Title	説明可能な機械学習とマルチソース空間データに基づくグリッドレベルの雪害リスク評価とレジリエンスモデリング
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論 文 題 目	Grid-Level Snow Disaster Risk Assessment and Resilience Modeling Based on Interpretable Machine Learning and Multi-Source Spatial Data
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論文の内容の要旨

Approximately 60% of Japan’s land area and 20% of its population are affected by heavy snowfall each year. Snow disasters often trigger traffic accidents and congestion, resulting in significant casualties and economic losses. These events pose severe challenges to urban transportation systems, residents’ travel safety, and regional emergency response capacity. Traditional disaster response models struggle to accurately and promptly identify high-risk areas, limiting the effective allocation of disaster prevention resources. Against this backdrop, developing snow disaster risk identification and resilience assessment models based on multi-source spatial data and explainable machine learning is of great significance for enhancing urban disaster preparedness and promoting sustainable regional development.

This study takes the 2018 heavy snowstorm in Fukui Prefecture as a case study and proposes a grid-scale risk modeling framework integrating multi-source spatial data, including mobile GPS data, road data, land use data, digital elevation models (DEM), urban area data, snow depth data, traffic congestion data, nighttime light data (DNB), and the Normalized Difference Vegetation Index (NDVI). The dissertation consists of four core components: (1) Based on KDTree nearest-neighbor matching and singular value decomposition (SVD), the study performs dimensionality reduction on the spatiotemporal OD matrix to analyze the evolution of intercity travel patterns during the snowstorm and reveal disruptions in transportation demand structures; (2) A grid-level analysis of major roads in Fukui Prefecture is conducted to identify critical congestion points along National Route 8 and the Hokuriku Expressway. A Random Forest-based traffic congestion identification model is developed to assess snowstorm-induced traffic bottlenecks；(3) A “triangular resilience framework” is established to evaluate robustness, vulnerability, and adaptability across land use types at a 500-meter grid level using elastic triangle theory, quantifying the disaster resilience of various urban functional zones; (4) Multiple machine learning models, including Multilayer Perceptron (MLP), Decision Tree (DT), Random Forest (RF), Support Vector Machine (SVM), Light Gradient Boosting Machine (LightGBM), and Extreme Gradient Boosting (XGBoost), are applied to classify high-risk snowstorm areas. SHapley Additive exPlanations (SHAP) values are used to interpret the models, revealing key influencing factors and nonlinear threshold effects, thereby generating interpretable spatial risk maps to support disaster early warning and emergency response.

The major findings are as follows:

(1) Using KDTree and SVD, the study identifies spatiotemporal patterns of transportation demand in Fukui during the snowstorm. The snow event can be divided into three phases: stable (Jan 27–Feb 2), disaster (Feb 3–Feb 11), and recovery (Feb 12–Feb 16). Intercity travel demand declined by 67.86% during the snowstorm. Demand patterns included regular demand (M_1) from cities such as Fukui, Sabae, Awara, and Sakai, and special demand (M_2), where northbound trips nearly ceased, shifting from a longitudinal pattern along National Route 8 and the Hokuriku Expressway to a horizontal pattern toward Ono and Katsuyama. Travel outflows from Sakai dropped significantly, while Tsuruga's inflows increased, indicating the snowstorm's primary impact on northern Fukui, particularly Fukui City and Sakai.

(2) GPS data effectively captures population dynamics along road networks. In the case of the 2018 Fukui snow disaster, all locations where traffic volume surged sharply during the snowstorm were situated in urban areas, with predominant land use types being fields and forests. This phenomenon may be attributed to factors such as inadequate transportation infrastructure, the urban heat island effect, and steep terrain conditions. By integrating remote sensing data and GPS data with machine learning models, congested road sections can be effectively identified. Feature importance analysis highlighted the most influential variables in predicting congestion as follows: Snow Depth > Nighttime Light Difference > Elevation > Slope Angle > Urban Area > NDVI > Population Change > Forest > Field > Low-rise Buildings (Sparse) > Low-rise Buildings (Dense).

(3) The resilience of different land use types is evaluated at the 500-meter grid scale using the triangular resilience method. The results show that factory zones, agricultural areas, building land, and mid-/high-rise buildings demonstrate strong resilience, especially in their ability to absorb and recover from shocks. Prioritizing resilient building forms in urban planning can significantly improve disaster readiness. In contrast, sparse low-rise housing, parks, facilities, and dense low-rise neighborhoods exhibit weaker recovery and require targeted strengthening measures.

(4) By combining XGBoost and SHAP, an interpretable spatial risk assessment model is developed. The model quantifies high-risk areas and identifies key drivers with nonlinear relationships and threshold effects. Elevation, slope, DNB, NDVI, road density, and road width show significant nonlinear influences on snow risk. Snowstorms primarily affect primary and secondary roads, while rural roads are relatively less impacted. Real-time GPS monitoring and optimized road layouts can help improve transportation resilience during snow disasters.

The main innovations of this study are as follows:

(1) Integration of multi-source spatial data (GPS, land use, DEM, road networks, nighttime light, NDVI), providing a solid data foundation for high-precision modeling and interpretability analysis; (2) Combination of SVD and trajectory analysis to reveal dynamic disruptions in transportation demand during snowstorms; (3) Proposal of a "triangular resilience index" system (robustness, vulnerability, adaptability) to quantify resilience at a 500-meter grid level; (4) Application of XGBoost and SHAP to identify nonlinear relationships and threshold effects of key factors, enhancing interpretability and practical usability; (5) The proposed modeling framework demonstrates strong adaptability and transferability, applicable to other natural disasters such as floods, typhoons, and tsunamis. It supports the investigation of critical impact mechanisms and resilience under different disaster scenarios.

This research provides scientific evidence for forecasting transportation risks during snow disasters in the Hokuriku region of Japan, optimizing urban functional zone layouts, and guiding disaster preparedness. It contributes to enhancing the overall resilience of urban systems in the context of climate change.

Keywords: Snow disaster; multi-source data; spatiotemporal characteristics; resilience; machine learning; SHAP

論文審査の結果の要旨

本論文では、多次元空間データと説明可能な機械学習による、日本における豪雪災害のリスク推定とレジリエンス評価の方法論を新たに提示した。日本では国土の約 6 割、人口の約 2 割が毎年豪雪の影響を受け、交通事故や渋滞による人的被害・経済損失が深刻である。従来の積雪時のリスク推定モデル・レジリエンス評価指標は、高リスク地域を迅速かつ正確に推定することに課題があり、資源配分の効果的な実施に限界があった。上記の課題を解決すべく、本研究は 2018 年福井豪雪を事例とし、GPS、道路、土地利用、標高、積雪深、交通データ、夜間光、NDVI などを統合したグリッド単位のリスクモデルを構築した。

研究は 4 つの柱から成る。まず、①KDTree と特異値分解による OD 行列解析で都市間交通需要の変化を把握し、②ランダムフォレストを用いた交通渋滞推定モデルで国道 8 号や北陸自動車道の中で渋滞の発生している箇所を推定、さらに③渋滞の発生から緩和までの時系列推移を表現した Triangular resilience model により土地利用に応じた脆弱性・適応性を評価した後、④XGBoost や SHAP による高リスク地域の分類とその要因の解明を行った。

その結果、福井の交通需要は豪雪期に約 68%減少し、北部都市への影響が顕著であることが示唆された。また、積雪深、夜間光変化、標高、傾斜が交通渋滞に強く影響することが判明した。工場地帯や中高層建築は強いレジリエンスを示す一方、低層住宅密集地や公園は脆弱であるという分析結果が得られた。さらに、道路密度や幅員、NDVI などもリスクに非線形的な閾値効果を持つことが示された。

研究の新規性に関する部分は、①多様な空間データ統合による高精度分析、②SVD と移動解析による交通需要変動の可視化、③500m グリッドでのレジリエンス指標の定量化、④XGBoost と SHAP による要因の解釈性の向上などが挙げられる。他の災害への応用可能性については、まだ課題があるが、本研究自体は豪雪災害時の交通リスク予測、都市機能配置の最適化、防災計画策定に資するものであり、気候変動下での都市システムの総合的レジリエンス向上に向けた示唆を得ることにつながったと考えられる。