

China's urban fringes are undergoing functional reorganization

Hedong Wang

Guangxi University

Liangen Zeng

zengliangen@pku.edu.cn

Guangxi University

Baoxi Pan

Guangxi University

Bohan Zeng

Guangxi University

Chengfeng He

Guangxi University

Tianyu Zeng

Guangxi University

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Abstract

Urbanization is reorganizing land-use and functional relationships around cities, yet urban-rural classifications and built-up expansion reveal little about how agricultural, production and living functions are transformed. We tracked functional data across the fringes of 15 Chinese cities from 2012 to 2022 and conditionally extended transitions to 2035. The share of the low-dominance mixed state (MF), where functions coexist, increased from 46.3% to 66.5%, while the eco-agriculture-dominant state (EA) declined from 45.9% to 29.7%. Changes were dominated by bidirectional transitions between EA and MF and shifts from production-and-office dominance to MF. Under historical continuation, modeled 2035 shares were 67.9% for MF and 25.5% for EA, with six minority states retaining 6.6%. Compared with ecological protection, development stress produced the largest EA reductions in Beijing, Changsha and Chongqing, whereas mixed-function guidance produced the largest MF increases in Shenzhen, Ningbo, Guangzhou, Chengdu and Chongqing. Responses varied among cities, supporting governance differentiated by ecological sensitivity, MF change and historical trajectory. High-risk eco-agricultural areas require protection and flood retention; mixed-function transitions require coordinated public services; and developed areas require stock upgrading. These findings support China's "three zones and three lines" spatial planning, urban renewal and progress towards sustainable cities, climate adaptation and terrestrial ecosystem protection.

1. Introduction

Urban fringes are where land expansion, population and industrial relocation, public-service provision, and ecological processes directly intersect, and where the pressures of urban growth are concentrated. In 2025, under the United Nations Degree of Urbanization classification, 44.8% of the global population lived in cities. Monitoring of 781 cities between 2020 and 2025 showed an annual land-consumption rate of 0.83%, only slightly above the annual population-growth rate of 0.81%, with the gap between the two narrowing markedly (United Nations Department of Economic and Social Affairs, Population Division, 2025; United Nations, 2026). In China, the share of permanent residents living in urban areas reached 67.89% in 2025 (National Bureau of Statistics of China, 2026). As demand for housing, production, transport, and services moves outward, it enters spaces that already support agricultural production, ecological buffering, and risk regulation, intensifying competition for limited land (Frolking et al., 2024; Chen et al., 2020; Seto et al., 2012; Güneralp et al., 2020). Change at the urban fringe is therefore expressed both as an increase in impervious surfaces and as the substitution, overlap, and recombination of land functions. Construction growth, lagging service provision, and pressure on eco-agricultural functions may coexist at the same location (Meerow et al., 2016; Elmqvist et al., 2019). Identifying these processes is essential for linking urban growth with Sustainable Development Goal 11, climate adaptation, and ecological conservation (United Nations General Assembly, 2015; United Nations, 2017; Intergovernmental Panel on Climate Change, 2022).

Long-term, cross-city monitoring still relies primarily on built-up-area growth, land-cover conversion, or urban-rural classifications to characterize changes in peripheral areas (Schneider & Mertes, 2014;

Cattaneo & Girgin, 2026; Mortoja et al., 2020; Shaw et al., 2020). These frameworks can identify the extent and density of expansion and its land-surface outcomes, but they cannot readily determine how residential, commercial, public-service, production, transport, and recreational functions are combined within areas assigned to the same land-cover class, or distinguish functions emerging in newly developed space from those being reorganized within existing space. Points of interest (POIs) and openly available social and geospatial data have increased the spatial resolution at which urban functions can be identified (Yuan et al., 2012; Gao et al., 2017; Hu et al., 2016), but they have rarely been combined with long-term land-cover records on a fixed spatial support. The multifunctionality, institutional ambiguity, and mixed land uses of urban fringes have been widely discussed (Allen, 2003; Simon et al., 2004; laquinta & Drescher, 2000; Zasada, 2011; Hedblom et al., 2017; Tian et al., 2017). However, the absence of a single dominant function does not necessarily indicate the coordinated coexistence of multiple functions; low-intensity or information-sparse grid cells may also appear mixed (Song et al., 2013). Direct evidence based on spatially comparable units across cities and observation periods remains limited, leaving unresolved whether peripheral areas follow a common trajectory of functional evolution or are shaped mainly by each city's inherited structure and historical pathway.

Converting observed functional reorganization at urban fringes into comparable longitudinal evidence requires addressing three interrelated identification challenges. First, if the fringe is redefined in each period using an updated built-up-area boundary, developed grid cells leave the sample while newly peripheral cells enter it, conflating boundary displacement with functional change at the same location. Second, comparing only the shares of states at the beginning and end of a period allows transitions in opposite directions to cancel each other and overlooks changes within grid cells that retain the same state; the same net change may reflect different transition pathways and governance implications (Lambin et al., 2001; Turner et al., 2007; Meyfroidt et al., 2018; Pontius & Millones, 2011). Third, the completeness of coverage and consistency of classification in historical POI snapshots vary among years. A change from zero to nonzero may reflect both changes in platform records and real spatial processes, while discrete categories may conceal changes in intensity and provide unreliable characterizations of information-sparse grid cells. A reliable framework therefore requires a fixed observation domain, preservation of origin–destination directionality, and continuous functional intensities. It must also use an independent activity indicator to assess state gradients and explicitly constrain interpretive bias arising from changes in POI archives, rather than treating increases or decreases in records directly as the entry or exit of facilities.

This study addresses three questions: How did the observed functional composition of fixed urban fringes change between 2012 and 2022? Which bidirectional pathways and within-state adjustments underlay the changes in net shares? Under constraints derived from historical flows, did the same conditional scenarios produce consistent responses across cities? Using the 2012 principal built-up area as a common spatial reference in 15 major Chinese cities, we established a fixed observation domain spanning the 0–10 km belt outside it, divided into 500 m grid cells. We tracked 152,873 city–grid instances using POI and land-cover records from 2012, 2014, 2016, 2017, 2020, and 2022. We transformed six POI-based functional measures and eco-agricultural cover into seven within-city, within-

year relative intensities, from which we identified seven dominant states and one low-dominance mixed state (MF). A complete 8×8 flow matrix and path-conditioned changes in functional intensity were used to distinguish net compositional change, bidirectional functional-state turnover, and within-state adjustment. Satellite nighttime lights, which did not enter the classification, provided an external check on the activity gradient. We then used rolling hindcasts to calibrate aggregate flows for 2022–2035 and compared four conditional scenarios: historical continuation, ecological protection, mixed-function guidance, and a development stress test. This design integrates fixed spatial support, directional flows, continuous intensities, external consistency, and explicit scenario boundaries within a single analytical framework.

2. Materials and methods

2.1 Study area

The study covered Beijing, Tianjin, Shanghai, Chongqing, Guangzhou, Shenzhen, Nanjing, Suzhou, Wuxi, Hangzhou, Ningbo, Qingdao, Wuhan, Changsha, and Chengdu. These cities were included because points of interest (POI), China Land Cover Dataset (CLCD), and coordinate data were jointly available for all six observation years; they do not constitute a probability sample of Chinese cities. The 30-m CLCD impervious-surface layer was aggregated to 500 m in the China Albers equal-area projection, and grid cells with an impervious fraction $\geq 70\%$ defined the candidate built-up area. After a 3×3 morphological closing operation, the principal connected patch containing the city-center seed was retained using eight-neighbor connectivity; if the seed did not fall within the candidate area, the nearest principal patch was selected. Using the 2012 principal built-up area as the reference, we extracted grid cells in the urban fringe located 0–10 km beyond its outer edge and outside the core area; this fixed observation domain was used for 2012, 2014, 2016, 2017, 2020, and 2022. The sample comprised 152,873 city–grid instances and 917,238 city–grid–year records, corresponding to 146,118 unique grid cells; 6,755 instances (4.42%) overlapped across cities. City-level summaries therefore describe city-specific observation domains, and the 15 cities were not treated as strictly independent spatial replicates.

2.2 Data processing and identification of functional states

Urban functions were derived from historical Amap (Gaode Map) point-of-interest (POI) archives for the six observation years. After harmonizing dBASE (DBF) and comma-separated values (CSV) fields, records were grouped using a fixed crosswalk into residential and daily-life services (RL), commercial consumption (CC), public services (PS), production and office activities (PO), transport and logistics (TL), and leisure and tourism (LT). Records were deduplicated within each city–year combination using a stable ID when available; otherwise, a composite key comprising the standardized name, coordinates to six decimal places, and functional category was used. No cross-year entity matching was performed. After projection from the World Geodetic System 1984 (WGS84), records were assigned to 500-m grid cells (Yuan et al., 2012; Gao et al., 2017; Hu et al., 2016). Land cover was obtained from the annual 30-m raster product of CLCD v01 (Yang & Huang, 2021). Class 8 represented impervious surface, whereas

classes 1–5 and 9 (cropland, forest, shrubland, grassland, water bodies, and wetlands) represented eco-agricultural cover; snow and ice and bare land were excluded from the indicators. Pixels were aggregated to 500 m in an equal-area projection. CLCD was used to delineate the fixed observation domain and measure eco-agricultural intensity; peripheral areas newly developed after 2012 were not added to the sample.

Within each city–year–function combination, positive counts for each of the six POI categories were assigned average empirical ranks and divided by the total number of grid cells in the fixed observation domain; zero counts remained 0. Eco-agricultural cover underwent the same empirical percentile transformation. The seven 0–1 scores indicate relative intensity only within the same city and year and do not represent absolute levels of provision that are comparable across cities. The dominance margin was defined as the difference between the highest and second-highest scores, $m = q(1) - q(2)$. Applying Otsu's method to the pooled distribution of all 917,238 records yielded $\theta = 0.415039$ (Otsu, 1979). When $m \geq \theta$, a cell was assigned according to its highest score to RL, CC, PS, PO, TL, LT, or the eco-agriculture-dominant state (EA); when $m < \theta$, it was classified as the low-dominance mixed state (MF). MF indicates that no single dimension achieved sufficient dominance; it does not imply that multiple functions were all actually present. Because no minimum total intensity or minimum number of nonzero dimensions was imposed, low-information and all-zero cells could also be classified as MF. The study did not use manual ground-truth validation.

2.3 Observed transitions and external consistency

Between adjacent observation years t_0 and t_1 , the functional-state turnover rate was calculated as $T = (1/N) \sum I(S_{i,t_0} \neq S_{i,t_1})$, where N included all fixed city–grid instances. We also report $T/(t_1 - t_0)$ to compare intervals of unequal length; this quantity is an interval-standardized descriptive rate, not a continuous-time annual transition probability. The complete 8×8 origin–destination matrix retained directionality: diagonal elements represented persistence, whereas off-diagonal elements represented conditional exit pathways (Pontius & Millones, 2011). Using 2012 and 2022 as endpoints, path-conditioned changes in functional intensity were calculated as the endpoint-minus-starting-point difference in each of the seven scores for EA-to-MF, MF-to-EA, PO-to-MF, EA-to-EA, and MF-to-MF. Path-specific means were first calculated within each city and were then aggregated with equal weights across the 15 city-specific observation domains. Descriptive 95% intervals based on the t distribution summarize variation across cities and were not used for inference based on independent samples.

External consistency was assessed using AllAngle_Composite_Snow_Free radiance from the NASA Visible Infrared Imaging Radiometer Suite (VIIRS) VNP46A4 Collection 2 annual nighttime light product at 15 arc-second resolution (NASA VIIRS Land Science Investigator-led Processing System, 2025; Román et al., 2018). The primary rule retained pixels with a quality flag of 0, 1, or 2, an observation count > 0 , and radiance ≥ 0 ; the strict rule retained only quality flags 0 or 1. Values for 2012, 2014, 2020, 2022, and 2023 were assigned to grid-cell centers by nearest-pixel matching. Change was calculated using $\ln(1 + \text{radiance})$, and city–year empirical percentiles were used for cross-city comparisons. VIIRS did not enter the state threshold, historical transitions, or the 2035 model. It was used only to assess consistency with

an external activity gradient and cannot establish event-level POI transitions or multifunctionality within MF (Li et al., 2026).

2.4 2035 baseline and conditional scenarios

The 2035 analysis estimated aggregate state flows separately from the illustrative allocation of those flows to 500-m cells. For a historical interval of d years, the persistence probability was annualized as $[p_{aa}(d)]^{(1/d)}$, and exit probabilities were allocated according to the observed proportions among competing destinations. A Jeffreys smoothing constant of 0.5 was added to each matrix cell, and estimates were pooled using origin-state sample sizes as weights (Jeffreys, 1946). Each city-specific transition row was partially pooled toward the overall 15-city matrix using $n/(n + \tau)$, and persistence probabilities were adjusted uniformly on the logit scale. The values of τ and the offset were selected using the 2016–2017, 2017–2020, and 2020–2022 rolling folds, jointly ranking the Jensen–Shannon divergence in flows, compositional difference, total-turnover error, and state-persistence error; the selected values were $\tau = 100$ and an offset of -1.0 (Lin, 1991). The calibrated annual matrix was raised to the 13th power to obtain the 2022–2035 target flows. The 3×3 neighborhood support and 2022 relative functional suitability were used only for within-city allocation; iterative proportional fitting and the largest-remainder method then restored the target margins (Deming & Stephan, 1940).

The historical continuation, ecological protection, mixed-function guidance, and development stress test scenarios all used this baseline. Transition potential was fitted separately for each of the eight origin states using scikit-learn's HistGradientBoostingClassifier (`learning_rate = 0.08`, `max_iter = 120`, `max_leaf_nodes = 15`, `min_samples_leaf = 80`, `l2_regularization = 1.0`, `random_state = 20260817`). An empirical-class fallback was used when the sample contained < 80 observations or only one destination class. Predictors comprised distance from the core boundary, the 2-km distance band, $\log(1 + \text{total POI count})$, number of nonzero functions, functional diversity, dominance margin, built-up status, impervious-surface and eco-agricultural shares, within-city risk percentile, standardized row and column positions, first year of development, data-source availability, the seven functional scores, and city dummy variables. The historical-interval model additionally included 500-m eight-neighbor support, an inertia term, and constraints on city-level state counts. Clipped cell-level log-probability ratios between each scenario and the baseline were combined with the calibrated baseline; iterative weighting (raking) and minimum-change allocation then recovered the city–origin–destination totals.

2.5 Validation, sensitivity analyses, and interpretive boundaries

Rolling hindcasts reported origin–destination flow discrepancy, state composition, turnover error, state persistence, and the cell-level macro-averaged F1 score (macro-F1) relative to a persistence-only baseline. Parameter selection targeted aggregate flows, composition, and the persistence of minority states rather than cell-level classification. The fixed observation domain was recalculated using impervious-surface thresholds of 50%, 60%, 70%, and 80%, and VIIRS was evaluated under both quality rules. Because POI snapshot coverage changed over time, no cross-year entity matching was performed,

MF can include low-information cells, and city-specific fixed observation domains overlap, the statistics provide descriptive evidence of observed functional reorganization only and cannot be equated with the actual entry or exit of facilities. The archived risk raster lacked a verifiable product version and event definition, and missing values entered scenario selection as a separate layer. It was therefore used only as exploratory spatial context and does not represent flood exposure, losses, or causal moderation. The model did not extrapolate future population, gross domestic product (GDP), roads, or statutory planning boundaries. Inference is more defensible for city-level composition and aggregate flows than for cell-level allocation; each 2035 map is only one configuration that satisfies the total-flow constraints and is not intended for parcel approval, city ranking, or causal policy assessment (Clarke et al., 1997; Verburg et al., 2002; van Vliet et al., 2016; Liu et al., 2017; Liang et al., 2021).

3. Results

3.1 Observed changes over the past decade

Between 2012 and 2022, the fixed urban fringe observation domains of the 15 large cities shifted from a balance between the eco-agriculture-dominant state and the low-dominance mixed state to a configuration dominated by the latter. The share of the low-dominance mixed state (MF) increased from 46.3% to 66.5% (+ 20.1 percentage points), whereas that of the eco-agriculture-dominant state (EA) decreased from 45.9% to 29.7% (– 16.2 percentage points); net changes in the other six states were small (Fig. 1c). Across adjacent observation periods, the mean functional-state turnover rate was 17.2%, with city-level values ranging from 12.1% to 21.9% (Fig. 1b). These proportions describe turnover in the observed configuration jointly represented by POIs and land cover, rather than net entries or exits of facilities confirmed through entity tracking.

Relative to the 2012 built-up boundary, areas with slower change were 4.91 km away on average, and newly added impervious surfaces accounted for only 4.0%. Areas where multiple observed functional intensities increased jointly were an average of 3.57 km from the boundary, with newly added impervious surfaces accounting for 22.7%; grid cells already classified as MF at the beginning of the study were an average of 3.61 km from the boundary, with newly added impervious surfaces accounting for 28.0%. The three patterns remained interspersed at comparable distances, indicating that distance from the urban core alone was insufficient to determine the observed functional configuration. Patterns in the six representative cities formed dispersed patches and localized nodes rather than a continuous outward-expansion front (Fig. 1a).

The POI-coverage sensitivity analysis also revealed an interpretive boundary that must be retained. The proportion of grids with nonzero POI coverage increased from 31.71% to 58.23%; after removing city means, the correlation coefficient between coverage and the MF share was 0.9707. Among grids undergoing EA-to-MF transitions between 2012 and 2022, 94.42% simultaneously changed from zero to nonzero POI coverage. For MF-to-EA transitions in 2017–2020, 97.75% changed from nonzero to zero coverage, whereas for EA-to-MF transitions in 2020–2022, 98.96% changed from zero to nonzero

coverage. Historical flows therefore incorporate both real spatial change and changes in the completeness of platform snapshots; the subsequent pathway analysis is used only to characterize the structure of the observed signals.

3.2 State flows and path-conditioned changes in functional intensity

Across the five adjacent observation intervals, the raw proportions of city–grid instances that changed state were 7.6%, 16.6%, 8.9%, 25.4%, and 26.4%, respectively; after division by interval duration, the corresponding values were 3.8%, 8.3%, 8.9%, 8.5%, and 13.2% per year. Of all observed transitions, EA-to-MF accounted for 40.8%, MF-to-EA for 22.5%, and PO-to-MF for 8.5% (Fig. 1d). MF-to-EA dominated in 2017–2020, whereas in 2020–2022 the share of EA-to-MF rose to 51.2%, showing that net compositional change concealed substantial exchange in opposing directions.

The complete eight-state flow matrix showed adjacent-period persistence rates of 82.2% for EA and 88.6% for MF. The most common off-diagonal destination from EA was MF (17.2%), and the most common destination from MF was EA (7.1%). The persistence rate of PO was 44.3%, with 52.4% transitioning to MF. Persistence rates for RL, CC, PS, TL, and LT ranged from 29.0% to 36.1%, and MF was likewise their most common destination (Fig. 2a,b).

For EA-to-MF transitions, the mean changes in the relative intensities of PO, CC, RL, LT, TL, and PS, calculated by weighting cities equally, were + 0.358, + 0.288, + 0.255, + 0.250, + 0.240, and + 0.130, respectively, whereas EA intensity decreased by 0.048. For MF-to-EA transitions, most relative urban-function intensities decreased in the opposite direction. Even among grids that remained in MF, the relative intensities of TL, RL, and CC increased by 0.297, 0.226, and 0.191, respectively (Fig. 2c). The incidence shares of the three main pathways varied substantially across cities (Fig. 2d), but these values were affected by changes in snapshot coverage and should not be interpreted as facility effects.

3.3 Nighttime activity differences across functional states

To assess whether the POI-derived states corresponded to an independent signal of urban activity, we compared them with VIIRS nighttime lights, which were not used in classification or modeling. In 2022, the within-city radiance rank of the low-dominance mixed state (MF) exceeded that of the eco-agriculture-dominant state (EA) in all 15 cities, with a median difference of 0.252 (Fig. 3b). In all 15 cities, the change in $\ln(1 + \text{radiance})$ was greater for grid cells undergoing EA-to-MF transitions than for those remaining in EA. By contrast, the comparison between MF-to-EA and persistent MF was positive in only 6 cities, and that between PO-to-MF and persistent PO was positive in only 8 cities (Fig. 3c).

This correspondence remained stable between adjacent years: across 119 city–state groups, the overall correlation coefficient between radiance ranks in 2022 and 2023 was 0.994, and the median city-level correlation coefficient was 0.976 (Fig. 3d). Nighttime lights therefore support an overall activity gradient

among the states, but they cannot demonstrate the entry or exit of individual POIs or independently establish whether MF contains a genuinely multifunctional configuration.

3.4 Conditional baseline for 2035

Subject to constraints on flows, starting-state persistence, and partial pooling across cities, the 2035 historical continuation baseline yielded a modeled composition of 67.9% MF, 25.5% EA, and 2.6% PO, with RL, CC, PS, TL, and LT each accounting for 0.7%–0.9%. The six minority states together accounted for 6.6%; part of their retention arose from smoothing and minimum-cell constraints and cannot be treated as independent evidence that minority states will necessarily persist (Fig. 4a,b).

The distance gradients in the modeled composition converged. Between the observed 2022 composition and the modeled 2035 composition, the EA share changed from 19.4% to 21.5% and the MF share from 75.4% to 71.8% within 0–2 km of the 2022 built-up boundary; at 8–10 km, the EA share changed from 39.1% to 29.3% and the MF share from 58.0% to 64.0% (Fig. 4c,d). In the illustrative allocation satisfying the target flows, 45.6% of city–grid instances changed state; the most common directions remained EA-to-MF (19.3%) and MF-to-EA (16.2%). These values are model quantities obtained by extrapolating historical flows, not changes that have already occurred.

City-level MF shares were higher in Chengdu, Shenzhen, Ningbo, and Guangzhou, whereas EA shares were higher in Tianjin, Beijing, Qingdao, and Wuhan. These intercity differences arose from the initial composition and historical flow matrices. Grid-level entropy indicates only the dispersion of probabilities within the specified model and does not incorporate uncertainty in POI coverage, model structure, or future policy.

3.5 Intercity differences across conditional scenarios

In the Chongqing example, the historical continuation scenario produced EA and MF shares of 23.7% and 70.5%, respectively. Under ecological protection, the corresponding shares were 24.1% and 70.0%, and 0.5% of grids changed relative to the baseline. Under mixed-function guidance, the shares were 21.4% and 72.7%, with 2.3% of grids changing; under the development stress test, they were 18.1% and 76.0%, with 5.6% changing (Fig. 5a). Differences in aggregate composition were limited, but the corresponding spatial reallocations were unevenly distributed (Fig. 5b).

City-level differences were concentrated in a small number of combinations. Relative to the development stress test, ecological protection increased the EA share by 6.8, 6.5, and 6.0 percentage points in Beijing, Changsha, and Chongqing, respectively. Relative to historical continuation, mixed-function guidance increased the MF share by 14.2, 9.3, 6.1, 5.3, and 2.3 percentage points in Shenzhen, Ningbo, Guangzhou, Chengdu, and Chongqing, respectively. Relative to 2022, historical continuation reduced the MF share in Changsha, Chongqing, and Chengdu, but increased it in Qingdao, Tianjin, Shanghai, and Beijing (Fig. 5c). These comparisons are conditional differences under empirical constraints, not causal effects of policy treatments.

Figure 5. Conditional scenarios for 2035 and intercity heterogeneity. a, Illustrative allocations under historical continuation, ecological protection, mixed-function guidance, and the development stress test in Chongqing. b, Cell-level difference in the modeled probability of the eco-agriculture-dominant state (EA) between ecological protection and the development stress test (protection minus stress). c, Three scenario-based or historical contrasts within the city-specific observation domains of the 15 cities. d, Distribution of the cell-level difference in the modeled probability of the low-dominance mixed state (MF) between the development stress test and historical continuation (stress minus continuation), by distance band and quartile of the archived relative-risk background. Panel d is exploratory only; grids with missing risk values were excluded from this panel.

4. Discussion

4.1 From net expansion to observed functional reorganization

The fixed observation domain anchored to the 2012 built-up area shows that the urban fringe cannot be reduced to a unidirectional intermediate stage between rural and urban conditions (Cattaneo & Girgin, 2026; Allen, 2003; Simon et al., 2004; Iaquina & Drescher, 2000). At similar distances, the data show persistence of the eco-agriculture-dominant state (EA), bidirectional exchange between EA and the low-dominance mixed state (MF), transitions from the production-and-office-dominant state (PO) to MF, and internal reallocation within MF. Net-area summaries obscure these opposing flows, whereas a moving boundary can misrepresent the replacement of sampled locations as functional change (Mortoja et al., 2020; Shaw et al., 2020; Turner et al., 2007; Meyfroidt et al., 2018). These findings support reporting fixed spatial support, the complete flow matrix, and continuous functional scores together in urban fringe studies.

Observed functional reorganization, however, is not equivalent to actual turnover of facilities. The dominant EA-to-MF and MF-to-EA pathways coincided closely with shifts between zero and nonzero POI coverage, indicating that changes in platform coverage are an important component of the results. The correspondence with VIIRS indicates an activity gradient among states but cannot identify the entry or exit of individual POIs. The best-supported conclusion is therefore that the current archives reveal substantial reorganization of the observed functional configuration and marked bidirectional exchange; the magnitude of the underlying socioeconomic change requires confirmation using stable registries, cross-year entity matching, or sample-based manual validation.

4.2 Functional configurations and sustainability risks

A low-dominance mixed state does not automatically represent high-quality or coordinated development (Zasada, 2011; Tian et al., 2017; Song et al., 2013). Residential, commercial, and production activities may agglomerate rapidly, whereas public services, drainage, and transport capacity are often provided more slowly (Meerow et al., 2016; Elmqvist et al., 2019). If development precedes service provision,

urban fringes may become mixed spaces with inadequate facilities. If transport and built-up land intensify while residential functions weaken, established nodes may also shift toward commuter or logistics uses. Because the MF label also includes low-information grids, future research should distinguish genuine multifunctional synergies from the absence of a clearly dominant function.

Changes in eco-agricultural space are not simply a matter of area. Peripheral cropland, forest, water bodies, and wetlands may provide ecological buffers, attenuate hazards, and constrain disorderly expansion (Foley et al., 2005; Grimm et al., 2008; Bai et al., 2018; Tellman et al., 2021; Chan et al., 2022). The archived risk surface used here is insufficient to quantify flood exposure. Any planning application should therefore impose independently verified hydrological risk, public-service capacity, and statutory boundaries as constraints; POI-derived states should not substitute for them.

4.3 City-specific planning implications

The conditional scenarios show that the same modeled flow perturbation yielded different conditional compositional changes across cities. Beijing, Changsha, and Chongqing showed larger modeled contrasts between ecological protection and the development stress test, whereas Shenzhen, Ningbo, Guangzhou, Chengdu, and Chongqing showed larger modeled contrasts under mixed-function guidance. These results do not rank cities as better or worse; instead, they identify pathways that warrant priority examination. Cities under greater EA pressure should jointly review permanent basic farmland, ecological conservation redlines, urban development boundaries, and verifiable risk areas. Cities with rapidly increasing MF should also examine whether public services and infrastructure are keeping pace (Liu & Zhou, 2021; Jiang et al., 2016; Huang et al., 2019).

This typology is compatible with China's existing territorial spatial governance framework, but its value lies in diagnosis rather than direct prescription. Protecting eco-agricultural space can contribute to SDGs 11, 13, and 15, whereas closing service gaps in areas of functional growth is relevant to inclusion, resource efficiency, and accessibility (United Nations General Assembly, 2015; United Nations, 2017; Intergovernmental Panel on Climate Change, 2022). Actual policy choices still require evidence on population, employment, fiscal costs, engineering capacity, and statutory planning.

5. Conclusions

Within the fixed observation domain anchored to the 2012 built-up area, POI and land-cover records for the urban fringes of 15 large Chinese cities show that net compositional change between 2012 and 2022 comprised substantial bidirectional turnover and within-state reallocation. Neither a single urban–rural classification nor a moving boundary can represent this process. VIIRS provides consistency evidence for an overall activity gradient, but changes in POI snapshot coverage and low-information grids assigned to the low-dominance mixed state (MF) limit interpretation of actual facility transitions.

The 2035 model calibrated through rolling hindcasting is better suited to comparing city-level aggregate flows and conditional scenarios than to predicting states for individual grid cells. For urban governance,

the central task is not to identify a single 'best' pattern, but to determine whether each city primarily faces pressure on eco-agricultural space, inadequate service provision, or adjustment of existing functions, and then examine these issues further using verifiable data on land, population, services, and risk. This approach can move urban fringe research from aggregate expansion toward a transparent and reproducible analysis of observed functional reorganization that reflects intercity differences.

Declarations

Declaration of generative AI use

During the preparation of this manuscript, the authors used OpenAI Codex to assist with language editing, structural reorganization, and document formatting. The authors reviewed and edited all outputs and take full responsibility for the content of the manuscript.

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Author Contribution

H.W. and L.Z. conceived and designed the study. H.W. curated the data, developed the methodology, performed the formal analyses, prepared the figures and wrote the original manuscript. L.Z. supervised the research, administered the project, contributed to the interpretation of the results and critically revised the manuscript. B.P., B.Z., C.H. and T.Z. contributed to data processing, validation, interpretation and manuscript revision. All authors reviewed and approved the final manuscript.

Data and code availability

CLCD and NASA Black Marble data are available from the data sources cited in the manuscript. Historical Amap POI data are subject to the data provider's terms and cannot be redistributed with the manuscript. Derived grid-level aggregates, the variable dictionary, and analysis code can be provided to reviewers subject to the licensing terms of the original data.

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Figures

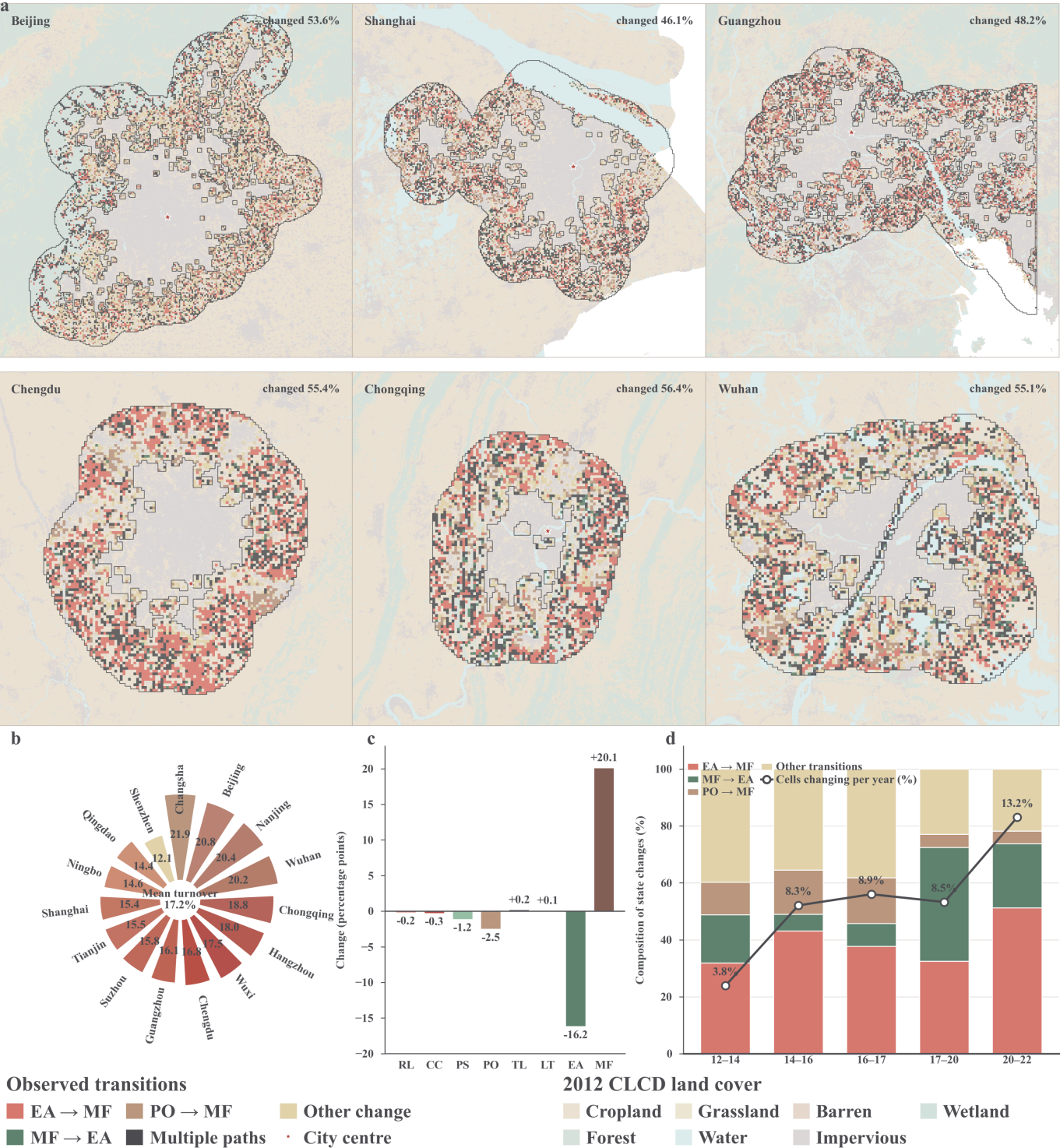


Figure 1

Observed functional reorganization and spatial patterns within the fixed urban fringe observation domains of 15 large Chinese cities. a, Locations of major transition pathways, multiple pathways, and other changes in Beijing, Shanghai, Guangzhou, Chengdu, Chongqing, and Wuhan. b, Mean functional-state turnover rates between the six observations for the 15 cities. c, Net changes in the shares of the eight operational states between 2012 and 2022. d, Composition of state changes across the five historical intervals and interval-standardized change rates. The map background shows the 2012 CLCD in muted colors, and the thick line delineates the outer boundary of the fixed 500-m urban fringe cells.

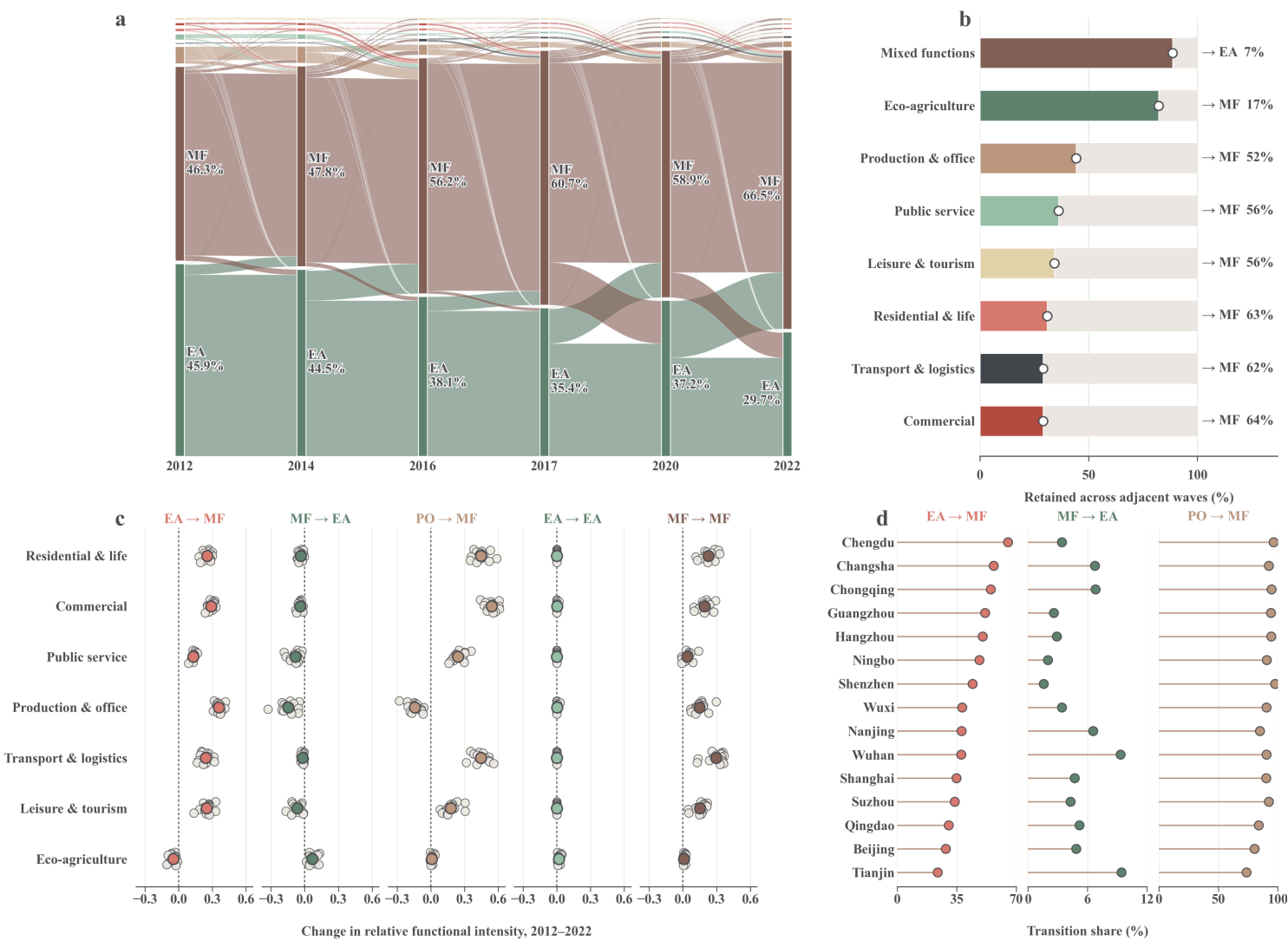


Figure 2

Flows among the eight operational states and their internal changes. a, State flows across six observations for 152,873 city–grid instances. b, Adjacent-period persistence rates and the leading alternative destination for each starting state. c, Path-conditioned changes in the seven relative functional intensities along three directional transitions and two persistence pathways. d, Incidence shares of three pathways within the city-specific observation domains of the 15 cities. Small points

denote city estimates; large points denote means weighted equally across cities, and error bars denote descriptive 95% intervals based on the t distribution.

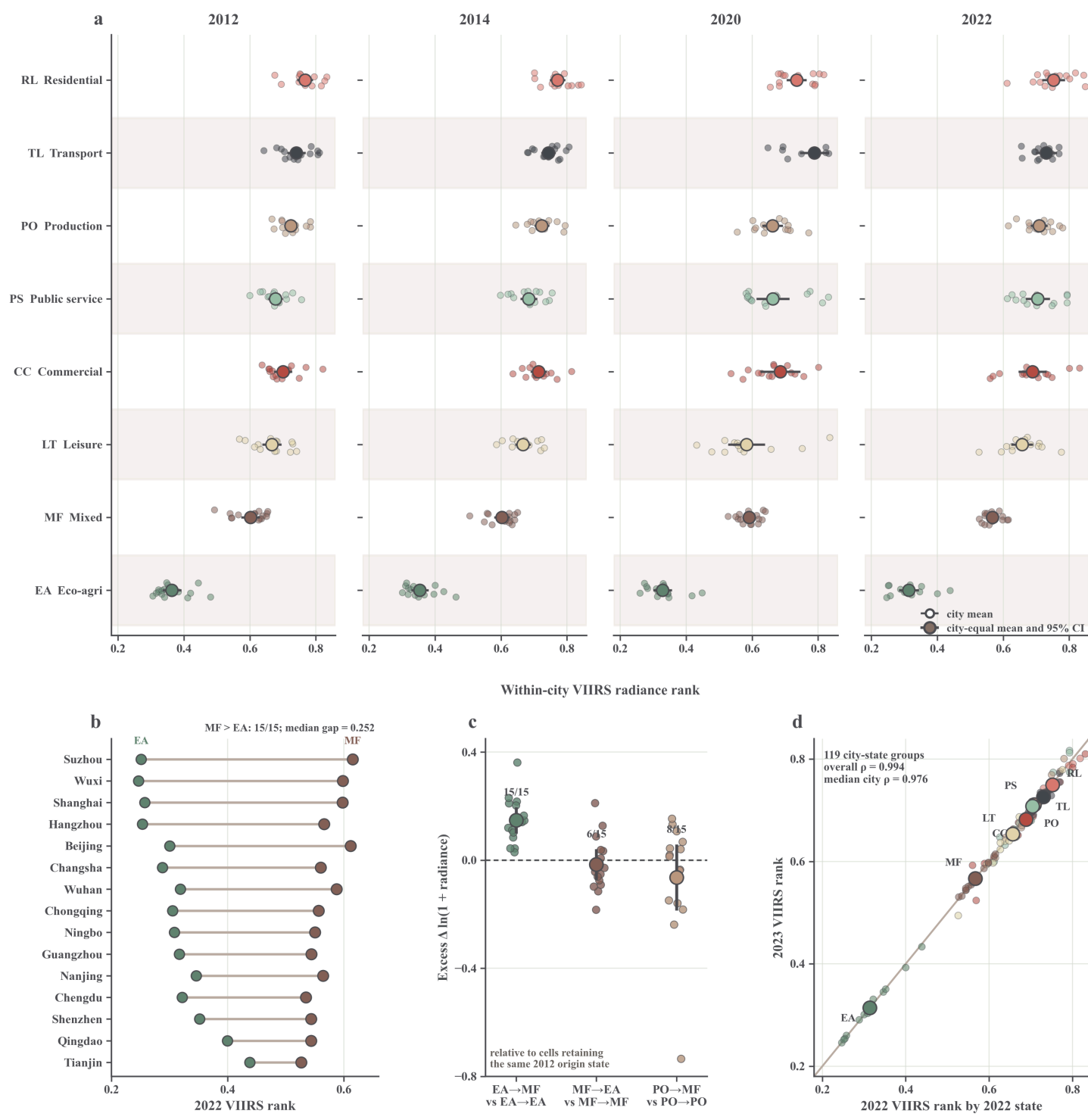


Figure 3

External consistency check of operational states and transition signals using VIIRS nighttime lights. a, Within-city radiance ranks by state in 2012, 2014, 2020, and 2022 from VNP46A4. b, City-level

comparison between the low-dominance mixed state (MF) and the eco-agriculture-dominant state (EA) in 2022. c, Radiance changes along three directional pathways relative to persistence pathways with the same starting state. d, Consistency of city–state radiance ranks between 2022 and 2023. VIIRS was not used for state identification or 2035 modeling.

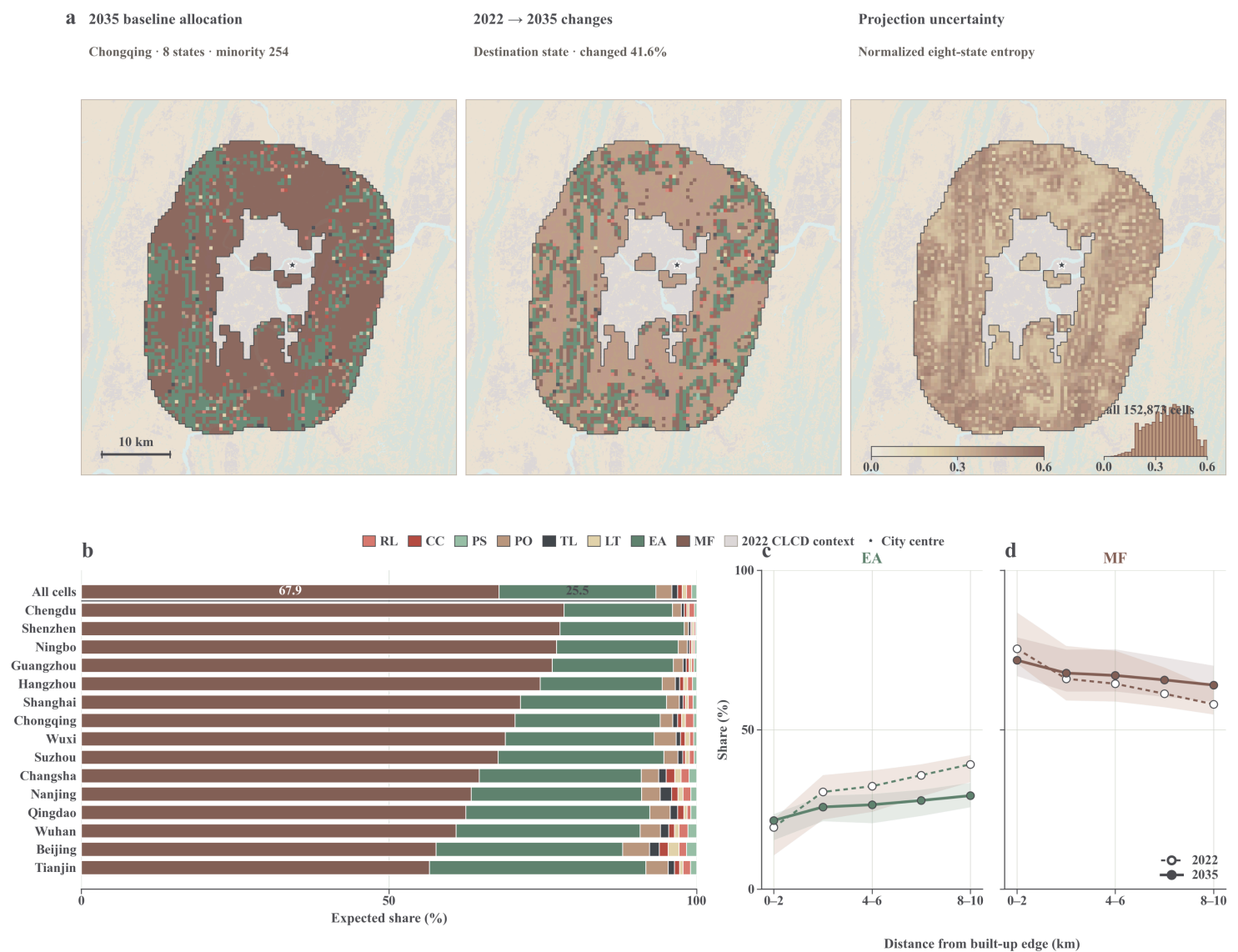


Figure 4

Conditional baseline for 2035 calibrated to aggregate flows. a, Illustrative constrained allocation for Chongqing, grids that changed relative to 2022, and within-model normalized Shannon entropy. b, Modeled composition across all city–grid instances and within the city-specific observation domains of the 15 cities. c,d, Observed 2022 and modeled 2035 shares of the eco-agriculture-dominant state (EA) and the low-dominance mixed state (MF) across five distance bands. The displayed dominant-state configuration is one spatial realization satisfying the target-flow constraints, not a grid-level prediction.

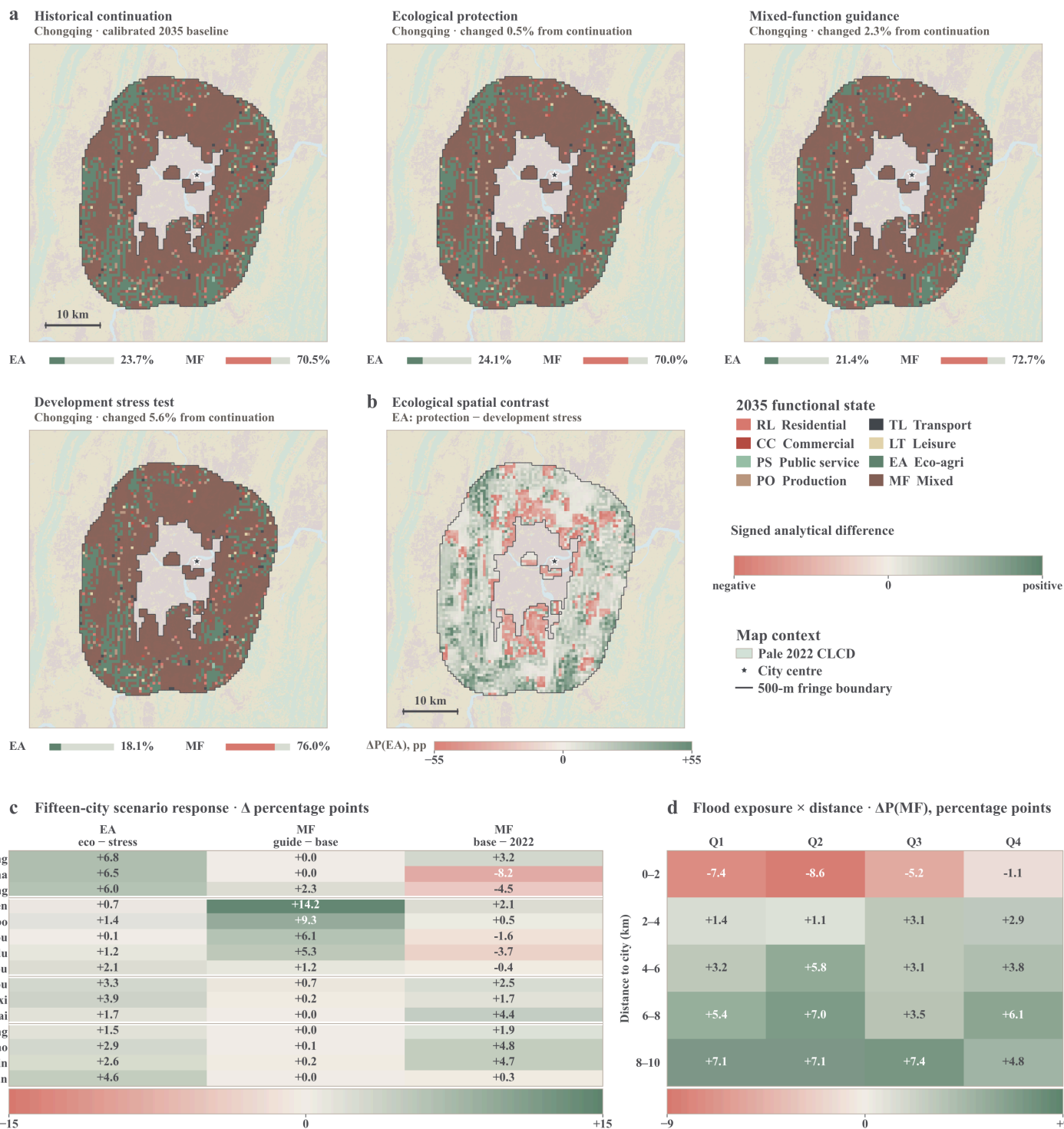


Figure 5

Conditional scenarios for 2035 and intercity heterogeneity. a, Illustrative allocations under historical continuation, ecological protection, mixed-function guidance, and the development stress test in Chongqing. b, Cell-level difference in the modeled probability of the eco-agriculture-dominant state (EA) between ecological protection and the development stress test (protection minus stress). c, Three scenario-based or historical contrasts within the city-specific observation domains of the 15 cities. d, Distribution of the cell-level difference in the modeled probability of the low-dominance mixed state (MF)

between the development stress test and historical continuation (stress minus continuation), by distance band and quartile of the archived relative-risk background. Panel d is exploratory only; grids with missing risk values were excluded from this panel.

Supplementary Files

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