Predicting Marine Hypoxia in the Gulf of Mexico Using Machine Learning

DSAN 5550: Data Science and Climate Change

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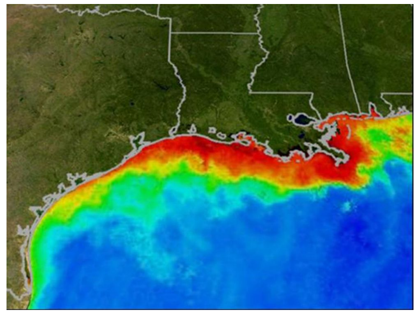
Introduction

- Dead zones occur when oxygen drops below 2 mg/L, killing marine life
- Gulf of Mexico has 2nd largest hypoxic zone globally (~15,000 km²)
- Threatens $2.4B fishing industry and 400+ species
- Caused by agricultural runoff from Mississippi River watershed

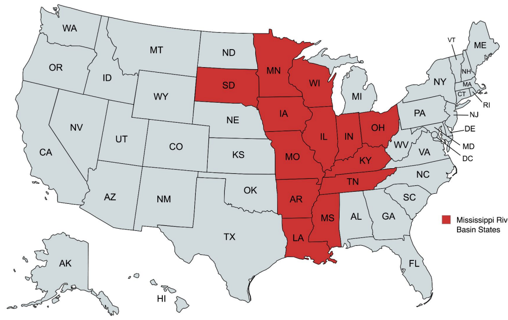


Research Question & Data

Objective: Predict hypoxia extent 1-4 months in advance

Data Sources (2001-2024):

- **NOAA** (ocean): Monthly hypoxia measurements, Buoy water temperature, Wind speed/direction
- **USGS**: Mississippi River discharge
- **NOAA** (land): Regional precipitation (3 regions)
- **USDA**: Crop acreage - corn & soy (13 states)



Data Processing

Feature Engineering

- Created temporal sequences with variable lengths (3-6 months)
  - 38 features per timestep: discharge, precipitation, crops, wind, temperature, lagged hypoxia
- Standardized all features using training data statistics

Data Split:

- Combined train+val: 2003-2021 (18 years, 54 samples)
  - Excluding 2020, 2022 (no hypoxia measurements);
  - 5-fold cross-validation for evaluation

Models

Bidirectional LSTM

- Captures temporal patterns in sequential data
- **2 BiLSTM layers** (64→32 units) + dropout
- 89,906 parameters
- Handles variable-length sequences with masking

Random Forest

- Ensemble of **100 decision trees**
- Max depth=5, regularized to prevent overfitting
- Flattened 6-month sequences (**228 features**)

Evaluation

5-Fold Cross-Validation

- Robust evaluation across multiple data splits
- Same data (**2 zones**: Louisiana & Texas only)
- Accounts for small dataset size (**54 samples**)

Metrics

- **MAE (Mean Absolute Error)**, R^2
- **Sustainability**: Tracked CO_2 emissions using CodeCarbon, Compared computational efficiency

Results

Model Comparison

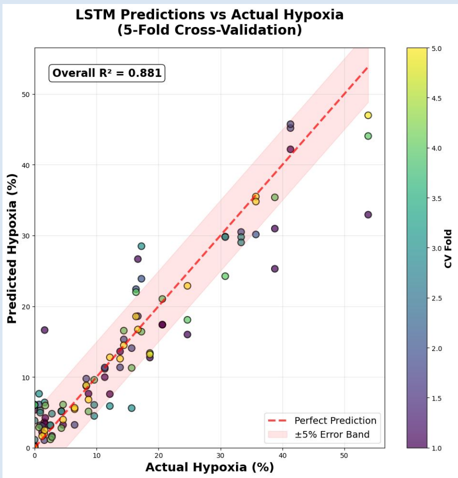
Model	MAE (%)	R^2	Duration	CO_2(g)
LSTM	3.90 ± 2.26	0.609± 0.320	1.07 min	0.318
Random Forest	5.61± 1.18	0.400± 0.382	0.09 min	0.027

The Bidirectional LSTM significantly outperforms Random Forest

- 30% lower prediction error
- 52% better explanatory power
- Explains 61% of hypoxia variability using temporal patterns
- LSTM excelled at capturing seasonal and year-to-year trends

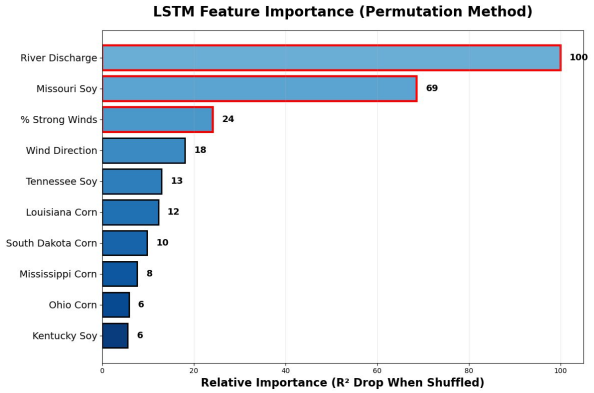
LSTM Model Performance

Model performs best on typical years; struggles with extreme events (2016 mega-hypoxia outlier, 2012 low hypoxia).



LSTM Predictions vs Actual Hypoxia (5-Fold Cross-Validation)

LSTM Feature Importance - Permutation



- River Discharge - River flow proxy for nutrient loading
- Crops - Soy, especially in specific states, lead to variation in fertilizer use
- Wind Speed - Critical for water column mixing/stratification

Conclusion

Temporal Models Are Essential

- LSTM's **52% improvement** over RF shows time patterns matter

Actionable Early Warnings

- **3.90%** MAE enables 1-4 month advance predictions
- Sufficient accuracy for agriculture practices, watershed management

Limitations:

- Extreme events remain challenging (2016 mega-hypoxia, 2012 zero-hypoxia)
- Missing: hurricanes, ocean currents, direct nutrient measurements

Impact: Machine learning provides actionable early warnings using readily available data, informing adaptive management to protect Gulf ecosystems