A Calibrated Spatio-Temporal Machine Learning Model for Tropical Peatland Fire Risk

Riset Internasional ITB

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Abstract

Tropical peatland fires are complex environmental hazards with significant impacts. However, existing fire risk approaches, including empirical drought-fire indices and machine learning models that focus on either spatial or temporal aspects, remain limited in representing the dynamics of fire occurrence across heterogeneous peatland landscapes. Here, we develop an integrated spatio-temporal machine learning model with a probabilistic calibration method to analyze and predict tropical peatland fire risk. The framework employs a Convolutional Neural Network (CNN) to extract spatial features, Convolutional Long Short-Term Memory (ConvLSTM) to capture temporal dependencies, and isotonic regression to calibrate predicted fire probabilities. We employ meteorological, hydrological, land cover, anthropogenic, and historical fire data from tropical peatlands in Kalimantan, Indonesia. The proposed model achieves good performance and produces probability of fire maps that are consistent with observed fire hotspot distributions. Furthermore, the forecasting results show that the model can identify shifting fire risk patterns across peatland areas over different time horizons. These findings demonstrate that the proposed framework provides not only a predictive tool but also actionable information for early warning, risk assessment, and fire mitigation in tropical peatland ecosystems.

Keyword: Tropical peatland, Fire risk, Spatio-temporal model, Probability of fire, Machine learning model.

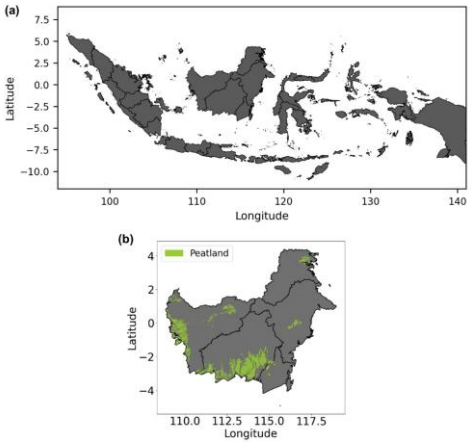
Introduction

Tropical peatland fires are significant environmental hazards influenced by complex processes that evolve simultaneously across space and time. Analyzing and forecasting tropical peatland fire risk, including the location and timing of fire occurrence, can support risk assessment and fire mitigation efforts. This paper develops an integrated spatio-temporal machine learning model with a probabilistic calibration method to analyze and predict tropical peatland fire risk. The proposed framework combines three complementary methods. Convolutional Neural Network (CNN) is used to learn spatial patterns and identify areas with higher fire susceptibility. Convolutional Long Short-Term Memory (ConvLSTM) is applied to capture temporal dependencies and represent the evolution of fire prone conditions over time. Finally, isotonic regression is employed to calibrate the predicted fire probabilities, improving the consistency between model outputs and observed fire occurrence frequencies.

Research Method

Study area

The study area is located in Kalimantan, Indonesia, which contains one of the largest tropical peatland ecosystems in Southeast Asia (**Picture 1**). Peatlands in this region cover approximately 4.54 million hectares, representing about 33.8% of total Indonesian peatlands (Anda et al., 2021).



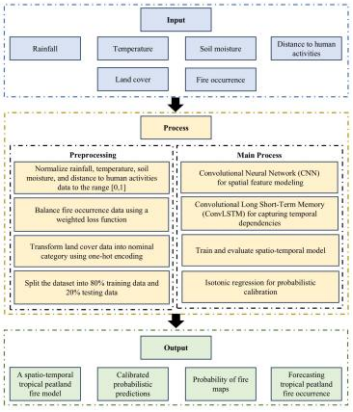
Picture 1. Location of the study area. (a) Map of Indonesia showing the geographic position of Kalimantan Island and (b) the distribution of tropical peatlands in Kalimantan, Indonesia.

Model

CNN is employed to extract spatial features from tropical peatland fire predictor maps at each observation time (**Picture 2**) (Khirani et al., 2026; Yar et al., 2023; Zelioli et al., 2025). The main operation in CNN is the convolution process, which is defined as

$$F_t(i,j) = \sum_m \sum_n X_t\,(i-m, j-n)\,K(m,n)$$

The spatial feature maps extracted from several consecutive time steps are arranged into a spatio-temporal sequence and passed to a ConvLSTM layer.



Picture 2. Conceptual diagram of the proposed model consisting of input, process, and output stages.

$$i_t = \sigma(W_{xi} * F_t + W_{hi} * H_{t-1} + b_i)$$

$$f_t = \sigma(W_{xf} * F_t + W_{hf} * H_{t-1} + b_f)$$

$$o_t = \sigma(W_{xo} * F_t + W_{ho} * H_{t-1} + b_o)$$

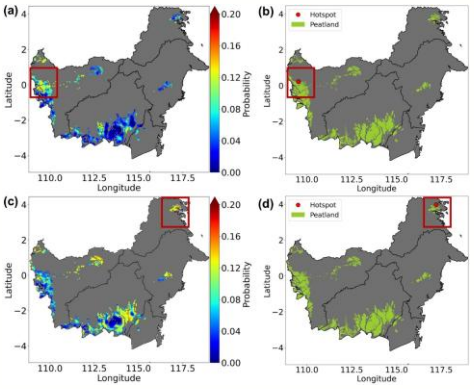
$$\tilde{C}_t = \tanh(W_{xc} * F_t + W_{hc} * H_{t-1} + b_c)$$

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t$$

$$H_t = o_t \odot \tanh(C_t)$$

Discussion & Result

The forecasting capability of the proposed spatio-temporal modeling framework is evaluated by comparing the predicted probability of fire maps for the next three and ten days with the observed hotspots (**Picture 3**). In terms of spatial prediction, the forecast fire risk patterns are in agreement with the actual hotspot occurrences, because the observed hotspots are located within or adjacent to the elevated risk zones identified by the model.



Picture 3. Comparison between forecasted fire probability from the proposed model and actual fire hotspots for (a, b) the next three-day forecast and (c, d) the next ten-day forecast. The red box highlights areas where high predicted fire probability aligns with observed fire hotspots.

Conclusion

This study developed a spatio-temporal framework to analyze and predict tropical peatland fire risk by integrating a Convolutional Neural Network (CNN) for spatial feature extraction, Convolutional Long Short-Term Memory (ConvLSTM) for temporal dependency learning, and isotonic regression for probability calibration. Through this integrated structure, the proposed model is able to identify areas with increased fire probability and produces probability of fire maps that are consistent with observed hotspot distributions.