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RESEARCH ARTICLE

Transformation of social-ecological systems in the Songhua River Basin, Northeast China: Lessons for a more sustainable development

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Abstract

1. Social-ecological systems (SES) are coupled systems formed by the intricate interactions between humans and nature. Our movement towards sustainable lifestyles requires a robust understanding of these interactions. Achieving a sustainable win-win situation for both social and ecological systems, therefore, necessitates a sound scientific framework outlining the direct and indirect interdependence between a region's inhabitants and the changing natural environment they live in.
2. We developed an archetype-network framework combining hierarchical clustering, interaction network analysis and catastrophe theory to quantify SES transformations. Analysing 20 indicators across 134 counties in 2000 and 2020, we identified distinct SES archetypes, mapped transition hotspots and assessed inherent sustainability via structural reconfigurations of social-ecological linkages. This approach captures the nonlinear interactions within SES.
3. Findings indicate five SES archetypes emerging by 2020 that represent a diversification from three types in 2000, with 80 counties shifting archetypes. Key transitions occurred at mountain–plain interfaces: 42.67% of the 2020 agriculture archetype (SES 02) shifted to SES 01 (urban archetype), SES 03 (green development-archetype) or SES 04 (ethno-regional fragmented synergy archetype), while 39.58% of nature archetypes transitioned to the enhanced nature archetype (SES 05). Network analysis revealed the dominance of socio-economic factors. Urban systems (SES 01) showed severe decoupling (network density = 0.14) and the lowest sustainability (0.579), whereas enhanced natural archetypes (SES 05) scored highest (0.787). Sustainability was closely associated with network density (R^2 = 0.62), indicating that archetypes with tighter linkages tended to be more resilient.
4. Sustainability transitions in the Songhua River Basin require tailored, context-specific strategies. Urban areas need innovation-driven recoupling policies while

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agricultural regions should adopt circular farming practices to reduce ecological risks. In nature-dominated areas, ecological restoration must be coupled with sustainable economic opportunities that balance conservation and development, while in ethnically diverse regions, cultural preservation should be combined with environment-focussed governance for sustainable land management. These findings underscore the need for spatially differentiated, policy-driven solutions to address the complex SES transformation challenges in the Anthropocene.

KEYWORDS
human–nature interactions, network analysis, SES transformative change, visions of sustainability

1 | INTRODUCTION

Since the late 1990s, China has initiated multi-scale ecological restoration programs to combat ecosystem service degradation, with objectives evolving from single-focus goals (e.g. forest conservation) to broader aims of restoring biodiversity and ecosystem integrity (Fu et al., 2023; Li, Wu, et al., 2024). Monitoring data confirm significant progress in natural restoration outcomes, including increased vegetation cover (Cai et al., 2022), coupled with some reversal in desertification (Xu et al., 2025) and a population recovery of many endangered species (Xu & Zang, 2023). However, evidence shows that neglecting socio-political dimensions, such as governance, cultural values and economic incentives, can undermine long-term restoration success (Cumming & Allen, 2017; Lofqvist et al., 2023). This has driven a paradigm shift towards viewing large-scale restoration initiatives as a co-evolutionary process in which social and ecological subsystems interact through multidirectional feedbacks (Fischer et al., 2021; Mansourian et al., 2019; Tedesco et al., 2023). A thorough understanding of these human–ecological interactions is crucial to predict system responses to Anthropocene challenges and to move towards the UN Sustainable Development Goals.

Social-ecological systems (SES) are complex, adaptive systems composed that can be understood as networks of relationships and interactions between humans and nature (Ostrom, 2009). SES theory provides essential lenses for deciphering these interdependencies (Guerrero et al., 2018; Reyers et al., 2018), with demonstrated efficacy across fisheries (Basurto et al., 2013), forest conservation (Fischer, 2018), agroforestry (Plieninger et al., 2021) and climate adaptation (Hossain et al., 2023). The telecoupling framework—which examines distal social-ecological interactions mediated by material flows and policy transfers—further extends this perspective (Liu, 2023). SES transformation refers to the fundamental reorganization of societal interactions with ecosystems in the face of complex challenges such as climate change, ecological degradation or social inequalities (Barnes et al., 2017). These changes arguably require multi-level governance with knowledge co-production among diverse stakeholders and the integration of social innovation (Folke et al., 2016; Westley et al., 2011). Analysing drivers of SES transformations through changes in the relationships among its components provides an effective means to understand associated relational adjustments and their long-term local and spillover effects (Wu et al., 2020). Despite the significant progress made in SES research, there remains a lack of analysis of the spatial and temporal heterogeneity of nonlinear interactions across systems, and particularly a quantification of policy-driven SES transformations and human–nature feedback loops (Schlüter et al., 2019). Here, the inherent nonlinear dynamics of SES, characterized by resilience thresholds, self-organization and emergent complexity (Fischer et al., 2015), pose fundamental analytical challenges. The associated knowledge gap highlights the need for new analytical approaches to characterize the structural reconfiguration of human–nature interactions during SES transitions, and to quantify sustainability challenges under diverse transition trajectories.

Archetype analysis is a promising approach to address this challenge, by identifying recurrent patterns while preserving contextual specificity (Oberlack et al., 2019; Sietz et al., 2019). Empirical applications—from agricultural transitions in Europe (Levers et al., 2015) to land-use dynamics in China (Mengxue et al., 2022) and the sustainable development challenges in Spain's Andalusian region (Pacheco-Romero et al., 2021)—demonstrate its utility in cross-scale comparisons. Yet, existing archetype constructions face critical limitations: reliance on linear correlations between explicit indicators often obscure nonlinear synergies among system elements, potentially misidentifying leverage points for sustainability transformations (Brondízio et al., 2021) and constraining this approach's ability to explain underlying drivers of SES dynamics (Meyfroidt, 2015; Partelow et al., 2024).

Network analysis offers complementary insights (Bascompte, 2009; Sayles et al., 2019). By mapping topological features such as centrality and modularity, network approaches can unveil latent element interaction pathways and tipping dynamics (Kluger et al., 2020; Stanworth et al., 2024; Wu et al., 2023). Integrating archetype analysis with network analysis in this context could significantly enhance explanatory power while informing actionable governance strategies (Yang, Bao, et al., 2023). SES frequently exhibit abrupt, nonlinear transitions in response to gradual, long-term pressures. Catastrophe theory—a mathematical framework for analysing discontinuous transitions in nonlinear systems

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(Zeeman, 1976)—offers a robust way of analysing these transformations. For each nested subsystem of a SES, catastrophe theory formulas handle the indicators in a structured yet weight-free manner. Its modular models can accommodate varying numbers of variables, allowing subsystem scores to be directly integrated into an overall sustainability index and thus enabling the assessment of sustainability index changes in social-ecological systems (Li et al., 2018; Zhang et al., 2021). Therefore, in this study, we adopt an approach that integrates archetype-network framework analysis with catastrophe theory models. Our approach advances SES research in two novel ways: (1) by quantifying structural reconfigurations of human–nature relationships during SES transitions, and (2) by comparing sustainability outcomes across spatially heterogeneous transition trajectories.

We specifically apply this framework to the Songhua River Basin (119°52′–132°31′ E, 41°42′–51°38′ N), a heterogenous social-ecological system in Northeast China spanning 556,800 km^2 of mountainous, floodplain and urban–rural landscapes (Figure 1a). This spatial heterogeneity, coupled with intensive human interventions over the past two decade (Fu et al., 2023; Mao et al., 2019), has produced a mosaic of tightly coupled SES configurations. The basin has undergone profound transformations through large-scale ecological restoration projects (Figure 1b) and social-ecological policies (Figure 2) that reconfigured resource use and altered human–nature interactions (Song et al., 2021; Wang et al., 2021; You et al., 2021).

This study aimed to answer three key questions: (1) Can distinct SES archetypes be identified that characterize the Songhua River Basin, and how have these archetypes changed between 2000 and 2020? (2) Which social-ecological interactions drive archetype configurations and their temporal dynamics? (3) What sustainability patterns emerge across archetypes, and how can these inform targeted governance interventions? By addressing these questions, we provide actionable insights for balancing ecological resilience and human well-being in rapidly changing SES, contributing to the broader challenge of navigating sustainability in the Anthropocene.

2 | MATERIALS AND METHODS

Based on the natural boundaries of the Songhua River Basin, and aiming to maintain the integrity of the prefecture-level administrative division units, we selected 134 counties in 28 cities at prefecture or higher level (autonomous prefectures and leagues) within the Songhua River watershed as study units.

Our approach involved three steps (Figure 3). We first compiled a comprehensive dataset with indicators representing the three main components of SES functioning, that is the social system, the ecological system and human–environmental interactions—including human impacts on nature and nature's contribution to people. This allowed us to classify counties based on similar performance across all indicators (Figure 3a). We second estimated the interactions among SES indicators to identify key elements characterizing SES archetypes (Figure 3b). We finally analysed the differences in sustainability scores for each SES archetype to understand how these scores relate to the elements characterizing the types in both 2000 and 2020 (Figure 3c).

2.1 | Database development and data sources

To characterize SES archetypes, we relied heavily on the framework provided by Ostrom (Ostrom, 2009), which views the world as an interconnected system composed of both social and ecological components, emphasizing the complex relationships between people and their environments. The list of specific variables included as potential indicators was based on the list presented as described previously (Pacheco-Romero et al., 2021; Pacheco-Romero et al., 2022) and was amended according to our research context and data availability at the county scale. As a result, we developed a dataset of 20 indicators using open-access regional databases (Table 1) to establish and map SES archetypes.

Within the social system component, we used 11 indicators to characterize three dimensions. The Human population dynamics dimension was explained by population density, population movement, population ageing and the proportion of ethnic minorities. Economic Development was integrated as the GDP per unit area, GDP per capita, disposable income per capita and index of advanced industrial structure. Well-being and governance dimensions were inferred from the density of healthcare facilities, general public budget expenditure per capita and the proportion of the population in employment. For the ecological system component, we used three indicators that explained two dimensions describing organic carbon dynamics and climatic conditions. To characterize the organic carbon dynamics dimension, we used net primary productivity (NPP) as a key descriptor of ecosystem functioning. Mean annual precipitation and mean annual temperature, respectively, were recorded to characterize the climate dimension. Interactions between humans and nature were established through six indicators characterizing four distinct dimensions. Linking ecological to social systems, we introduced grain production (provisioning services) and natural land coverage (supporting service) as indicators of ecosystem service supply. Linking social to ecological systems, we incorporated ecosystem service demand via the appropriation of land for agriculture. In addition, we characterized a human action on the environment dimension through indicators representative of carbon emission, night-time light intensity, and artificial surface coverage as representing land-use intensity.

We then harmonized all indicators at the county level ($n=134$ counties) for the Years 2000 (t1) and 2020 (t2), as these years offered the greatest data availability while allowing for a 20-year time span to analyse change. For indicator data unavailable for either t1 or t2, we used the data from the closest available date. Our dataset included both categorical and continuous indicators. We aggregated these to the county level by computing the spatial mean for continuous indicators and the relative area share of specific classes for categorical indicators, which were available as raster or shapefile data. To account for differences in county size and population, we normalized

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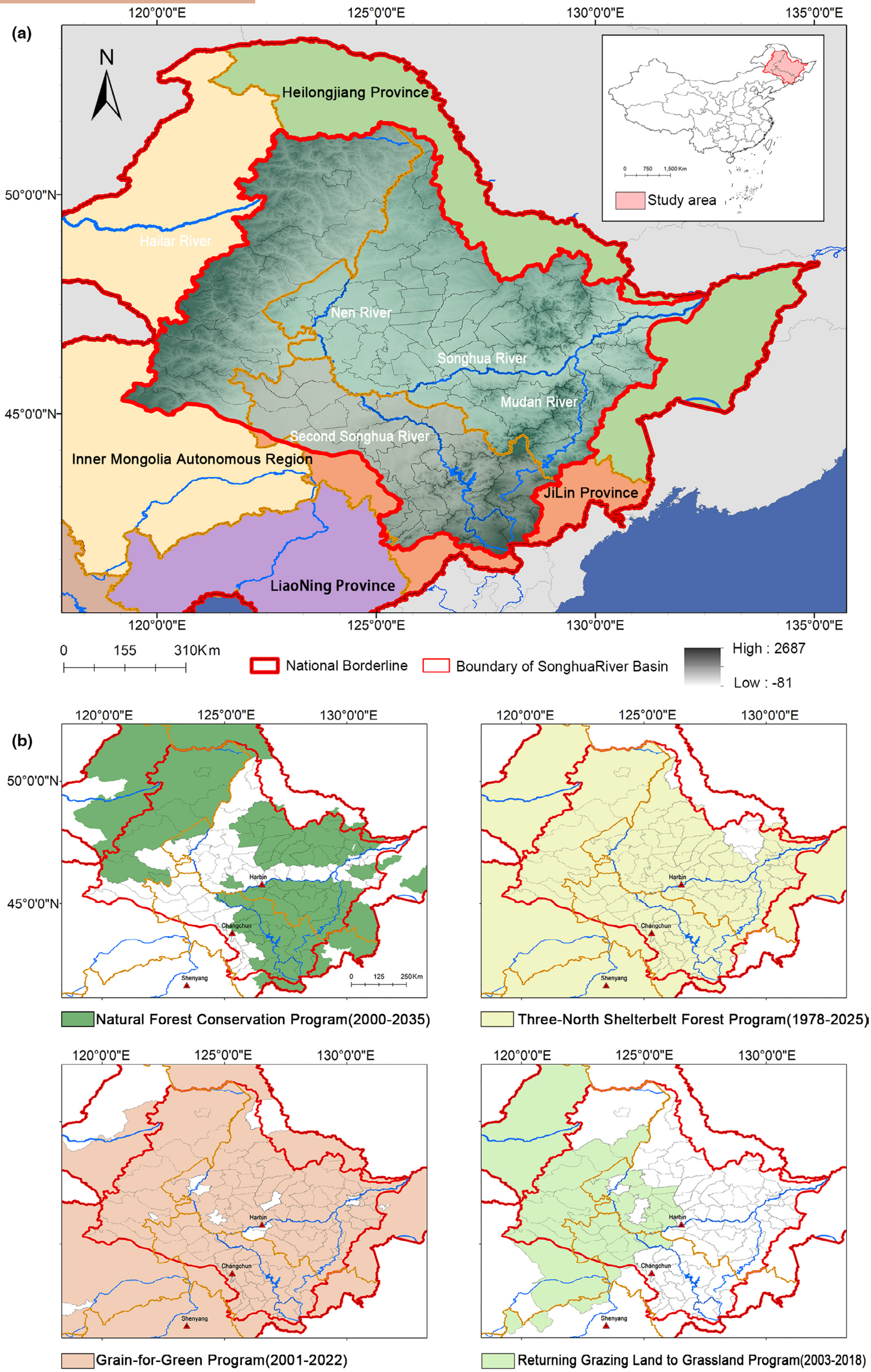

FIGURE 1 Maps of (a) the Songhua River Basin and (b) the spatial extent of major ecological restoration programs in northeast China (Shao et al., 2022).

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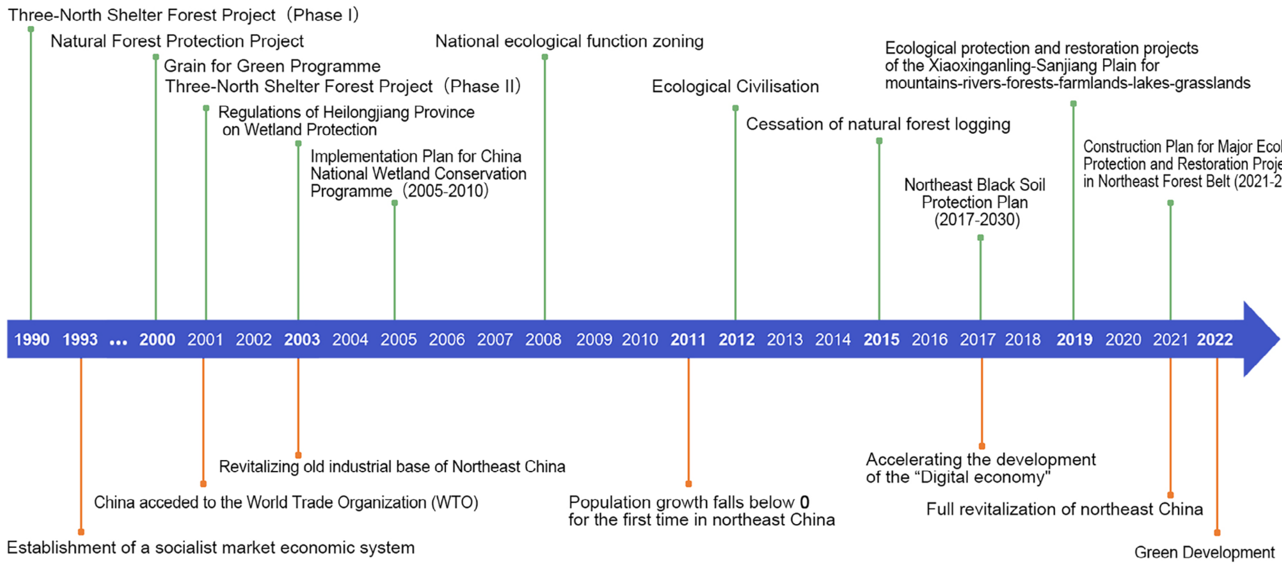

FIGURE 2 Relevant ecological programs (green) and socio-economic policies (orange) affecting the region's social-ecological systems between 1990 and 2022.

the indicator values by calculating them per unit area or per capita, respectively, ensuring comparability across counties. Most socio-economic and demographic data integrated in this study were obtained from the China Statistical yearbook, the national population census of China and the National Economic and Social Development Bulletin. Land-use data were generated from the China land cover dataset (CLCD) (Yang & Huang, 2021). For further descriptions of indicator sources and explanations, see Table S1.

2.2 | Detection, mapping and comparison of typical SES and social-ecological changes

We used hierarchical cluster analysis to classify and map typical SES in 2000 and 2020, grouping similar counties. We applied the Manhattan distance and Ward's methods to minimize the total variance within clusters, using the R packages tidyverse, ggdendro and ggplot2. This approach has been widely employed in previous studies to cluster different regions or countries based on their similarity in multidimensional characteristics (Pacheco-Romero et al., 2021; Wu et al., 2023). To determine the best number of clusters, we used the R package NbClust (R Core Team, 2023). After clustering the counties, we used Kruskal–Wallis tests to summarize each group of counties in terms of their socio-economic and ecological characteristics and social-ecological interaction characteristics.

To characterize typical SES, we assessed the magnitude and direction of impact of each indicator for each cluster (Levers et al., 2015; Pacheco-Romero et al., 2021). We first averaged indicator values across all counties in a specific cluster, and then calculated the deviation (in standard deviations) of the cluster mean to the overall mean of the entire study area (Table 2). Positive deviances refer to above-average values and negative deviances to below-average values. Combining our detailed understanding of the study area with the results showing the impact of indicators on each cluster, we then classified, labelled, and described SES archetypes based on their unique characteristics and spatial patterns. Finally, we overlaid SES archetypes from the Years 2000 and 2020 to identify spatial SES archetype changes.

2.3 | SES indicators interactions and network analysis for different groups of counties

For each group of counties, we estimated the Spearman's rank correlation coefficient between SES indicators by conducting a network analysis (Wu et al., 2023). The estimated association coefficients that significantly ($p < 0.05$) differ from zero were retained for further analysis. In this context, positive values represent synergies, whereas negative values represent trade-offs, while the absolute values of the coefficient represent interaction strength. Spearman's rank correlation coefficients between SES indicators for each group of counties were converted to network graph objects using the R igraph package. In these networks, the nodes represent SES indicators, while links between nodes represent positive or negative associations between two indicators and the strength of each link indicates the associated Spearman correlation coefficient.

To analyse the characteristic and structural importance of SES indicators in the interaction networks, we first used the network density to measure the closeness of elemental linkages between different SES archetypes in 2000 and 2020. Network density was defined as the ratio between the actual number of edges and the maximum possible number of edges in the network, with a high-density value representing a close network with cohesive nodes. On the other hand, a low-density value represents a less connected network (Sayles & Baggio, 2017). We then calculated the eigenvector centrality for each node. Eigenvector centrality is a measure of

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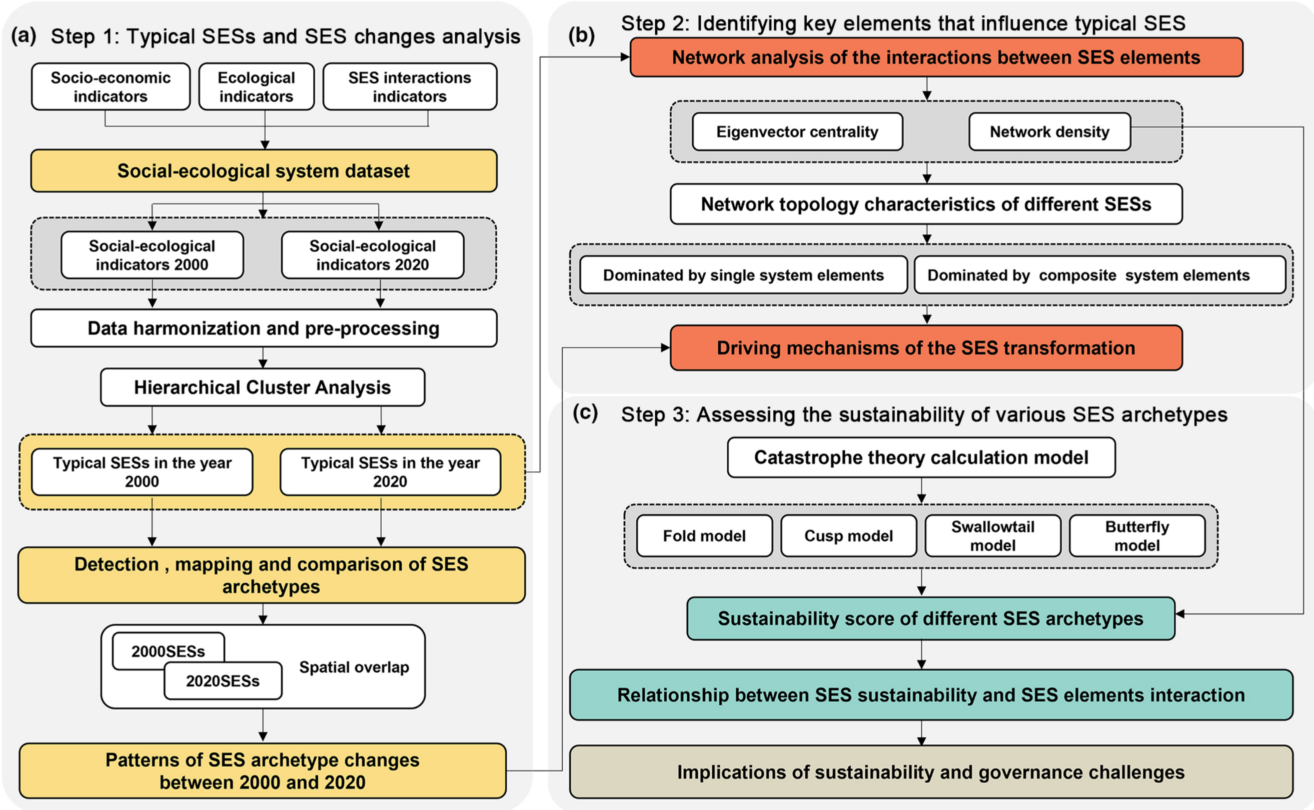

FIGURE 3 Flow chart illustrating our analytical steps.

the influence of a node in a connected network. A node with high eigenvector centrality has significant indirect effects on other nodes and not only on those with which it connects directly (Dawes, 2022). Thus, higher scoring SES elements indicate a higher influence on the respective SES archetype. These two factors are used to compare SES indicator networks in 2000 and 2020 and to investigate how changes in social-ecological factors may underpin SES transformations.

2.4 | Quantifying SES sustainability using catastrophe theory models

Catastrophe theory incorporates four models with different equilibrium surfaces (Zhang et al., 2021) named Fold, Cusp, Swallowtail and Butterfly (Table 3). The dimension of control variables in a subsystem dictates the calculation model. As catastrophe theory follows a hierarchical process, the sustainability index is calculated from indicator to sub-system (Figure S1). Since the units and dimensions of selected variables differ, and these variables include both positive and negative indicators that affect sustainability, we normalized these variables for comparison (Table S4). Positive indicator values were normalized using formula (1), while negative indicator values were processed by formula (2). All variables were normalized to range between 0 and 1, with a larger normalized value indicating a better situation in a given dimension.

$$X'_{ij} = \frac{X_{ij} - \min\{X_i\}}{\max\{X_i\} - \min\{X_i\}}, \tag{1}$$

$$X'_{ij} = \frac{\max\{X_i\} - X_{ij}}{\max\{X_i\} - \min\{X_i\}}. \tag{2}$$

In these formulas, X_{ij} represents the score of variables i in year j, and $\min\{X_i\}$ and $\max\{X_i\}$ are the minimum and maximum values of variables i, respectively.

3 | RESULTS

3.1 | Spatiotemporal differentiation of SES archetypes and associated transition hotspots

Hierarchical clustering identified three SES archetypes in 2000 (Figure 4a; Table S2a): an 'Urban archetype' (SES 01; 5.58% coverage), characterized by a high population density (average 400 people/km^2) and high carbon emissions (average 1.7 kt/km^2); an 'Agricultural archetype' (SES 02; 54.42% coverage), spanning the Songnen Plain with extensive cropland cover (average 71.1%) and grain production (average 46.46×10^4 t); and a 'Natural archetype' (SES 03; 40.00% coverage), concentrated in the mountainous regions (e.g. Greater and Lesser Khingan Mountains), with high

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TABLE 1 Indicators used for representing SES.

Variable	Indicator	Unit
Social system		
Population dynamics	(1) Population density	People/km^2
	(2) Population movement	%
	(3) Proportion of ageing population	%
	(4) Proportion of minorities	%
Economic development	(5) GDP per unit area	10^4 yuan/km^2
	(6) GDP per capita	10^4 yuan/person
	(7) Disposable income per capita	10^4 yuan/person
	(8) Index of advanced industrial structure	—
Well-being	(9) Density of healthcare facilities	Number of hospital beds/10^4 person
	(10) General public budget expenditure per capita	yuan/person
	(11) Proportion of population employment	%
Ecological system		
Organic carbon dynamics	(12) Net primary productivity (NPP)	kgC/m^2/year
Climate	(13) Mean annual precipitation	mm/year
	(14) Mean annual temperature	°C
SES interactions		
Ecosystem service supply	(15) Grain production	10^4 ton
Ecosystem service demand	(16) Proportion of cropland area	%
Physical and experiential interactions	(17) Natural land coverage	%
Human actions on the environment	(18) Carbon emission	ton/km^2
	(19) Night-time light	Index
	(20) Artificial surface coverage	%

'natural' land coverage (average 82.5%) and low anthropogenic pressure (Figure 4b; Table S3a,b).

By 2020, the area's SES were more strongly differentiated into five distinct archetypes (Figure 5a; Table S2b). An 'Urban archetype' (SES 01) with an increased cover of 7.09%, clustering around the Harbin–Changchun urban agglomerations. These areas exhibited a high night-time light index (average 3.09) and artificial surface coverage (average 24.93%), with a stagnated population density (average population density: 406 people/km^2) (Figure 5b; Table S3c,d). An 'Enhanced natural archetype' (SES 05; 19.45% coverage), emerged as a distinct archetype encountered at legally protected mountainous zones in the Great and Lesser Khingan Mountains and the Changbai Mountain Range. These regions showed the highest NPP (average 5.4 kgC/m^2/year) and natural land coverage (average 89.96%). Their extend was linked to conservation policies such as the Natural Forest Conservation Program (NFCP) and a cessation of natural forest logging. Compared to 2000, the agriculture-dominated SES archetypes were significantly reduced and more concentrated in the Songnen Plain hinterland. They were differentiated into an 'Intensive cropping archetype' (SES 02; 28.22% coverage), with the highest cropland cover (average 82.34% coverage) and grain production (average 137.4×10^4 T), and a high population density (average 95 people/km^2) and employment rate (average 54.64%).

In contrast, a 'Green development archetype' (SES 03; 37.83% coverage) was differentiated as a transition zone between the Greater and Lesser Khingan Mountains and the agricultural plains. It presents a semi-ring-shaped agricultural-natural habitat mosaic landscape. This area has transitioned from being more strongly agriculture-dominated in 2000 to increased nature-dominated characteristics. Areas within this archetype are associated with a high NPP (average 4.9 kgC/m^2/year) and a great extent of natural land coverage (average 53.98%), linked especially to a rebalancing of agricultural and natural land use under the Grain for Green Program (GFGP). This archetype also harbours an above-average proportion of the older population (16.74%) and a low public budget expenditure per capita (average 13k yuan/capita).

Some counties in the Inner Mongolia Autonomous Region, located to the west of the Songnen Plain, shifting into an entirely new class of their own. Parts of this land falls under the key areas for the implementation of the Returning Grazing Land to Grassland Program (RGLGP). Based on their characteristics (Figure 4b), we named this new archetype an 'Ethno-regional fragmented synergy archetype' (SES 04; 7.41% coverage). The associated counties harboured the highest proportion of ethnic minorities (average 58.95%),

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TABLE 2 Descriptive statistics of the social-ecological indicators for the study area.

Indicator	Unit	2000		2020	
		Mean	SD	Mean	SD
(1) Population density	People/km^2	120	137	107	199
(2) Population movement	%	−2.65	7.77	−18.87	16.75
(3) Proportion of ageing population	%	5.44	1.09	15.97	2.32
(4) Proportion of minorities	%	11.88	17.11	11.06	17.27
(5) GDP per unit area	10^4 yuan/km^2	110.93	261.32	483.12	1293.29
(6) GDP per capita	10^4 yuan/person	0.85	1.09	4.03	1.74
(7) Disposable income per capita	10^4 yuan/person	0.42	0.18	2.90	0.58
(8) Index of advanced industrial structure	—	1.25	0.55	3.45	2.32
(9) Density of healthcare facilities	Number of hospital beds/10^4 person	28	18	62	22.33
(10) General public budget expenditure per capita	yuan/person	473.94	285.30	15,391	7151.69
(11) Proportion of population employment	%	65.70	9.67	51.02	8.69
(12) Net primary productivity (NPP)	kgC/m^2/year	3446.03	1350.39	4338.11	1048.48
(13) Mean annual precipitation	mm/year	482.04	137.41	762.93	124.04
(14) Mean annual temperature	°C	3.30	1.84	4.74	1.62
(15) Grain production	10^4 ton	34.01	32.46	88.27	67.72
(16) Proportion of cropland area	%	46.21	32.85	49.29	29.51
(17) Natural land coverage	%	50.15	30.85	45.19	32.21
(18) Carbon emission	ton/km^2	306.39	696.48	1218.23	2801.10
(19) Night-time light	Index	0.20	0.75	0.44	1.43
(20) Artificial surface coverage	%	3.54	5.51	6.10	10.91

TABLE 3 Formulas for the four models of Catastrophe theory. The catastrophe function $f(x)$ represents the potential function of the state variable x.

Model	Control variables	Potential function	Bifurcation point sets	Normalization formula
Fold	1	$f(x) = x^3 + ax$	$a = -3x^2$	$x_a = a^{1/2}$
Cusp	2	$f(x) = x^4 + ax^2 + bx$	$a = -6x^2$ $b = 8x^3$	$x_a = a^{1/2}$ $x_b = b^{1/3}$
Swallowtail	3	$f(x) = x^5 + ax^3 + bx^2 + cx$	$a = -6x^2$ $b = 8x^3$ $c = -3x^4$	$x_a = a^{1/2}$ $x_b = b^{1/3}$ $x_c = c^{1/4}$
Butterfly	4	$f(x) = x^6 + ax^4 + bx^3 + cx^2 + dx$	$a = -10x^2$ $b = 20x^3$ $c = -15x^5$ $d = 4x^5$	$x_a = a^{1/2}$ $x_b = b^{1/3}$ $x_c = c^{1/4}$ $x_d = d^{1/5}$

Note: The coefficients *a*, *b*, *c*, and *d* of the state variable *x* serve as that variable's control variables.

and a high level of per capita GDP (average 6.05×10^4 yuan/capita) and per capita disposable income (average 3.40×10^4 yuan/capita), a high cover of natural habitats (average 68.33%) synergized with a high food production (average 111.42×10^4 t).

By analysing the spatial overlap between the SES archetypes in 2000 and 2020, fundamental changes in SES archetypes are strongly linked to the junction of mountains and plains (Figure 6). Clearly, the parameters characterizing each archetype changed over time, which means that none of the archetypes are, strictly speaking, identical. However, both urbanization (SES01) and agricultural (SES02) archetypes in 2020 still share key characteristics within their indicators with the respective 2000 archetypes, while the three newly formed archetypes in 2020 exhibit distinctly different sets of indicator characteristics to the sets used to classify any of the types in 2000, hence arguably forming entirely new SES archetypes reflecting, to some extent, the substantial temporal changes experienced by the system. Under the assumption that SES 01 and SES 02 represent identical archetypes in 2000 and 2020, a total of 80 counties

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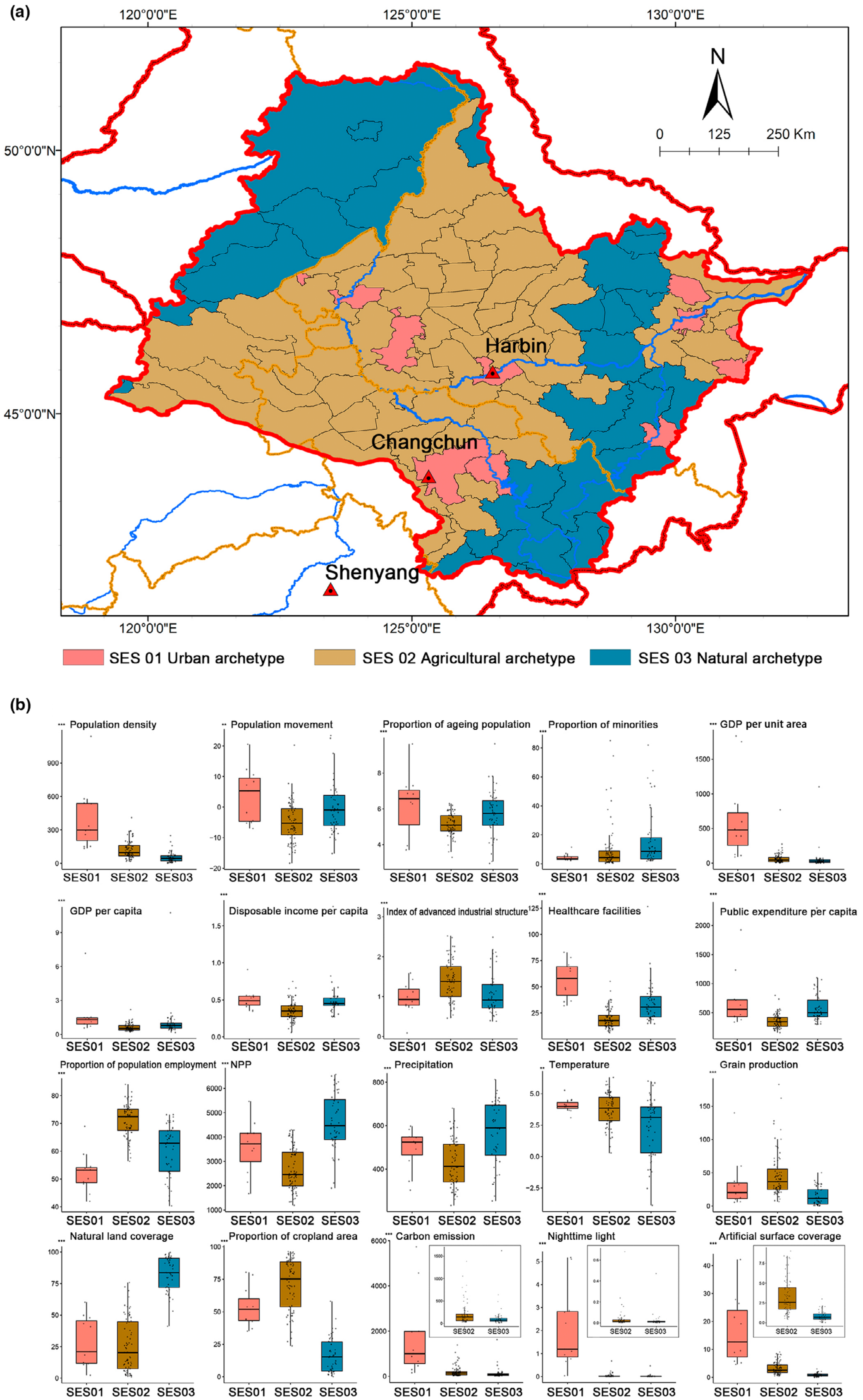

FIGURE 4 Spatial distribution of the three distinct SES archetypes, differentiated by county, in the Year 2000 (a); Comparisons of individual indicators among the three SES archetypes. Boxplots with different letters at the top differ significantly among the groups: ** $p < 0.01$; *** $p < 0.001$ (b).

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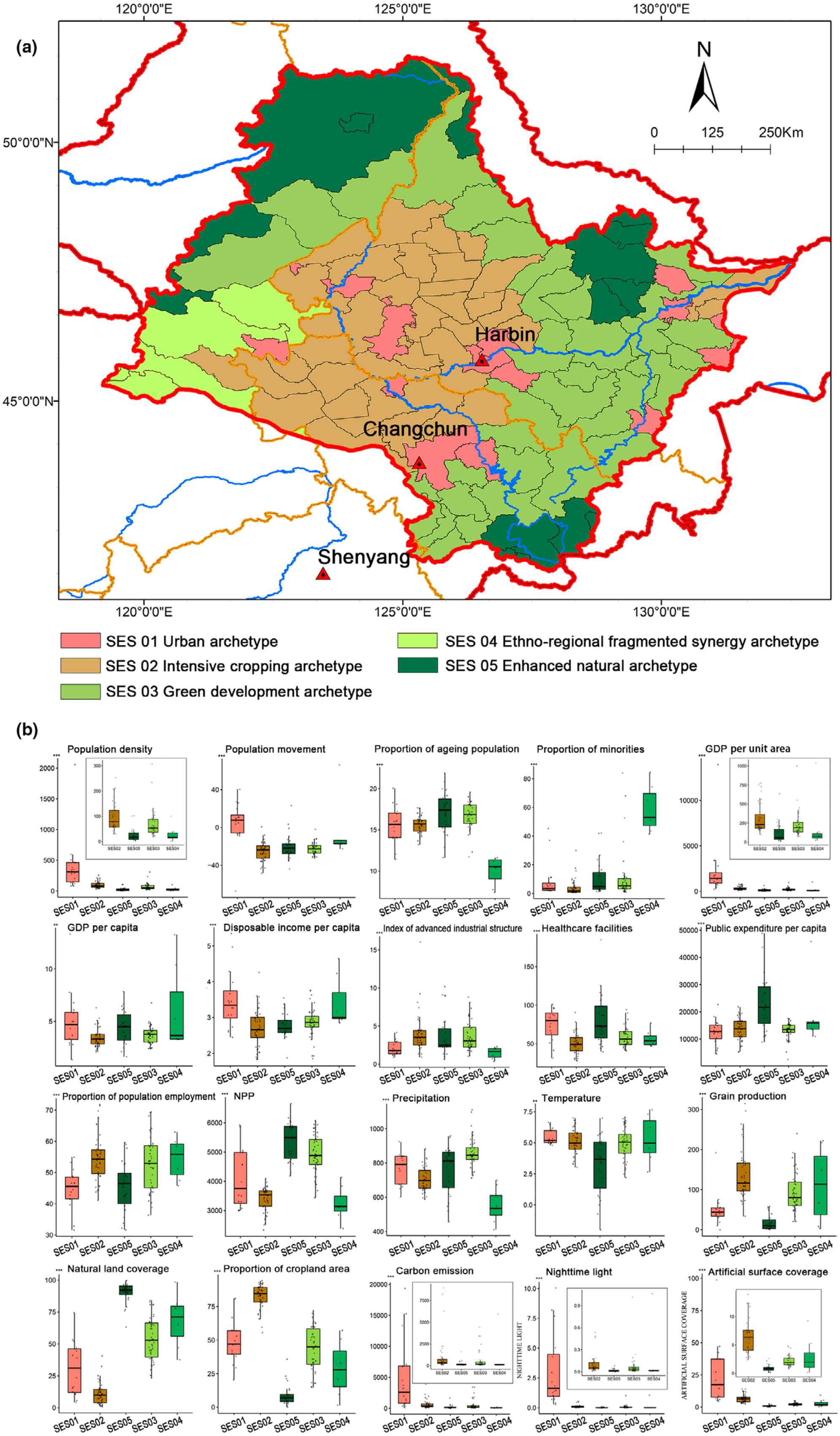

FIGURE 5 Spatial distribution of the five distinct SES archetypes, differentiated by county, in the Year 2020 (a); Comparisons of individual indicators among the five SES archetypes. Boxplots with different letters at the top differ significantly among the groups: $^{**}p<0.01$; $^{***}p<0.001$ (b).

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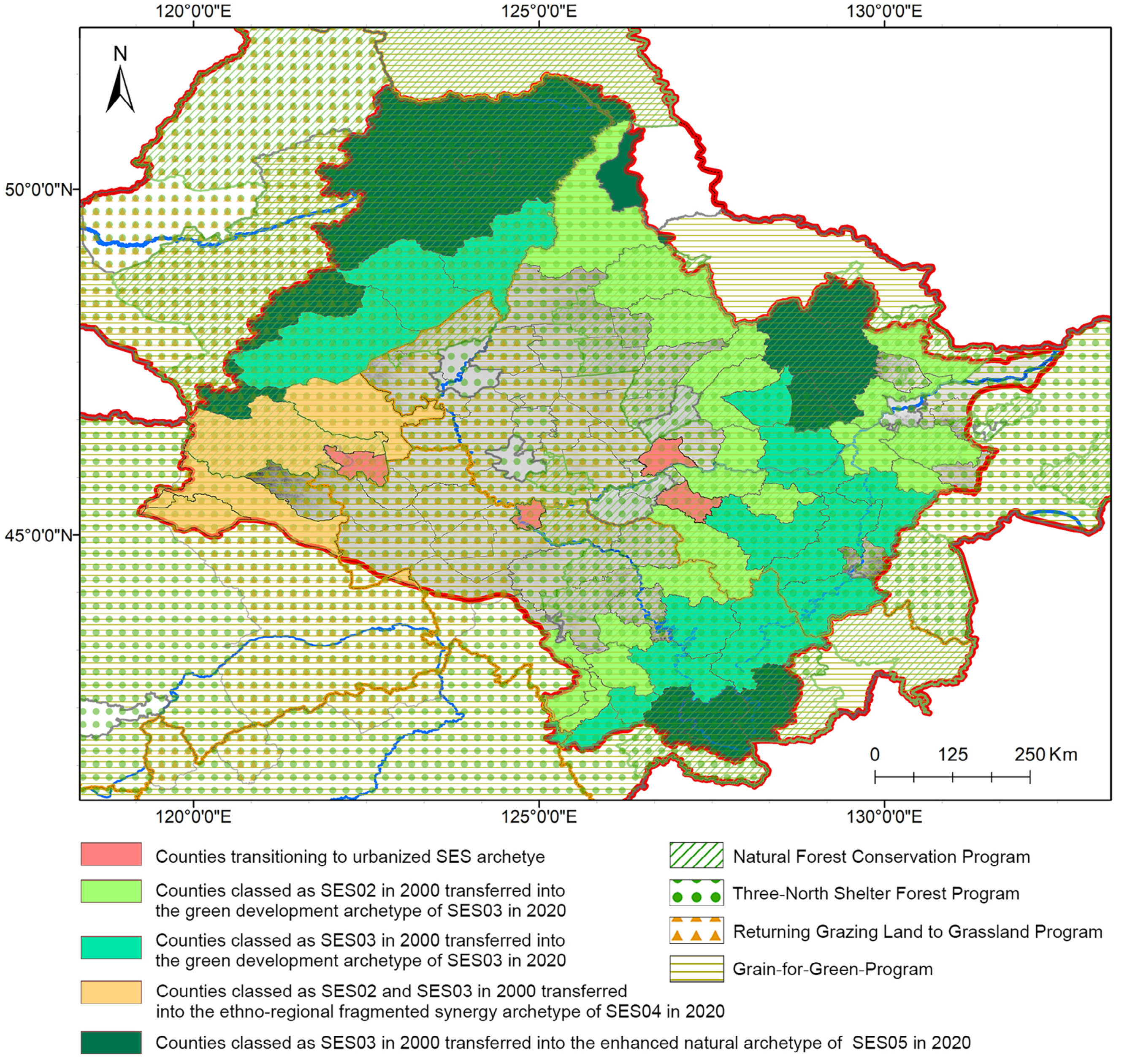

FIGURE 6 Typical changes in SES archetypes and their spatial distribution between 2000 and 2020.

experienced a distinct shift in their archetypes. These dominated in SES 02 (the agriculture archetypes), where 32 counties changed their classification (42.67% of the total number of SES 02 in 2000), with 23 counties shifting to SES 03 (green development archetype), 5 to SES 04 (ethno-regional fragmented synergy archetype) and 4 counties shifting to SES 01 (urban archetype). Within the original 'Natural Archetype' SES 03, 19 counties (40% of the total number of SES 03 in 2000) transferred into the green development archetype, while a further 26 counties fell into the enhanced natural archetype (SES 05) that most closely resembled the original SES 03. Of the remaining three counties, two shifted to SES 04 (ethno-regional fragmented synergy archetype) and one to SES 01 (urban archetype). The overall spatiotemporal differentiation highlights transition hotspots at the aforementioned ecological gradients (mountain–plain interfaces), as well as associated policy frontiers, where competing land-use pressures and demographic shifts have reconfigured SES trajectories.

3.2 | Dominance of socio-economic indicators in SES network interaction pathways

Network patterns from both years show that socio-economic factors act as central hubs for most archetypes (Tables 4 and 5; Figure S2a,b). In 2000, SES 01 (urban archetype) exhibited the lowest network density (0.24), indicating a weak integration among elements and a dominance of socio-economic factors, with GDP per

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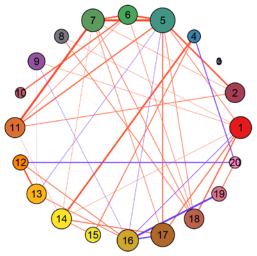
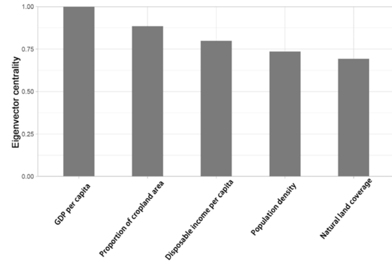
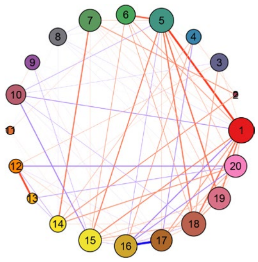
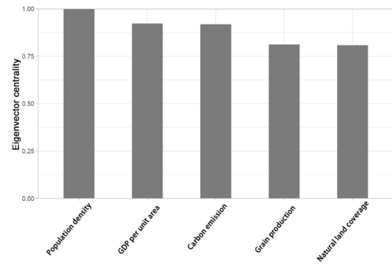
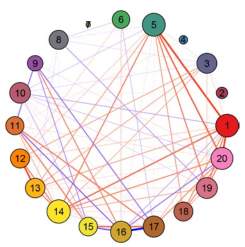
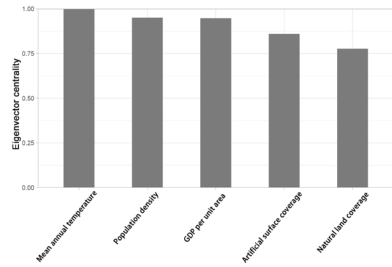
TABLE 4 SES indicators interaction networks for the three SES archetypes in 2000.

SES archetype	Network properties	Eigenvector centrality ranking (top 5)
	SES 01 Edges: 46 Network density: 0.24	
	SES 02 Edges: 86 Network density: 0.45	
	SES 03 Edges: 84 Network density: 0.44	

Note: The lines are associations that significantly ($p < 0.05$) differ from zero, of which the width represents the association strength (Figure S2a). Red lines indicate positive associations; blue lines indicate negative associations. Node sizes correspond to the eigenvector centrality (see Table 1 for information on numberings).

unit area (eigenvector centrality = 1), cropland coverage (0.88) and population density (0.74) acting as central nodes (Table 4), emphasizing the importance of land-intensive economic activities in urbanization, coupled with a continued influence of agricultural land use in the urban landscapes. The negative correlations (Figure S2a) between GDP per unit area and natural land coverage as well as NPP highlight the trade-offs between urban expansion and ecological preservation.

In the agricultural archetype SES 02, population density (eigenvector centrality = 1), carbon emissions (0.92) and GDP per unit area (0.92) had a high eigenvector centrality, emphasizing the dominant role of demographic and economic factors in shaping this archetype. Population density and GDP per unit area form a strong feedback loop with grain production, underlining the reliance on labour- and land-intensive agricultural practices. The high centrality of carbon emissions further highlights the environmental impact of the underlying agricultural expansion. Additionally, negative correlations between cropland area and ecological factors such as natural land coverage indicate trade-offs between agricultural growth and ecological sustainability within this archetype.

Counties in 2000 falling into SES 03 (natural archetype) exhibited a network density of 0.44 that was therefore almost identical to that of SES 02 (0.45), again indicating a relatively high level of integration between socio-economic and natural factors when compared to SES 01. Air temperature (eigenvector centrality = 1), population density (0.95) and GDP per unit area (0.95) had high eigenvector centrality, highlighting the central role of climate and socio-economic factors in shaping the underlying system. Air temperature and NPP further emphasize the strong interplay ($r = 0.68$) between climate conditions and ecological processes, setting SES 03 apart from the other archetypes.

In 2020, the correlation values between most of the factors in type SES 01 (Urban archetype, network density = 0.14) are fairly low, showing that this system remains less strongly integrated, and each factor may be influencing outcomes independently from other factors, while also showing a decoupling of social-ecological elements (Table 5; Figure S2b). The network characteristics of SES 02 (intensive agriculture archetype, network density = 0.32) in the Songnen Plain hinterland show an economic structure shifting towards diversification. The contribution of agriculture to GDP is declining, with non-agricultural sectors (such as industry and services) and high-value-added agriculture (e.g. food processing) emerging as new drivers. This trend aligns with labour movement and technological progress, as seen in the decoupling of population density from agriculture, reflecting both, increased mechanization and

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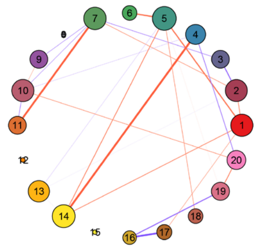
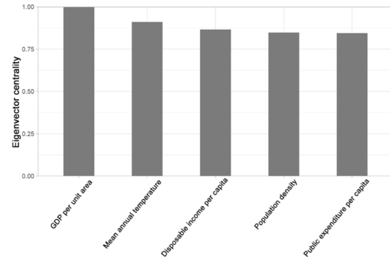
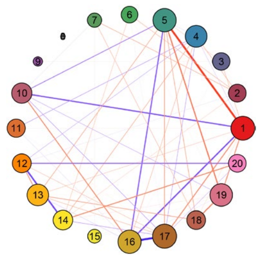
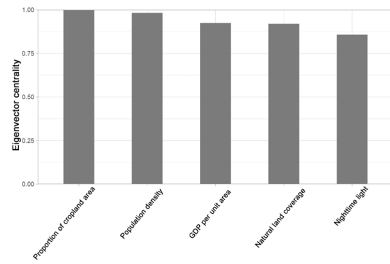
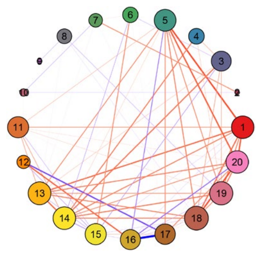
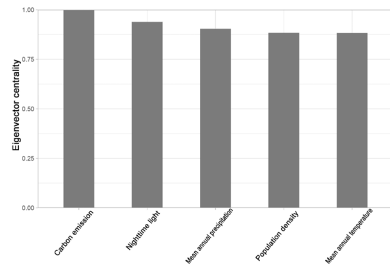
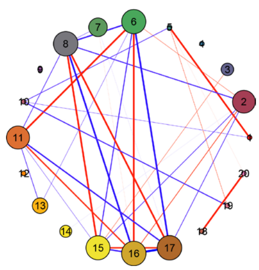
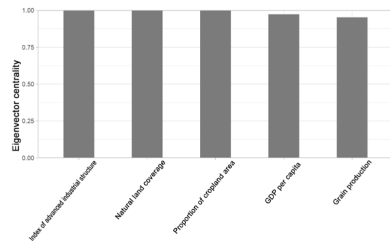
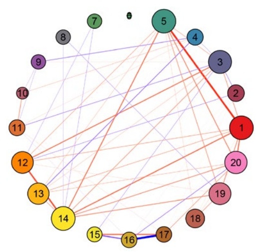
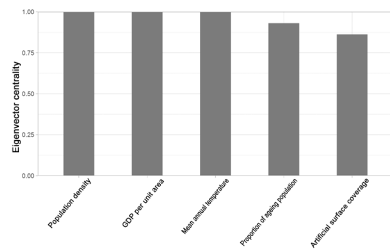
TABLE 5 SES indicators interaction networks for the five SES archetypes in 2020.

SES archetype	Network properties	Eigenvector centrality ranking (top 5)
	SES 01 Edges: 26 Network density: 0.14	
	SES 02 Edges: 61 Network density: 0.32	
	SES 03 Edges: 74 Network density: 0.39	
	SES 04 Edges: 36 Network density: 0.18	
	SES 05 Edges: 54 Network density: 0.28	

Note: The lines are associations that significantly ($p < 0.05$) differ from zero, of which the width represents the association strength (Figure S2b). Red lines indicate positive associations; blue lines indicate negative associations. Node sizes correspond to the eigenvector centrality.

rural-to-urban migration (Xin et al., 2020). This trend is consistent with the typical path of agricultural intensification across Eastern Asia (Prabhakar, 2021). Meanwhile, the increasingly significant and strong negative correlations between GDP per unit area、population density and natural land cover ($r = -0.68$ and -0.73, respectively) reflect that the expansion of GDP and the concentration of population are increasing ecological pressures in this archetype.

Areas in SES 03 (green development archetype, network density = 0.39) in the transitional zone between the Songnen Plain and the surrounding mountain ranges have undergone a distinct transformation from a dominance of agriculture to a dominance of characteristics linked to urbanization and socio-economic activity, accompanied by clear trade-offs between agricultural land and natural surface area ($r = -1$). Carbon emissions act as the most influential

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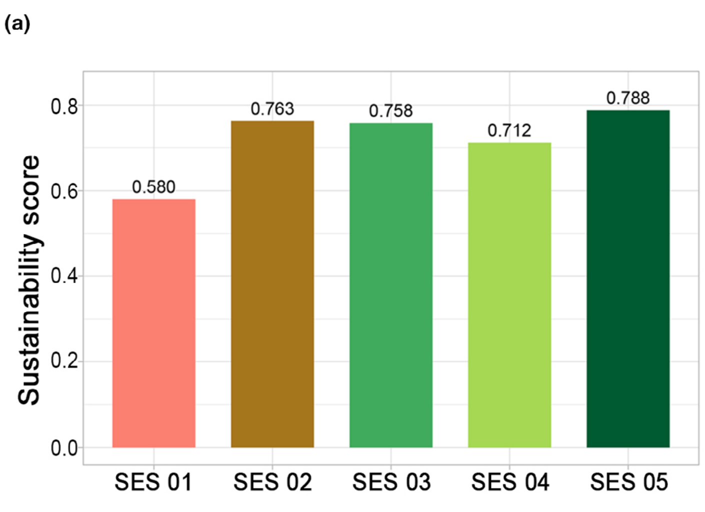
node (eigenvector centrality = 1), reflecting their systemic importance in driving environmental pressures linked to urbanization in this type. The high centrality of precipitation (0.90) emphasizes its dual role as both a crucial resource not least for agriculture and a risk linked to floods or droughts. Additionally, the positive correlation between GDP per unit area, population density and artificial surface coverage (r = 0.83 and 0.77, respectively) suggests that economic development and urban expansion represent primary transformative driving forces. Meanwhile, the strong positive relationship between NPP and natural land coverage (r = 0.75) implies a dominant role of natural land cover in carbon sequestration within this area.

The network structure of SES 04 (ethno-regional fragmented synergy archetype, network density = 0.18) reflects distinct polycentric features, dominated by the three factors advanced industrial structures, natural land coverage and cropland coverage (eigenvector centrality = 1.0 for all). The negative relationships between the GDP per capita index linked to advanced industrial structure (r = −0.93) and the GDP per capita index linked to grain production (r = −0.89), and the strong positive GDP per capita correlations with natural land coverage (r = 0.96) and employment (r = 0.96) suggest that people are likely to benefit from natural conservation (e.g., in the form of ecological compensation or ecotourism income) (Hou et al., 2021), rather than from agricultural and industrial activities. It is important to note that, despite the high eigenvector centrality of natural land coverage, it represents a trade-off with production-related indicators in the archetype. This suggests a lack of endogenous momentum for economic development and highlights a significant trade-off between conservation and economic development.

As the region with the highest natural land coverage (89.96%) and NPP (5381.92 kgC/m^2/year) among the five archetypes in 2020, SES 05 (enhanced natural archetype, network density = 0.18) is linked to a strong focus on ecological conservation. Population density (eigenvector centrality = 1), GDP per unit area (eigenvector centrality = 1), temperature (0.99) and the proportion of ageing population (0.93) are core elements in the network. The lowest annual average temperature (3.24°C) and high temperature centralization illustrate the constraints of climatic factors. A high proportion of an ageing population (17.14%) is significantly negatively correlated with employment rate (r = −0.55), pointing to the constraints of shrinking labour forces on economic vitality. While the population density is highly positively correlated with GDP (r = 0.93), the overall low population density (26 people/km^2) and GDP (115.10 × 10^4 yuan/km^2) indicate that the region mainly relies on a low-value-added, rather than a technology or capital-driven economy. Ecological service advantages include high natural land coverage (89.96%) and a strong associated carbon sequestration capacity (NPP = 5.4 kgC/m^2/year), reflecting ecological dividends have not translated into economic value.

3.3 | Sustainability of the different archetypes

Results from the catastrophe theory model indicates that all five SES archetypes differentiated in 2020 scored relatively poorly on the sustainability score (Figure 7a). The urban archetype (SES 01) received the lowest score of 0.58, primarily due to social-ecological decoupling. The enhanced natural archetype (SES 05) achieved the highest score of 0.79. The intensive agriculture archetype (SES 02) scored 0.76, suggesting a moderate level of sustainability. This was followed closely by the green development archetype (SES 03), also reaching a score of 0.76, and the ethno-regional fragmented synergy archetype (SES 04) with a score of 0.71. Overall, the sustainability score demonstrated a strong association with an archetype's network density (R^2 = 0.62, p = 0.12), indicating that SES archetypes with denser social-ecological linkages exhibited greater systemic cohesion and an enhanced capacity to withstand environmental or socio-economic shocks (Figure 7b). In this context, it is nonetheless noteworthy that SES 05, while achieving the highest sustainability score, only ranked third in terms of network density. Our social-ecological network findings align with ecological network theory, emphasizing the role of



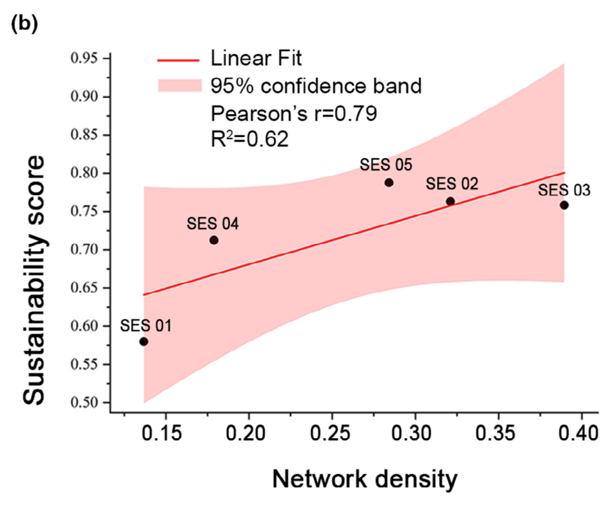


FIGURE 7 Sustainability scores for the five SES archetypes in 2020 (a); Regression analyses of network density and sustainability scores for five SES archetypes in 2020 (b).

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critical nodes, redundancies, and the importance of external governance interventions in inducing system change.

Studies of ecological networks generally highlight that stability can hinge on just a few, key nodes rather than on overall connectivity (Bodin & Crona, 2009). In accordance, the exceptionally high net primary productivity (NPP) and extensive natural land coverage function as keystone factors driving system resilience of SES05 are akin to the role of keystone species in food webs, where a single well-connected species can uphold ecosystem stability (Estes et al., 2011; O'Gorman & Emmerson, 2009). Additionally, self-organized systems are known to develop natural redundancy and feedback loops that enable stability with minimal connections (Biggs et al., 2012). In SES 05, key ecological functions, such as carbon sequestration and habitat preservation, arguably reinforce system resilience even in the absence of dense socio-economic interactions.

Our results furthermore demonstrate that effective policy interventions may compensate for low internal connectivity by providing external stabilization mechanisms. Similar findings in South African conservation areas revealed that the most resilient networks were not necessarily the densest, but those with well-balanced connectivity complemented by strong governance support (Maciejewski & Cumming, 2015). This suggests that SES 05's sustainability is reinforced by a combination of moderate network density, influential ecological nodes, and effective ecological restoration policy interventions, making it a robust system despite its comparably low network density.

4 | DISCUSSION

Our integrated archetype-network framework reveals three critical insights into the transformation of SES in the Songhua River Basin. First, the spatiotemporal differentiation of SES archetypes reveals that transition hotspots are primarily concentrated at ecotones between distinct ecosystems and in ecologically vulnerable areas. Second, the dominance of socio-economic drivers in shaping interaction pathways highlights the unequal influence of policy interventions and market forces on ecological feedbacks in the study systems. Third, despite notable achievements in ecological restoration, the consistently low to intermediate levels of sustainability across SES archetypes suggest a decoupling between ecological recovery and socio-economic equity. These findings further recognize SES as co-evolving systems governed by nonlinear trade-offs, and enable us to identify areas likely facing specific sustainability challenges, which may require context-specific, spatially targeted policy responses.

4.1 | Spatial differentiation of transformations in the study systems

The spatial settings of counties strongly shaped the local evolution of archetype patterns (Mengxue et al., 2022). In 2020, counties undergoing rapid urbanization transitions were concentrated at major river confluences and around the existing Harbin and Changchun urban agglomerations (Figure S3a). Proximity to these urban centres and to transportation networks also fostered rapid economic growth. In the resulting urban archetype (SES 01), local human and environment connections have weakened, while processes of globalization, urbanization and industrialization have intensified, leading to couplings through trade, migration, investment and other flows (Liu, 2023). This has produced a pattern of local social-ecological decoupling alongside long-distance coupling in the urban archetype.

In the border areas between the Songnen Plain and the Greater and Lesser Khingan Mountains area (Figure S3b), large-scale ecological restoration programs such as the Grain-for-Green Project (GFGP), the Returning Grazing Land to Grassland Program (RGLGP) and the Natural Forest Conservation Program (NFCP) have driven significant land-use and land-cover changes since 2000 (Tian et al., 2020), with local inhabitants increasingly shifting away from traditional agriculture and diversifying their livelihoods. As non-farm income rises and younger generations migrate to urban areas that present better job and income perspectives (Liu et al., 2020), rural areas exhibit heightened spatial heterogeneity—paralleling rural transition patterns across the globe (Sreeja et al., 2015). The resulting declining dependence on arable farming weakens community ties to the land, which has led to a transition of SES archetypes in the study ecotone areas towards the two new archetypes we recorded.

In the mountainous area (Figure S3c), themselves, afforestation programs (e.g. the aforementioned TNSFP, GFGP and NFCP) have given rise to an enhanced natural archetype (SES 05), characterized by high natural land cover and carbon sequestration rates. However, these ecological benefits have come with economic challenges, particularly where the labour force is shrinking due to ageing populations and outmigration. This leads to a 'ecology high –economy low' paradox, where ecological restoration successes do not translate into improved local livelihoods. This pattern aligns with the critical threshold identified in rural China, where ageing rates exceeding 15% trigger systemic labour shortages and cropland abandonment (Ren et al., 2023). SES 05's elderly proportion (17.14%) is approaching this critical threshold. This reflects the ageing threshold and ecological lock-in characteristics of the SES 05.

4.2 | Nonlinear interactions of social-ecological elements promoting SES transformation

Our findings indicate that SES transition trajectories are governed by nonlinear interactions among policy interventions, geographic thresholds, and socio-demographic feedbacks—resulting in a 'policy-geography-population' coupling. Policy interventions have been central drivers of change, especially in mountain and transition zones where programs have fostered the new archetypes SES 03–05. However, despite policies aimed at improving ecological quality

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and social welfare, geographic limitations, such as harsh mountain climates, and demographic trends often impede the achievement of these goals.

In the Songnen Plain hinterland, the establishment of the intensive agriculture archetype (SES 02) is offsetting grain production losses from farmland retirement in the mountains due to the GFGP. Market incentives (e.g. crop price supports) encourage the sustained transitioning towards a 'high-input, high-output' model of agriculture (Liu et al., 2022) that nonetheless does not provide for strong sustainability. Temporarily boosting local food production, this system also degrades Northeast China's black soil and triggers wetland degradation (Li, Hu, et al., 2024; Mao et al., 2019). Arguably, the agricultural intensification in one region creates not only local ecological risks but also amplifies ecological risks in neighbouring areas, for example, further down the catchment, and these interactions are often mediated by delayed responses, exemplifying the potential trade-offs and nonlinear feedbacks inherent in SES transformations that act both in temporal and spatial dimensions.

Further elaborating on the above, the ethno-regional fragmented synergy type SES 04 illustrates a trade-off between traditional cultural preservation and technological development. In areas with large ethnic minority communities, efforts to maintain traditional lifestyles can limit industrial diversification. Policy-driven ecological restoration may unintentionally exacerbate this by prioritizing conservation over investments in economic development (West et al., 2006). This dynamic creates a feedback loop in SES 04: cultural preservation efforts constrain modernization, and limited economic opportunities reinforce reliance on traditional practices, posing challenges for long-term economic sustainability and development.

4.3 | Place-based measures to improve the sustainability of SES

To translate the results of this investigation into targeted action, we propose differentiated strategies tailored to each SES archetype:

1. SES 01 (urban archetype) would benefit from innovation-driven recoupling. Urban areas currently show limited additional development potential (Tian et al., 2020) and socio-ecological decoupling. Strategies that integrate green technology, spatial restructuring and institutional innovation are critical to reconnect social and ecological systems. For example, expanding the winter 'ice-and-snow' economy can turn the region's cold climate resources into engines of growth (Yang, Wang, et al., 2023). In future, these areas could also draw extensively on telecoupling forces to activate city endogenous power.
2. For SES 02, the intensive agriculture archetype, shifting to more sustainable circular agricultural systems preserving favourable growing conditions seems highly warranted. Here, agriculture will remain an important part of the regional economy. To maintain national food security while promoting regional economic development, the central government could strengthen policy support for regional development of such circular agriculture systems (Islam & Zheng, 2024) aimed at restoring soil fertility, reducing environmental pollution and increasing agricultural resilience in the region.
3. In relation to the green development archetype SES 03, holistic integrated planning appears as the best way forward. Ensuring long-term sustainability in green-development regions requires comprehensive land-use planning that incorporates climate adaptation and circular economy principles. For example, watershed management programs could restore wetlands, improve water quality and enhance biodiversity. Additionally, shifting from passive protection to active value-added strategies (as seen in the EU carbon trading system) could monetize the basin's carbon sequestration capacity, turning natural capital into tradable assets for sustainable development (Liu & Sun, 2021; Teixidó et al., 2019).
4. For SES 04, the ethno-regional fragmented synergy archetype, cultural-ecological collaborative governance might generate pathways to a more sustainable future. In ethnically diverse regions, governance should integrate cultural preservation with associated sustainable ecological management (Molnar & Babai, 2021), building on local ecological knowledge. Policies could establish local governance structures that give ethnic minority communities a leading role in determining land management, ensuring that both ecological sustainability and cultural preservation are prioritized and harmonized.
5. For SES 05, the enhanced natural archetype of the mountainous regions, the appreciation of the natural capital seems key. In areas dominated by natural ecosystems, policies should recognize and capture the economic value of associated ecosystem services such as carbon sequestration, water purification and biodiversity conservation (Kaiser et al., 2023). By recognizing these services as valuable assets (through payments for ecosystem services, carbon markets, etc.), such policies could promote ecological sustainability while providing financial benefits to local communities. This aligns environmental conservation with regional development goals, helping to resolve the ecology high–economy low imbalances.

4.4 | Limitations and perspectives

Exploring the sustainability of large watersheds is clearly an ambitious task, and our study is chiefly based on a macro-data-driven top-down analysis of SES type identification, classification and temporal changes and transitions. It is hence important to point out that our analysis emphasizes broadscale patterns and trends that may not always hold at finer, more local scales. Furthermore, although the SES framework has been widely used, challenges such as inconsistencies in variable definitions and measurement indicators, and in data transformation, remain pertinent. This may curtail the ability to conduct meaningful comparative studies across cases way (Partelow, 2018).

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Nonetheless, our results show that using network analysis was effective in revealing intricate interactions of drivers affecting SES transformations and their sustainability performance. To further improve results, it is important to appreciation that our study was limited by two static network analyses carried out a specific time points, making it difficult to capture the overall dynamic evolution of underlying interactions. A more continuous, for example annual data analysis could identify changes in key elements and their thresholds during the transformation of the SES more accurately. Additionally, we recognize that the Year 2020 coincided with the outbreak of COVID-19, which may have introduced anomalies in specific social or economic indicators linked for example to a reduced mobility and temporary business closures. From a multi-decadal perspective, such pandemic effects likely constitute a short-term disturbance against broader trends shaped by long-standing policies and social-ecological changes. Nonetheless, we caution that future work incorporating continuous time-series data would help isolate the pandemic's unique impacts and more fully capture any abrupt shifts in human–nature interactions that arose in 2020. It should also be emphasized that, a more integrated bottom-up analysis of human–nature interactions may significantly enhance the effectiveness of local studies. In future, a 'top-down/bottom-up' hybrid model could be constructed combining participatory mapping (PPGIS) and oral histories (Dou et al., 2020; Pacheco-Romero et al., 2021; Quintas-Soriano et al., 2021).

A further limitation of our study when exploring the relationship between network density and sustainability scores of the SES archetypes is the small sample size resulting in only five archetypes, which may inflate effect estimates. Although a substantial proportion of the variance in sustainability was linked to network density, the results should still be interpreted with caution. Future research incorporating additional archetypes based on extended datasets could reduce this uncertainty and provide a more robust basis for generalizing the findings regarding the relationship between network density and sustainability.

5 | CONCLUSIONS

First, by identifying distinct SES archetypes in 2000 and 2020, and by analysing associated spatial changes, we successfully demonstrate that an interplay of policy, geography, population and economic dynamics shapes sustainability challenges in the study region. Macro-level social-ecological policies, filtered through geographical gradients and interacting with micro-level demographic trends, drive these changes. Second, the transition hotspots at mountain–plain interfaces, where 42.7% of counties initially classed as agricultural changed archetype, and in mountain areas where 39.6% of natural counties changed, show how telecoupled forces, land-use trade-offs, and local demographic thresholds jointly produce nonlinear system shifts. Third, although we observed a moderate positive relationship between network density and sustainability scores ($R^2 = 0.62$), overall network density alone does not fully determine sustainability. Identifying and reinforcing critical system elements and supportive policies emerge as a more robust pathway to strengthening SES sustainability.

These findings call for a shift from one-size-fits-all policies to more spatially differentiated governance. Our archetype-specific recommendations illustrate that sustainability transitions require context-specific solutions rather than uniform interventions. By using our framework to both diagnose SES archetypes and tailor solutions to each configuration, we offer a practical tool that can be applied to other regions—particularly to reconcile ambitious ecological restoration goals with on-the-ground demographic and economic realities.

Future research could focus on two key areas: (1) identifying early warning indicators for different archetypes through longitudinal time-series analysis, and (2) cross-basin comparisons to better understand the dynamics of archetypes in different contexts. For policymakers, adopting this archetypal identification method can help China's ecological civilization construction move from isolated projects to a transformation that is more spatially adaptable and resilient.

AUTHOR CONTRIBUTIONS

Na Sa and Weiguo Sang conceived the ideas and designed methodology; Na Sa, Jinyu Zhao and Xuyang Kou collected the data; Na Sa analysed the data; Na Sa led the writing of the manuscript; Jan Christoph Axmacher, Shuanning Zheng and Zhaohua Lu reviewed and edited the manuscript; Weiguo Sang acquired the funding and supervised the research; All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

This study was conducted using social-ecological data, as detailed in Table S1. The original data are publicly available from Zenodo at https://doi.org/10.5281/zenodo.15555273.

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REFERENCES

Barnes, M. L., Bodin, Ö., Guerrero, A. M., McAllister, R. R. J., Alexander, S. M., & Robins, G. (2017). The social structural foundations of adaptation and transformation in social–ecological systems. *Ecology and Society*, *22*(4), 16. https://doi.org/10.5751/es-09769-220416

Bascompte, J. (2009). Disentangling the web of life. *Science*, *325*(5939), 416–419. https://doi.org/10.1126/science.1170749

Basurto, X., Gelcich, S., & Ostrom, E. (2013). The social–ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change*, *23*(6), 1366–1380. https://doi.org/10.1016/j.gloenvcha.2013.08.001

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Bodin, Ö., & Crona, B. I. (2009). The role of social networks in natural resource governance: What relational patterns make a difference? *Global Environmental Change*, *19*(3), 366–374. https://doi.org/10.1016/j.gloenvcha.2009.05.002

Brondízio, E. S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M. F., Galvin, K., Reyes-García, V., McElwee, P., Molnár, Z., Samakov, A., & Shrestha, U. B. (2021). Locally based, regionally manifested, and globally relevant: Indigenous and local knowledge, values, and practices for nature. *Annual Review of Environment and Resources*, *46*(1), 481–509. https://doi.org/10.1146/annurev-environ-012220-012127

Cai, Y., Zhang, F., Duan, P., Yung Jim, C., Weng Chan, N., Shi, J., Liu, C., Wang, J., Bahtebay, J., & Ma, X. (2022). Vegetation cover changes in China induced by ecological restoration-protection projects and land-use changes from 2000 to 2020. *Catena*, *217*, 106530. https://doi.org/10.1016/j.catena.2022.106530

Cumming, G. S., & Allen, C. R. (2017). Protected areas as social-ecological systems: Perspectives from resilience and social-ecological systems theory. *Ecological Applications*, *27*(6), 1709–1717. https://doi.org/10.1002/eap.1584

Dawes, J. H. P. (2022). SDG interlinkage networks: Analysis, robustness, sensitivities, and hierarchies. *World Development*, *149*, 105693. https://doi.org/10.1016/j.worlddev.2021.105693

Dou, Y., Yu, X., Bakker, M., De Groot, R., Carsjens, G. J., Duan, H., & Huang, C. (2020). Analysis of the relationship between cross-cultural perceptions of landscapes and cultural ecosystem services in Genheyuan region, Northeast China. *Ecosystem Services*, *43*, 101112. https://doi.org/10.1016/j.ecoser.2020.101112

Estes, J. A., Terborgh, J., Brashares, J. S., Power, M. E., Berger, J., Bond, W. J., Carpenter, S. R., Essington, T. E., Holt, R. D., Jackson, J. B. C., Marquis, R. J., Oksanen, L., Oksanen, T., Paine, R. T., Pikitch, E. K., Ripple, W. J., Sandin, S. A., Scheffer, M., Schoener, T. W., … Wardle, D. A. (2011). Trophic downgrading of planet earth. *Science*, *333*(6040), 301–306.

Fischer, A. P. (2018). Forest landscapes as social-ecological systems and implications for management. *Landscape and Urban Planning*, *177*, 138–147. https://doi.org/10.1016/j.landurbplan.2018.05.001

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. V., Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., & Tenhunen, J. (2015). Advancing sustainability through mainstreaming a social–ecological systems perspective. *Current Opinion in Environmental Sustainability*, *14*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002

Fischer, J., Riechers, M., Loos, J., Martin-Lopez, B., & Temperton, V. M. (2021). Making the UN decade on ecosystem restoration a social-ecological Endeavour. *Trends in Ecology & Evolution*, *36*(1), 20–28. https://doi.org/10.1016/j.tree.2020.08.018

Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, *21*(3), 41. https://doi.org/10.5751/es-08748-210341

Fu, B., Liu, Y., & Meadows, M. E. (2023). Ecological restoration for sustainable development in China. *National Science Review*, *10*(7), nwad033. https://doi.org/10.1093/nsr/nwad033

Guerrero, A. M., Bennett, N. J., Wilson, K. A., Carter, N., Gill, D., Mills, M., Ives, C. D., Selinske, M. J., Larrosa, C., Bekessy, S., Januchowski-Hartley, F. A., Travers, H., Wyborn, C. A., & Nuno, A. (2018). Achieving the promise of integration in social-ecological research: A review and prospectus. *Ecology and Society*, *23*(3), 38. https://doi.org/10.5751/es-10232-230338

Hossain, M. S., Basak, S. M., Amin, M. N., Anderson, C. C., Cremin, E., & Renaud, F. G. (2023). Social-ecological systems approach for adaptation to climate change. *Sustainable Development*, *32*(3), 2766–2778. https://doi.org/10.1002/sd.2801

Hou, L., Xia, F., Chen, Q., Huang, J., He, Y., Rose, N., & Rozelle, S. (2021). Grassland ecological compensation policy in China improves grassland quality and increases herders' income. *Nature Communications*, *12*(1), 4683. https://doi.org/10.1038/s41467-021-24942-8

Islam, M. Z., & Zheng, L. (2024). Why is it necessary to integrate circular economy practices for agri-food sustainability from a global perspective? *Sustainable Development*, *33*(1), 600–620. https://doi.org/10.1002/sd.3135

Kaiser, J., Haase, D., & Krueger, T. (2023). Collective payments for ecosystem services: A counterpart of commodification and privatization trends in nature conservation? *Ecology and Society*, *28*(1), art13. https://doi.org/10.5751/es-13549-280113

Kluger, L. C., Gorris, P., Kochalski, S., Mueller, M. S., Romagnoni, G., & Ban, N. (2020). Studying human–nature relationships through a network lens: A systematic review. *People and Nature*, *2*(4), 1100–1116. https://doi.org/10.1002/pan3.10136

Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M. R., Metzger, M. J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P. H., Verkerk, P. J., & Kuemmerle, T. (2015). Archetypical patterns and trajectories of land systems in Europe. *Regional Environmental Change*, *18*(3), 715–732. https://doi.org/10.1007/s10113-015-0907-x

Li, B. V., Wu, S., Hua, F., & Mi, X. (2024). The past and future of ecosystem restoration in China. *Current Biology*, *34*(9), R379–R387. https://doi.org/10.1016/j.cub.2024.03.057

Li, W., Hu, B., Yan, Z., Liu, S., Shi, P., Zhu, Y., & Li, H. (2024). The socio-ecological implications of shifting patterns of cropland use in northeast China. *Journal of Cleaner Production*, *443*, 141050. https://doi.org/10.1016/j.jclepro.2024.141050

Li, Y., Kappas, M., & Li, Y. (2018). Exploring the coastal urban resilience and transformation of coupled human-environment systems. *Journal of Cleaner Production*, *195*, 1505–1511. https://doi.org/10.1016/j.jclepro.2017.10.227

Liu, H., Hao, H., Hu, X., Du, L., Zhang, Z., & Li, Y. (2020). Livelihood diversification of farm households and its impact on cultivated land utilization in agro-pastoral ecologically-vulnerable areas in the northern China. *Chinese Geographical Science*, *30*(2), 279–293. https://doi.org/10.1007/s11769-020-1111-6

Liu, J. (2023). Leveraging the metacoupling framework for sustainability science and global sustainable development. *National Science Review*, *10*(7), nwad090. https://doi.org/10.1093/nsr/nwad090

Liu, J., Fang, Y., Wang, R., & Zou, C. (2022). Rural typology dynamics and drivers in peripheral areas: A case of Northeast China. *Land Use Policy*, *120*, 106260. https://doi.org/10.1016/j.landusepol.2022.106260

Liu, Z., & Sun, H. (2021). Assessing the impact of emissions trading scheme on low-carbon technological innovation: Evidence from

25758314, 2025, 7, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.70086 by University College London UCL Library Services, Wiley Online Library on [22/09/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

China. *Environmental Impact Assessment Review*, *89*, 106589. https://doi.org/10.1016/j.eiar.2021.106589

Lofqvist, S., Kleinschroth, F., Bey, A., de Bremond, A., DeFries, R., Dong, J., Fleischman, F., Lele, S., Martin, D. A., Messerli, P., Meyfroidt, P., Pfeifer, M., Rakotonarivo, S. O., Ramankutty, N., Ramprasad, V., Rana, P., Rhemtulla, J. M., Ryan, C. M., Vieira, I. C. G., … Garrett, R. D. (2023). How social considerations improve the equity and effectiveness of ecosystem restoration. *BioScience*, *73*(2), 134–148. https://doi.org/10.1093/biosci/biac099

Maciejewski, K., & Cumming, G. S. (2015). The relevance of socioeconomic interactions for the resilience of protected area networks. *Ecosphere*, *6*(9), 1–14. https://doi.org/10.1890/es15-00022.1

Mansourian, S., Parrotta, J., Balaji, P., Bellwood-Howard, I., Bhasme, S., Bixler, R. P., Boedhihartono, A. K., Carmenta, R., Jedd, T., de Jong, W., Lake, F. K., Latawiec, A., Lippe, M., Rai, N. D., Sayer, J., Van Dexter, K., Vira, B., Visseren-Hamakers, I., Wyborn, C., & Yang, A. (2019). Putting the pieces together: Integration for forest landscape restoration implementation. *Land Degradation & Development*, *31*(4), 419–429. https://doi.org/10.1002/ldr.3448

Mao, D., He, X., Wang, Z., Tian, Y., Xiang, H., Yu, H., Man, W., Jia, M., Ren, C., & Zheng, H. (2019). Diverse policies leading to contrasting impacts on land cover and ecosystem services in Northeast China. *Journal of Cleaner Production*, *240*, 117961. https://doi.org/10.1016/j.jclepro.2019.117961

Mengxue, C., Xiaoyan, L., Zhangxuan, Q., Xiaolin, L., & Fei, L. (2022). Social-ecological system changes in China from 1990 to 2018. *Ecological Indicators*, *139*, 108926. https://doi.org/10.1016/j.ecolind.2022.108926

Meyfroidt, P. (2015). Approaches and terminology for causal analysis in land systems science. *Journal of Land Use Science*, *11*(5), 501–522. https://doi.org/10.1080/1747423x.2015.1117530

Molnar, Z., & Babai, D. (2021). Inviting ecologists to delve deeper into traditional ecological knowledge. *Trends in Ecology & Evolution*, *36*(8), 679–690. https://doi.org/10.1016/j.tree.2021.04.006

Oberlack, C., Sietz, D., Bürgi Bonanomi, E., de Bremond, A., Dell'Angelo, J., Eisenack, K., Ellis, E. C., Epstein, G., Giger, M., Heinimann, A., Kimmich, C., Kok, M. T. J., Manuel-Navarrete, D., Messerli, P., Meyfroidt, P., Václavík, T., & Villamayor-Tomas, S. (2019). Archetype analysis in sustainability research: Meanings, motivations, and evidence-based policy making. *Ecology and Society*, *24*(2), 26. https://doi.org/10.5751/es-10747-240226

O'Gorman, E. J., & Emmerson, M. C. (2009). Perturbations to trophic interactions and the stability of complex food webs. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(32), 6.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–422. https://doi.org/10.1126/science.1172133

Pacheco-Romero, M., Kuemmerle, T., Levers, C., Alcaraz-Segura, D., & Cabello, J. (2021). Integrating inductive and deductive analysis to identify and characterize archetypical social-ecological systems and their changes. *Landscape and Urban Planning*, *215*, 104199. https://doi.org/10.1016/j.landurbplan.2021.104199

Pacheco-Romero, M., Vallejos, M., Paruelo, J. M., Alcaraz-Segura, D., Torres-García, M. T., Salinas-Bonillo, M. J., & Cabello, J. (2022). A data-driven methodological routine to identify key indicators for social-ecological system archetype mapping. *Environmental Research Letters*, *17*(4), 045019. https://doi.org/10.1088/1748-9326/ac5ded

Partelow, S. (2018). A review of the social-ecological systems framework: Applications, methods, modifications, and challenges. *Ecology and Society*, *23*(4), art36. https://doi.org/10.5751/es-10594-230436

Partelow, S., Villamayor-Tomas, S., Eisenack, K., Epstein, G., Kellner, E., Roggero, M., & Tschopp, M. (2024). A meta-analysis of SES framework case studies: Identifying dyad and triad archetypes. *People and Nature*, *6*(3), 1229–1247. https://doi.org/10.1002/pan3.10630

Plieninger, T., Flinzberger, L., Hetman, M., Horstmannshoff, I., Reinhard-Kolempas, M., Topp, E., Moreno, G., & Huntsinger, L. (2021). Dehesas as high nature value farming systems: A social-ecological synthesis of drivers, pressures, state, impacts, and responses. *Ecology and Society*, *26*(3), art23. https://doi.org/10.5751/es-12647-260323

Prabhakar, S. V. R. K. (2021). A succinct review and analysis of drivers and impacts of agricultural land transformations in Asia. *Land Use Policy*, *102*, 105238. https://doi.org/10.1016/j.landusepol.2020.105238

Quintas-Soriano, C., Brandt, J., Baxter, C. V., Bennett, E. M., Requena-Mullor, J. M., & Castro, A. J. (2021). A framework for assessing coupling and de-coupling trajectories in river social-ecological systems. *Sustainability Science*, *17*(1), 121–134. https://doi.org/10.1007/s11625-021-01048-0

R Core Team (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ren, C., Zhou, X., Wang, C., Guo, Y., Diao, Y., Shen, S., Reis, S., Li, W., Xu, J., & Gu, B. (2023). Ageing threatens sustainability of smallholder farming in China. *Nature*, *616*(7955), 96–103. https://doi.org/10.1038/s41586-023-05738-w

Reyers, B., Folke, C., Moore, M.-L., Biggs, R., & Galaz, V. (2018). Social-ecological systems insights for navigating the dynamics of the anthropocene. *Annual Review of Environment and Resources*, *43*(1), 267–289. https://doi.org/10.1146/annurev-environ-110615-085349

Sayles, J. S., & Baggio, J. A. (2017). Social-ecological network analysis of scale mismatches in estuary watershed restoration. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(10), E1776–E1785. https://doi.org/10.1073/pnas.1604405114

Sayles, J. S., Mancilla Garcia, M., Hamilton, M., Alexander, S. M., Baggio, J. A., Fischer, A. P., Ingold, K., Meredith, G. R., & Pittman, J. (2019). Social-ecological network analysis for sustainability sciences: A systematic review and innovative research agenda for the future. *Environmental Research Letters*, *14*(9), 1–18. https://doi.org/10.1088/1748-9326/ab2619

Schlüter, M., Haider, L. J., Lade, S. J., Lindkvist, E., Martin, R., Orach, K., Wijermans, N., & Folke, C. (2019). Capturing emergent phenomena in social-ecological systems: An analytical framework. *Ecology and Society*, *24*(3), art11. https://doi.org/10.5751/es-11012-240311

Shao, Q., Liu, S., Ning, J., Liu, G., Yang, F., Zhang, X., Niu, L., Huang, H., Fan, J., & Liu, J. (2022). Assessment of ecological benefits of key national ecological projects in China in 2000–2019 using remote sensing. *Acta Geographica Sinica*, *77*(9), 20. https://doi.org/10.11821/dlxb202209001

Sietz, D., Frey, U., Roggero, M., Gong, Y., Magliocca, N., Tan, R., Janssen, P., & Václavík, T. (2019). Archetype analysis in sustainability research: Methodological portfolio and analytical frontiers. *Ecology and Society*, *24*(3), 34. https://doi.org/10.5751/es-11103-240334

Song, F., Su, F., Mi, C., & Sun, D. (2021). Analysis of driving forces on wetland ecosystem services value change: A case in Northeast China. *Science of the Total Environment*, *751*, 141778. https://doi.org/10.1016/j.scitotenv.2020.141778

Sreeja, K. G., Madhusoodhanan, C. G., & Eldho, T. I. (2015). Transforming river basins: Post-livelihood transition agricultural landscapes and implications for natural resource governance. *Journal of Environmental Management*, *159*, 254–263. https://doi.org/10.1016/j.jenvman.2015.05.021

Stanworth, A., Peh, K. S. H., & Morris, R. J. (2024). Linking network ecology and ecosystem services to benefit people. *People and Nature*, *6*(3), 1048–1059. https://doi.org/10.1002/pan3.10632

Tedesco, A. M., Lopez-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Perez-Hammerle, K. V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological

25758314, 2025, 7, Downloaded from https://besjournals.onlinelibrary.wiley.com/doi/10.1002/pan3.70086 by University College London UCL Library Services, Wiley Online Library on [22/09/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

transformation. *Trends in Ecology & Evolution*, *38*(7), 643–653. https://doi.org/10.1016/j.tree.2023.02.007

Teixidó, J., Verde, S. F., & Nicolli, F. (2019). The impact of the EU emissions trading system on low-carbon technological change: The empirical evidence. *Ecological Economics*, *164*, 106347. https://doi.org/10.1016/j.ecolecon.2019.06.002

Tian, J., Wang, B., Zhang, C., Li, W., & Wang, S. (2020). Mechanism of regional land use transition in underdeveloped areas of China: A case study of northeast China. *Land Use Policy*, *94*, 104538. https://doi.org/10.1016/j.landusepol.2020.104538

Wang, L.-J., Ma, S., Zhao, Y.-G., & Zhang, J.-C. (2021). Ecological restoration projects did not increase the value of all ecosystem services in Northeast China. *Forest Ecology and Management*, *495*, 119340. https://doi.org/10.1016/j.foreco.2021.119340

West, P., Igoe, J., & Brockington, D. (2006). Parks and peoples: The social impact of protected areas. *Annual Review of Anthropology*, *35*(1), 251–277. https://doi.org/10.1146/annurev.anthro.35.081705.123308

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., & van der Leeuw, S. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio*, *40*(7), 762–780. https://doi.org/10.1007/s13280-011-0186-9

Wu, X., Fu, B., Wang, S., Song, S., Lusseau, D., Liu, Y., Xu, Z., & Liu, J. (2023). Bleak prospects and targeted actions for achieving the sustainable development goals. *Science Bulletin (Beijing)*, *68*(22), 2838–2848. https://doi.org/10.1016/j.scib.2023.09.010

Wu, X. T., Wei, Y. P., Fu, B. J., Wang, S., Zhao, Y., & Moran, E. F. (2020). Evolution and effects of the social-ecological system over a millennium in China's loess plateau. *Science Advances*, *6*(41), eabc0276. https://doi.org/10.1126/sciadv.abc0276

Xin, F., Xiao, X., Dong, J., Zhang, G., Zhang, Y., Wu, X., Li, X., Zou, Z., Ma, J., Du, G., Doughty, R. B., Zhao, B., & Li, B. (2020). Large increases of paddy rice area, gross primary production, and grain production in Northeast China during 2000-2017. *Science of the Total Environment*, *711*, 135183. https://doi.org/10.1016/j.scitotenv.2019.135183

Xu, Y., & Zang, R. (2023). Conservation of rare and endangered plant species in China. *iScience*, *26*(2), 106008. https://doi.org/10.1016/j.isci.2023.106008

Xu, Z., Liang, W., Lei, J., Wu, Y., & Wang, Z. (2025). Monitoring and assessment of desertification reversal in ecologically fragile areas: A case study of the Mu Us Sandy Land. *Journal of Environmental Management*, *373*, 123695. https://doi.org/10.1016/j.jenvman.2024.123695

Yang, J., & Huang, X. (2021). The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth System Science Data*, *13*(8), 3907–3925. https://doi.org/10.5194/essd-13-3907-2021

Yang, J., Wang, Y., Tang, F., Guo, X., Chen, H., & Ding, G. (2023). Ice-and-snow tourism in China: Trends and influencing factors. *Humanities and Social Sciences Communications*, *10*(1), 826. https://doi.org/10.1057/s41599-023-02288-4

Yang, Y., Bao, W., & de Sherbinin, A. (2023). Mapping fine-resolution nested social-ecological system archetypes to reveal archetypical human-environmental interactions. *Landscape and Urban Planning*, *239*, 104863. https://doi.org/10.1016/j.landurbplan.2023.104863

You, H., Yang, J., Xue, B., Xiao, X., Xia, J., Jin, C., & Li, X. (2021). Spatial evolution of population change in Northeast China during 1992–2018. *Science of the Total Environment*, *776*, 146023. https://doi.org/10.1016/j.scitotenv.2021.146023

Zeeman, E. C. (1976). *Catastrophe theory*. Scientific American, Inc.

Zhang, L., Huang, Q., He, C., Yue, H., & Zhao, Q. (2021). Assessing the dynamics of sustainability for social-ecological systems based on the adaptive cycle framework: A case study in the Beijing-Tianjin-Hebei urban agglomeration. *Sustainable Cities and Society*, *70*, 102899. https://doi.org/10.1016/j.scs.2021.102899

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1: Indicators used for identifying and mapping of typical social-ecological systems (extended version of Table 1).

Table S2: (a) Counties of the three SES archetypes in the year 2000. (b) Counties of the five SES archetypes in the year 2020.

Table S3: (a) Characteristics of each identified SES archetype in 2000. (b) Description and spatial coverage of SES archetype in 2000. (c) Characteristics of each identified SES archetype in 2020. (d) Description and spatial coverage of typical social-ecological systems (SES) in 2020.

Table S4: The dimension of control variables in a sub-system dictates the calculation model.

Table S5: The sustainability scores among the five SES archetypes in 2020.

Figure S1: The framework for calculating the sustainability of SES based on catastrophe theory.

Figure S2: (a) Correlation analysis of the elements of the 2000 SES archetypes. (b) Correlation analysis of the elements of the 2020 SES archetypes.

Figure S3: (a) Counties in transition to the urbanized SES 01 in 2020. (b) Counties in SES 02 in 2000 transition to the SES 03 (green) and SES 04 (orange) in 2020. (c) Counties in SES 03 in 2000 transition to the SES 03 (bright green) and SES 04 (orange) and SES 05 (dark green) in 2020.

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