

Article

Spatiotemporal Evolution and Multidimensional Synchronicity of Cultivated Land Use Transition: Evidence from the Spatial–Functional–Modal Triad in the Nanjing Metropolitan Area, China

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Abstract

Rapid urbanization can shrink and fragment cultivated land while raising agricultural productivity, creating mismatches among spatial configuration, functional performance, and management modes. These dimensions are rarely assessed in a unified, value-neutral framework. We developed a Spatial–Functional–Modal (SFM) framework to evaluate multidimensional synchronicity in 46 county-level units of the Nanjing Metropolitan Area, China, using Period 6 data spanning 2000–2022. We combined 18 entropy-weighted indicators with coupling and coupling coordination degree (CCD) models at county and municipal scales. Regional SFM-CCD rose from 0.304 to 0.327 but remained in the model-defined near-misalignment category, while average coupling declined from 0.747 to 0.740. All pairwise CCDs increased, but coupling trajectories differed: spatial–functional coupling weakened, spatial–modal coupling diverged between Jiangsu and Anhui, and functional–modal coupling strengthened. Anhui’s SFM-CCD increased more consistently and surpassed Jiangsu in later years. Nanjing remained a relative synchronicity trough, reflecting weaker alignment among normalized dimensions rather than lower absolute agricultural capacity. Alternative weights and $\pm 10\%$ and $\pm 20\%$ perturbations largely preserved relative rankings and the overall temporal pattern, but absolute values and categories remained method-sensitive. The framework diagnoses asynchronous transitions and can inform differentiated governance in other rapidly urbanizing regions.

Keywords: cultivated land use transition; multidimensional synchronicity; coupling coordination degree; Spatial–Functional–Modal framework; metropolitan region

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1. Introduction

Land systems are coupled social–ecological systems that support food production, rural livelihoods, biodiversity, and climate regulation [1]. Rapid urban expansion places disproportionate pressure on cropland, especially in metropolitan and peri-urban areas where competition for land is intense [2,3]. Agricultural intensification, technological change, and organizational adjustment can nevertheless raise output from the remaining land. Cultivated-land extent, functional performance, and management practices therefore need not change at the same pace or in the same direction. Cropland may contract and fragment while productivity rises, and management practices may adjust only

partially. Such asynchronous transitions can conceal trade-offs among food provision, ecological pressure, farm livelihoods, and territorial specialization. The relevant question is not whether all dimensions move uniformly, but whether their trajectories remain aligned without transferring disproportionate costs across places or functions [1,4].

Research on cultivated land use transition has developed along three main but often separate lines. Spatial studies examine changes in land quantity, location, fragmentation, and landscape configuration using remote sensing and land change analysis [5–8]. Functional studies assess how cultivated land supports production, livelihoods, and ecological services, including grain supply, agricultural employment, and environmental regulation [9–11]. Modal studies focus on management through input intensity, mechanization, irrigation, technological substitution, and changes in farm organization [2,12]. International research on urban and peri-urban agriculture shows that cultivated land performs different roles along urban–rural gradients [2], while land system and telecoupling research places local land change within wider flows of commodities, capital, labor, and environmental effects [13,14]. These perspectives explain important drivers and consequences, but they do not directly diagnose whether spatial carriers, functional outcomes, and management practices remain aligned within a regional transition.

Cultivated land use transition describes long-term changes in land use forms associated with socioeconomic development and changing human–land relations [15,16]. Existing studies have examined spatial restructuring, multifunctional change, and management transformation [17–19], and coupling coordination studies have related land use change to urbanization [20,21], urban–rural integration [22,23], and ecological conditions [24]. Three limitations remain. First, the spatial, functional, and modal components are rarely specified as an integrated internal system. Second, aggregate assessments can obscure which pair of dimensions is converging or diverging. Third, interactions among subsystems are often conflated with their composite development levels. The scientific gap is therefore not the absence of another coupling-model application. It is the lack of a diagnostic framework linking the spatial carrier of cultivated land, its functional outputs, and the management practices through which those outputs are produced.

To address this gap, we develop a Spatial–Functional–Modal (SFM) framework. Spatial transition describes changes in cultivated-land quantity, use structure, and landscape form. Functional transition captures production, livelihood-supporting, and ecological performance. Modal transition denotes changes in inputs, technology, resource use, and operational practices. This carrier–output–practice structure connects the three-dimensional system with its spatial–functional, spatial–modal, and functional–modal relationships. The coupling degree (C) describes mathematical similarity among normalized subsystem magnitudes, whereas the coupling coordination degree (CCD) combines coupling with their composite normalized level. We use “multidimensional synchronicity” as a value-neutral interpretation and retain CCD only as the established model name. Neither high nor low CCD is direct evidence of sustainability, policy success, or absolute agricultural capacity. Cropland contraction, accompanied by higher unit productivity, for example, may represent metropolitan specialization rather than deterioration.

The Nanjing Metropolitan Area, China, provides an informative case because rapid metropolitan expansion, a pronounced core–periphery structure, and cross-provincial governance across Jiangsu and Anhui expose cultivated land to heterogeneous pressures. Using 46 county-level units observed at six time points from 2000 to 2022, this study addresses the following questions: (1) how did the spatial, functional, and modal dimensions evolve; (2) how did triadic and pairwise synchronicity vary across county and municipal scales, and which dimensions accounted for the main spatial differences; and (3) were the main temporal patterns and relative rankings robust to alternative weights and weight perturbations? The study contributes an explicit SFM diagnostic, combines triadic and

pairwise analysis at two spatial scales, and quantifies sensitivity to weighting uncertainty. It should be noted that the framework is intended for context-sensitive diagnosis, not for prescribing a universally optimal level of synchronicity.

2. Materials and Methods

2.1. Study Area

The Nanjing Metropolitan Area is a cross-provincial metropolitan region in the lower Yangtze River region of eastern China. Its planned area includes Nanjing, Zhenjiang, Yangzhou, Huai'an, Ma'anshan, Chuzhou, Wuhu, and Xuancheng, together with Liyang City and Jintan District of Changzhou. It extends from 29°57' to 34°06' N and from 117°09' to 119°58' E, covering approximately 65,400 km². The region has a subtropical monsoon climate, with a mean annual temperature of approximately 16–17 °C and annual precipitation of 1000–1400 mm. Its terrain comprises plains, hills, low uplands, and mountains, resulting in substantial variation in cultivated-land distribution and agricultural production conditions. Following the original analytical design, selected urban districts were merged to ensure that each evaluation unit contained cultivated land, producing 46 county-level units (Figure 1).

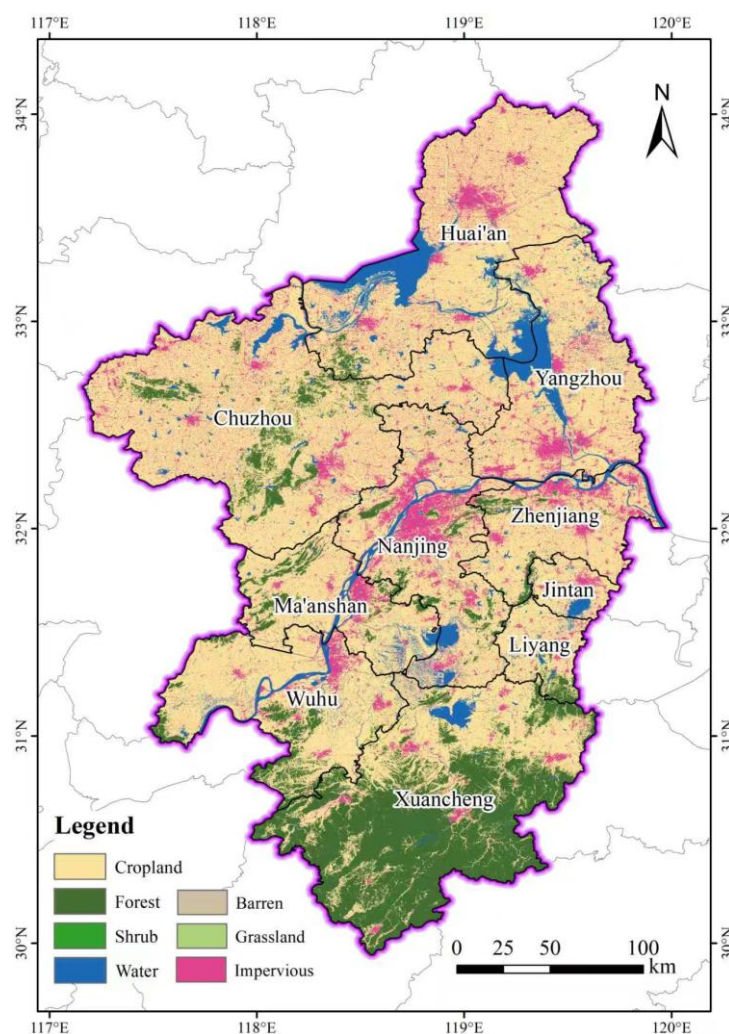


Figure 1. Land use of the Nanjing Metropolitan Area in China in 2022. The land use data were obtained from the Resource and Environmental Science Data Center, Chinese Academy of Sciences. <https://www.resdc.cn/> (accessed on 18 February 2025).

The region provides an informative setting for examining cultivated land use transition because it combines a highly urbanized metropolitan core with peri-urban and peripheral agricultural counties. These areas differ in urban expansion pressure, cultivated-land fragmentation, agricultural specialization, and management capacity. The metropolitan area also spans Jiangsu and Anhui, where cultivated-land conditions and governance arrangements differ despite increasing regional integration. This core–periphery and cross-provincial structure enables the analysis to identify whether spatial configuration, functional performance, and management practices evolve synchronously under rapid urbanization. The case is not assumed to represent all metropolitan regions; instead, it offers a structured comparison of contrasting transition trajectories within a single metropolitan system. It should be noted that the geospatial datasets were preprocessed, and quantitative spatial analysis was performed within ArcGIS Desktop 10.8, to quantify spatial patterns and generate thematic maps for the study area.

2.2. Data Sources

The analysis data covers 2000, 2005, 2010, 2015, 2020, and 2022. Socioeconomic indicators were compiled from the Jiangsu Statistical Yearbook [25–30], Anhui Statistical Yearbook [31–36] and Statistical Communiqués on National Economic and Social Development issued by the relevant prefecture-level cities. In this study, GDP is converted into values at constant prices with 2000 as the base year, which ensures cross-year comparability. The land use data were obtained from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (<https://www.resdc.cn/>). The 30 m dataset was derived from Landsat imagery through human–computer interactive interpretation and had a reported overall interpretation accuracy of 88.95%. Administrative-boundary data were obtained from the National Catalogue Service for Geographic Information (<https://www.tianditu.gov.cn/>). All datasets were harmonized to the six observation years and aggregated to the 46 evaluation units before indicator calculation.

2.3. Conceptual Framework and Indicator Rationale

The SFM framework conceptualizes cultivated land use as a linked carrier–output–practice system [37]. The spatial dimension represents the physical carrier and captures land quantity, use structure, and landscape configuration. The functional dimension represents production, livelihood-supporting, and ecological outcomes or pressures associated with cultivated land [10,38]. The modal dimension represents the management practices and capacities through which those outcomes are generated, including irrigation, mechanization, resource use, and chemical inputs [17,39]. Many coupling studies relate land use transition to external systems, including urbanization, urban–rural integration, and ecological conditions [23,24]. By contrast, SFM diagnoses internal mismatches among the spatial carrier of cultivated land, its functional outputs, and its management practices. The three dimensions are related but not interchangeable because similar outputs can arise from different spatial structures and practices.

The 18 indicators were selected according to conceptual relevance, consistent county-level availability, and comparability across 2000–2022 (Table 1). Spatial indicators describe land quantity, use structure, and fragmentation, following land use transition and landscape change research [7,19]. Functional indicators represent agricultural production, livelihood support, and ecological pressure or diversity-related attributes [22,38]. Modal indicators capture management capacity and resource or environmental pressure, including machinery, irrigation, pesticide, agricultural film, and energy use [17,39]. Agricultural labor per hectare is treated as a negative land intensity indicator, whereas the agricultural employment share captures the livelihood role of farming. The selected indicators are operational proxies rather than an exhaustive measurement of each dimension. Soil quality,

tenure arrangements, farm size, and farmer behavior were excluded because consistent county-level observations were unavailable for all six years.

Table 1. Evaluation index system for the transition of cultivated land use in the Nanjing Metropolitan Area, China.

Target Layer	Factor Layer	Indicator Layer	Indicator Definition	Nature of Indicator	Indicator Weight
Spatial Transition (A)	Quantity	A1-1 Per Capita Cultivated Land Area	Cultivated Land Area/Population	+	0.075
		A1-2 Land Reclamation Rate	Cultivated Land Area/Total Land Area	+	0.049
	Structure	A2-1 Multiple Cropping Index	Total Sown Area of Crops/Cultivated Land Area	+	0.029
		A2-2 Sown Proportion of Food Crops	Sown Area of Food Crops/Cultivated Land Area	+	0.047
		A2-3 Ratio of Food Crops to Sown Area of Food Crops/Sown Cash Crops	Area of Food Crops/Sown Area of Cash Crops	+	0.201
	Morphology	A3-1 Cultivated Land Landscape Fragmentation Index	Number of Cultivated Land Patches/Total Cultivated Land Area	−	0.009
Functional Transition (B)	Production	B1-1 Per-Hectare Total Agricultural Output Value	Total Agricultural Output Value/Cultivated Land Area	+	0.149
		B1-2 Per-Hectare Grain Yield	Total Grain Output/Cultivated Land Area	+	0.027
		B1-3 Per-Hectare Agricultural Labor Force	Number of Agricultural Employees/Cultivated Land Area	−	0.021
	Living	B2-1 Per Capita Grain Supply	Total Grain Output/Population	+	0.120
		B2-2 Proportion of Agricultural Employment	Number of Agricultural Employees/Total Labor Force	+	0.094
	Ecology	B3-1 Per-Hectare Chemical Fertilizer Non-Point Source Pollution	Total Chemical Fertilizer Application/Cultivated Land Area	−	0.020
		B3-2 Farmland Diversity Index	Richness of Farmland Biodiversity	+	0.008
Modal Transition (C)	Green Production	C1-1 Per-Hectare Pesticide Use	Total Pesticide Application/Cultivated Land Area	−	0.009
		C1-2 Per-Hectare Agricultural Film Use	Total Agricultural Film Application/Cultivated Land Area	−	0.020
	Resource Conservation	C2-1 Per-Hectare Total Agricultural Machinery Power	Total Agricultural Machinery Power/Cultivated Land Area	+	0.061
		C2-2 Per-Hectare Agricultural Energy Consumption	Total Agricultural Energy Consumption/Cultivated Land Area	−	0.022
		C2-3 Effective Irrigation Rate	Effective Irrigated Area/Cultivated Land Area	+	0.037

The dimensions may evolve asynchronously [12,13]. Spatial contraction or fragmentation may coexist with higher yields, while management practices may change before or after functional outcomes. The framework therefore treats synchronicity as a descriptive property rather than a universally desirable outcome. Operationally, C measures similarity among normalized subsystem scores, whereas CCD combines that similarity with their composite normalized level, as detailed in Section 2.4. Aggregate and pairwise results

must be interpreted together because a low triadic value may arise from one specific mismatch rather than from all three dimensions simultaneously.

2.4. Methods

2.4.1. Comprehensive Measurement Model

We constructed spatial, functional, and modal transition indices from the 18 indicators described above (Table 1). The selection balances conceptual coverage with the need for a consistent county-by-year panel. Positive indicators denote higher normalized subsystem scores, whereas negative indicators denote greater land use intensity or environmental pressure. The entropy method assigns larger weights to indicators with greater cross-sectional and temporal information dispersion; it does not establish their normative importance.

Original values were standardized with an improved extreme-value method, indicator weights were calculated by the entropy method, and weighted sums were used to obtain the three subsystem indices. All standardization and weighting operations were performed on the same analytical panel so that county and year comparisons used a common scale:

$$U_{A/B/C} = \sum_{i=1}^n W_j X_{ij} \quad (1)$$

where U_A , U_B , and U_C denote the spatial, functional, and modal transition indices, respectively; W_j is the weight of indicator j ; X_{ij} is the standardized value of indicator j for evaluation unit i ; and n is the number of indicators in the relevant subsystem.

2.4.2. Degree of Coupling Model

We used the modified coupling model reported by Zhang et al. [21] to summarize the mathematical similarity among the normalized subsystem indices:

$$C = \sqrt{\left[1 - \frac{\sum_{i>1, j=1}^n \sqrt{(U_i - U_j)^2}}{\sum_{m=1}^{n-1} m}\right]^{\frac{1}{n-1}}} \times \left(\prod_{i=1}^n \frac{U_i}{\max U_i}\right) \quad (2)$$

where C ranges from 0 to 1. For a given set of non-negative normalized subsystem indices, C increases as their magnitudes become more similar and decreases as they become more uneven. It should therefore be read as a dimensionless measure of relative similarity or interdependence, not as observed flows of resources, information, or energy.

For two subsystems ($n = 2$), Equation (2) reduces to:

$$C = \sqrt{[1 - (U_2 - U_1)] \times \frac{U_1}{U_2}} \quad (3)$$

where U_1 and U_2 are the two normalized subsystem indices.

For the three SFM subsystems ($n = 3$), the expression is:

$$C = \sqrt{\left[1 - \frac{\sqrt{(U_3 - U_1)^2} + \sqrt{(U_3 - U_2)^2} + \sqrt{(U_2 - U_1)^2}}{3}\right]} \times \left(\sqrt{\frac{U_2}{U_3}} \times \sqrt{\frac{U_1}{U_3}}\right) \quad (4)$$

where U_1 , U_2 , and U_3 are the spatial, functional, and modal indices.

Equation (4) was used for the triadic SFM system, and Equation (3) was used for the spatial–functional (SF), spatial–modal (SM), and functional–modal (FM) pairs. C describes similarity among normalized subsystem magnitudes. A high C means that the relevant indices are close to one another; it does not imply high absolute performance, sustainability, efficient exchange, or beneficial causality. We use four model-defined descriptive bands—low coupling, antagonism, running-in, and high coupling—to facilitate mapping and comparison (Table 2). The labels are mathematical categories rather than stages that every region should seek to traverse.

Table 2. Model-defined classification of coupling degree (C) and coupling coordination degree (CCD) categories for cultivated land use transition in the Nanjing Metropolitan Area, China.

Metric	Model-Defined Category	Interval
Coupling (C)	Low Coupling Period	[0.0, 0.4)
Coupling (C)	Antagonism Period	[0.4, 0.6)
Coupling (C)	Running-in Period	[0.6, 0.8)
Coupling (C)	High-Coupling Period	[0.8, 1.0)
CCD	Severe Misalignment	[0.0, 0.2)
CCD	Mild Misalignment	[0.2, 0.3)
CCD	Near Misalignment	[0.3, 0.4)
CCD	Basic Coordination	[0.4, 0.5)
CCD	Moderate Coordination	[0.5, 0.6)
CCD	Good Coordination	[0.6, 0.8)
CCD	High Coordination	[0.8, 1.0)

2.4.3. Degree of Coupling Coordination Model

Because C does not account for the overall magnitude of the normalized subsystem indices, we also calculated the coupling coordination degree (CCD):

$$T = \alpha U_1 + \beta U_2 + \gamma U_3 \quad (\alpha + \beta + \gamma = 1) \quad (5)$$

$$T_1 = \alpha U_1 + \beta U_2, T_2 = \beta U_2 + \gamma U_3, T_3 = \alpha U_1 + \gamma U_3 \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

In Equations (5)–(7), T is the composite normalized development index, D is CCD, and C is the coupling degree. The spatial, functional, and modal subsystem coefficients were set to 0.34, 0.33, and 0.33, respectively; pairwise calculations used 0.5 and 0.5. The near-equal triadic coefficients reflect the framework's treatment of the three dimensions as co-equal analytical components. Indicator-level weights within each subsystem were estimated by entropy weighting, whereas subsystem coefficients were kept nearly equal to avoid giving one dimension an unsupported conceptual priority. The distinction between C and CCD is substantive: high C with low CCD denotes similar but jointly low normalized subsystem levels, whereas a higher CCD reflects both greater similarity and a higher composite normalized level. Neither measure infers causality nor distinguishes rational specialization from dysfunctional imbalance. CCD values were assigned to seven model-defined descriptive bands (Table 2), which should not be interpreted as universal sustainability grades.

As a robustness check, we reproduced the entropy-weighted SFM-CCD baseline for all 276 county-year observations, recalculated CCD using equal, coefficient-of-variation (CV), and CRITIC weights, and applied 1000 independent Monte Carlo weight perturbations at $\pm 10\%$ and $\pm 20\%$. Agreement was assessed using MAD, RMSE, Spearman and Kendall rank correlations, model-defined category agreement, meaning 95% interval width, and the proportion of observations retaining their baseline category. AHP was not used because no expert-elicitation dataset was available to support defensible pairwise judgments.

3. Results

3.1. Spatiotemporal Variation in SFM Coupling

We calculated SFM coupling for 46 evaluation units at six time points and mapped the resulting values (Figure 2). Table 3 reports on the share of units in each model-defined coupling category. Because C is determined by the relative magnitudes of the three

normalized subsystem indices, the maps show where spatial, functional, and modal transitions were similar, not where agriculture performed best in absolute terms.

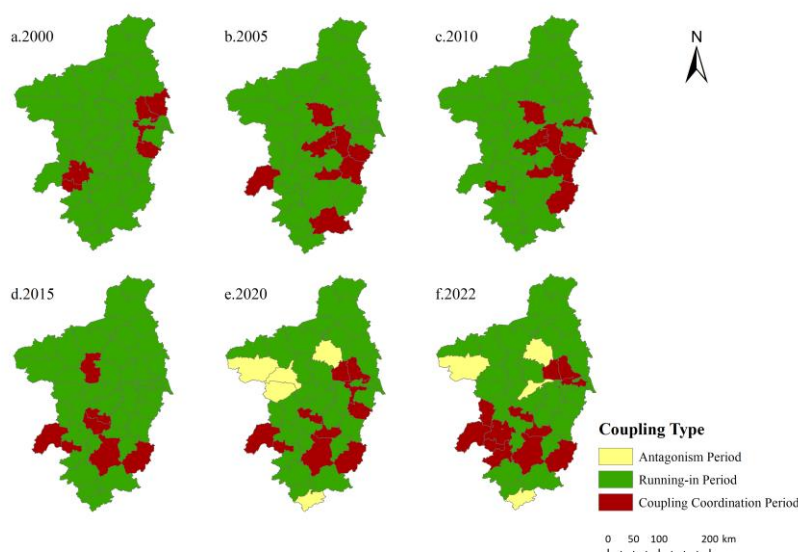


Figure 2. Spatial distribution of the coupling degree of the spatial–functional–modal (SFM) cultivated land use transition system in the Nanjing Metropolitan Area, China, 2000–2022. Colors represent model-defined coupling categories.

Table 3. Percentage of county-level units in each model-defined SFM coupling category, 2000–2022.

Model-Defined Coupling Category	2000	2005	2010	2015	2020	2022
Low Coupling Period	0	0	0	0	0	0
Antagonism Period	0	0	0	0	10.87	8.7
Running-in Period	86.96	82.61	78.26	84.78	67.39	65.22
High-Coupling Period	13.04	17.39	21.74	15.22	21.74	26.09

The county-level mean SFM coupling degree decreased slightly from 0.7468 in 2000 to 0.7398 in 2022, with intervening fluctuations. In 2000, values ranged from 0.6698 in Quanjiao County to 0.8356 in the Yangzhou urban districts; 86.96% of units were in the running-in category and 13.04% were in the high-coupling category. The mean rose to 0.7699 in 2005, when Gaochun District recorded 0.8755 and the high-coupling share increased to 17.39%.

After 2010, high-coupling units became more concentrated along the southeastern boundary, while lower values appeared in several interior units. Fanchang District reached 0.9637 in 2010, but the regional mean declined to 0.7568 by 2015. The antagonism category first appeared after 2015 and accounted for 10.87% of units in 2020, including Dingyuan County (0.5365). By 2022, the mean recovered to 0.7398 and 12 units (26.09%) were in the high-coupling category (Table 3). The simultaneous increase in high-coupling units and emergence of antagonistic units indicates greater spatial dispersion rather than uniform convergence.

The provincial subsets followed different paths (Figure 3). In Anhui, mean SFM coupling was 0.7438, 0.7654, 0.7570, 0.7673, 0.7222, and 0.7324 across the six years. The mean remained in the running-in category but ended 1.5% below its 2000 value. The distribution also widened in later years as several units moved into the antagonism category.

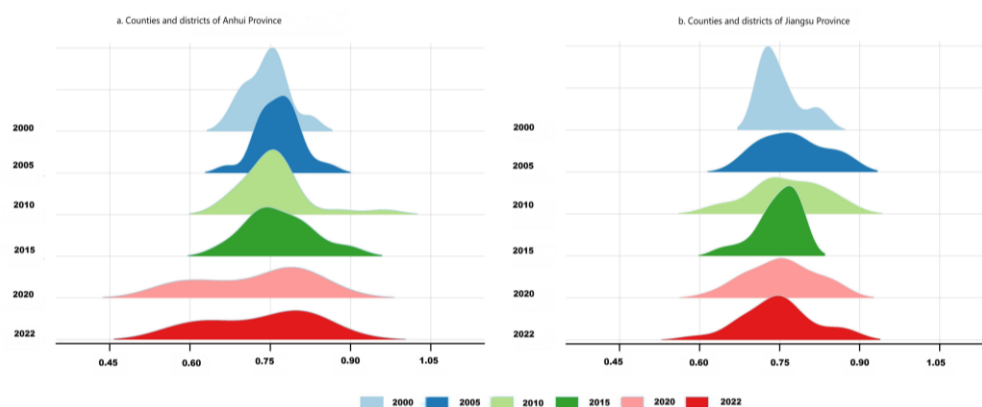


Figure 3. County-level spatial distribution of SFM coupling in the Anhui and Jiangsu parts of the Nanjing Metropolitan Area, China, 2000–2022: (a) Anhui; (b) Jiangsu. Colors represent model-defined coupling categories.

Jiangsu showed less net change: the corresponding means were 0.7498, 0.7745, 0.7630, 0.7464, 0.7531, and 0.7527, a cumulative increase of 0.38%. Most units remained in the running-in category, with fewer low-valued outliers than in Anhui. These results describe differences in the similarity of normalized SFM indices; they do not establish that one province has superior agricultural performance.

At the municipal scale, coupling increased in Wuhu, Xuancheng, Ma’anshan, and Huai’an. Wuhu, Ma’anshan, and Huai’an moved from the running-in to the high-coupling category, while Xuancheng remained in the high-coupling category despite a temporary decline before 2010 (Figure 4).

Coupling declined with fluctuations in Chuzhou, Nanjing, Changzhou, Zhenjiang, and Yangzhou. Nanjing moved from the running-in to the antagonism category, and Changzhou recorded the largest proportional decline. The early Jiangsu advantage was less evident by 2022 because several Anhui municipalities converged with or exceeded their Jiangsu counterparts. This shift concerns normalized cross-dimensional similarity, not absolute development capacity.

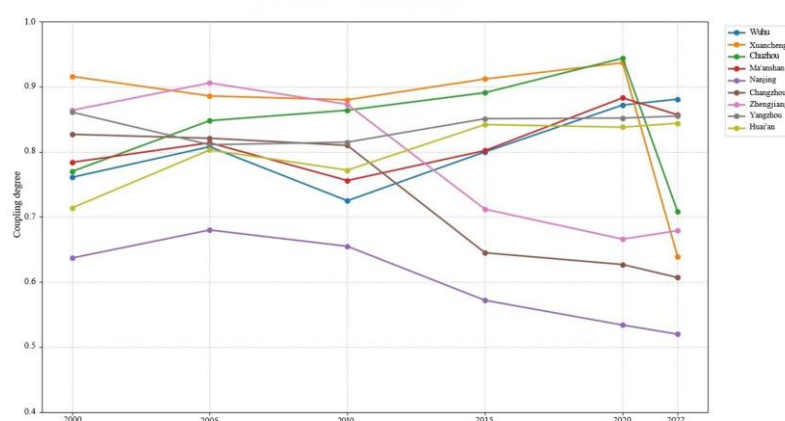


Figure 4. Changes in the SFM coupling degree across nine municipal areas in the Nanjing Metropolitan Area, China, 2000–2022.

3.2. Spatiotemporal Variation in SFM Coupling Coordination Degree

Figure 5 presents SFM-CCD for the 46 evaluation units in 2000, 2005, 2010, 2015, 2020, and 2022; Table 4 summarizes the model-defined categories.

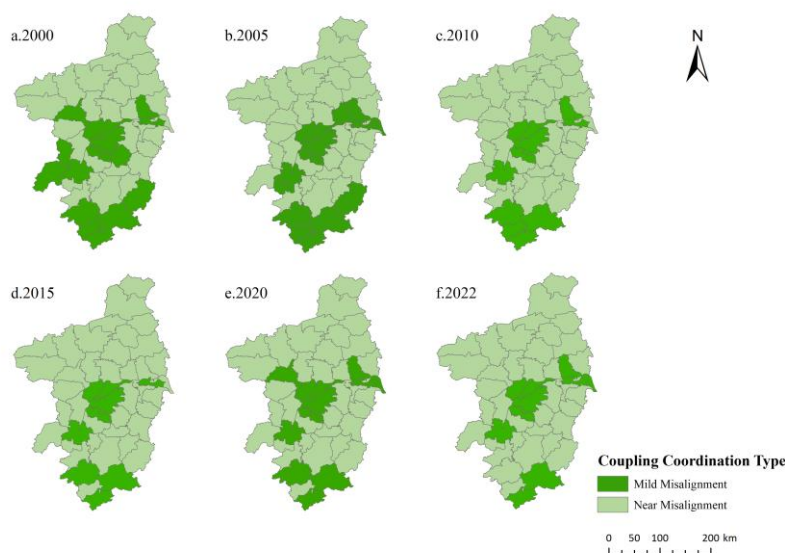


Figure 5. Spatial distribution of the SFM coupling coordination degree (SFM-CCD) in the Nanjing Metropolitan Area, China, 2000–2022. Colors represent model-defined CCD categories.

Table 4. Percentage of county-level units in each model-defined SFM-CCD category, 2000–2022.

Model-Defined CCD Category	2000	2005	2010	2015	2020	2022
Mild Misalignment	34.78	32.61	23.91	19.57	26.09	21.74
Near Misalignment	65.22	67.39	76.09	80.43	73.91	78.26
Basic Coordination	0.00	0.00	0.00	0.00	0.00	0.00

The mean SFM-CCD increased from 0.3039 in 2000 to 0.3268 in 2022 but remained in the near-misalignment category. In 2000, values ranged from 0.2436 in the Nanjing urban districts to 0.3335 in Dantu District. Mild-misalignment units accounted for 34.78% of the sample and near-misalignment units for 65.22%. Higher values were concentrated mainly in the north, while lower values occurred in Nanjing and parts of Xuancheng and Wuhu.

From 2005 to 2015, the mild-misalignment share fell from 32.61% to 19.57%, and Hongze County reached 0.3804 in 2015. A small reversal occurred in 2020, including a return to mild misalignment in the Chuzhou urban districts, but the regional mean reached 0.3268 in 2022 and Jinhu County recorded the maximum of 0.3941. Nanjing remained the regional minimum. This relative trough indicates weaker alignment among its normalized spatial, functional, and modal indices; it does not indicate lower absolute agricultural resources or total economic capacity.

Anhui's mean SFM-CCD increased from 0.3004 in 2000 to 0.3285 in 2022, a cumulative rise of 9.3% (Figure 6). Although the provincial mean remained in the near-misalignment category, the county distribution became more concentrated, indicating convergence in normalized SFM alignment.

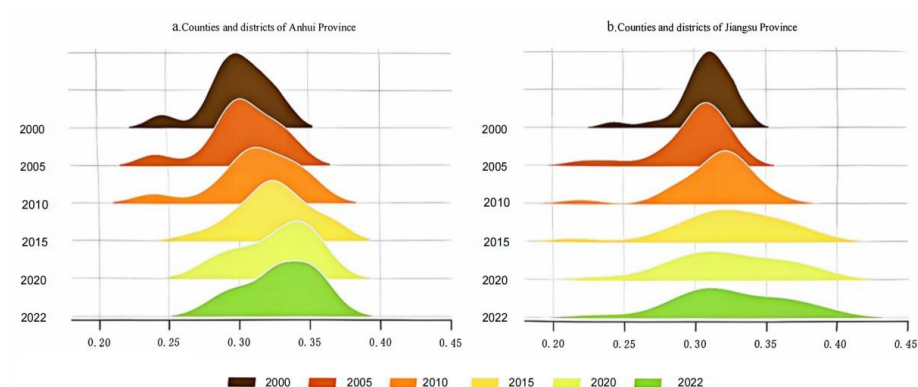


Figure 6. County-level spatial distribution of SFM-CCD in the Anhui and Jiangsu parts of the Nanjing Metropolitan Area, China, 2000–2022: (a) Anhui; (b) Jiangsu.

Jiangsu followed a non-monotonic path, increasing from 0.3065 to 0.3249 overall but moving through a decrease–increase–decrease sequence. Its county distribution flattened over time, indicating wider within-province dispersion. The provincial mean briefly entered mild misalignment in 2005 before returning to near misalignment.

Anhui began below Jiangsu but surpassed it in the later years because its SFM-CCD increased more consistently. The contrast is best interpreted as a difference in the trajectories and dispersion of normalized cross-dimensional alignment, rather than as evidence that one province achieved universally better cultivated-land outcomes.

At the municipal scale, SFM-CCD increased in most areas. Huai'an showed the largest increase and moved from near misalignment to basic coordination, becoming the highest-valued municipality by 2022 (Figure 7).

Zhenjiang, Nanjing, and Changzhou declined. Zhenjiang fell from 0.3531 in 2000 to 0.3206 in 2022. Nanjing and Changzhou followed decrease–increase–decrease paths: after peaking in 2010 at 0.2937 and 0.3489, respectively, they declined to 0.2723 and 0.3005 by 2022.

Most municipalities remained in near misalignment, but the spread between the highest and lowest values widened. Nanjing's persistent minimum is consistent with weaker normalized alignment, especially in relationships involving the spatial dimension. Metropolitan expansion, a smaller cultivated-land share, and stronger non-agricultural specialization are plausible contextual explanations, but the analysis does not directly observe the capital, labor, land quota, commodity, or policy flows needed to establish a causal mechanism.

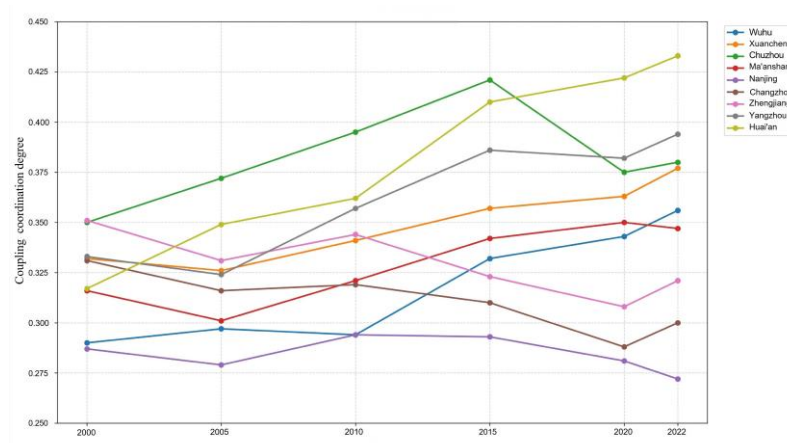


Figure 7. Changes in SFM-CCD across nine municipal areas in the Nanjing Metropolitan Area, China, 2000–2022.

3.3. Pairwise Relationships Among SFM Dimensions

3.3.1. Pairwise Coupling Degree

Mean spatial–functional (SF) coupling declined from 0.8928 in 2000 to 0.8579 in 2022 (Figure 8). Although the mean remained in the high-coupling category, the share of units in that category decreased from 95.65% to 76.09%, while the running-in share rose. Nanjing's value fell from 0.7245 in 2000 to 0.6127 in 2010.

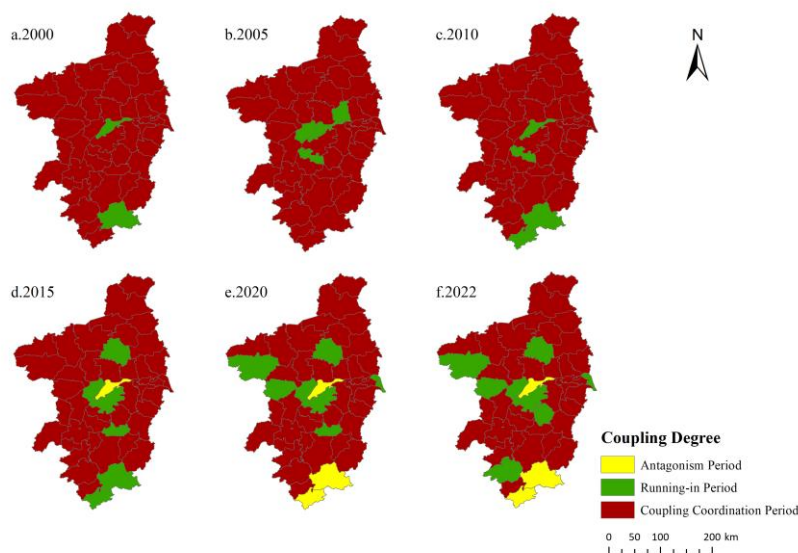


Figure 8. Spatial distribution of spatial–functional (SF) coupling in the Nanjing Metropolitan Area, China, 2000–2022.

The distribution became more polarized after 2015. Gaoyou reached 0.9968, whereas Nanjing entered the antagonism category at 0.5828. By 2022, 6.52% of units were in antagonism and 17.39% were in the running-in category. Thus, high average SF similarity coexisted with a growing lower tail.

Lower SF values first appeared in the metropolitan core and later in several adjacent units, producing an uneven north–south pattern. The spatial association is consistent with shared urbanization and land use pressures, but it cannot be treated as evidence of spillover because cross-regional flows were not measured.

Mean spatial–modal (SM) coupling fluctuated around the running-in category, rising from 0.7016 in 2000 to 0.7177 in 2005 before declining to 0.7064 in 2010 (Figure 9A). Both the antagonism and high-coupling shares increased in the early period, showing that the regional mean concealed widening dispersion.

Internal polarization continued after 2010. In 2020, the mean was 0.7006 and the low-coupling category appeared for the first time (2.17% of units). The contraction of high-coupling units in parts of the south indicates a widening mismatch between spatial structure and management mode in those locations.

By 2022, the north generally recorded higher SM coupling than the south. This inversion from the earlier spatial pattern was driven by divergent municipal trajectories rather than a uniform regional change: Jiangsu municipalities other than Nanjing increased, whereas the four Anhui municipalities declined.

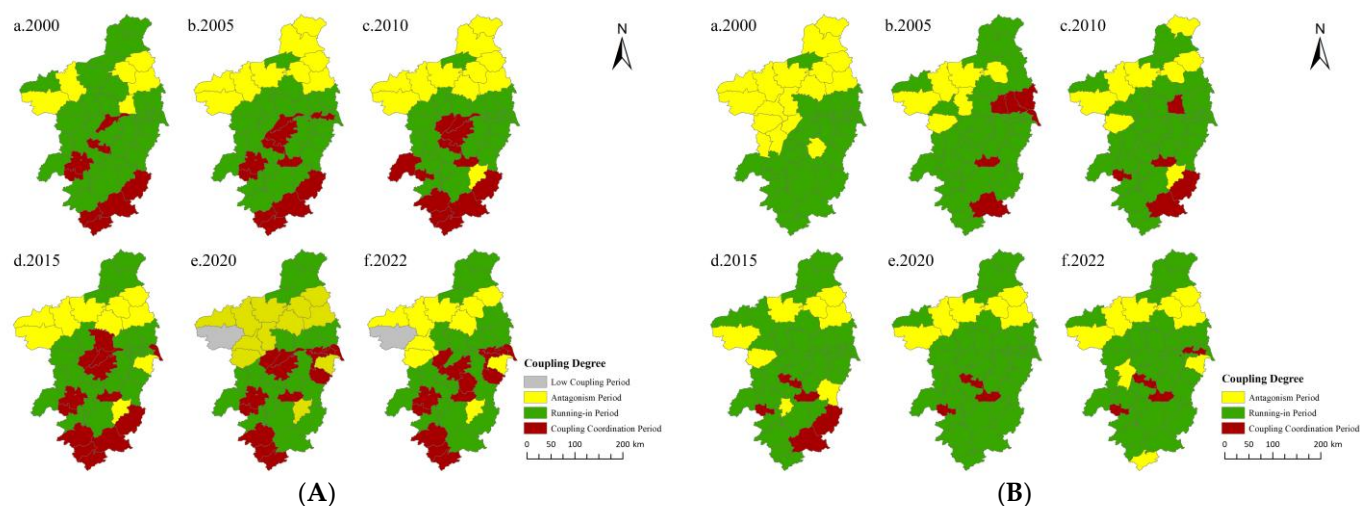


Figure 9. Spatial distribution of spatial-modal (SM) (A) and spatial distribution of functional-modal (FM) (B) coupling in the Nanjing Metropolitan Area, China, 2000–2022.

Mean functional-modal (FM) coupling increased from 0.6357 in 2000 to 0.6736 in 2022, with fluctuations, and remained in the running-in category (Figure 9B). In 2000, Dingyuan County recorded the minimum of 0.5245; 36.96% of units were in antagonism and 63.04% were in the running-in category (Table 5).

FM coupling peaked at 0.6915 in 2005, when the antagonism share fell to 13.04% and the high-coupling share reached 13.04%. It then declined to 0.6791 in 2010. Gaochun District (0.9501) and Xuyi County (0.5198) marked the upper and lower ends of the distribution, respectively.

The high-coupling share reached its minimum of 6.52% in 2020. By 2022, the mean recovered to 0.6736, but the antagonism share rose to 19.57%; Dingyuan County (0.4956) and the Ma'anshan urban districts (0.9384) remained widely separated. The net increase in FM coupling therefore occurred alongside persistent spatial heterogeneity.

Table 5. Percentage of county-level units in each model-defined pairwise coupling category, 2000–2022.

Subsystem Coupling	Model-Defined Coupling Category	2000	2005	2010	2015	2020	2022
Spatial-Functional	[0, 0.4) Low-coupling Phase	0.00	0.00	0.00	0.00	0.00	0.00
	[0.4, 0.6) Antagonistic Phase	0.00	0.00	0.00	2.20	6.50	6.50
	[0.6, 0.8) Running-in Phase	4.35	8.70	8.70	13.04	15.22	17.39
	[0.8, 1) High-Coupling Phase	95.65	91.30	91.30	84.78	78.26	76.09
Spatial-Modal	[0, 0.4) Low-coupling Phase	0.00	0.00	0.00	0.00	2.17	2.17
	[0.4, 0.6) Antagonistic Phase	13.04	19.57	23.91	21.74	26.09	21.74
	[0.6, 0.8) Running-in Phase	69.57	56.52	50.00	50.00	43.48	47.83
	[0.8, 1) High-Coupling Phase	17.39	23.91	26.09	28.26	28.26	28.26
Functional-Modal	[0, 0.4) Low-coupling Phase	0.00	0.00	0.00	0.00	0.00	0.00
	[0.4, 0.6) Antagonistic Phase	36.96	13.04	17.39	17.39	13.04	19.57
	[0.6, 0.8) Running-in Phase	63.04	73.91	71.74	71.74	80.43	71.74
	[0.8, 1) High-Coupling Phase	0.00	13.04	10.87	10.87	6.52	8.70

Municipal pairwise trajectories differed. SF coupling declined in most municipalities, including reductions of 25.47–37.55% in Chuzhou, Changzhou, and Zhenjiang. Xuancheng and Yangzhou remained in the high-coupling category despite small

decreases, while Wuhu, Ma'anshan, and Huai'an increased; Ma'anshan reached 0.995 after a 22.49% rise.

SM coupling increased in every Jiangsu municipality except Nanjing but declined in all four Anhui municipalities. Huai'an rose by 28.54% and entered the high-coupling category. FM coupling increased in most municipalities, led by Wuhu (25.87%), but declined in Changzhou and Zhenjiang; Changzhou fell by 30.67% and moved from high coupling to antagonism.

Nanjing recorded the largest reductions in SF (37.55%) and SM (41.59%) coupling, both ending in antagonism, while its FM coupling increased slightly and remained in the running-in category. The triadic trough is therefore associated mainly with relationships involving the spatial dimension. Because all indices are normalized, this pattern denotes lower internal similarity, not lower absolute agricultural capacity.

3.3.2. Pairwise Coupling Coordination Degree

Mean SF-CCD increased from 0.3659 in 2000 to 0.3849 in 2022 (Figure 10) and remained in the near-misalignment category. In 2000, values ranged from 0.2557 in the Nanjing urban districts to 0.4399 in Dingyuan County; 23.91% of units were in basic coordination, 71.74% in near misalignment, and 4.35% in mild misalignment.

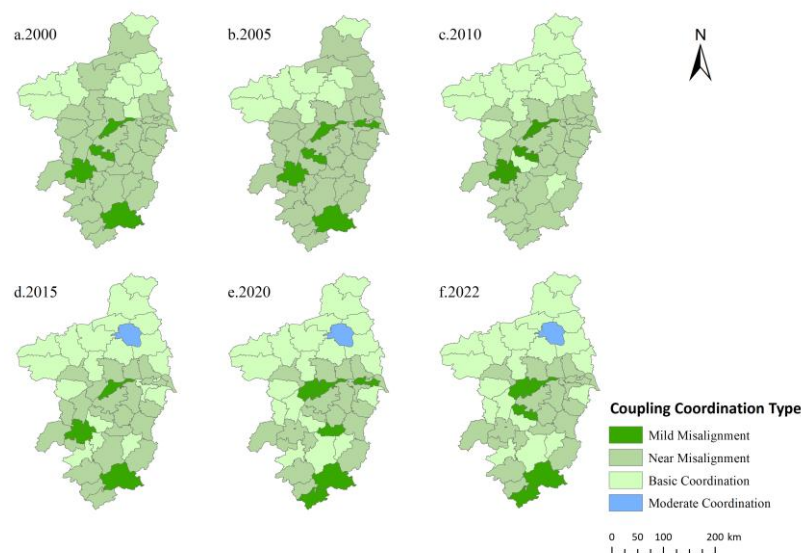


Figure 10. Spatial distribution of the spatial–functional coupling coordination degree (SF-CCD) in the Nanjing Metropolitan Area, China, 2000–2022.

The basic-coordination share rose to 41.30% by 2015, and Jinhu County entered moderate coordination at 0.5003. Higher values were concentrated in the north, while the central and southern parts of the study area generally remained lower.

SF-CCD changed little between 2020 and 2022. By 2022, 43.48% of units were in basic coordination and Jinhu remained the only unit in moderate coordination. Nanjing stayed in mild misalignment throughout the study period, confirming that its spatial–functional relationship was a persistent component of the metropolitan synchronicity trough.

Mean SM-CCD increased from 0.2689 in 2000 to 0.2947 in 2022 but remained in the mild-misalignment category (Figure 11). In 2000, values ranged from 0.2278 in the Wuhu urban districts to 0.2936 in Yangzhong, and all units were classified as mild misalignment.

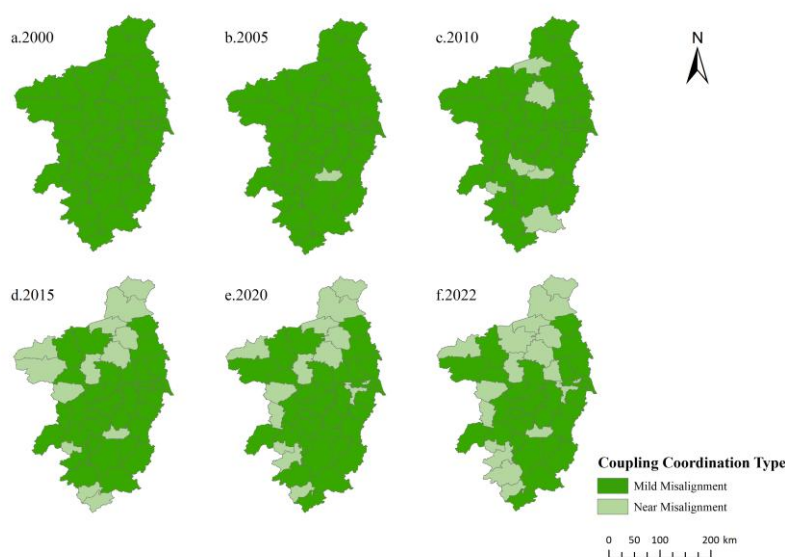


Figure 11. Spatial distribution of the spatial-modal coupling coordination degree (SM-CCD) in the Nanjing Metropolitan Area, China, 2000–2022.

Near misalignment first appeared in Gaochun District in 2005 (0.3069) and accounted for 28.26% of units by 2015. Hongze District recorded 0.3419, while the Nanjing urban districts remained the minimum at 0.2084. The distribution consequently widened, with higher values in the northwest and lower values in the south and metropolitan core.

By 2022, 36.96% of units were in near misalignment and 63.04% remained in mild misalignment. The improvement in the regional mean was therefore gradual and spatially uneven, with the northwestern and western margins advancing more than the central and eastern corridors.

Mean FM-CCD increased from 0.2707 in 2000 to 0.3001 in 2022, moving from mild misalignment to near misalignment (Figure 12). In 2000, all units were in mild misalignment, with values ranging from 0.2291 in the Wuhu urban districts to 0.2950 in Dangtu County.

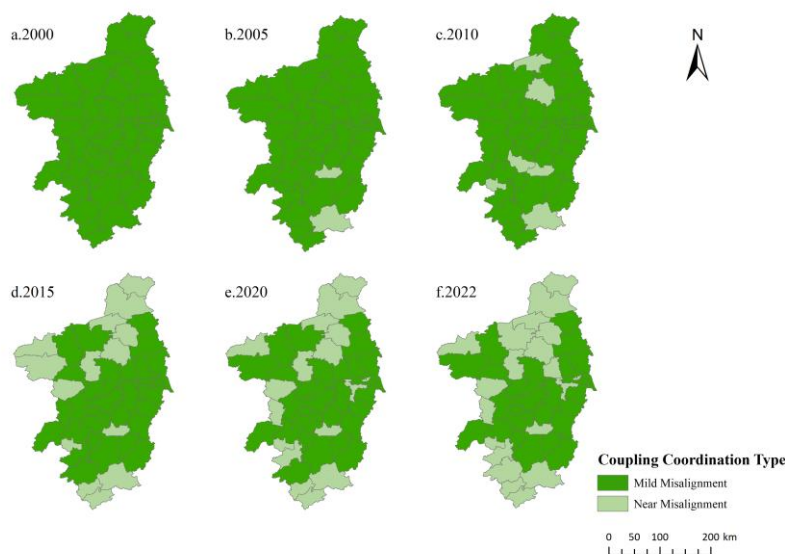


Figure 12. Spatial distribution of the functional-modal coupling coordination degree (FM-CCD) in the Nanjing Metropolitan Area, China, 2000–2022.

Gaochun District reached 0.3070 in 2005, one of the first two near-misalignment observations. The near-misalignment share then increased from 13.04% in 2010 to 30.43% in 2015. Gaochun remained the maximum at 0.3448, while the Nanjing urban districts recorded the minimum of 0.2454.

In 2020–2022, the near-misalignment share reached 34.78%. Hongze County recorded the 2022 maximum of 0.3541 and the Yangzhou urban districts the minimum of 0.2593. The upward shift was broad but did not remove the contrast between county-level units and several major urban districts (Table 6).

Table 6. Percentage of county-level units in each model-defined pairwise CCD category, 2000–2022.

Subsystem Coupling Coordination	Model-Defined CCD Category	2000	2005	2010	2015	2020	2022
Spatial-Functional	[0.2, 0.3) Mild Misalignment	4.35	8.70	6.52	6.53	13.04	10.87
	[0.3, 0.4) Near Misalignment	71.74	71.74	60.87	50.00	41.30	43.48
	[0.4, 0.5) Basic Coordination	23.91	19.57	32.61	41.3	43.48	43.48
	[0.5, 0.6) Moderate Coordination	0.00	0.00	0.00	2.17	2.17	2.17
Spatial-Modal	[0.2, 0.3) Mild Misalignment	100.00	97.83	86.96	71.74	71.74	63.04
	[0.3, 0.4) Near Misalignment	0.00	2.17	13.04	28.26	28.26	36.96
	[0.4, 0.5) Basic Coordination	0.00	0.00	0.00	0.00	0.00	0.00
Functional-Modal	[0.2, 0.3) Mild Misalignment	100.00	95.65	86.96	69.57	65.22	58.70
	[0.3, 0.4) Near Misalignment	0.00	4.35	13.04	30.43	34.78	41.30
	[0.4, 0.5) Basic Coordination	0.00	0.00	0.00	0.00	0.00	0.00

At the municipal scale, SF-CCD increased in most areas. Huai'an rose from 0.3923 to 0.4767 and moved from near misalignment to basic coordination; Ma'anshan and Yangzhou made the same categorical transition. Nanjing declined to 0.2399 and moved from near to mild misalignment, becoming the regional minimum.

SM-CCD also increased in most municipalities. Huai'an rose by 50.5% to 0.4101 and entered basic coordination, while Wuhu entered near misalignment. Nanjing remained in mild misalignment; Changzhou temporarily fell into mild misalignment before returning to near misalignment by 2022.

FM-CCD increased in most municipalities, with Wuhu and Xuancheng approaching 0.4000. Huai'an was the only municipality to reach basic coordination and increased by 32.4%. Ma'anshan and Zhenjiang showed temporary declines before recovering.

Together, the pairwise results show that the three relationships did not evolve uniformly. Huai'an improved across all pairs, whereas Nanjing remained lowest in relationships involving the spatial dimension. These contrasts motivate separate interpretation of pairwise and triadic indices rather than a single normative ranking.

The reproduced entropy baseline closely matched the original SFM-CCD results across 276 observations (MAD = 0.003124; RMSE = 0.004717; Spearman ρ = 0.9820; Kendall τ = 0.9136; category agreement = 93.84%). Rank correlations with the entropy baseline

were 0.8785 for equal, 0.9566 for CV, and 0.8516 for CRITIC weights. Under $\pm 10\%$ and $\pm 20\%$ Monte Carlo perturbations, Spearman ρ remained 0.9812 and 0.9795, respectively, while full category stability declined from 73.55% to 56.52%. Relative rankings and the broad temporal pattern were therefore more stable than absolute CCD values and threshold-based categories.

4. Discussion

4.1. Interpreting the Divergence Between Coupling and CCD

The central result is the divergence between coupling and CCD. Mean SFM coupling decreased from 0.7468 to 0.7398, while mean SFM-CCD increased from 0.304 to 0.327. Because C is highest when normalized subsystem magnitudes are similar, the decline signals a slight increase in relative imbalance; CCD nevertheless rose because the composite normalized subsystem level increased enough to offset that decline. The two indices therefore describe different properties: coupling captures relative similarity, whereas CCD combines similarity with the overall normalized level. Neither directly measures sustainability. The robustness checks reinforce the need for cautious interpretation: alternative weights and weight perturbations preserved relative rankings and the broad temporal pattern, but absolute CCD values and threshold-based categories were more method-sensitive. We therefore emphasize temporal direction, relative position, and pairwise divergence rather than treating category boundaries as fixed performance grades.

This divergence reflects three concurrent mechanisms operating in the Nanjing Metropolitan Area. First, urban expansion created spatial pressure: the built-up area of Nanjing proper increased by 68% between 2000 and 2020, displacing peri-urban cultivated land and fragmenting the remaining parcels [40]. Second, agricultural policies shifted emphasis from quantity security to quality and efficiency: the Provincial Farmland Protection Regulation prioritized permanent basic farmland demarcation and high-standard farmland construction, raising per-hectare yields while stabilizing total area [41]. Third, technological adoption accelerated unevenly: precision agriculture, drip irrigation, and soil testing spread rapidly in suburban counties but lagged in core urban districts where remaining cultivated land became residual and underinvested [42]. These mechanisms explain why functional outputs (reflected in yield and value-added) improved faster than spatial configuration adapted.

4.2. Theoretical Contribution and Relation to Previous Studies

Quantitative comparison with other rapidly urbanizing metropolitan regions reveals a common pattern with local variations. In the Pearl River Delta, mean cultivated land per capita declined 43% (1990–2015) while grain yield per hectare rose 35%, producing a similar coupling-CCD divergence [42]. Jakarta's peri-urban fringe exhibited even sharper spatial loss (52% reduction, 2000–2020) but modest yield gains (18%), resulting in lower CCD improvement [43]. Sao Paulo's sugarcane belt showed the opposite: spatial expansion with productivity stagnation, reflecting different agronomic and policy contexts [41]. The Nanjing case occupies a middle position—moderate spatial contraction with strong functional upgrading—suggesting that metropolitan land system transitions cluster into recognizable types depending on the relative pace of urban encroachment, agricultural investment, and governance intervention.

The SFM framework contributes an internal carrier–output–practice diagnosis to cultivated land use transition research. Existing spatial studies identify changes in cultivated land extent and configuration, multifunctionality studies assess outputs and services, and management studies examine inputs and practices [2,18,19]. Integrating these strands makes it possible to ask not only whether cultivated land is changing, but whether its

spatial carrier, functional outputs, and management practices are changing synchronously. Decomposing the triad into SF, SM, and FM relationships then identifies where divergence occurs. This matters because the regional mean concealed contrasting trajectories: SF coupling weakened, FM coupling strengthened, and SM coupling varied across provincial and municipal contexts. The contribution is therefore the explicit integration and diagnostic decomposition of established transition dimensions, not a claim that the CCD formula itself is new.

The SFM framework aligns with middle-range land system theories that emphasize multi-scale interactions and feedback loops [4,44]. Telecoupling research demonstrates that metropolitan cultivated-land outcomes are co-produced by local land use decisions, regional food supply chains, national grain security mandates, and global commodity markets [4]. The spatial subsystem in this study reflects local land cover configuration; the functional subsystem captures output shaped by regional demand and provincial targets; the modal subsystem represents management practices influenced by technology diffusion and subsidy programs spanning county to national scales. By measuring synchronicity among these subsystems, the SFM-CCD indicator diagnoses whether cross-scale governance is producing coherent land system change or generating internal friction.

The findings accord with international land system research showing that urban expansion can reduce cropland while intensification and peri-urban specialization reshape the functions of the remaining land [2,3]. Similar patterns have been documented in the Pearl River Delta [42], Sao Paulo metropolitan region [45], and Jakarta's peri-urban fringe [43]. They also support the broader view that land system outcomes emerge through interactions among places and governance scales [1,4,13]. Telecoupling frameworks emphasize that metropolitan land use outcomes are shaped by distant connections and cross-scale feedback [4,44]. Within China, previous studies have connected cultivated-land transition with rural transformation, urban–rural integration, multifunctionality, and ecological conditions [16,23,41]. The present results extend this literature in two respects: metropolitan averages can mask pair-specific divergence, and cross-provincial integration does not necessarily produce synchronous internal transition. These comparisons are conceptual rather than numerical or causal because the cited studies use different indicators, normalization procedures, and spatial units.

International cases reveal that low spatial extent with high functional output is not pathological but reflects rational metropolitan land division. In the Netherlands, intensive greenhouse horticulture concentrates on less than 2% of agricultural land yet generates 25% of sectoral value-added, producing low coupling but high functional performance. Tokyo's peri-urban agriculture occupies fragmented parcels averaging 0.8 ha but delivers fresh vegetables, agritourism, and flood regulation, again privileging function over extent. The key distinction is whether low coupling results from deliberate specialization (desirable) or policy neglect (problematic). The SFM framework cannot make this judgment automatically; contextual interpretation—such as comparing Nanjing's core-city low CCD with its sustained investment in suburban high-standard farmland—is required.

4.3. Contextual Interpretation and Governance Implications

Nanjing's low relative values require a non-normative interpretation. Its SFM-CCD trough does not mean that the provincial capital has weaker total development capacity or a larger absolute cultivated-land problem. The indicators describe per capita, per-hectare, proportional, and structural conditions after standardization. Lower CCD therefore indicates weaker alignment among Nanjing's remaining cultivated-land structure, functions, and management practices, particularly in the SF and SM relationships. Similarly, Anhui's later CCD advantage over Jiangsu indicates more consistent alignment among normalized dimensions, not a higher absolute level of agricultural or socioeconomic

development. Strong urban pressure and agricultural specialization provide plausible context for Nanjing, but rational division of labor can also generate asynchrony. Without direct data on capital, labor, land quotas, commodity flows, or policy implementation, the analysis cannot distinguish specialization from dysfunctional imbalance or attribute the pattern to a metropolitan “siphon effect”.

The governance implication is to diagnose the dominant mismatch before selecting an intervention. In Nanjing and other core urban districts, priorities may include protecting high-quality remaining cultivated land, limiting fragmentation, and supporting peri-urban multifunctional agriculture. Where SM alignment is weak, land consolidation, irrigation, mechanization services, and input reduction technologies should be planned jointly rather than as separate programs. Where FM alignment is weak, output targets should be linked to fertilizer and pesticide reduction and biodiversity-friendly management. Across Jiangsu and Anhui, shared monitoring standards, data exchange, ecological compensation, and coordinated farmland protection responsibilities could improve cross-provincial consistency. These recommendations remain conditional: a low CCD should initiate contextual diagnosis, not automatic pursuit of uniform subsystem values.

Differentiated governance strategies require spatially explicit diagnosis. The results suggest a three-tier management approach. Core urban counties (Nanjing, Zhenjiang central districts) should adopt a functional-first strategy: protect ecologically sensitive and socially valued, cultivated parcels (e.g., heritage rice paddies, community-supported agriculture sites) while accepting spatial decline elsewhere and invest in vertical farms or peri-urban precision horticulture to maintain local food production. Suburban counties (Jurong, Lishui, Liyang) should pursue coordination optimization: synchronize high-standard farmland construction with mechanization services and digital extension to maximize all three subsystems simultaneously. Peripheral counties (Hongze, Xuyi) with high CCD should adopt efficiency enhancement: introduce water-saving irrigation, integrated pest management, and crop rotation planning to sustain their relative advantage while preventing modal subsystem lag.

4.4. Limitations and Future Research

Comparative governance experiences from other metropolitan regions offers instructive lessons. The Greater Tokyo Area employs a productive green space designation that exempts urban and peri-urban cultivated land from inheritance tax if owners maintain active farming, thereby slowing spatial loss while preserving multifunctionality. The Randstad in the Netherlands uses a red-green zoning compact that prohibits urban sprawl into designated agricultural zones and channels development into compact corridors, producing higher coupling between spatial and functional subsystems. Sao Paulo’s green belt program—intended to protect peri-urban agriculture—failed because it lacked complementary modal support (credit, extension, market access), illustrating that spatial protection alone cannot sustain coordination [45]. For the Nanjing Metropolitan Area, these cases suggest that effective governance must bundle spatial regulation (permanent basic farmland demarcation), functional investment (high-standard farmland construction, irrigation), and modal support (mechanization subsidies, training, cooperatives) into integrated policy packages tailored to each county’s CCD profile.

Several limitations bound these conclusions. C and CCD are deterministic functions of normalized indices and specified weights; they do not infer causality, identify a universally optimal state, or distinguish rational specialization from dysfunctional imbalance. The indicator system omits soil quality, tenure, farm size, and farmer behavior because comparable county-level data were unavailable. Although the sensitivity tests supported the stability of relative rankings and the broad temporal pattern, the movement of absolute values and threshold categories shows that CCD should not be used as a stand-alone

performance criterion. Recent critiques of composite indices in sustainability assessment emphasize similar cautions [46]. Future research should incorporate commodity, labor, capital, and policy flow data; test alternative indicator definitions and normalization strategies; and compare the SFM diagnosis across other rapidly urbanizing regions. Such extensions would help separate contextually rational specialization from persistent cross-dimensional mismatch.

5. Conclusions

This study developed an SFM framework to examine the synchronicity of the spatial carrier, functional outputs, and management practices of cultivated land use across 46 county-level units from 2000 to 2022. Regional SFM-CCD increased from 0.304 to 0.327, whereas mean coupling declined from 0.747 to 0.740. Composite normalized subsystem levels therefore rose while relative similarity weakened slightly; the region remained in the model-defined near-misalignment category.

Pairwise, trajectories were asynchronous. SF coupling weakened, FM coupling strengthened, and SM coupling diverged between provinces and municipalities. Anhui's SFM-CCD increased more consistently and surpassed Jiangsu in later years. Nanjing remained a relative synchronicity trough, driven mainly by relationships involving spatial dimension. This denotes weaker normalized alignment, not lower absolute agricultural capacity, and may reflect either metropolitan specialization or mismatch.

Alternative weighting and weight perturbation tests largely preserved relative rankings and the broad temporal pattern, although absolute CCD values and categories were method-sensitive. The SFM framework can support differentiated diagnosis in other rapidly urbanizing regions if model outputs are interpreted with local land use functions, governance conditions, and causal evidence rather than as universal performance grades.

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Abbreviations

The following abbreviations are used in this manuscript:

SFM	Spatial–Functional–Modal
CCD	Coupling Coordination Degree
SF	Spatial–Functional
SM	Spatial–Modal
FM	Functional–Modal
SF-CCD	Spatial–Functional Coupling Coordination Degree
SM-CCD	Spatial–Modal Coupling Coordination Degree

FM-CCD Functional–Modal Coupling Coordination Degree

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