Using Machine Learning and Explainable AI to Model Disaster Impacts on Human Migration in United States

Xiang Li, Yi Qiang*

School of Geosciences, University of South Florida

Corresponding author: qiangy@usf.edu

Introduction

- **Migration under pressure:** Disasters can cause both immediate displacement and permanent migration due to cumulative impacts or degraded living conditions.
- **Different disasters, different effects:** Disaster-related migration patterns vary considerably across geographic areas, time periods, and disaster types.
- **Complex factors:** migration patterns during and after disasters are influenced by a complex interplay of environmental, economic, and social factors.
- **Research Gaps:** Existing studies focus on individual disaster events or types, lacking cross-disaster comparisons and quantitative isolation of the independent effects of disasters on migration.
- This study uses **explainable AI (XAI)** to examine the associations of four disaster types (floods, hurricanes, wildfires, and tornadoes) with county-level human migration across the contiguous United States (CONUS) from 2000 to 2020.

Research Questions

(1) How are the different types of natural disasters associated with human migration patterns across spatial and temporal dimensions?
(2) How can we isolate the effects of disasters from socio-economic variables to quantify their independent impact on migration?

Materials and Methods

Data sources

- Migration: Annual net migration rate (NMR) in counties from 2000 to 2020 from US Census (Figure 1)
- Disasters: Disaster numbers, property losses, fatalities, injuries in counties from SHELDUS (Figure 2)
- Socio-economic variables: U.S. Census (Table 1)

Analysis

- Temporal analysis: line charts were created to compare annual NMR with per capita damage related to disasters. GAM panel regression was applied to quantify the relations between disaster variables with annual NMR in the current year and 1-year lag.
- Spatial analysis: using 20-year aggregated data to assess long-term associations between disasters and migration via automated machine learning (AutoML) models.

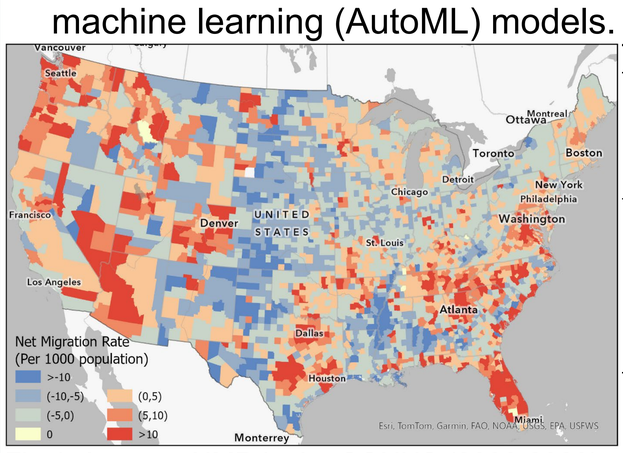

Fig 1. Average NMR in the CONUS (2000-2020)

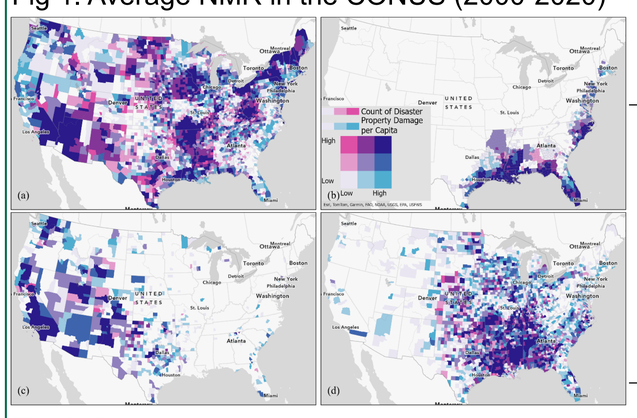

Fig 2. Disaster counts and per capita damage for floods(a), hurricanes(b), wildfires(c), & tornadoes(d).

Table 1. Variables Table

Categories	Variables	Datasets
Disaster (Flood, Hurricane, Wildfire, Tornado)	Disaster Counts	SHELDUS
	Disaster Induced Economic Loss	
	Disaster Induced Fatalities	
	Disaster Induced Injuries	
House Affordability	Median Household Income / Median House Value	Census Bureau
	% Change of Median Household Income / % Change of Median House value	ACS
	House Affordability Index	HUD
House Condition	% of Mobile Home	ACS
	% of Multi-unit House	
	% of Group Quarter	
	% of House Population > Room	
	% of Single-Parent Household	
	% of No Vehicle Household	
Socio-Economic	Population Density	Census Bureau
	Median Household Income	
	% Change of Median Household Income	ACS
	% of Unemployment	
	Per Capita Income	
	% Below Poverty	
	% of Adults without High School Diploma	
	% of Age5+ with Limited English	
Demographic	% of Elder than 65	ACS
	% of Younger than 18	
	% of Minority	
Natural Amenities	Natural Amenity Scale	USDA

Results

- **Average NMR is usually lower in high-impact disaster areas** (Figure 3). Counties with high disaster impact often exhibit the lowest NMR compared to moderate- or high-impact counties, especially for floods and tornadoes. Additionally, average NMR appears to respond to disaster-related property damage in specific years.

Fig 3. Time series analysis plots in high-impact (red), moderate-impact (yellow), and low-impact counties (blue) for flood (a), hurricanes (b), wildfires (c), and tornadoes (d).

- **Annual floods and hurricanes conditions have significantly current and lag effects on NMR** (Figure 4). Floods show the approximately linear effects on NMR. More flood events are slightly associated with higher NMR, while greater flood-induced damage relates to lower NMR. By contrast, hurricanes show clearly non-linear patterns. Extreme damage causes sharp drops for NMR within current-year and rebound pattern occur at a 1-year lag.

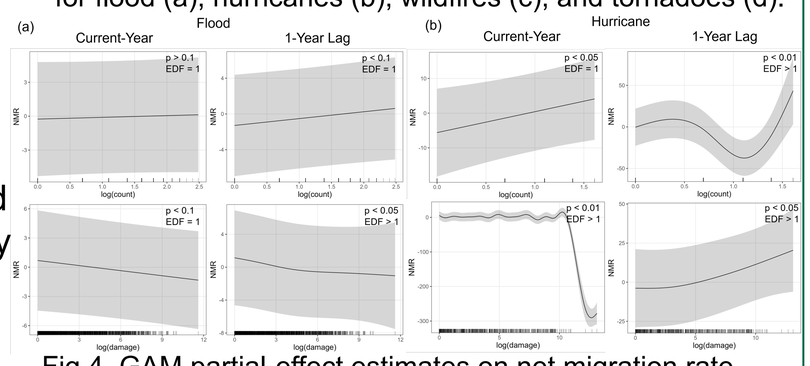

Fig 4. GAM partial-effect estimates on net migration rate (NMR) for high-impact counties: (a) floods and (b) hurricanes.

- **Flooding and hurricane have moderate effects on disasters** (Figure 5). Socio-economic conditions including population density, the income-to-house-value ratio, and % no-vehicle households remain primary migration drivers. Comparing the models with and without disaster variables, flooding and hurricanes show observable and moderate contribution to the prediction of migration rate. Specifically, larger flood-induced loss are associated with lower NMR, and hurricane counts show the same direction. These suggest that severe or frequent disasters tend to deter in-migration and/or lead to out-migration.

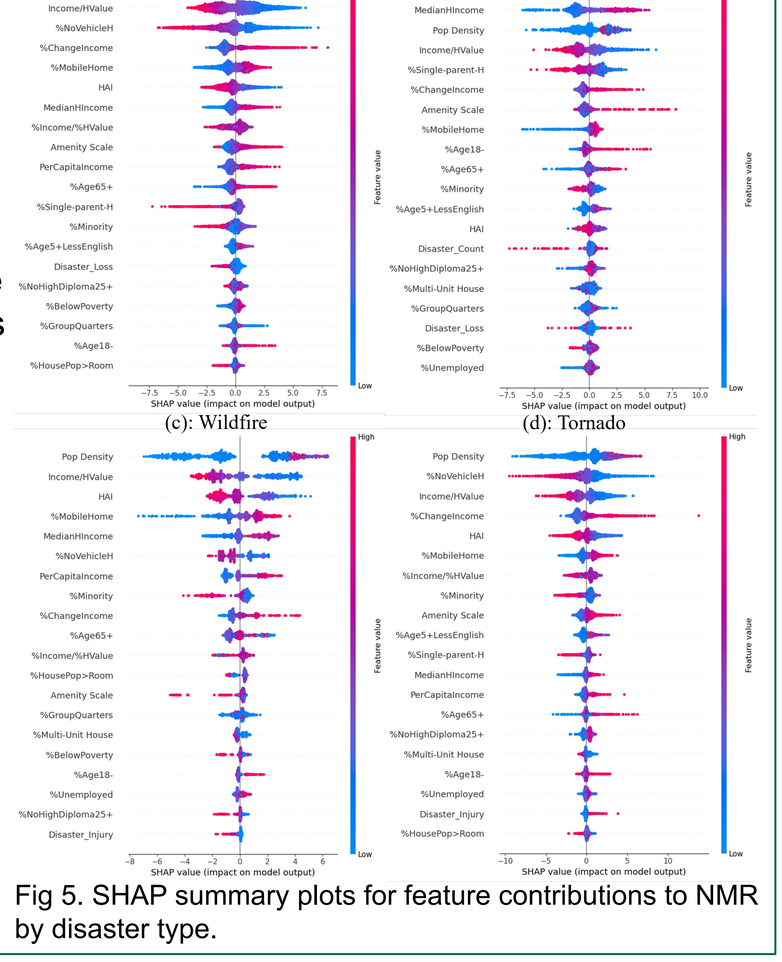

Fig 5. SHAP summary plots for feature contributions to NMR by disaster type.

Conclusion

- This study examines how four major natural disasters affect county-level migration across the CONUS from 2000 to 2020.
- Floods and hurricanes have the strongest negative impacts on NMR, with both current-year and lagged effects. In contrast, wildfires and tornadoes show weaker and inconsistent associations with migration.
- SHAP values show that socio-economic factors are still the dominant drivers of migration. Disaster variables act more as stress multipliers than primary motivators.
- This study demonstrates the value of explainable AI in capturing the complex dynamics between disasters and human migration and offers insights into the varying impacts of different disaster types on migration patterns.

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