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

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Abstract:

Climate change is intensifying the frequency and severity of natural disasters, which profoundly impact the health, wellbeing and long-term sustainability of human communities (Ma et al., 2025; McConnell et al., 2024). These events may trigger both short-term displacement and long-term migrations as communities seek safety, stability, and sustainability (Huang et al., 2012; Li et al., 2024). Understanding how disasters influence population movement is essential for effective disaster management, resilience planning, and fostering long-term sustainability. This study addresses this gap by analyzing the influence of four major including disaster types, floods, hurricanes, wildfires, and tornadoes, on county-level net migration rates (NMR) across the contiguous U.S. (CONUS) from 2000 to 2020.

We integrate disaster records from SHELDUS, migration estimates from the U.S. Census Bureau's Population Estimates Program (PEP), and a broad array of socio-economic and environmental variables from the American Community Survey and HUD datasets. Our analysis combines fixed-effects panel regression and an explainable machine learning framework using Automated Machine Learning (AutoML), enabling us to quantify both short-term and long-term migration responses to disasters while isolating their effects from confounding factors.

Results of panel regression reveal that disaster impacts on migration vary considerably across types and temporal scales. Floods and hurricanes exhibit the most consistent associations with NMR. Flood frequency and damage are significantly correlated with population outflows both in the same year and the following year, indicating their disruptive and persistent nature. Similarly, hurricane-related fatalities and damage reduce NMR in the year of occurrence. Surprisingly, the simple occurrence of hurricanes is positively associated with NMR, suggesting that economic or amenity-driven in-migration continues in hurricane-prone areas, despite the associated risks. By contrast, wildfires and tornadoes show inconsistent or minimal influence on migration, likely due to their more localized and short-term impacts.

To assess long-term effects, we use AutoML to model average NMR from 2000 to 2020. A suite of tree-based machine learning models—including CatBoost, LightGBM, and XGBoost—were trained with over 25 disaster and socio-economic variables. The models explain 61–72% of the variance in NMR, significantly outperforming benchmark OLS regression. Notably, models with disaster variables performed better than those without in the case of floods and hurricanes, but not for wildfires and tornadoes, suggesting that only certain disasters systematically shape migration over time.

To interpret these models, we apply SHapley Additive exPlanations (SHAP), which quantify the contribution of each variable to model predictions. SHAP results show that socio-economic factors, particularly population density, housing affordability, and income levels, dominate migration outcomes. High population density and income correlate with net in-migration, while limited vehicle access, high mobile home percentages, and poor housing quality are associated with out-migration. Additionally, SHAP values reveal that housing affordability as an important contribution to human migration. Unaffordable counties experienced out-migration, while very affordable counties attracted in-migration, even if disaster risk remained high. This supports the idea that residents may trade risk exposure for lower living costs. Such complexity underscores the importance of modeling interactions between environmental and economic conditions. Finally, disaster variables made modest and measurable contributions in flood and hurricane models: event counts and property damage were negatively associated with NMR, indicating disaster-related deterrents to migration.

Our findings support the interpretation of disasters as stress multipliers rather than primary drivers of migration. Socio-economic conditions, especially housing affordability and employment, remain the most significant determinants of population movement. However, disasters can tip the balance, particularly in already vulnerable communities. This dynamic highlights the need for policies that not only address immediate disaster response, but also invest in long-term resilience and economic opportunity.

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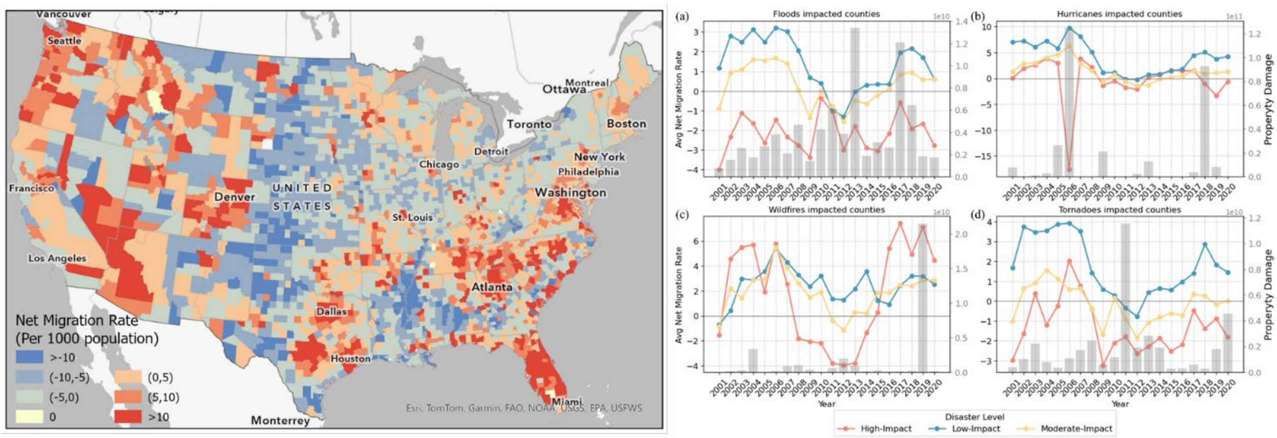
Overall, this study demonstrates the value of combining panel regression and explainable AI to capture both causal relationships and predictive insights. AutoML, paired with SHAP, provides a powerful tool to identify and interpret the relative influence of complex, interacting variables in human mobility studies. This approach enhances transparency and enables data-driven planning for climate adaptation and disaster risk reduction. Our findings support the interpretation of disasters as stress multipliers rather than primary drivers of migration. While floods and hurricanes exert measurable pressure on population change, economic opportunity, housing affordability, and social vulnerability remain the primary drivers of migration. As climate change increases the frequency and cost of disasters, understanding these interdependencies is essential for designing equitable, resilient communities.



(a) (b)

Figure 1. (a): Average NMR in CONUS from 2000 to 2020. (b): Annual NMR and per capita damage caused by flooding, hurricanes, wildfires and tornados

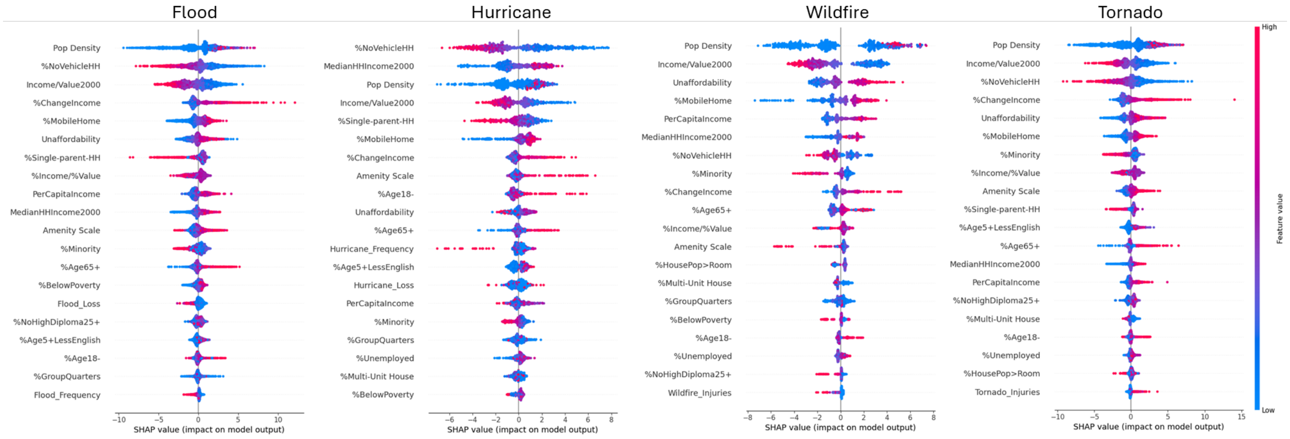


Figure 2. Average net migration rate in the CONUS from 2001 to 2020

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