E213

An Agent-Based Model Integrating Demographic and Household Dynamics for Counterfactual Regional Exposure

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Introduction

Flood impact studies often infer disaster effects by comparing outcomes before and after the event. However, identifying a credible no-disaster baseline, noted as the counterfactual trajectory that would have occurred without the event, remain challenging.

This study aims to develop an agent-based model (ABM) framework to generate a no-flood counterfactual population distribution for 2020 in the Kuma River Basin. We diagnose event-period deviation by comparing the counterfactual to the observed 2020 census (after the 2020 flood), and analyze these deviations across municipalities, flood/non-flood zones, demographic and household subgroups. Results indicate that the proposed framework can plausibly capture normal demographic dynamics and provides a useful baseline for diagnosing flood-consistent redistribution patterns.

Study Area and Materials

The study area is located in central Kyushu, western Japan. The Kuma River is approximately 115 km long and drains an area of 1880 km^2. This study integrates multiple geospatial and statistical datasets to support micro-scale agent-based simulations.

Populations datasets for 2000, 2005, 2010, 2015 and 2020 were obtained from include ESRI Demographics (down to the third-level administrative scale) and official statistics from e-Stat for the 11 target municipalities in Kuma River region (Figure 1). In addition, night-time population data for 2005 were utilized for mesh-scale processing.

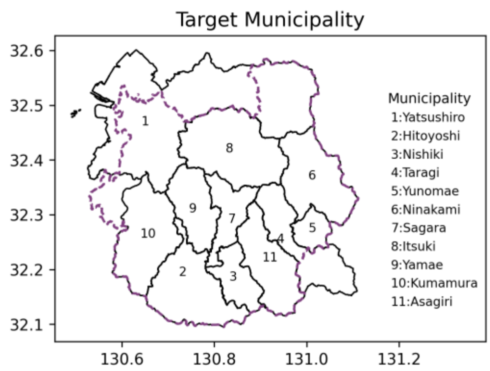

Figure 1 11 target municipalities in Kuma River Basin

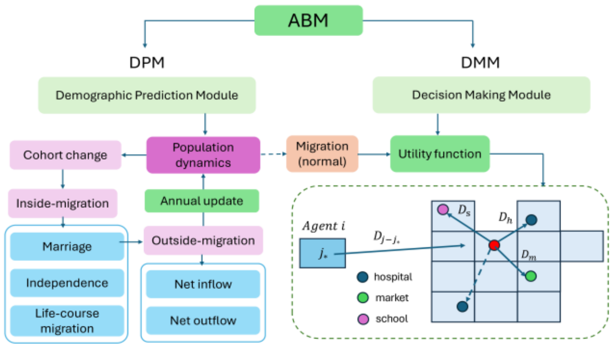

Figure 2 Agent-based model composition

To represent local amenities, geospatial layers for markets, hospitals and schools were compiled. Land-use data were also employed to define migration candidate sets under different development assumptions. These geospatial datasets were obtained from Geospatial Information Authority of Japan.

Methodology

Agent-based models simulate interactions between agents (here, households) and the environment (living area). In this study, household relocation is parameterized using a utility function that incorporates amenity accessibility and place attachment. The model is calibrated using the 2010-2015 period, validated on

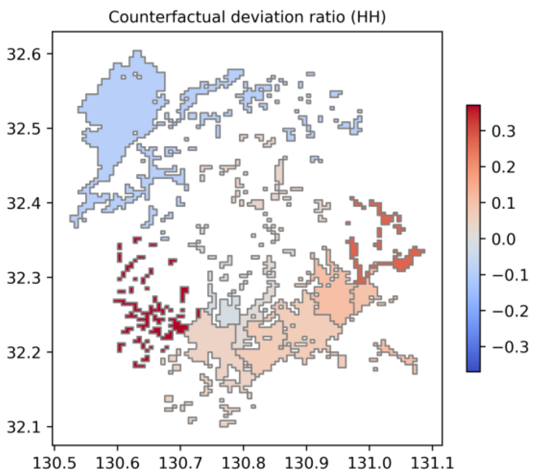

Figure 3 Relative deviation of reality from the 2020 counterfactual baseline

an independent period 2000-2005, and then applied to generate a 2020 no-flood counterfactual.

(1) Agent-based Model

The proposed ABM (Figure 2) is mainly composed by a Demographic Prediction Module (DPM) and a Decision-Making Module (DMM). The population dynamics are represented using cohort analysis. Household spatial distribution evolves through life-course events (e.g., marriage and independence) and migrations processes (e.g., in-out flow). Migration destinations are selected through a utility function related to amenity distances and place attachment, expressed as:

$$U_{i,j} = N_l^{-\alpha_y \cdot \delta(j-j_*)} \cdot D_{j-j_*}^{-\alpha_D} \cdot D_s^{-\alpha_{ds}} \cdot D_h^{-\alpha_{dh}} \cdot D_m^{-\alpha_{dm}}$$

(2) Calibration and Validation

Utility parameters were calibrated to reproduce normal-period redistribution using 2010-2015 census data via grid search, shown in Table 1.

Table 1 Calibrated utility parameters

Para.	α_y	α_{ds}	α_{dh}	α_{dm}	α_D	α_{dh_e}	α_{D_f}
Value	0.5	0.3	0.8	0.4	0.7	0.75	0.8

The calibrated parameter set was then evaluated on 2000-2005 period. Model performance was assessed using relative error (RE) denoted as $RE = (P-O)/O$, at the municipal scale (e.g., Table 2 shows the result in terms of total household).

Table 2 Validation results in municipal

Muni.	1	2	3	4	5	6
RE	-0.04	0.10	0.17	0.15	0.11	0.25
Muni.	7	8	9	10	11	
RE	0.03	0.04	0.00	0.04	0.10	

(3) Application for 2020 counterfactual

Using the 2015 census as the input, the 2020 no-flood counterfactual population distribution was generated. The relative deviation between the counterfactual baseline and the observed outcome is shown in Figure 3.

Table 3 Simulation evaluation on four scenarios

Scenario	S0	S1	S2	S3
Children	0.40	0.38	0.37	0.37
Elder	0.48	0.34	0.31	0.35
Agri. HH.	0.57	0.79	0.58	0.51

Analysis and Conclusion

(1) Calibrated utility parameters

The calibrated parameters suggest that households exhibit relatively weaker dependence to school and market accessibility, but stronger dependence to hospital accessibility. Households generally show a preference for relocating closer to their current residence, and this place-attachment tendency is stronger for agriculture-related households.

(2) Regional exposure changes across groups

Exposure changes for specific groups are quantified at multiple scales (e.g., municipality level and flood/non-flood zones), showing that flood-related responses vary across both space and social groups.

(3) Land-Use and residential preferences

Four land-availability scenarios were examined (Table 3): S0, all meshes are available; S1, Urban meshes only; S2, Urban and Paddy; and S3, Urban, Paddy and Cropland meshes. The results evaluated by RRMSE indicate that households generally tend to be more concentrated in urban-related areas, while agriculture-relate household show a stronger preference for agriculture-dominated areas.

Acknowledgement: This study was supported by JST SICORP Grant Number JPMJSC2312, Japan.