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Driving Factors of Coordinated Development in Chinese Border Cities: A Case Study of Lincang City in Southwest China

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Abstract: In the context of the "Belt and Road Initiative", the sustainable development of border cities is paramount for facilitating intergovernmental exchanges. Using the system dynamics approach, we integrated border policy factors to create the Border City Coordinated Development (BCCD-SD) model, encompassing three dimensions: Economic, Social, and Resource-Environment. Furthermore, a comprehensive evaluation indicator, the City Coordinated Development Index (CCDI), was devised. Using Lincang City in Southwest China as a case study, this article examines the trends in city development under three scenarios: Inertial Development, Rapid Development, and Green Development. The research findings demonstrate that the model adeptly captures trends in the city coordinated development indicators. Among the three scenarios, the rapid development scenario stands out, yielding the most favorable economic indicators, superior public infrastructure, and the highest employed population. However, the rapid development path, which is heavily focused on economic growth, intensifies resource and environmental pressures, giving rise to sustainability challenges. In contrast, although the green development scenario trails slightly in economic performance compared to rapid development, it fosters a larger urban population and transition of the employed population into citizens while excelling in resource and environmental aspects. Overall, the CCDI attains its highest score under the green development scenario, surpassing those of rapid and inertia development, signifying superior city development coordination along the green path. This scenario effectively combines economic growth, social progress, and resource-environment protection. This study also emphasizes the pivotal role of ports in the coordinated development of border cities and underscores the necessity of expediting the transition from a "gateway" economy to a "port+" economy. One objective of this article is to encourage border cities to serve as more effective windows to the outside world, promote regional coordination, and achieve high-quality development.

Key words: system dynamics; Lincang City; coordinated development; border policy; Southwest China border

1 Introduction

The establishment of sustainable cities and communities is one of the critical objectives of the United Nations sustainable development goals (United Nations, 2015). As intermediaries for intergovernmental communication and cooperation, border regions are occupied by more than one-sixth of the global population (within a 60-km buffer zone) (Xiao et al., 2022). Therefore, the sustainable development of border cities holds immense significance. In particular, many of China's border regions face challenges such as inadequate transportation connectivity and relatively limited resources (Feng and Ding, 2005). These areas often have sparsely distributed populations and limited economic development potential, leading to a relatively slow urban de-

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velopment process (Song and Zhu, 2020). To some extent, this also affects border security (Zhang et al., 2018). As regional cooperation and integration continue to advance, border cities serve as hubs for international exchange (Tang et al., 2016) and have become vital pillars for promoting regional economic development and cooperation (Choi et al., 2020).

The Chinese government attaches great importance to the development of border cities and launched the "Vitalizing Border Areas and Enriching the People" action in 2000. Over the past two decades, significant achievements have been made in the development of border regions, but issues of imbalanced and insufficient development persist (Zhang et al., 2020). As an important ecological functional zone, approximately 80% of China's border population is located in China's southwestern border region (You et al., 2015), and this region serves as a key node in the China-Indochina Peninsula Economic Corridor (CIPEC) within the "Belt and Road Initiative" (You et al., 2022). Lincang City, located in the southwestern border and adjacent to Myanmar, also faces challenges related to its fragile ecological environments and population outflow, two issues that are common among many of China's inland border cities (Fan, 2015; Song and Zhu, 2020). During the "Thirteenth Five-Year Plan" period (2016–2020), Lincang City successfully obtained approval as a national innovation demonstration zone for sustainable development agendas. As a border city, it leads in terms of the number of ports and border economic cooperation zones, and the development of these ports has driven socio-economic growth (Li, 2019). Given the constraints of resources and the environment, it is essential to investigate how border cities can seize the development opportunities presented by the "Belt and Road Initiative" and drive sustainable development. Lincang City is a typical case that can provide valuable insights. Therefore, this study takes Lincang City in China's southwestern border region as an example and conducts an in-depth analysis of the driving factors behind city coordinated development in border areas. This study holds great importance for optimizing China's urban structure and achieving high-quality development.

Many scholars have conducted in-depth studies on urban development patterns at the global scale (Hoi, 2020; Wu et al., 2020; Zou et al., 2020; Shi et al., 2021). The urban development process and its dynamic mechanisms have become hot topics in geography research, with geographers exploring the mechanisms influencing urban development from multiple perspectives. In general, the factors driving urban development are diverse, with factors related to the environment, planning, community, and accessibility closely linked to urban development (Azhdari et al., 2018). The development of metropolitan regions is influenced by factors such as road distance, building density, building distance, open farmland density, availability, and altitude (Shafizadeh-Moghadam and Helbich, 2015). In the context of China, market forces play a primary role, followed by endogenous forces, administrative forces, and external forces (Chen et al., 2009). Among these, transportation plays a critical role in urban development and is an important factor in shaping the spatial morphology of regional urban agglomerations (Feng et al., 2023). For prefecture-level cities, factors like labor force, investment level, economic development, government capacity, infrastructure, and industrial structure have positive promoting effects on urban development (Wang et al., 2016). In the case of county-level cities in China, the main factors influencing development include the stage of economic development, fixed asset investment, distance from the central city, levels of the secondary and tertiary industries, rural per capita net income, and population density (Liu and Yang, 2012). Overall, scholarly research on urban development tends to focus on municipal and county-level areas in developed regions, with limited attention to border areas. However, due to their unique geographical characteristics, China's border regions often face fragile environmental conditions, and their urban development lags behind other domestic regions due to their relatively distant locations from the regional economic centers (Song and Zhu, 2020). This implies that the driving mechanisms for urban development in border cities must differ significantly from those in other regions. In-depth research into the characteristics of border city development is particularly important for promoting regional coordinated development. Currently, China's policy of enriching border areas and benefiting the people has been in place for over two decades, and border policies play an important role in resource integration and organizational coordination (Zhang et al., 2020; Gao and Zhen, 2021). However, relevant quantitative analyses of the impacts of that policy are relatively lacking. Furthermore, establishing causal relationships between the factors affecting urban coordinated development may be challenging. Given that the coordinated development of border cities involves complex interactions among policy, social, economic, and natural factors, the simulation methods used in existing research may be inadequate for achieving the desired results.

System Dynamics (SD), introduced in the 1950s, was initially used for analyzing complex industrial processes (Zhang and Yuan, 2010). As a modeling framework, it is often employed to understand the interactions and feedback loops between human and natural systems, allowing for qualitative and quantitative descriptions within SD models. SD has advantages in handling highly nonlinear, interdependent, and multivariate issues (Mirchi et al., 2012). The applications of SD are extensive, covering areas such as urban planning, ecological environmental planning, land carrying capacity assessment, and wastewater reuse assessment (Qin et al., 2012; Rahmani and Zarghami, 2015; Sun et al., 2016; Wang et al., 2017). In recent years, SD research in urban development has grown, with applications in understanding the dynamic mechanisms for achieving "carbon neutrality" goals in cities (Zeng et al., 2022), and the factors affecting land use changes in urban development processes (Cao et al., 2021), among many others. Therefore, SD models have become valuable tools for analyzing regional urban development and can be employed to explore the dynamic mechanisms of coordinated development in border cities.

In this study, we utilized the System Dynamics approach, considering border policy factors comprehensively, to construct the Border City Coordinated Development Sustainable Development (BCCD-SD) model from economic, social, and resource environmental perspectives. Building upon this, we introduced and developed the City Coordinated Development Index (CCDI). Using Lincang City in Southwest China's border region as an example, and based on statistical data and remote sensing data from 2010 to 2020, we designed three scenarios of inertia development, rapid development, and green development, to simulate the urban development trends in Lincang City from 2010 to 2030. The aim of this study was to explore models for achieving coordinated development in Chinese border cities, promoting their role as gateways to the outside world, and realizing regional coordination and high-quality development goals.

2 Data and methods

2.1 Study area

Lincang is located in the southwestern part of Yunnan Province. It shares a border with Myanmar, and both the Lancang River and the Nujiang River flow through the city. Lincang's geographic coordinates range from approximately 23°05′N to 25°03′N and from 98°40′E to 100°32'E, covering a total area of 23600 km^2 (Fig. 1a). Lincang experiences a multi-year average annual precipitation of 1145 mm and maintains an average annual temperature of 19.2 ℃. The city boasts a high forest coverage rate of up to 70% (Fig. 1b). In terms of major function area planning, Lincang primarily focuses on being a major agricultural production area and an ecological functional zone (Fan, 2015). During the "Thirteenth Five-Year Plan", Lincang successfully obtained recognition as a national innovation demonstration zone for sustainable development agendas. By 2030, the new China-Myanmar-Indian Ocean corridor will become one of the significant trade routes between China and the Indian Ocean region, further highlighting the strategic importance of Lincang. From 2010 to 2020, the urban population of Lincang increased from 845000 to 1038000 (Fig. 2a). The city's economy has been developing continuously, with the per capita GDP increasing from 10300 yuan in 2010 to 36200 yuan in 2020 (Fig. 2b). By the end of 2020, Lincang had established three national-level open ports. As indicated in Fig. 2, excluding the impact of the COVID-19 pandemic in 2020, the value-added contributions of the secondary and tertiary industries and the port-based economy have significantly grown since 2010, leading to a continuous increase in the employed population.

2.2 BCCD-SD model design

The model developed in this study considers various factors that influence the coordinated development of border cities. The model is divided into three subsystems: city economy, city society, and city resource-environment. The "Vitalizing Border Areas and Enriching the People" policy (VBEP) promotes border development by influencing these subsystems. Figure 3a presents the conceptual model, including the urban economic subsystem, urban social subsystem, urban resource-environment subsystem, and their interactions. The urban economic subsystem primarily includes indicators such as per capita GDP, value-added contributions of the secondary and tertiary industries, port imports and exports (Liu and Yang, 2012; Cao, 2020), and others. The urban social subsystem comprises the urban population, employed population, and various indicators reflecting public infrastructure, such as road mileage and healthcare levels (Lv and Liu, 2022; Ye and Fan, 2023), among others. The urban resource environment subsystem covers factors like solid waste emissions, water resources, and effective irrigated

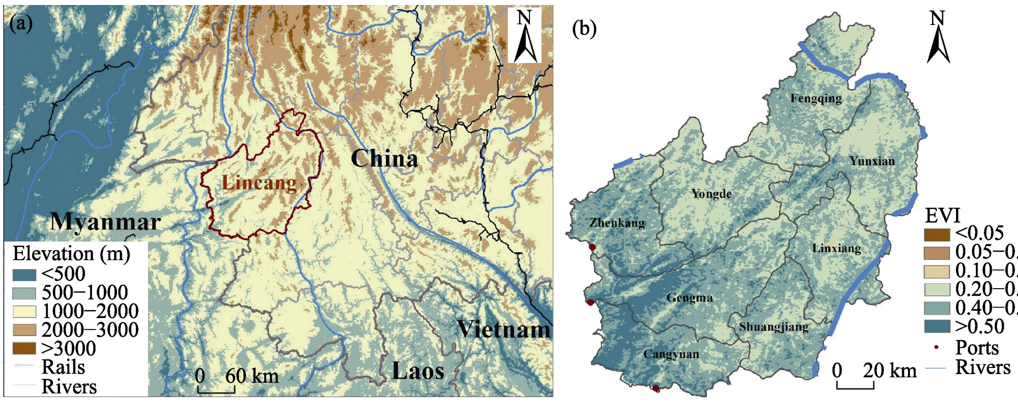

Fig. 1 Overview of the natural conditions of Lincang City

Note: (a) Displays the topographic elevation map of Lincang City and its location along the southwestern border of China, while (b) Illustrates the Enhanced Vegetation Index (EVI) in Lincang City.

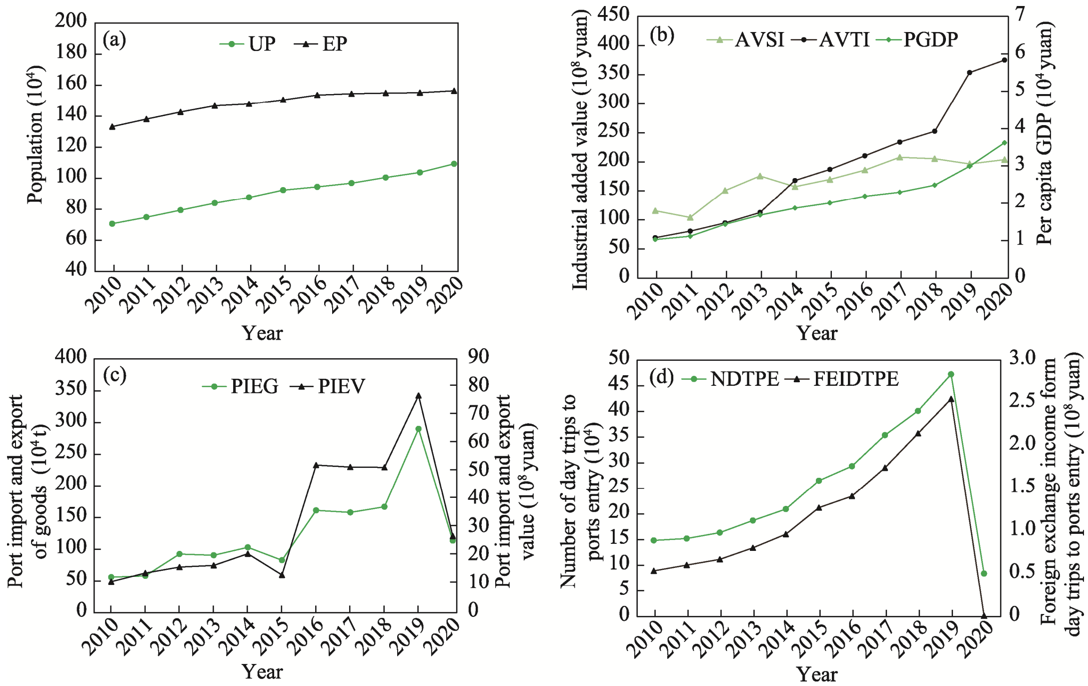

Fig. 2 Overview of the economic and social conditions in Lincang City

Note: (a) Depicts the urban population and employed population (UP, EP) of Lincang City; (b) Shows the per capita GDP and the value-added contributions of the secondary and tertiary industries (PGDP, AVSI, AVTI) in Lincang City from 2010 to 2020; (c) Displays the volumes and values of imports and exports through the ports (PIEG, PIEV) in Lincang City; and (d) Illustrates the number of inbound one-day tourists and the foreign exchange income generated from inbound one-day tourists (NDTPE, FEDTPE) at the ports.

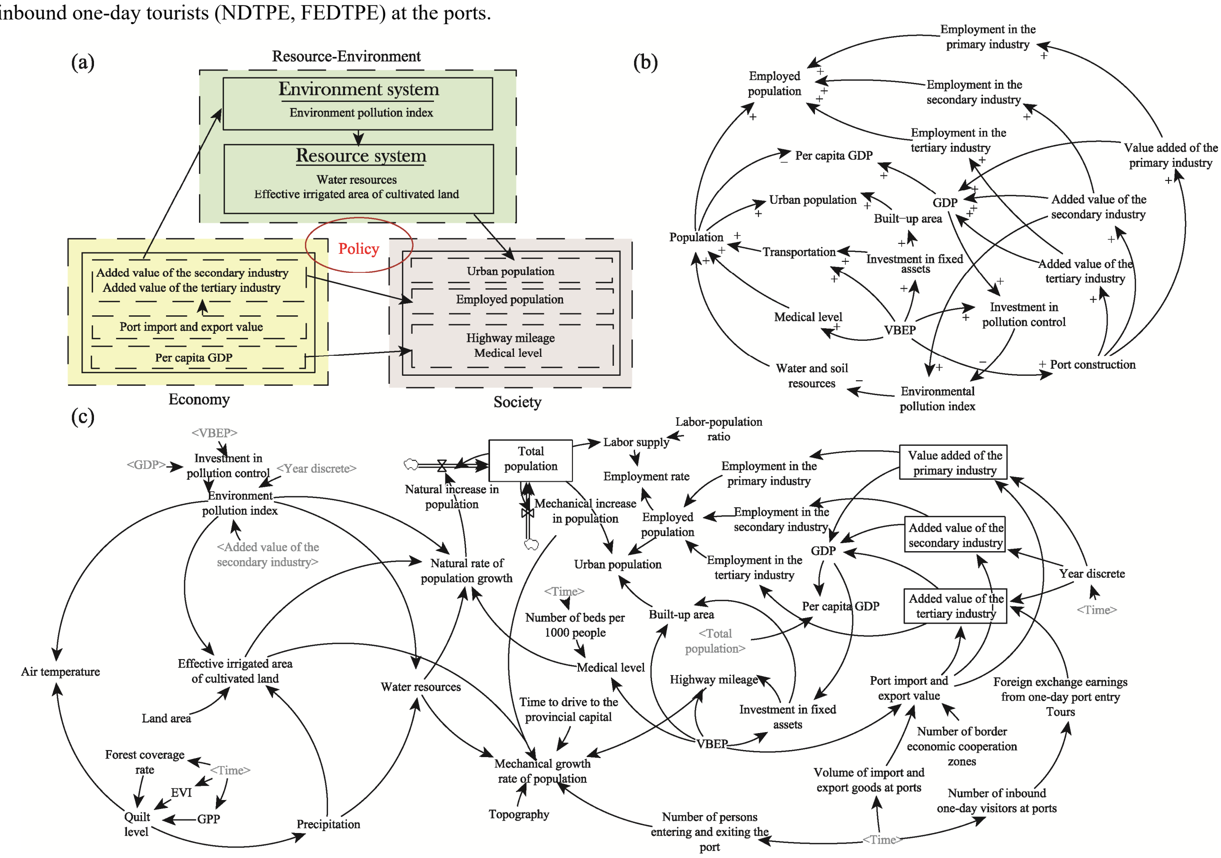

Fig. 3 BCCD-SD model construction diagram

Note: (a) Depicts the conceptual model of BCCD-SD, listing only a subset of key indicators. (b) Presents the causal loop diagram of the model, with each arrow indicating the feedback direction. The polarity (“+” for positive, “–” for negative) on each connecting line represents the direction of change caused by that factor. (c) Shows the complete flowchart of the BCCD-SD model. In this figure, VBEP represents China’s “Vitalizing Border Areas and Enriching the People” policy, and the Environmental Pollution Index is synthesized by averaging the weighted values of solid waste emissions, wastewater emissions, and sulfur dioxide emissions.

farmland area (Zhang et al., 2017; Song and Zhu, 2020), among others. Figure 3b shows the identified elements and their causal loops, including core indicators, feedback loops, and loop dominance. Figure 3c demonstrates the constructed comprehensive system dynamics model.

2.3 Data sources

The sources of the data used in this study include three categories: 1) Social and economic data from various publications such as "China Population Census Almanac" (2010–2020), "Yunnan Statistical Yearbook" (2010–2020), "China Urban Statistical Yearbook" (2010–2020), "China Social Statistical Yearbook" (2010–2020), "Yunnan Statistical Yearbook" (2010–2020), "Lincang Statistical Yearbook" (2010–2020), "Lincang City National Economic and Social Development Statistics Bulletin" (2010–2020), and "China Port Yearbook" (2010–2018); 2) Transportation and topographical data from sources such as AMAP and Open Street Map; and 3) Resource and environmental data from the Resource and Environment Science and Data Center, MOD13A2 (2010–2020), and MOD17A2H (2010–2020). The simulation period of the model was from 2010 to 2030, with a time step of one year. The data from 2010 to 2020 were used for model accuracy verification. The input data included three types: table functions, constants, and initial values. The BCCD-SD model in this study adopted certain assumptions, including: 1) Normal diplomatic relations between China and Myanmar from 2020 to 2030; 2) Based on the requirements of the "Vitalizing Border Areas and Enriching the People Plan for the 13th Five-Year Plan", this study assumed that China's policy influences the economic, social, and resource-environment subsystems by acting on fixed asset investment, road mileage, healthcare levels, port imports and exports, and pollution control investments; 3) Exclusion of factors outside the system boundaries; and 4) Causal relationships between the BCCD-SD model indicators were based on the literature and the authors' research experience.

2.4 Core model formulas

Based on extensive tracking of the published literature and data analysis, this study selected 44 core variables from the economic, social, resource-environment, and border policy perspectives. Equations were constructed for these variables based on the logical and quantitative relationships between them (Table 1).

2.5 City Coordinated Development Index

With reference to the Social and Economic Development Composite Index (SDI) proposed by You et al. (2020) and related literature, this study introduces the City Coordinated Development Index (CCDI). This index is determined by economic, social, and resource-environment factors, and the specific indicator composition is based on random forest contribution analysis. A larger CCDI value corresponds to a stronger ability for urban coordinated development. The Equation is as follows:

$$CCDI = CEI \times CSI \times CREI \tag{1}$$

In Equation (1), *CCDI* stands for the City Coordinated Development Index; *CEI* represents the City Economic Index; *CSI* corresponds to the City Social Index; and *CREI* stands for the City Resource-Environment Index.

$$CEI = \left(PGDP + AVSI + AVTI + PIEV \right) / 4 \tag{2}$$

In Equation (2), *CEI* stands for the City Economic Index, where *PGDP*, *AVSI*, *AVTI*, and *PIEV* respectively represent normalized per capita GDP, secondary industry value added, tertiary industry value added, and port imports and exports value.

$$CSI = \left(UP + EP + HM + ML \right) / 4 \tag{3}$$

In Equation (3), *CSI* represents the City Social Index, where *UP*, *EP*, *HM*, and *ML* respectively represent normalized urban population, employment population, road mileage, and medical level.

$$CREI = \left(-EIC + WR + EPI \right) / 3 \tag{4}$$

In Equation (4), *CREI* represents the City Resource-Environment Index, where *EIC*, *WR*, and *EPI* respectively represent normalized environmental pollution index, water resources, and effective irrigated area of farmland.

Figure 4 visually presents the three-dimensional structure of the CCDI, where the value of CCDI corresponds to the volume of the red cube. It is worth noting that when CREI is negative, the value of CCDI corresponds to a negative volume of the red cube.

2.6 Scenario simulation

This study conducted a reconstruction and simulation analysis of the coordinated development system in Lincang City. According to the development trends of border cities, three scenarios were assessed: The Inertia Development Scenario, the Rapid Development Scenario, and the Green Development Scenario. The Inertia Development Scenario assumes that the coordinated development system of Lincang City will remain unchanged, with border policies, resource environment, and economic and social growth rates continuing as they are currently. The Rapid Development Scenario is built upon the Inertia Development Scenario, but it adjusts the values of VBEP and industrial growth rates to higher levels. Specifically, VBEP, the added value of the secondary industry, and the added value of the tertiary industry are adjusted to 1.1 times, 1.2 times, and 1.2 times of the Inertial Development Scenario, respectively. The Green Development Scenario emphasizes the protection of resources and the environment during urban development, so it explores a sustainable development model for Lincang City, building upon the Inertia and Rapid Development scenarios. Specifically, VBEP remains consistent with the Rapid Development Scenario, while the added value of the secondary industry and the added value of the tertiary industry are both increased to 1.1 times of the Inertial Development Scenario.

Table 1 BCCD-SD model variables and fitting formulas

Class	Variable	Abbreviation	Formula
Economy	Added value of the primary industry	AVPI	$AVPI$ = –31732.40+15.82×YD+$PIEV$/3
	Added value of the secondary industry	AVSI	$AVSI$ = 9.47×YD+0.05×$PIEV$–18916.10
	Added value of the tertiary industry	AVTI	$AVTI$ = 29.61×YD+0.24×$PIEV$–59474.10
	Foreign exchange earnings from one-day port entry tours	FEDTPE	$FEDTPE$ = 0.06×$NIDVP$–0.35
	GDP	GDP	GDP =$AVPI$+$AVSI$+$AVTI$
	Number of border economic cooperation zones	NBECZ	$NBECZ$=1
	Per capita GDP	PGDP	$PGDP$=GDP/TP
	Port import and export value	PIEV	$PIEV$=–7.69+0.16×$VIEGP$×$VBEP$×$NBECZ$
	Time to drive to the provincial capital	TDPC	$TDPC$=5.25
	Investment in fixed assets	IFA	IFA=630.11–3.66×GDP×$VBEP$/2+0.0079×(GDP)^2
	Built-up area	BUA	BUA =23.24–4017.38/(IFA×$VBEP$)
	Number of inbound one-day visitors at ports	NIDVP	
	Number of persons entering and exiting the port	NPEP	Table functions
	Volume of import and export goods at ports	VIEGP	
Society	Employed population	EP	EP=1815.79–0.70×$EIPI$+0.10×P×LA
	Employment in the primary industry	EIPI	$EIPI$=$AVPI$–0.12+92.87
	Employment in the secondary industry	ESI	ESI=AVSI×0.06+10.00
	Employment in the tertiary industry	ETI	ETI=0.07×$AVTI$+36.40
	Employment rate	ER	ER=EP/LS
	Highway mileage	HM	HM=14293.8+1.8788×IFA×$VBEP$/2+ 0.0002×(IFA)^2
	Labor supply	LS	LS=LPR×TP
	Labor-population ratio	LPR	LPR=0.645
	Mechanical growth rate of population	MGRP	$MGRP$=((HM+WR/10+EIC+$NPEP$)/$TDPC$/8.5–T×4)/10000/240
	Mechanical increase in population	MIP	MIP=$MGRP$×TP
	Number of beds per 1000 people	NBP	Table functions
	Medical level	ML	ML=$VBEP$×NBP
	Natural increase in population	NIP	NIP=$NRPG$×TP
	Natural rate of population growth	NRPG	$NRPG$=(0.012×ML+10/(1+EPI)+WR×0.0128+EIC×0.0084)/(3E+06)+ 0.0006
	Total population	TP	TP=$INTEG$ (MIP+NIP, 241.39)
	Urban population	UP	UP=–160.29+0.38×TP+1.46×BUA+ 0.88×EP
Resource/ Environment	Air temperature	AT	AT=EPI×(6.76E–05)+QL×4.91+11.64
	Effective irrigated area of cultivated land	EIC	EIC=1815.79–0.70×EPI+0.10×P×LA
	Environment pollution index	EPI	EPI=2026.71+2×$AVSI$–20.03×IPC×8
	Investment in pollution control	IPC	IPC=GDP×0.007×$VBEP$
	Land area	LA	LA=2.36
	Precipitation	P	P=QL×750
	Quilt level	QL	QL=EVI+GPP+FCR
	Topography	T	T=1631.54
	EVI	EVI	
	Forest coverage rate	FCR	Table functions
	GPP	GPP	
	Water resources	WR	WR=108.51–0.03×EPI+0.05×P
Policy	Vitalizing Border Areas and Enriching the People	VBEP	$VBEP$ =2
Others	Year discrete	YD	2010—2030
	Time	Time	A time variable used to represent the dynamics

Note: Due to space limitations, the table function formulas are no longer listed.

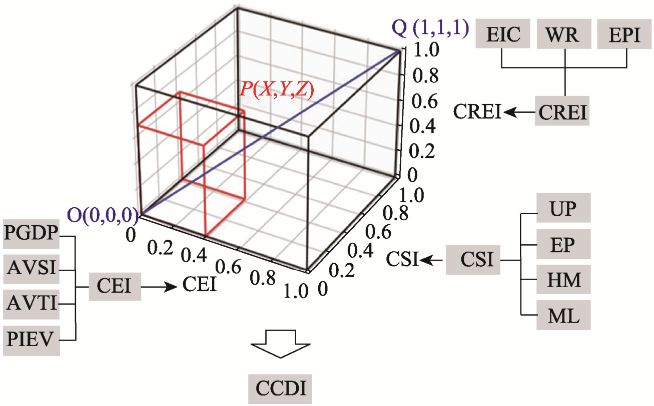

Fig. 4 Three-dimensional diagram of the CCDI based on the BCCD-SD model

3 Results

3.1 Historical validation

To assess the reliability of the model, the simulated results were compared with existing historical data to evaluate the degree of similarity between the two data sets (Wang and Huang, 2021). If the error rate between the simulated values and real values is below 10%, the model is considered to be reliable (Liu et al., 2010; Zhou et al., 2018). In this study, the year 2010 was taken as the base year, and the simulated values for the period of 2010–2022 were examined. Due to the large number of variables involved in the model and the fact that some data for 2022 had not been published at the time of data collection, six indicators related to urban economy, society, and resource environment were selected for the historical validation. These indicators were added value of the secondary industry (AVSI), built-up area (BUA), GDP, total population (TP), air temperature (AT), and effective irrigated area of cultivated land (EIC). Figure 5 presents the actual values of these six indicators from 2010 to 2022 and compares them with the simulated values under the Inertia Development Scenario. The results show that, except for a few individual years, the errors between the simulated values under the Inertia Development Scenario and the actual values are below 10%. Therefore, our model can effectively perform the simulations based on historical data and currently exhibits a good fit for capturing the trends in various indicators of coordinated development in Lincang City.

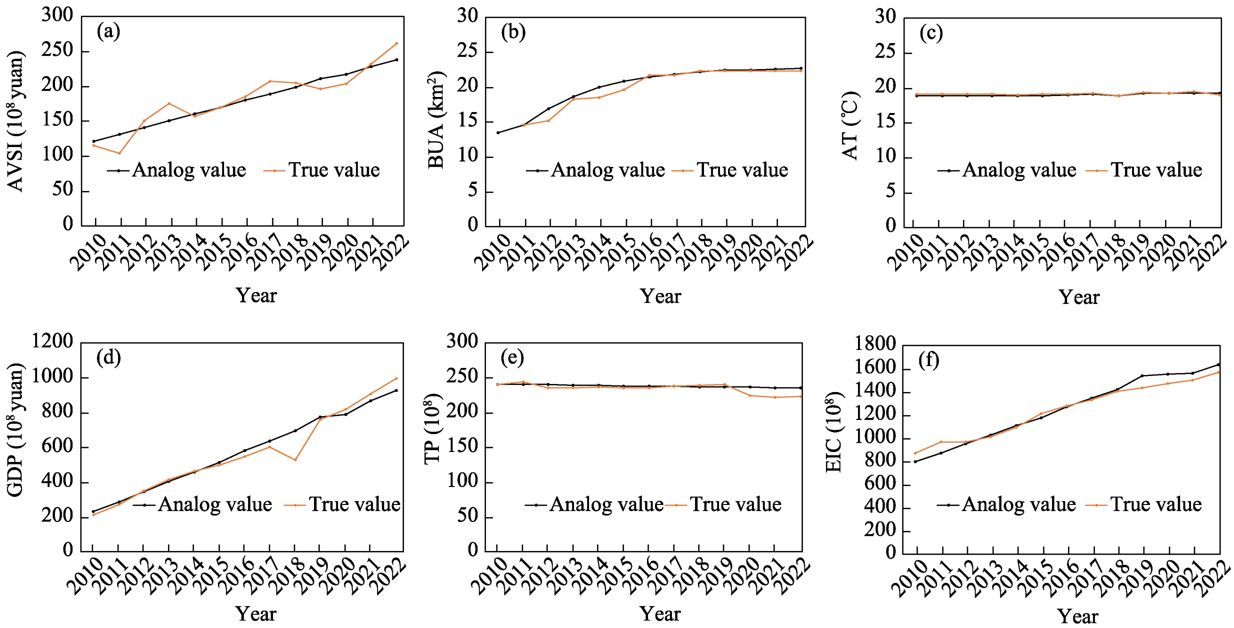

Fig. 5 Comparisons between the simulated values of six indicators under the inertia development scenario and their actual values from 2010 to 2022

3.2 Assessment of the city economic, social, and resource-environment subsystems

Based on Figures 6 to 9, the development trends and structures of the economic and social subsystems are generally similar across the three scenarios, while there are significant differences in the resource-environment aspect. Furthermore, when examining the specific indicators within each subsystem, the differences in the magnitudes of changes in these indicators are more apparent.

In terms of the city economy, from 2010 to 2030, the City Economic Index (CEI) under all three scenarios shows an upward trend (Fig. 9b), and per capita GDP (PGDP), added value of the secondary industry (AVSI), added value of the tertiary industry (AVTI), and port import and export value (PIEV) all experience varying degrees of growth (Fig. 6). It is noteworthy that the Rapid Development Scenario exhibits the most impressive performance in CEI and consistently

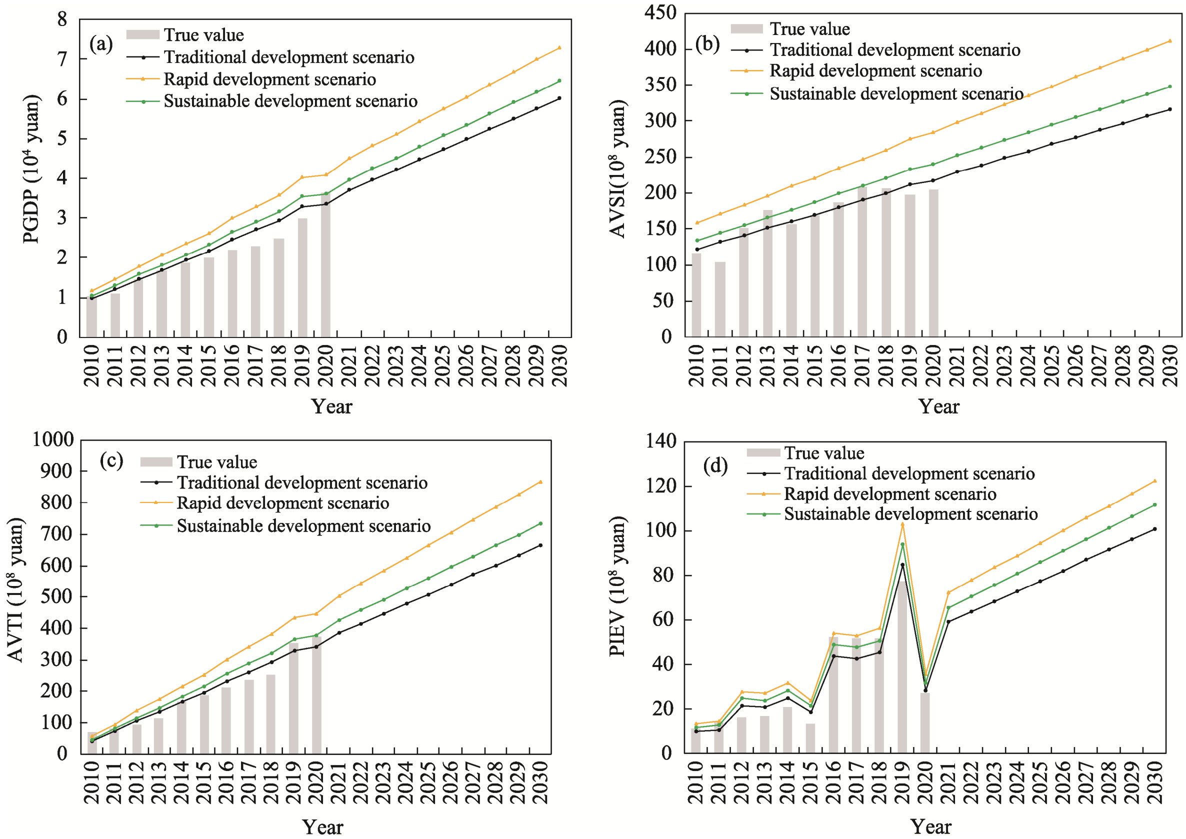

Fig. 6 The city economy subsystem under the three scenarios from 2010 to 2030

outperforms the Inertia and Green Development Scenarios in the four sub-indicators of PGDP, AVSI, AVTI, and PIEV. Particularly after 2020, the gaps between PGDP, AVSI, and AVTI under the Rapid Development Scenario and those under the other scenarios widen further, highlighting the growth advantage of the Rapid Development Scenario in the city economic domain. Of particular concern is the ongoing deepening of cooperation between China and the countries in the Indochina Peninsula, driven by the continuous implementation of the Belt and Road Initiative. Lincang City has been actively enhancing its cooperation with Myanmar (Li, 2019; Zhang, 2019). Since 2016, Lincang City's port trade has shown a rapid growth trend, reaching its historical peak in 2019. However, the outbreak of the COVID-19 pandemic in 2020 disrupted bilateral trade, resulting in a sharp decline in PIEV. Overall, the port economy plays a significant role in driving the development of border cities (Wang, 2019). Since 2016, CEI has shown clear upward trends under all three scenarios.

In the aspect of city society, from 2010 to 2030, Lincang City shows upward trends in City Society Index (CSI) under all three scenarios (Fig. 9c). However, starting from 2013, the Rapid Development Scenario clearly surpasses the other two scenarios in terms of CSI. Among the four sub-indicators of urban population (UP), employed population (EP), highway mileage (HM), and medical level (ML), all experience varying degrees of growth under the three scenarios. Particularly noteworthy are the upward trends in UP under all three scenarios, with the Green Development Scenario consistently maintaining the highest urban population level. The primary reason for this trend is the emphasis on balancing economic growth and environmental protection under the green development concept, which attracts more people to urban areas (Department of Trade and Industry, 2003). Regarding the employed population, EP significantly increases under all three scenarios, mainly benefiting from the rapid development of the port economy, leading to an increase in job opportunities. Specifically, under the Rapid Development Scenario, the growth rate of EP is significantly higher than those of the Inertia and Green Development Scenarios. Similarly, in terms of road mileage, HM under the Rapid Development Scenario is slightly higher than under the Green Development Scenario, while HM under the Inertia Development Scenario is the lowest. The main reason for this phenomenon is that economic activities in both the Rapid Development and Green Development Scenarios increase compared to the Inertia Development Scenario, leading to an increased demand for transportation and thus driving the expansion of road infrastructure (Zhang et al., 2013). Regarding the level of medical care, ML is higher under both the Rapid Development and Green Development Scenarios than under the Inertia Development Scenario. In these two scenarios, significant investments have been made to improve the level of medical care, which has motivated

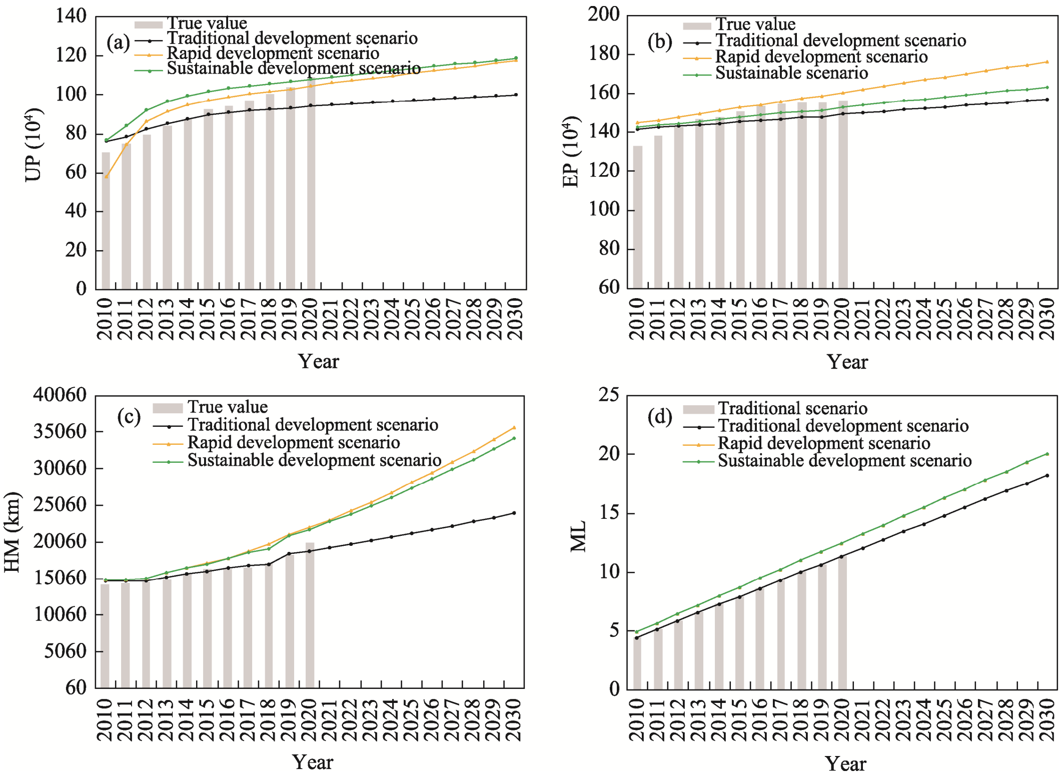

Fig. 7 The city society subsystem under the three scenarios from 2010 to 2030
Note: In Fig. 7d, the curve representing the green development scenario overlaps with that of the rapid development scenario.

more people to migrate to the urban areas (Chen and Zhang, 2022).

Resources and the environment serve as the cornerstone of human existence and development (Zhu, 1990). Under the three scenarios, from 2010 to 2030, the Green Development Scenario exhibits the best performance in terms of City Resource-Environment Index (CREI) (Fig. 9d). Particularly in the resource aspect, effective irrigated area of cultivated land (EIC) and water resources (WR) consistently maintain leading positions under the Green Development Scenario (Fig. 8a, 8b). Specifically, EIC shows significant growth trends in both the Inertia and Green Development Scenarios, with the most prominent growth rate observed under the Green Development Scenario. However, in the Rapid Development Scenario, due to rapid economic growth leading to excessive land development, the growth rate of EIC noticeably slows down after 2020. In terms of water resources, WR shows the most positive growth trend from 2010 to 2030 under the Green Development Scenario. However, in the Rapid Development Scenario, rapid economic expansion leads to water pollution issues, especially after 2020, which causes WR growth to be gradually restricted. In the environmental aspect, Environment pollution index (EPI) significantly declines under the Green Development Scenario, primarily attributed to the various environmental protection policies implemented in this scenario, which effectively reduce environmental pollution (Zhuo et al., 2021). However, in the Rapid Development Scenario, despite the increased investment in pollution control due to high economic growth, that growth also escalates the risks of environmental pollution and resource consumption (Guo et al., 2018). Figure 8c shows that after 2020, the rate of the

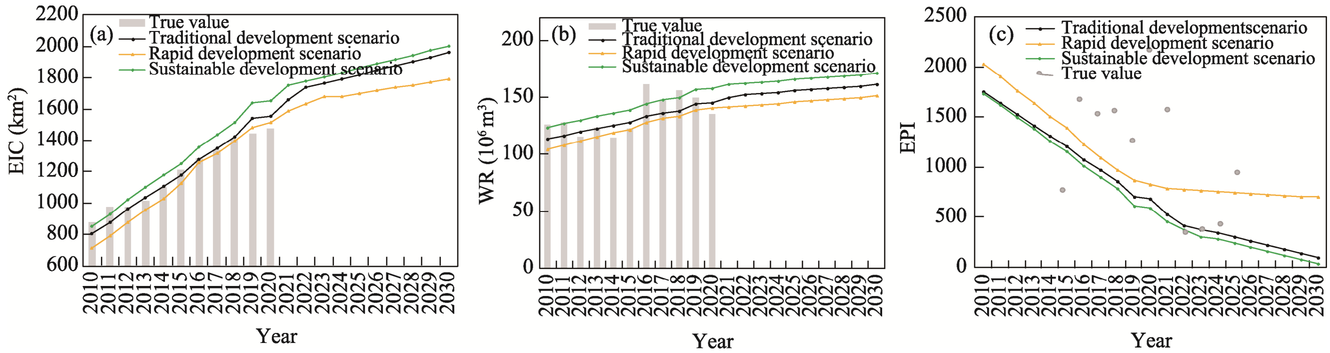

Fig. 8 The city resource-environment subsystem under the three scenarios from 2010 to 2030

EPI decline in the Rapid Development Scenario slows down compared to the Inertia and Green Development scenarios, indicating a significant constraint on the pace of resource and environmental improvement.

3.3 Analysis of the City Coordinated Development Index (CCDI)

Figure 9a illustrates the City Coordinated Development Index (CCDI) of Lincang City under the three scenarios. Overall, from 2010 to 2030, the CCDI shows upward trends in all three scenarios. Between 2010 and 2015, there is little difference in the CCDI among the various development scenarios, and the values remain close to zero. In the early stages of border city development (2010–2015), cities accumulate less in terms of economic and social aspects, resulting in small differences in the social levels and economic development among the different development scenarios, as reflected in the closeness of the City Economy Index (CEI) and City Society Index (CSI) values under the three scenarios (Fig. 9b, c). Additionally, although there are differences in the demand for resources and the environment among the different development scenarios, their impacts during this period are relatively limited. This is reflected in Fig. 9d, where the City Resource-Environment Index (CREI) values show no significant differences among the three scenarios. Therefore, before 2015, the CCDI differences among the three development scenarios are small, and there is a similar degree of coordination in terms of the economy, society, and resource environment.

However, after 2015, CCDI exhibits significant differences. Particularly in 2019, the CCDI under the three scenarios experiences a notable increase, mainly attributed to the role of port trade in driving urban development (Wang, 2019). However, the outbreak of the COVID-19 pandemic in 2020 hindered export trade and led to a certain degree of economic stagnation, causing the CCDI to decline under all three scenarios. Specifically, under the Green Development Scenario, CCDI continues to rise, and the level of city coordinated development is much higher than in the other two scenarios. The Inertia Development Scenario shows a CCDI trend similar to the Green Development Scenario but with a relatively slower growth rate. Under the Rapid Development Scenario, the CCDI value falls between the other two scenarios, especially after 2020, when it starts to lag significantly behind the Green Development Scenario. This suggests that rapid economic growth in the process of border city development may gradually cause issues like resource consumption and environmental pollution to become more apparent (Guo et al., 2018), causing the level of city coordinated development to lag behind that of the Green Development Scenario.

3.4 Comprehensive evaluation of the city coordinated development level

Figure 10 clearly illustrates the evolution of the city coordinated development levels in the Inertia, Rapid, and Green Development scenarios for the years 2010, 2020, and 2030. In all three scenarios, the length of OP has significantly in-

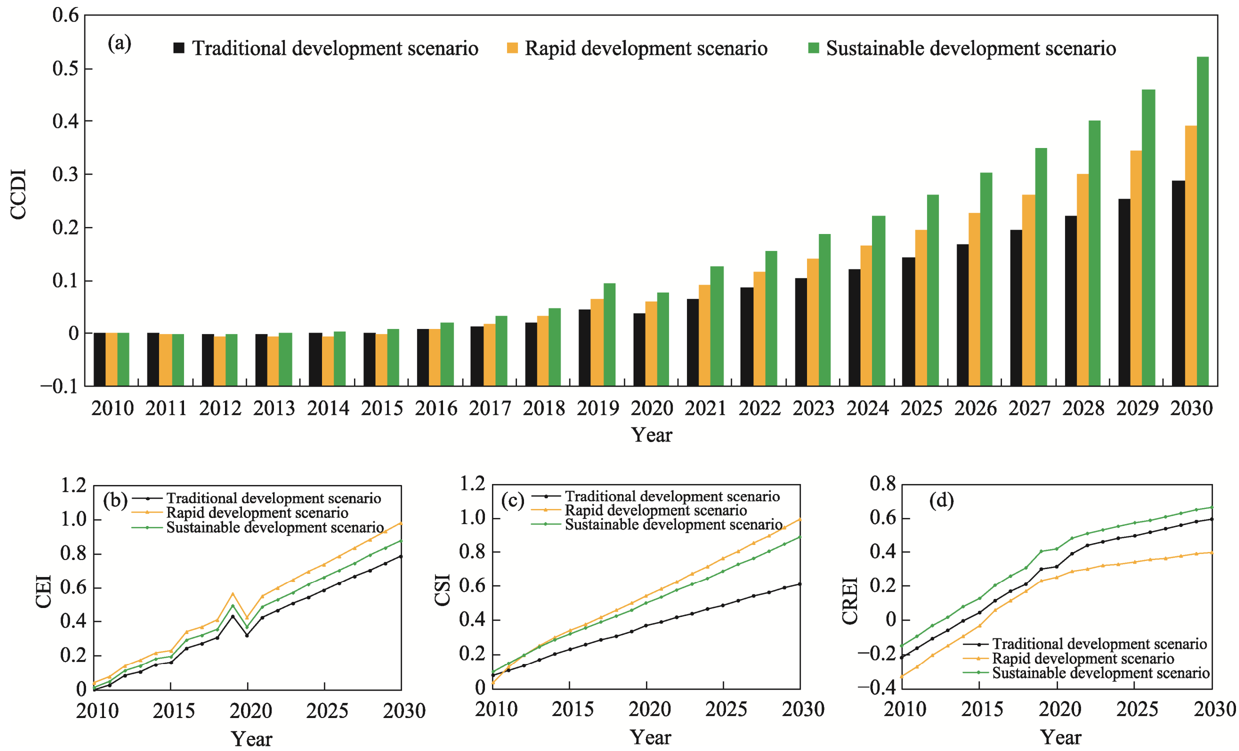

Fig. 9 The CCDI , CEI, CSI and CREI under the three scenarios from 2010 to 2030

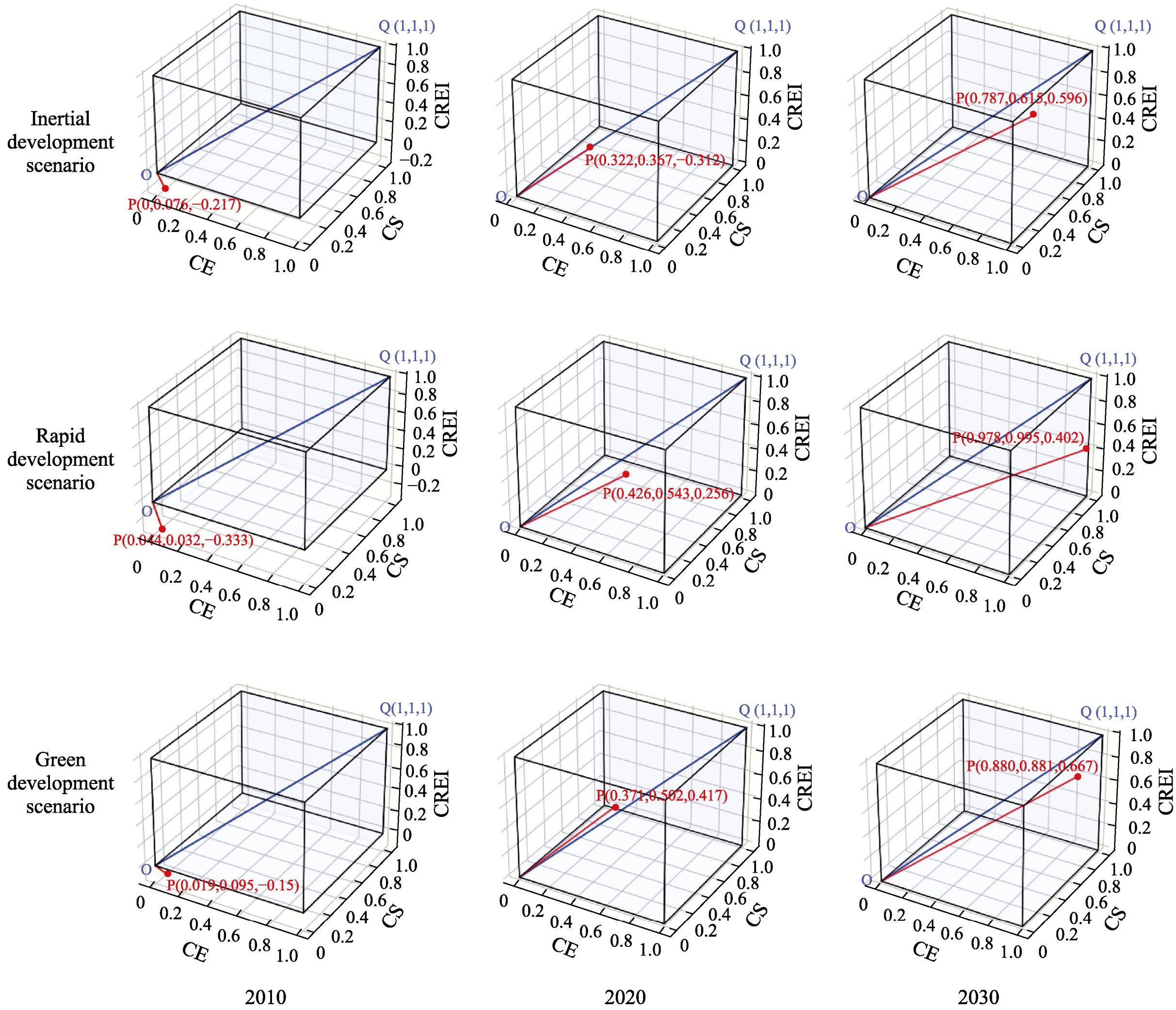

Fig. 10 Three-dimensional schematic diagrams illustrating the CCDI values in the three scenarios for the years 2010, 2020, and 2030

creased, corresponding to the continuous expansion of the rectangular volume (representing CCDI), which indicates an overall improvement in the level of city coordinated development over two decades. However, what stands out is that ∠POQ (the angle between OP and OQ) shows significant differences, revealing different emphases and magnitudes of changes in the city economy, society, and resource environment across the different scenarios and time periods.

Specifically, in 2010, the CCDI values were negative in all three scenarios, indicating a low level of city coordinated development. Among them, the Rapid Development scenario had the largest ∠POQ, indicating an imbalance in the economic, social, and resource environmental aspects in the early stage of urban development. In 2020, compared to the other two scenarios, the Inertia Development scenario had the smallest CCDI, with OP closest to OQ. This suggests that there was the smallest difference between City Economy Index (CEI), City Society Index (CSI), and City Resource-Environment Index (CREI), and the city economy, society, and resource environment exhibited slow and balanced growth. In contrast, although the Rapid Development scenario had a higher CCDI than the Inertia Development scenario, it had the largest ∠POQ. The CEI and CSI were significantly higher than CREI, indicating that prioritizing economic development hindered resource and environmental protection to some extent. On the other hand, the Green Development scenario performed better, with a higher CCDI than the other two scenarios and a smaller ∠POQ angle. The rhythm of improving the economy and society, and protecting the resource environment was relatively consistent, contributing to urban sustainability. The data for 2030 shows that the level of city coordinated development continues to rise in all three scenarios, with a significantly strengthened development structure. The Inertia Development scenario continues to maintain a slow and balanced development pattern, with the lowest CCDI in 2030, and ∠POQ is still relatively small. The Rapid Development scenario has a higher CCDI than the Inertia Development scenario, but its growth model focused on economic development exacerbates the contradiction between socio-economic development and the resource environment, which is reflected in the CEI and CSI values being close to 1, while CREI is only 0.4, and ∠POQ reaches an extreme value. In contrast, the scenario aimed at green development achieves an effective integration of economic growth, social progress, and resource and environmental protection. This is manifested in the highest CCDI, the smallest ∠POQ, and a relatively balanced pace of growth in the three subsystems of economy, society, and resource environment. Among the three scenarios, the Green Development scenario achieves the optimal level of city development coordination.

4 Discussion

In 2020, China's import and export volume reached 32.16 trillion yuan, equivalent to 31.65% of China's total GDP. Under "the Belt and Road" initiative, border ports, as critical hubs for international trade, play a key role in promoting domestic and international trade cooperation and economic growth (Mu and Xiong, 2022; Chai and Ma, 2023). The research results presented in this paper also indicate that in all three scenarios, border ports have a significant positive impact on border city economic development. To further analyze the pathways through which border ports influence the coordinated development of border cities, a mechanism diagram is shown in Fig. 11 which considers various factors, but excludes religious, ethnic, and other considerations.

Under the guidance of China's policies for promoting economic development in border regions, the construction of border ports helps to reduce operational costs, promotes the prosperity of port economies, and subsequently stimulates the development of related industries. This, in turn, drives the expansion of border cities and the construction of public infrastructure (Cohen and Monaco, 2008). As a result, more employment opportunities are created, and the population tends to migrate to the urban areas. During this process, the city's development generates a demand for various production factors, leading to the cross-border flow of resources, populations, capital, technology, and other factors through the border port channels, which have mutual influences with neighboring countries (Chai and Ma, 2023). Furthermore, the coordination of border cities in their economic, social, and environmental aspects creates the conditions for further development of border ports, forming a positive feedback loop. Border cities, as the crucial carriers of border ports, engage in import and export, trade interactions, and cross-border circulation through port channels, facilitating cross-border circulation and resource allocation. The prosperity of port economies directly benefits border cities. In this context, during this important phase of China's economic transformation, border regions should focus on promoting "port+" development, explore new models of port economic development led by technological innovation and resource integration, accelerate the transition and upgrading from "passage" economics to port economics, and establish an economic development layout radiating from the ports to the surrounding areas (Wang, 2019). This approach can promote regional coordination and sustainable development in the border regions.

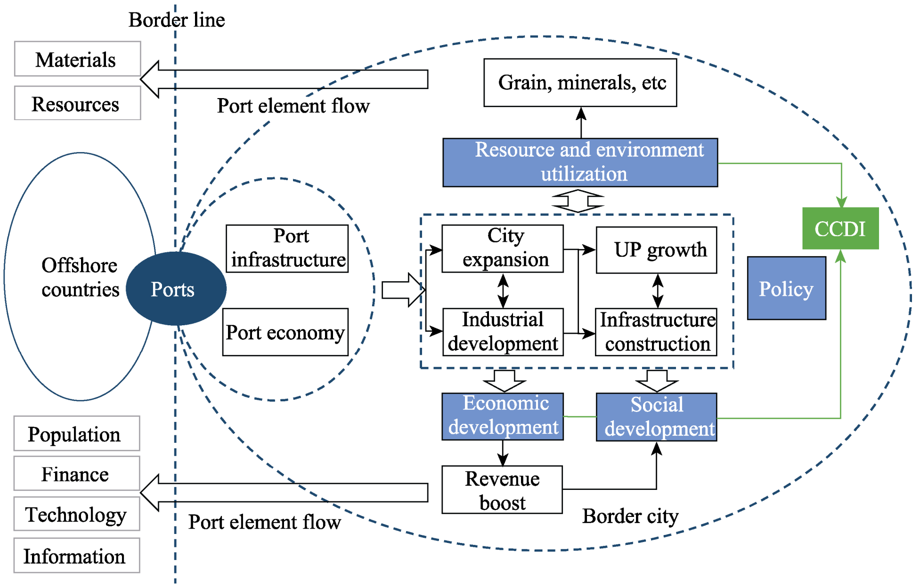

Fig. 11 Mechanism by which ports promote the coordinated development of border cities

Although this study has achieved some useful results, there are still certain limitations to consider. Firstly, regarding data selection, it should be noted that China has a large number of border cities, and collecting comprehensive data for all of them would be challenging. Therefore, this study chose Lincang City as a representative sample, although this choice may limit the applicability of the model to some extent. Furthermore, due to limited data availability for the period before 2010, especially in terms of resources and the environment, this study based its BCCD-SD model on data from 2010 to 2020 and simulated data for the period from 2010 to 2030. While the data used in this study are relatively limited, it is worth noting that other studies have made predictions for longer timeframes based on only a decade of data (Chen et al., 2023; Sheng and Zeng, 2024). This suggests that the data used in this study are generally suitable for research purposes.

In terms of model construction, this study built a model from the perspectives of the economy, society, and resource-environment. However, the concept of city coordinated development is multifaceted, so in addition to these three aspects, factors like urban-rural coordination and regional coordination are also important. Due to considerations of data availability and the complexity of system construction, these factors were not included in the model. Additionally, system dynamics inherently involves evaluating and comparing different policies and decision scenarios, and the results of simulations are heavily dependent on the settings of various parameters. Any changes in Lincang City's future economic trends or diplomatic relations with Myanmar could lead to deviations between real-world data and simulation results. However, it is important to note that the main focus of this study is not to precisely predict the specific economic, social, and resource-environment indicators for Lincang City, but rather to simulate potential trends in urban coordinated development under different policy scenarios. This focus can help to identify border policies that align more closely with the requirements of high-quality development. In future research, the authors will continue to expand their research approaches and explore new scenarios to make the future studies more comprehensive.

5 Conclusions

This study employed a system dynamics approach, incorporating border policy factors and focusing on three dimensions: city economy, society, and resource-environment. It constructed the BCCD-SD model and introduced the City Coordinated Development Index (CCDI). Using Lincang City in Southwest China as a case study, three scenarios were designed—Inertial Development, Rapid Development, and Green Development—to simulate city coordinated development from 2010 to 2030 and explore the mechanisms behind border city development. The key conclusions are as follows.

(1) Through historical validation, the effectiveness of the model was demonstrated, with simulation errors in the Inertial Scenario for the years 2010–2022 consistently below 10%. Thus, the model successfully captures the trends in various city coordinated development indicators.

(2) The findings can be considered in terms of the three subsystems. For the City Economy, the Rapid Development Scenario exhibits significant economic growth advantages, with port-related economic activities playing a crucial role. For the City Society, the Rapid Development Scenario provides more public infrastructure and employment opportunities. Meanwhile, the Green Development Scenario consistently maintains the highest urban population level, facilitating effective urbanization. For the City Resource-Environment, the Green Development Scenario shows the best performance in terms of resource-environment indicators. However, the Rapid Development Scenario may exacerbate pressures on resources and the environment.

(3) The comprehensive index reveals that from 2015 to 2030, the CCDI in the Green Development Scenario consistently surpasses those in the Rapid and Inertial Development Scenarios, indicating the highest level of city coordinated development. In contrast, the Rapid Development Scenario's rapid economic growth gradually exposes resource and environmental issues, leading to a lag in urban coordinated development.

(4) Regarding the development structure, the Rapid Development Scenario exhibits imbalances among the economic, social, and resource-environment aspects from the early stages, which then expand over time. Conversely, the three sub-indicators in the Inertial Development Scenario consistently show slow and balanced growth. By comparison, the Green Development Scenario maintains a relatively balanced pace of growth across the three sub-indicators, highlighting its advantages in coordinated development and effectively integrating economic growth, social progress, and resource-environment protection.

(5) Lastly, the role of ports in border city development was discussed. During the economic transformation phase, border ports should expedite the transition from a "gateway" economy to a "port+" economy. This shift will help the cities to better serve as international gateways, fostering regional coordination and achieving high-quality development. Overall, this study offers valuable insights into city coordinated development in border cities by considering various scenarios and emphasizing the role of port economies in driving growth and sustainability.

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中国边境城市协调发展的动力机制——以西南边境临沧市为例

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摘　要：在共建“一带一路”的背景下，作为国家间交流的中介区域，边境城市的可持续发展愈发重要。本文基于系统动力学方法，纳入边境政策因素，从经济、社会和资源环境三个维度构建了边境城市协调发展的BCCD-SD模型，并创建了城市协调发展指数（CCDI）作为综合评价指标。基于此，文章以中国西南边境的临沧市为例，模拟了惯性发展、快速发展和绿色发展情景下临沧市的城市协调发展趋势。研究结果表明，该模型灵活地捕捉了城市协调发展指标的趋势。在三种场景中，快速发展情景脱颖而出，产生最高的经济水平、最好的公共基础设施以及最多的就业人口。然而，以经济增长为主要关注点的快速发展路径加剧了资源和环境压力，带来了可持续性挑战。相比之下，绿色发展情景虽然在经济表现上略逊于快速发展，但城市人口领先，促进了就业人口向市民的过渡，在资源和环境方面表现出色。总体而言，CCDI在绿色发展情景下得分最高，超过了快速和惯性发展，这一情景有效地融合了经济增长、社会进步和资源环境保护。本文还探讨了口岸在边境城市协调发展中的关键作用，强调了从“门户”经济向“口岸+”经济转变的必要性，旨在促进中国边境城市更好地发挥对外窗口作用，实现区域协调与高质量发展。

关键词：系统动力学；临沧市；协调发展；边境政策；中国西南边境