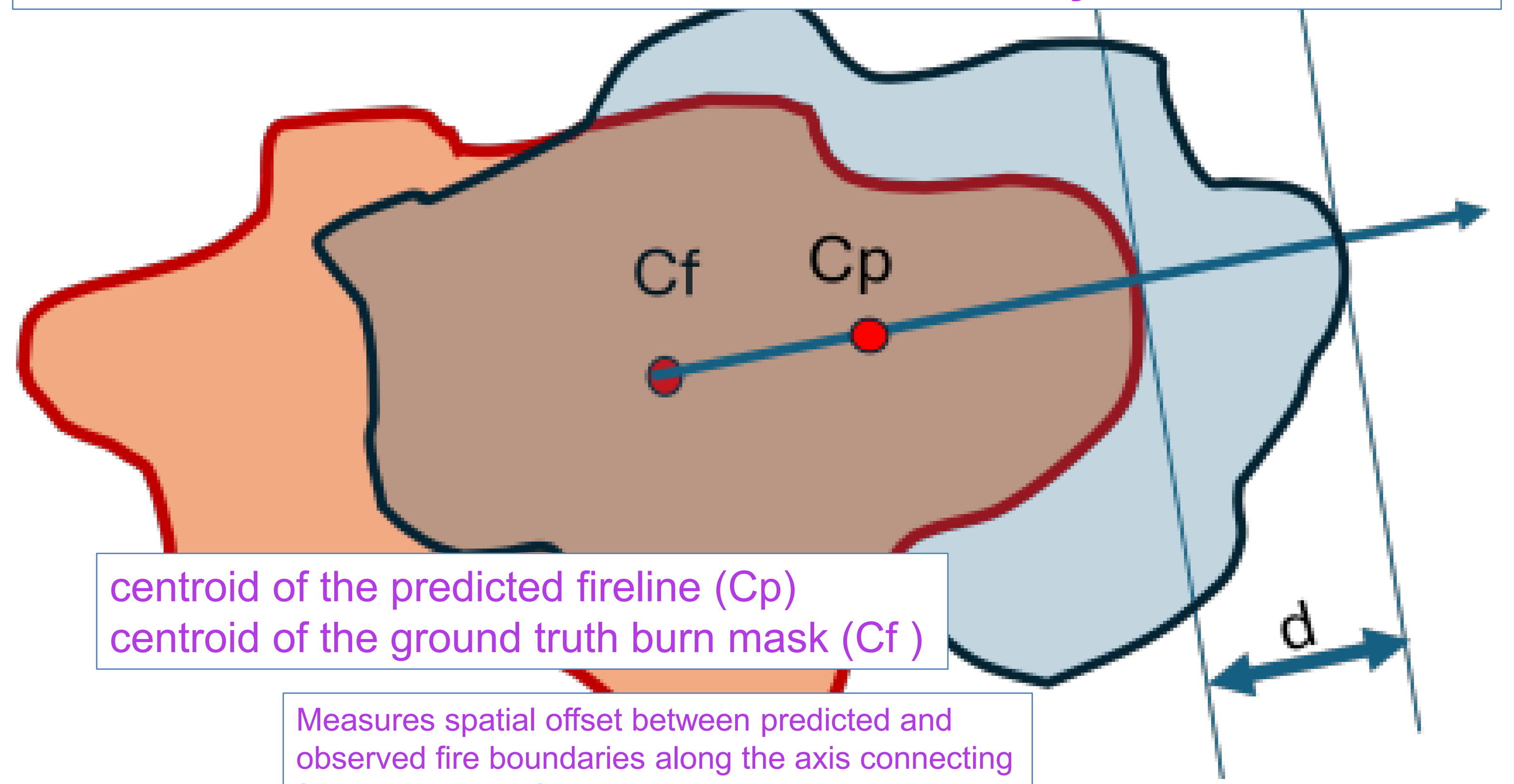
Metric	MC Dropout	BNN	Deep Ensemble
ECE	0.536 ± 0.015	0.525 ± 0.014	$\mathbf{0.512 \pm 0.018}$
Brier Score	0.294 ± 0.012	0.283 ± 0.019	$\mathbf{0.265 \pm 0.009}$
NLL	0.805 ± 0.020	0.794 ± 0.054	$\mathbf{0.731 \pm 0.023}$

✓ Deep Ensembles show best calibration (ECE: 0.512, Brier: 0.265, NLL: 0.731)
✓ MC Dropout provides reliable uncertainty estimates
✓ BNN shows improvements but higher computational cost



- **Large** fires (125.6 acres): U/C sharply localized near fire perimeter
- **Medium** fires (52.3 acres): Moderate uncertainty at boundaries
- **Small** fires (5.2 acres): More diffuse and spatially ambiguous

NOVEL METRIC: Centroid-Oriented Boundary Distance



Measures spatial offset between predicted and observed fire boundaries along the axis connecting fire centroid and false positive centroid

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

BROADER IMPACT

-First pixel-level uncertainty analysis for operational wildfire forecasting

- Enables human-in-the-loop deployment with transparent confidence

- Supports safer resource allocation and evacuation planning

- Foundation for uncertainty-aware wildfire management systems