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Research article

An adaptive cycle resilience perspective to understand the regime shifts of social-ecological system interactions over the past two millennia in the Tarim River Basin

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A R T I C L E I N F O

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A B S T R A C T

Socio-ecological systems (SESs) in arid regions have experienced multiple transformations throughout history due to human activities and natural forces. However, few studies have used the resilience cycle model to explain the resilience status and determinants of SESs over the past two millennia. This study proposes the adaptive cycle resilience (ACR) perspective to investigate regime shifts of socio-ecological system interactions in the Tarim River Basin (TRB) over the past two millennia. An ACR framework combining a piecewise linear regression model (PLR), ACR theory, and physical resilience models has been built to assess and quantify socio-ecological system resilience. Key indicators such as climate variability, settlement numbers, war frequency, glacier accumulation, and oasis area changes are identified and quantified to evaluate SESs adaptability and transformability. Glacier accumulation serves as a proxy for long-term climate change, while oasis area changes reflect the direct impact of human activities and environmental feedback on ecosystem productivity. Population and war indicators provide insights into social system stability and the impact of conflicts on SESs dynamics. The findings reveal that the 7th century and 1850s are critical points of regime shifts in the ACR. 200s BC-350s AD and 700s AD-900s AD are in the forward loop (r-K) period of the ACR. 350s AD-700s AD and 900s AD-1850s AD are the adaptive resilience backward loop (Ω-α) phase. Assessing the historical socio-ecological system resilience and identifying key transition points can inform proactive measures to mitigate potential regime shifts. Combining historical data with resilience theory provides a deep understanding of the ACR of SESs and their driving factors. This enriches the theoretical understanding of SESs and offers a robust case study for future resilience assessments and scenario analyses in arid regions.

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1. Introduction

The pursuit of a balance between socio-economic development and ecological preservation while achieving human development goals and safeguarding vital natural resources, has been at the center of global discussions and treaties on sustainable development [1]. Humans are an integral to the natural world. They rely on socio-ecological systems (SESs) for sustenance and exert continuous influence on SESs at local to global scales [2–5]. Over the past two millennia, humanity and nature have developed a mutually dependent relationship, with ecological shifts interacting with large-scale societal and economic changes. These interactions initiate feedback loops, mutations, instability, and increased exposure to new forms of risk [6–8]. The intricate interplay between humans and the natural environment has driven the complex evolution of SESs. Thus, understanding the intricate dynamics of human-environment interactions and their evolution over the last 2000 years is crucial. This understanding is essential for elucidating the evolutionary trajectory and guiding future long-term resource planning, and management policy.

SESs are complex coupled systems characterized by complexity, nonlinearity, uncertainty, and multi-layer nesting formed by human-environment interactions [9]. Due to these characteristics, SESs exhibit positive and negative feedback loops influenced by external pressures such as climate change and human activities. When external pressure exceeds the resilience of the ecosystem, positive feedback will dominate, causing in a sudden, drastic, and sustained transformation of the system's structure and function, known as a regime shift. This results in drastic deterioration of the ecological environment and other phenomena [10,11]. Regime shifts of one level or function may trigger transformation in related levels or functions through cascading effects, potentially causing the entire system to collapse due to the multi-level nested structure of SESs [9,12]. For example, the watersheds include agriculture, rural populations, water and soil resources, ecological environments, and other subsystems. Once the ecological environment is damaged, it may cause a vicious cycle of reduced agricultural production, economic decline, and population outflow. This cyclic feedback can cause significant structural and functional changes throughout the SESs, risking overall regime shifts and collapse. Therefore, understanding and identifying the key nodes, transformation types, and driving mechanisms of regime shifts in the SESs' interactions process are crucial for studying and managing this complex dynamic system [9,12,13].

Understanding the coupling of social systems and ecosystems requires a dynamic perspective to address intricate concepts like critical points for sustainable ecosystem management [14]. Resilience, a critical attribute of SESs, determines their capacity to adapt and recover from disturbances and stresses. This enables SESs to maintain their structure and function amid interference and stress. Enhanced resilience boosts SESs' capacity to adapt to change and enables humans to anticipate and shape future trajectories [4,15]. Conversely, diminished resilience increases SESs' vulnerability to external pressures, potentially leading to impaired function and regime shifts [16]. In some cases, even without evident interference, SESs may transform due to gradual changes, requiring restoration to the pre-transformation state for recovery [17]. Resilience theory, along with its concept of adaptive cycles, provides a framework for understanding the evolution of relationships between humans and social systems. This theory highlights SESs' capacity to self-organize, learn, and adapt in response to disturbances [18,19]. The adaptation cycle model of resilience theory explains SESs' evolution, detailing the system's dynamics across four stages: rapid growth and exploitation (r), conservation (K), release (Ω), and reorganization (α) [20,21].

Recently, more studies have applied adaptive cycle resilience (ACR) theory to elucidate the relationship between societal systems and ecosystems [4,22]. Previous research has established resilience assessment models for domains such as water resources, agriculture, wetlands, cities, and islands [21,23–26]. These studies analyze changes in system elements in recent decades and their potential impact on socio-ecological system resilience in the face of future shocks [23,24,27]. However, understanding socio-ecological system resilience requires a historical perspective spanning thousands of years to differentiate between the ultimate and proximate causes of socio-ecological system transitions, and identify mutational features throughout the ACR. Few studies have used the resilience cycle model to explain the resilience status and determinants of SESs over the past two millennia.

The Tarim River Basin (TRB), the largest inland river basin in China, was shaped by long-term transitions from sea to land and the coupling of basin and mountain [28]. Glacier and mountain snowmelt primarily contribute to runoff in the basin [28]. Over the past 2000 years, ecological changes from climate change and human activities have been closely linked to the rise and fall of civilization in the TRB. Contemporary society faces significant challenges from desertification expansion and climate warming [29]. This study focuses on the TRB offering a compelling case for examining regime shifts of socio-ecological system interactions in arid inland basins. This approach aids in gaining deeper insights into ecosystem evolution in arid regions, exploring the balance between ecological preservation and socio-economic progress, and fostering ecological civilization.

This paper proposes an ACR assessment framework for SESs by integrating ACR theory [20] and a piecewise linear regression (PLR) model [9] This study selected the TRB to investigate the interaction among climate, human activities, and environmental response through ACR. Key nodes of regime shifts in the SESs were identified using a PLR method. This study reveals the dynamics of socio-ecological system interactions in the TRB over the past 2000 years, aiming to understand resilience from a historical perspective using variables like climate change, temperature, population, war frequency, glacier accumulation, percentage of new and abandoned settlements, and standardized rainfall values. Additionally, drawing from literature, local chronicles, archaeological and sediment records, this study assesses the resilience dynamics of SESs evolution, elucidating the interaction between slow and fast processes in the adaptation cycle.

2. Material and methods

2.1. Study area

Tarim River Basin (73°10′E–94°50′ E, 34°55 ′N-43°50′ N) is in the southern part of Xinjiang Uygur Autonomous Region (Fig. 1). The TRB is bordered by the Tianshan Mountains to the northeast, the Kunlun Mountains to the southeast, and the Pamir Plateau to the west [30]. Covering approximately 102,000 square kilometers, it constitutes 61.4 % of Xinjiang's total land area. The TRB's topography includes 47 % mountains, 31 % deserts spanning, and 22 % plains. Historically, the TRB was China's largest inland river basin, with the Tarim River nourished by nine major tributaries. Recently, factors such as global climate change and extensive human interventions, especially the excessive development of oasis agriculture, have led to significant transformations. Currently, only four primary headstreams, namely the Hotan River, Yerqiang River, Aksu River, and Kaidu River, contribute to the main flow of the Tarim River [31].

The main course in the TRB stretches 1321 km, flowing from Aral to Lake Taitmar. This course can be categorized into the upper reaches from Aral to Imbaja, the middle reaches from Imbaja to Chala, and the lower reaches from Chala to Lake Taitma [28]. The TRB exhibits a typical arid continental climate with low precipitation, high evaporation rates, substantial windblown sand, and extended sunshine periods. The average annual precipitation is about 51.2 mm, with evaporation reaching 2000–3000 mm. Surface runoff is estimated at approximately 398 $\times$ 10^8 cubic meters, classifying the TRB as water-scarce [29]. The region experiences annual average temperatures from 11.5 °C to 12.9 °C with intense solar radiation and strong winds. Annual sunshine duration ranges from 2500 to 3550 h, with total annual radiation from 5000 to 6400 MJ/m^2. Wind speeds exceed 5 m per second for 202 days annually, with maximum speeds reaching 40 m per second [32].

2.2. ACR framework for SESs

The ACR framework examines the evolution of SESs, ACR, and methods for quantifying resilience (Fig. 2). First, by identifying

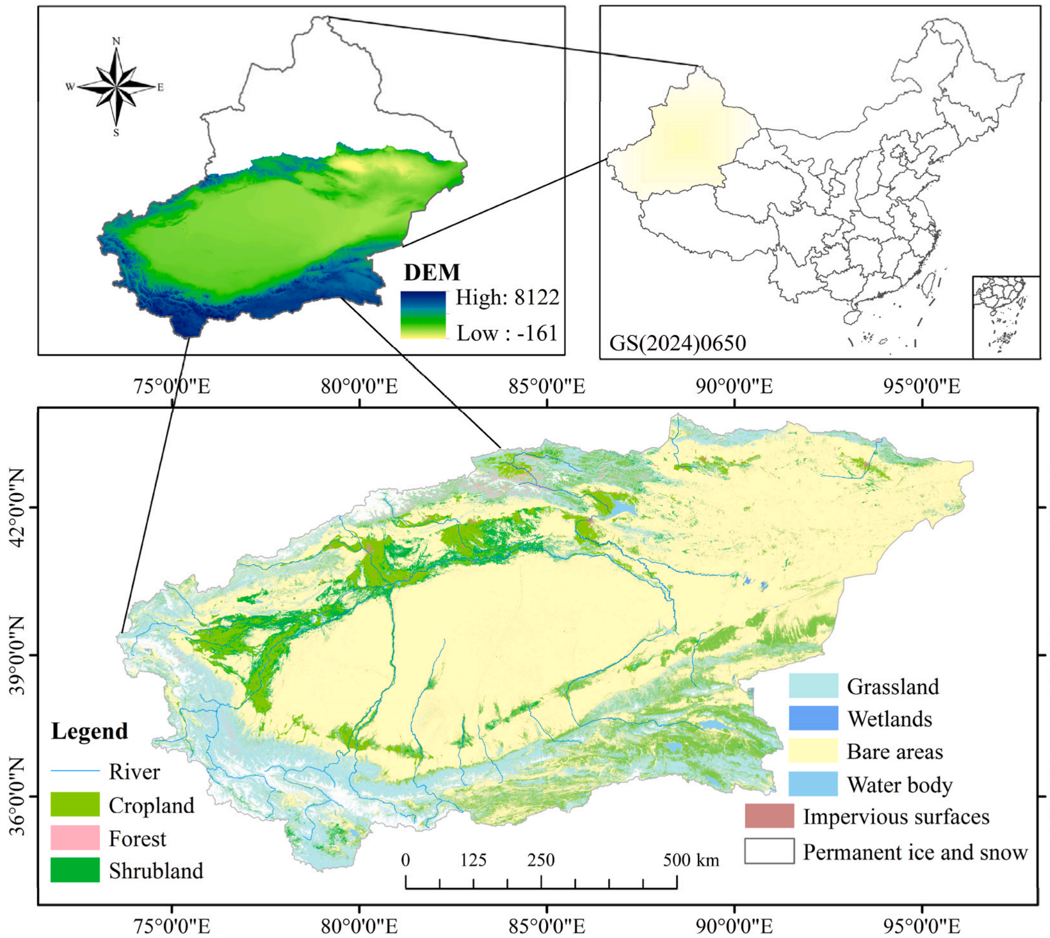

Fig. 1. Location of the Tarim River basin.

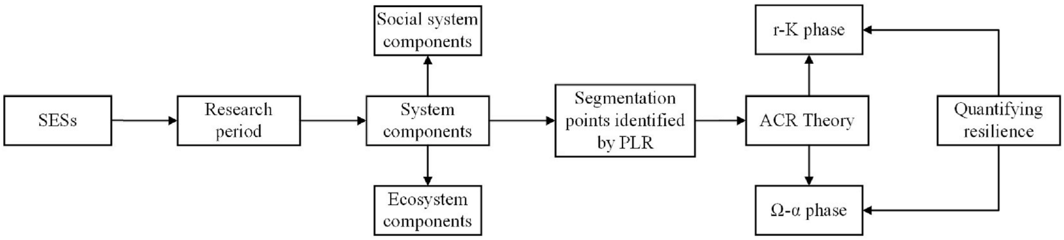

Fig. 2. Adaptive cycle resilience framework in this study.

driving factors such as climate change and human activities, we analyze the components of social and ecological subsystems. The PLR method segments the evolutionary stages of SESs by detecting breakpoints in the relationships between variables. Second, we introduce the ACR theory, which divides the relationships between the SESs components into phases from the front loop (r-K) to the back loop (Ω-α) of the ACR. Finally, a resilience model based on Hooke's law. The model quantifies socio-ecological system resilience by considering background resilience, sensitivity coefficients, external pressures, and influencing factors. The Mann-Kendall trend test detects the significance of trends in time series data. By calculating the statistical value S and the standardized statistic Z_c, the study evaluates the direction and significance of trends in time series data to determine the long-term trends of SESs.

2.2.1. Identification of the evolutionary phases of SESs

Climate change and human activities are driving factors determining the regime shifts of socio-ecological system interactions. Factors such as population, settlements, artificial oasis area, wars, agricultural technology, and management levels are components of the social subsystem. Indicators such as temperature anomalies, forest coverage, natural oasis area, and precipitation index are components of the ecological subsystem.

In this study, abrupt change points in socio-ecological system component relationships are analyzed using the PLR method. By determining periods when all relationships remain unchanged, we identify the resilience evolution stages of SESs and analyze their evolution. PLR is a statistical method providing separate results for different segments of an independent variable by switching regressions [33]. We performed linear regression in two segments using PLR. Assuming the relationships remain constant, the boundary time between segments is considered the abrupt change point [9]:

$$y = \begin{cases} k_1 x + m_1, t \leq t_1 \\ k_2 x + m_2, t_1 < t \leq t_2 \\ \ldots\ldots \\ k_n x + m_n, t_{n-1} < t \leq t_n \end{cases} \quad (1)$$

where y is the dependent variable and x is the independent variable. $k_1, k_2 \ldots. k_n$ is the rate of change of a linear line segment. $m_1, m_2. m_n$ is the intercept of a linear segment. $t_1, t_2 \ldots t_n$ is the abrupt change point, which is determined by the sum of the squares of the minimum residuals of the regression line and the p-value of the two regression lines before and after the turning point less than 0.05.

2.2.2. ACR model for SESs

The ACR theory describes how resilience system responds to continuous and changing disturbances, offering a basis for evaluating system evolution. The ACR is a basic unit of dynamic change with four stages: growth and exploitation (r), conservation (K), release (Ω) and reorganization (α) [20] (Fig. 3). SESs cycle through these stages to adapt to environmental changes.

ACR model strengthens the relationship between system resilience, change threshold and regime shifts [34]. The ACR can develop with both human and natural interference. At each scale, The ACR begins with system organization (r), leading to development (K). It then collapses into the disorder phase (Ω), followed by a period of creative exploration (α), eventually leading to a new renewal phase [35].

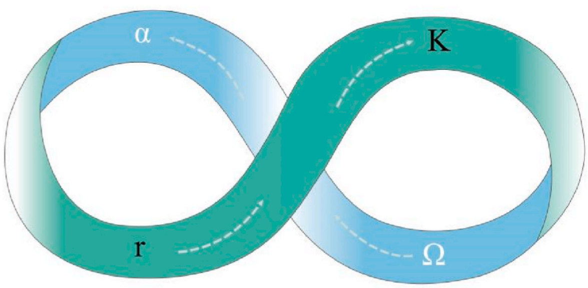

Fig. 3. Schematic diagram of "acr" model.

During the stable evolutionary phase of SESs, the interactions between subsystems remain unchanged. Thus, the relationship in SESs shifts from a predictable and slow forward loop (r-K) to a fast backward loop (Ω-α), or vice versa. Both represent the shift of SESs from one regime of evolution to another [36]. By detecting the abrupt changes among the socio-ecological system components, we can divide these relationships into the forward loop (r-K) phase and the backward loop (Ω-α) phase of the ACR.

2.2.3. Quantification of resilience in SESs interactions

The resilience model is based on Hooke's Law, which describes the resilience of materials, and the relative index values of SESs. The quantitative expression of resilience is given as [37]:

$$F_r = F_0 + \lambda \cdot S \tag{2}$$

where F_r is the resilience of SESs, F_0 is the inherent background resilience of the system related to its specific adaptation mechanisms, λ is the sensitivity coefficient reflecting the system's learning ability, and S represents external pressures, including human or natural disturbances.

$$\lambda = \frac{1}{1 + e^{-\sum_{i=1}^{n}\left(\theta_i\ g\omega_i'\right)}} \tag{3}$$

where ω represents factors affecting the resilience changes of SESs, n is the number of factors, and θ is the weight assigned to each factor. The weights are assigned based on linear regression. Factors include rainfall (ω_1), runoff (ω_2), oasis area (ω_3), GDP (ω_4), and population (ω_5).

Climate change and human activities are the main external pressures affecting the socio-ecological system resilience. Climate change primarily considers extreme temperature stress (S_T) and glacier retreat stress (S_G), while human activities consider war stress (S_W).

$$S_T = \begin{cases} \exp\left(\dfrac{T_{current}}{T_{\min}}\right), if\ T_{current} \le T_{\min} \\ 0, else \\ \exp\left(\dfrac{T_{current}}{T_{\max}}\right), if\ T_{current} \ge T_{\max} \end{cases} \tag{4}$$

$$S_G = \begin{cases} \exp\left(\dfrac{G_{current}}{G_{\min}}\right), if\ G_{current} \le G_{\min} \\ 0, else \end{cases} \tag{5}$$

$$S_W = \exp\left(\frac{W_{current}}{W_{\max}}\right) \tag{6}$$

where $T_{current}$, $G_{current}$ and $W_{current}$ represent the average temperature, glacier cumulative area ratio, and war frequency during the period, respectively. $T_{\max}$ and $T_{\min}$ represent extreme high and low temperatures. $G_{\min}$ represents the critical value of the glacier cumulative area ratio; for stable glaciers, the ratio is usually between 0.6 and 0.7. If the ratio falls below 0.5, it typically indicates glacier retreat, so $G_{\min} = 0.5$. Wmax represents the highest war frequency in the past 2000 years.

The resilience of SESs to extreme temperature ($F_{r\text{-}T}$), glacier retreat ($F_{r\text{-}G}$), and war (F_{r-W}) is expressed as:

$$F_{r-T} = F_{0-T} + \lambda_T \cdot S_T \tag{7}$$

$$F_{r-G} = F_{0-G} + \lambda_G \cdot S_G \tag{8}$$

$$F_{r-W} = F_{0-W} + \lambda_W \cdot S_W \tag{9}$$

where $F_{0\text{-}T}$, $F_{0\text{-}G}$, F_{0-W} represent the constant background resilience of SESs to extreme temperature, glacier retreat, and war, respectively, and λ_T, λ_G, λ_W represent the sensitivity of SESs to drought, floods, and water pollution, respectively.

Based on the resilience of SESs in different dimensions to extreme temperature, glacier retreat, and war, and according to the physical parallelogram law of forces, comprehensive resilience is given by:

$$F_R = \sqrt{{F_{r-T}}^2 + {F_{r-G}}^2 + {F_{r-W}}^2} \tag{10}$$

2.2.4. Mann-Kendall trend test

This study uses the Mann-Kendall trend test to examine the change trends of social and ecological indicators. For a time series X, the test statistic of the Mann-Kendall trend test is as follows [38]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{11}$$

where x_j is the j-th value of the time series, n is the length of the data sample, and sgn is the sign function defined as:

$$sgn(\theta) = \begin{cases} 1 & (\theta > 0) \\ 0 & (\theta = 0) \\ -1 & (\theta < 0) \end{cases}$$

Mann and Kendall demonstrated that when $n \geq 8$ [39,40], the test statistic S approximately follows a normal distribution with a mean of 0 and a variance given by:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{12}$$

The standardized test statistic Z_c is calculated as follows:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S+1}{\sqrt{Var(S)}} & (S < 0) \end{cases} \tag{13}$$

Thus, Z_c follows a standard normal distribution.

The indicator for measuring trend magnitude is:

$$\beta = Median\left(\frac{x_i - x_j}{i - j}\right) \tag{14}$$

where $(1 < j < i < n)$ and Median represents the median of series. A positive β value indicates an "upward trend," while a negative β value indicates a "downward trend."

The Mann-Kendall trend test procedure is as follows: the null hypothesis H_0: $\beta = 0$ is rejected when $|Z_c| > Z_{(1-\alpha)/2}$, where $Z_{(1-\alpha)/2}$ is the standard normal variate, and α is the significance level.

2.3. Data collection

The research period spans 10 ancient dynasties, the Republic of China, and the People's Republic of China (Table 1). Historical data primarily come from ancient books and documentary sources. We utilized remote sensing images, including historical documents, local chronicles, archaeological data, and historical climate records. Modern data after 1949 mainly come from observational and statistical data (Table 2). We collected data on settlements, cultivated oases, natural oases, population, temperature, glacier accumulation, war frequency, and standardized rainfall values from sources such as remote sensing data, the National Bureau of Statistics of China, the National Meteorological Administration of China, and relevant literature.

Table 1
Different periods over the past 2000 years.

Dynasty	Period	Length of dynasty(years)
Han Dynasty (Han)	206BC-220AD	426
Wei-Jin era (Wei-Jin)	220AD-420AD	140
Northern and Southern Dynasties (N–S)	420AD-589AD	169
Sui Dynasty (Sui)	589AD-618AD	29
Tang Dynasty (Tang)	618AD-907AD	289
Five dynasties and ten Kingdoms (FDTK)	907AD-979AD	72
Song Dynasty (Song)	960AD-1279AD	319
Yuan Dynasty (Yuan)	1279AD-1368 AD	89
Ming Dynasty (Ming)	1368AD-1644AD	276
Qing Dynasty (Qing)	1644AD-1912AD	267
Republic of China (ROC)	1912AD-1949AD	38
The Peoples' Republic of China (PRC)	Since1949AD-	Since1949AD-

Table 2
Datasets information in the TRB.

Dataset	Timescale	Source (Before1949)	Source (After1949)	Reference
Settlement	206BC-2000AD	Records of the Grand Historian; Han History; The Classic of Mountains and Rivers; Book of Wei; Book of Later Han Dynasty; Tang History; Song History; Yuan History; Ming History; Qing Dynasty National Chorography; Western Regions Annals; Xinjiang Annals;	National Bureau of Statistics of China	–
Cultivated oasis	206BC-2000AD			–
Natural oasis	206BC-2000AD			–
Population	206BC-220AD, 1644AD-2000AD			[1]
Abrupt event and extreme drought	350AD-1190AD		–	[41]
Rate of settlement change	206BC-1912AD		–	–
War frequency	206BC-1912AD	https://www.minzushi.org/minzushi/11547.html	–	–
Precipitation standardization	1450AD-2000AD	–	–	[41]
Climate change	206BC-2000AD	–	–	[1,42]
Temperature	206BC-2000AD	–	National Meteorological Administration of China	[43]
Glacial accumulation	300AD-2000AD	–	–	[41]

3. Results

3.1. Variations in the components of SESs over the past 2000 years

Extensive investigations, historical records, and cultural relic examinations reveal that early settlements in the TRB were primarily on river terraces in the piedmont region over the past 2000 years. This underscores the significance of the grassland area before the mountains as the primary site for early human activities.

Changes in settlements and oases in the TRB indicate that during the periods from the 3rd century BC to the early 3rd century AD, from the late 6th century to the early 10th century, and from the mid-17th century to the early 20th century, were times of great unification in Chinese history. During these times, Central Plains dynasties increased their management of the Western Regions, and

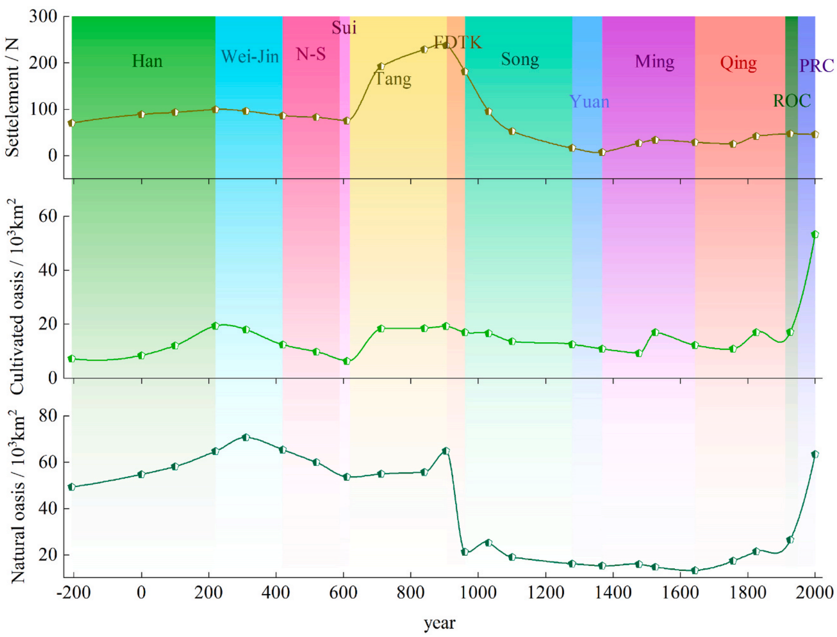

Fig. 4. Changes in SESs indicators over the past 2000 years.

large numbers of Central Plains farming peoples, along with their production methods, tools, and crops, entered the Western Regions. Numerous settlements were built and the population and cultivated oasis in the TRB increased. Thus, the population, settlements, and cultivated oasis area peaked during these periods, though the increase lagged behind the ruling periods (Fig. 4).

Conversely, the 3rd century BC to the 5th century AD, and the 10th century to the mid-17th century, were low periods for settlement construction, with many settlements being abandoned during these times. During these periods, with the decline of the Central Plains dynasties and the onset of great fragmentation periods, the influence of Central Plains farming peoples withdrew from the Western Regions, and the population in the Western Regions correspondingly decreased. Many settlements and cultivated oasis areas were abandoned during these periods, often before the fragmentation periods. The area of natural oases peaked from the 5th century to the late 6th century, then gradually decreased with dynastic changes, until it began to increase again in the mid-14th century.

Spatially, from the 3rd century BC to the early 3rd century AD, from the late 6th century to the early 10th century, and from the mid-17th century to the early 20th century, ancient settlements, population, and cultivated oases were mainly distributed throughout the TRB. In other historical periods, they were limited to parts of the TRB [44]. Before the 7th century AD, natural oases were widely distributed in the Weigan-Kuqa River Basin and the Kaidu-Kongque River Basin. From the mid-10th century to the mid-14th century, both artificial and natural oases in the northeast and southeast parts of the TRB gradually declined. From the mid-14th century to the early 20th century, the oasis area in the TRB increased again.

In different historical periods, climate changes significantly impacted on agricultural production and settlement patterns. During relatively stable climatic periods (e.g., from the 3rd century BC to the early 3rd century AD and from the late 6th century to the early 7th century AD), favorable climate conditions promoted agricultural production and population growth. However, during periods of significant climate fluctuations (e.g., from the 3rd century AD to the late 6th century AD and the 10th century AD), climate deterioration may have led to declines in agricultural production and population, resulting in the abandonment of settlements. As the population increased and agricultural activities expanded, overexploitation of resources may have led to environmental degradation. For example, overextraction of water resources and excessive land cultivation may have degraded oases and the intensified of desertification. Environmental issues likely have forced residents to migrate or abandon their settlements. The decline of natural oases is closely linked to climate change, overexploitation of resources, and human activities. For example, excessive agricultural cultivation

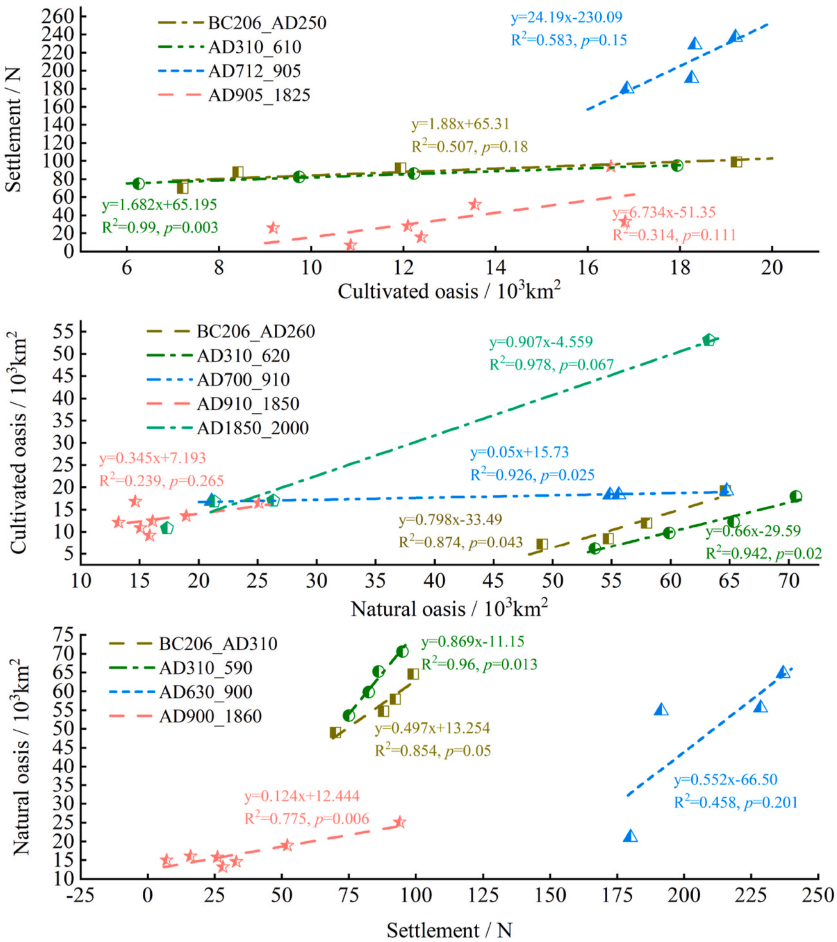

Fig. 5. Evolutionary phases of the social-ecological system in the TRB.

and water resource utilization during certain historical periods may have led to oasis degradation and water shortages. In some periods, strengthened resource management and advances in agricultural technology enabled oasis recovery. From the mid-14th century to early 20th centuries, the government implemented water conservancy projects and resource management policies likely contributed to this recovery.

3.2. Determine the evolutionary stages of SESs interactions

Based on PLR, we have divided the evolution of the SESs in the TRB over the past 2000 years into three stages. The first stage spans from early 3rd century BC to late 7th century AD. From the early 3rd century BC to the 350s AD, the number of settlements increased from 70 to 95, the area of cultivated oases expanded from 7.21×10^3 km^2 to 19.22×10^3 km^2, and the area of natural oases grew from 49.11×10^3 km^2 to 64.64×10^3 km^2. The number of settlements, and areas of cultivated and natural oases all increased over time. The number of settlements was positively correlated with cultivated oasis areas ($R^2 = 0.507$, $p = 0.18$) and natural oasis areas ($R^2 = 0.854$, $p = 0.05$). Natural and cultivated oasis areas were positively correlated ($R^2 = 0.874$, $p = 0.403$). This increase might be due to settlement growth promoting the development of agriculture and irrigation technologies, expanding arable land. Improved climatic conditions allowed natural oases to expand, providing a more suitable living environment. Population growth in the region drove the expansion of settlements and oases. From the 350s AD to the late 7th century AD, the number of settlements decreased from 99 to 75 and cultivated oasis areas shrinking from 19.23×10^3 km^2 to 6.25×10^3 km^2. The natural oasis area decreased from 70.61×10^3 km^2 to 53.57×10^3 km^2 (Fig. 5). The number of settlements, and areas of cultivated and natural oasis areas all decreased over time. The number of settlements was positively correlated with cultivated oasis areas ($R^2 = 0.99$, $p = 0.003$) and natural oasis areas ($R^2 = 0.942$, $p = 0.02$). Natural and cultivated oasis areas were positively correlated ($R^2 = 0.96$, $p = 0.013$). This decline might be due to drought or reduced rainfall causing natural oases to shrink, which affected the cultivated oasis areas. Frequent wars or political instability could have led to population decline and social upheaval.

The second stage spans from late 7th century AD to the 1850s. From the late 7th century AD to the 10th century, the number of settlements increased from 75 to 237. Cultivated oasis areas expanded from 6.26×10^3 km^2 to 19.21×10^3 km^2, and natural oasis areas increased from 53.57×10^3 km^2 to 64.75×10^3 km^2. Both cultivated and natural oases increased over time. The number of settlements was positively correlated with cultivated oasis areas ($R^2 = 0.583$, $p = 0.15$) and natural oasis areas ($R^2 = 0.458$, $p = 0.201$). Natural and cultivated oasis areas were positively correlated ($R^2 = 0.926$, $p = 0.025$). This indicates that this period was one of socioeconomic recovery, leading to the expansion of oases and flourishing settlements. Improvements in agricultural techniques and irrigation facilities enhanced land utilization. The wealth brought by Silk Road trade led to the rapid development of oasis cities. From the 10th century to the 1850s, the number of settlements decreased from 237 to 41. Cultivated oasis areas decreased from 19.2×10^3 km^2 to 16.79×10^3 km^2. Natural oasis areas shrank from 64.75×10^3 km^2 to 13.2×10^3 km^2 by the 17th century. The number of settlements, and area of cultivated oasis natural oasis areas fluctuated over time, showing an overall decreasing trend. The number of settlements was positively correlated with cultivated oasis areas ($R^2 = 0.314$, $p = 0.111$) and natural oasis areas ($R^2 = 0.775$, $p = 0.006$). Natural and cultivated oasis areas were positively correlated ($R^2 = 0.239$, $p = 0.265$). The decline might have been due to a drier and colder climate reducing natural oasis areas. Frequent wars and population movements during this period made land cultivation and settlement maintenance more difficult.

In the third stage (1850s to early 21st century), although the number of settlements decreased, the population of the TRB increased from over 1.5 million in the 1850s to more than 7.48 million in the early 21st century. Additionally, the cultivated oasis area expanded from 16.79×10^3 km^2 to 53.12×10^3 km^2, and the natural oasis area grew from 21.29×10^3 km^2 to 63.25×10^3 km^2. This suggests that with modern management and technology, population growth promoted agricultural development and effectively expanded the oasis areas. The application of modern agricultural machinery and irrigation technology significantly improved land use efficiency. The government development policies and investments facilitated the expansion of oasis farmlands.

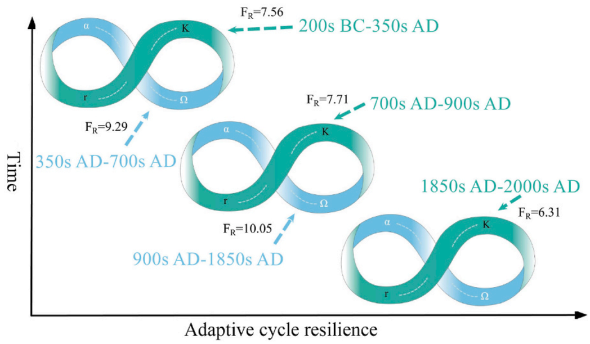

Fig. 6. Changes in socio-ecological system resilience over the past 2000 years.

3.3. Identification and quantification of the ACR stages and resilience of SESs

Driven by multiple factors, the historical environmental changes in the TRB have generally trended towards aridification, characterized by fluctuations between dry and wet periods. During dry periods, desertification expanded rapidly and occurred more frequently. During wet periods, the speed and frequency of desertification decreased. Over the past 2000 years, the ecological environment of the TRB has generally moved towards increased aridification, with the area of oases fluctuating between expansion and contraction. Additionally, due to factors such as wars and changes in river courses, human settlements were continuously established and abandoned.

In the ACR, socio-ecological system's resilience enters a growth phase during the "r" stage, marked by high resilience and rapid resource accumulation and expansion. By the "K" stage, SESs become highly mature and stable, with reduced resilience and increased vulnerability to external shocks. The analysis of socio-ecological system indicators reveals that during the early 3rd century to the 350s, the late 7th century to the 10th century, and the 1850s to the early 21st century, the indicators depicted a phase of resource accumulation and expansion. Therefore, these three periods were in the relatively slow "r-K" front loop phase of the ACR, featuring strong interconnections within the SESs and robust internal state regulation (Fig. 6). When socio-ecological system resilience enters the "Ω" phase, the system undergoes rapid breakdown and decomposition, with minimal resilience, meaning even minor shocks can lead to complete collapse. During the "α" phase, the system's vitality is reestablished, resilience gradually increases, and it begins to adapt to new environments and pressures. From the 350s to the late 7th century, and from the 10th century to the 1850s, the indicators overall depicted a phase of resource dissipation and contraction. Therefore, these two periods were in the rapid "Ω-α" back loop stage of the ACR, featuring weaker connections within the SESs and the system undergoing energy release and reorganization.

From the early 3rd century BC to the 350s ($F_R = 7.56$), the system underwent significant capital accumulation and infrastructure development, with rapid resource accumulation. Technological advancements, agricultural innovations, and relatively stable climate conditions during this period created favorable conditions for resource accumulation. From the 350s to the 700s ($F_R = 9.29$), the system experienced severe resource dissipation and settlement decline, characterized by rapid breakdown. Wars, social upheavals, and cooling climate led to resource depletion and increased ecosystem vulnerability. From the 700s to the 900s ($F_R = 7.71$), the system re-

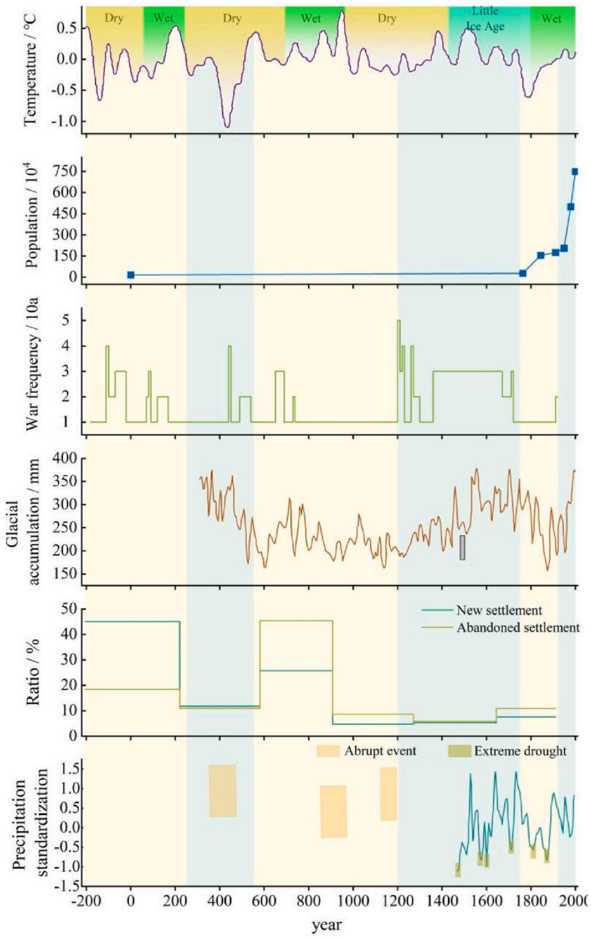

Fig. 7. Changes in SESs drive factors over the past 2000 years.

entered a phase of resource accumulation and expansion, with increases in settlement and oasis areas, and gradually recovering resilience. Improvements in agricultural technology, active trade, and relatively stable climatic conditions collectively drove resource accumulation during this period. From the 900s to the 1850s ($F_R = 10.05$), the system entered a phase of resource dissipation and contraction, with significant reductions in settlement numbers and oasis areas, and gradually increasing socio-ecological resilience. Climate changes, political instability, and environmental degradation during this period led to declines in system vitality and carrying capacity. From the 1850s to the 2000s ($F_R = 6.31$), the system again experienced rapid resource accumulation and expansion, driven by technological advancements, policy support, and population growth, leading to rapid resource growth.

In the ACR, when the F_R is in the range of 6.31–7.71, SESs in the TRB are in the resource accumulation and expansion “r-K” phase. SESs re-enters the stage of resource accumulation and expansion, with increases in the area of settlements and oases. When the F_R is in the range of 9.29–10.05, the SESs enter the resource dissipation and contraction “Ω-α” phase. The system then enters a resource dissipation and contraction phase, with a significant reduction in the number of settlements and the area of oases.

3.4. Driving factors of the SESs interactions in various stages

From the early 3rd century BC to the 3rd century AD, the TRB experienced a warm-wet climate phase. During this time, increased ice and snowmelt in the mountainous area of the TRB resulted in a warmer and more humid climate. Consequently, the water volume of TRB, Kongque River and Hotan River was at its peak. During this stage, the area of natural oases increased continuously, making a recovery phase for natural oases. After the Han Dynasty unified the Western regions through war, it established a capital guard in the Western Regions, strengthening economic and cultural exchanges between the mainland and the Western regions. With the introduction of farming and irrigation technology from the Central Plains, society became relatively stable, and agriculture developed significantly. During this time, the economy featured both animal husbandry and irrigation agriculture (Fig. 7).

Therefore, the area of cultivated oasis increased continuously, with a growth rate greater than that of natural oasis. Many wars occurred during this period, leading to the construction and abandonment of numerous cities. However, the overall proportion of new settlements was larger. From the 350s to the late 7th century, the TRB was in the cold and dry climate stage. The climate experienced fluctuation in precipitation and temperature, with the maximum accumulation of ice and snow in the TRB exceeded 350 mm. The water volume of the TRB and Lop Nur main stream decreased. Changes in the hydrological regime leads to more frequent river channel migration, and the connection between Niya River and the south river system of TRB begins to be interrupted. At the same time, the Kongque River lost contact with the northern main stream of the Tarim River, significantly reducing in the flow into Lop Nur. Desertification expanded rapidly and its frequency increased, causing the area of natural oasis to shrink significantly. The Central Plains were continuously divided, weakening the administration and rule of the western regions. Although the production tools and technology improved further, frequent damaged social production and the environment. Many settlements and cultivated oases were abandoned at this time.

From the late 7th century to the 10th century, the climate shifted from warm and wet. During this transition period, the accumulation of glaciers greatly reduced, and floods caused by snow and ice melt occurred frequently, leading to river channel migration. Overall, the area of natural oases increased during this period. From the middle of the 7th century to the end of the 8th century, the Tang Dynasty effectively reclaimed the Western regions by establishing administrative institutions and garrisoning armies, leading to the construction of numerous settlements and cultivated oases. However, in the 9th century, the Tang Dynasty was seriously challenged by Arab countries and gradually losing its influence on the Western regions over the Western regions, which became divided

Table 3
Mann-Kendall test for the trend of driving factors.

Variable	Period	β	Zc	Significance
Temperature	200s BC-350s AD	0.001	4.715	Insignificant
	350s AD-700s AD	0.003	7.390	Significant
	700s AD-900s AD	0.003	3.380	Significant
	900s AD-1850s AD	−0.001	−7.450	Insignificant
	1850s AD-2000s AD	0.003	3.232	Significant
Population	1760s AD-2000s AD	0.941	2.630	Significant
War frequency	200s BC-350s AD	0.001	−0.941	Significant
	350s AD-700s AD	0.013	−0.282	Significant
	700s AD-900s AD	0.033	−1.181	Significant
	900s AD-1850s AD	0.025	−2.191	Significant
	1850s AD-2000s AD	0.291	1.443	Significant
Glacial	300s AD-350s AD	−0.863	−2.746	Significant
	350s AD-700s AD	−0.357	−7.856	Insignificant
	700s AD-900s AD	−0.197	−3.352	Significant
	900s AD-1850s AD	0.497	2.320	Significant
	1850s AD-2000s AD	0.094	0.550	Significant
New settlement	200s BC-2000s AD	−0.050	−1.878	Significant
Abandoned settlement	200s BC-2000s AD	−0.755	−1.626	Significant
Precipitation	1450s AD-1850s AD	0.002	1.596	Significant
	1850s AD-2000s AD	0.013	2.968	Significant

Note: The significance level $\alpha = 0.05$.

once again. Due to war, river diversions, and other factors, many human settlements and cultivated oases were abandoned. Therefore, settlements from the Tang Dynasty had a high proportion of abandonment.

From the 10th century AD to the 15th century AD, climate change was characterized by alternating dry and cold. There was a Little Ice Age between the 15th and 18th centuries, peaking in the 17th century [1,45]. From the 10th to the 18th century, the Tarim River was characterized by the contraction of its main stream and tributaries, accompanied by the desert expansion, human migration and the abandonment of settlements. During the Yuan and Ming dynasties, frequent wars, political instability, and economic and cultural damage were prevalent. The protracted religious wars between the Kalakhan Dynasty of Kashgar, Khotan and the Uighurs of the Western Zhou Dynasty ended Buddhist rule in the Western Regions, destroying the prosperity [46]. By the 19th century, the TRB had evolved into the existing pattern of four sources and one main stream. The southern part of Tarim River underwent significant changes, gradually splitting into several smaller isolated water systems, with the southern main stream completely disappeared. Additionally, the northern main stream shrank significantly and no longer flowed into Lop Nur Lake as before.

Before the 1850s, the environmental changes in the TRB were mainly due to natural factors. Thus, population pressure on water resources and the environment was minimal. Changes in oases and the expansion of desertification in the past can be regarded as gradual environmental changes against the backdrop of an arid climate. However, since the 1850s, the population of the TRB has increased rapidly, and the area of cultivated oasis has expanded greatly. At the same time, the TRB has been dominated by warm and wet climate, leading to a continuous increase in the area of natural oases. With advancements in science and technology and the development of industrial and agricultural production, the rate of increase in planted oases is accelerating, leading to serious pressure on irrigation water in cultivated oases. The rapid increase in cultivated oases is also escalating the pressure on water resources and environment in TRB.

The driving factors of the SESs in the TRB were analyzed using the Mann-Kendall trend test (Table 3). During the periods of 700–900 AD and 1850–2000 AD, the temperature significantly increased ($\beta = 0.003$), with Z_c values of 3.38 and 3.232 respectively, both reaching significance, indicating that climate warming had a substantial impact on the ecosystem. From 1760 to 2000, population growth was significant ($\beta = 0.941$, $Z_c = -2.630$), likely intensifying the pressure on natural resources and leading to changes in land use patterns. The frequency of wars significantly decreased during the period of 900–1850 AD ($\beta = 0.025$, $Z_c = -2.191$), possibly reflecting changes in social structure and governance, which reduced damage to the ecosystem. Glaciers significantly decreased during 700–900 AD ($\beta = -0.197$, $Z_c = -3.352$), while they increased during 900–1850 AD, likely related to fluctuations in regional climatic conditions. Precipitation significantly increased during the period of 1850–2000 AD ($\beta = 0.013$, $Z_c = 2.968$), potentially positively impacting water resource availability.

The SESs in the TRB have been influenced by various factors such as climate change, population growth, and human activities over the past 2000 years. Climate change, particularly the increases in temperature and precipitation, has had a significant positive impact on the ecosystem. Significant population growth likely has intensified pressure on natural resources, while the decrease in the frequency of wars might have reduced the negative impact on the ecosystem. Changes in glaciers and increases in precipitation have significant implications for the stability of water resources and the ecosystem.

4. Discussion

4.1. Selection reasons of indicators in social and ecological subsystems

Primitive tribes settled in the TRB, at least since 2000 BCE, over the past 2000 years, the TRB has experienced climatic changes such as warm-wet, warm-dry, cold-wet, cold-dry periods, and glacial and interglacial periods [45]. These changes significantly impacted the storage and melting of snow and ice in the Tianshan and Kunlun Mountains, causing runoff fluctuations. Concurrently, river channel siltation and desert drifting frequently altered river courses, affecting the rise and fall of settlements and oases relied upon by humans and vegetation. As social productivity improved, human activities exacerbated ecological degradation and desertification, which in turn further affected human activities [1,47]. Human activities and the ecological environment in the TRB have undergone significant changes, documented by abundant literature and archaeological data [48,49]. Therefore, we selected the period from 206 AD to 2000 AD for our study [50].

Climate change, wars, river course changes, and human activities have driven interactions of the SESs in the TRB over the past 2000 years affecting the ACR of these systems. From the 2nd century BC to the 18th century AD, influenced by nomadic civilizations, fishing and herding were the main production methods, and SESs were in a natural phase dominated by natural factors like climate change. From the 18th to the mid-20th century, due to large-scale population migrations and advanced agricultural productivity, humans gradually became the dominant factor in the development phase. From the mid-20th to the early 21st century, modern agriculture and productivity achieved unprecedented development, and human activities intensified ecological changes, with SESs entering a degradation and recovery phase dominated by human mechanisms [1]. The dominant factors varied across periods, leading to changes in socio-ecological system resilience.

Over the past 2000 years in the TRB, the establishment and abandonment of settlements have been crucial factors influencing population migration, economic forms, and social structure. River cut-offs and course changes reduced oasis areas and caused human settlement migrations. Additionally, wars triggered by different dynasties and ethnic groups fighting for control of the Western Regions intensified human settlement migrations. Therefore, we selected human settlements as an indicator of the social subsystem components. Climate factors significantly affect the oasis areas and river runoff. Warm-dry climates positively feedback the expansion of oasis areas and increased runoff, while cold-wet climates negatively feedback the contraction of oasis areas and reduced runoff. Natural oases area reflects the ecosystem's productivity level. In the TRB, natural oases are rare ecosystems with high productivity and biomass and extensive vegetation coverage, reflecting the region's productivity limits. At the same time, natural oases in arid areas are highly dependent on water sources and are sensitive and fragile to environmental changes. Their changes can earlier reflect the impacts and pressures on arid ecosystem. Therefore, we selected natural oasis area as an indicator of the ecological subsystem components. Planted oases serve as a link between social and ecological subsystems. The irrigation, planting, and output of planted oases directly depend on the state of water and land resources, indicators of ecological subsystem components. The output of planted oases sustains community livelihoods, and changes in them can trigger population and social relationship changes, in turn affect the ecosystem. Therefore, we chose planted oasis areas as an important indicator of the social subsystem.

To reflect the complexity of SESs in the TRB, we selected driving factors such as climate change, temperature, population, war frequency, glacier volume, percentage of new and abandoned settlements, and standardized rainfall values to explain regime shifts in the resilience cycle of SESs in the TRB during historical periods.

4.2. Slow and fast processes between socio-ecological system interactions

This study explores the resilience dynamics of SESs in the TRB over the past 2000 years. Several ACR cycles have been observed, with driving factors such as climate fluctuations, conflict frequency, and river channels shifts prominently shaping socio-ecological system resilience. During the gradual forward loop phase (r-K) of the ACR, SESs showed an increasing trend in resource utilization and system vulnerability. However, they maintained robust adaptive capabilities and resilience. In contrast, during the rapid backward phase (Ω-α) of the ACR, SESs in the TRB faced challenges such as environmental degradation, economic decline, and social unrest. The system was vulnerable during this phase, but it also underwent reconstruction and transformation.

Previous research has used models and algorithms such as the TOPSIS algorithm, obstacle degree model, and Taiji-Tire model to elucidate the evolution characteristics and influencing factors of the TRB's SESs during historical periods [1,30]. These studies identify three transition periods in the TRB over the past 2000 years, highlighting channel migration and climate change as primary drivers before the 19th century. After the 19th century, human influence became the dominant factor. Notably, rapid population growth and land reclamation in the 19th century align with this study's findings [1].

A parallel study investigating the evolution of SESs in the Loess Plateau over the past 1000 years delineated five distinct stages. This analysis identified 1100 to the 1750s as a phase characterized by rapid cultivation expansion [9]. During this period, the TRB was in the rapid backward loop phase (Ω-α) of the ACR, and socio-ecological system indices experienced a relative decline. It is important to note that this result differs from the current study, possibly due to significant population displacement in the TRB at that time, triggered by factors like wars and climate changes, leading to the abandonment of cultivated oases [51–53].

By applying the ACR theory, this study provides insights into the resilience changes of SESs in the TRB over the past 2000 years. It pinpoints key driving factors affecting socio-ecological system changes during different historical periods, offering a reference for future analyses, scenario development, and risk assessments. Furthermore, this research expands the scope of ACR theory and provides a practical case study to support model enhancements [54]. Adopting an ACR perspective to analyze long-term socio-ecological system changes opens new theoretical avenues for the sustainable development of future SESs [55,56].

4.3. Updated resilience framework of SESs for the future directions

Our research on the resilience changes in the SESs of the TRB over the past 2000 years has revealed certain limitations and potential areas for improvement. Specifically, some reconstruction data do not provide comprehensive coverage for the entire research period [57,58]. Among vital parameters for environmental evolution, changes in water systems and oasis areas are significant importance. While historical records meticulously document the locations of ancient rivers, oases, and deserts, determining the precise boundaries of ancient oases and deserts remains challenging. Currently, the delineation of ancient oasis boundaries relies primarily on approximations based on the distribution of modern water systems and oases [59,60].

This study used PLR to identify tipping points of regime shifts in the evolution stages of SESs. Subsequently, driving factors were used to qualitatively describe the resilience within the adaptive cycle of these systems. Based on Hooke's Law, which describes the physical law of material resilience, and the relative indices of SESs, a semi-quantitative resilience model was established. This approach enhances the precise understanding of resilience fluctuations over time. Drawing inspiration from research on the resilience changes within the water resources system in Zhejiang Province, a quantitative assessment method using the physical resilience model was proposed [37]. Furthermore, this study emphasizes the interconnectedness of human managers within complex adaptive SESs, highlighting the importance of understanding and dynamically managing these systems. This framework has been proposed to guide future interdisciplinary research on sustainability and resilience building. It encourages adopting a dynamic perspective when studying coupled societies and ecosystems. The application of complex concepts, such as tipping points, in the management of sustainable SESs is highlighted [61]. Additional research examples, ranging from the analysis of ecosystem services in Bangladesh to an empirical study on socio-ecological resilience in New Zealand, demonstrate the versatility and applicability of the proposed framework in various contexts.

In future research, it is essential to strengthen interdisciplinary studies by integrating methodologies and findings from archaeology, history, geography, and ecology to comprehensively understand historical environmental changes in the TRB. For example, employing interdisciplinary research methods such as systems thinking, model building, and comprehensive analysis provides valuable insights. Regularly evaluating the efficiency and outcomes of interdisciplinary collaboration and adjusting based on feedback will enhance the effectiveness of these efforts. Integrating interdisciplinary expertise allows for establishing a data-sharing platform and organizing interdisciplinary academic seminars and workshops. This approach provides a more comprehensive and accurate perspective for researching socio-ecological system resilience identification. It also offers scientific evidence for policy-making, promoting the sustainable development of social and ecological systems. Additionally, enhancing the exploration and verification of historical data is crucial for improving data usability. This involves deeply mining historical documents, including local chronicles, travel notes, and historical records, which may contain detailed descriptions of ancient water systems, oases, and desert locations. By analyzing environmental samples such as soil and sediments, researchers can obtain information on ancient environmental changes, aiding in determination of the extents of ancient oases and deserts. Data acquisition can also involve establishing environmental evolution models to simulate and interpret missing parts of historical data. Improving data reconstruction will subsequently enhance resilience evaluations.

Future research should focus on collecting more quantitative data to supplement and validate qualitative judgments in semi-quantitative models. Using statistical methods to quantify qualitative data can gradually transform semi-quantitative models into more precise and reliable quantitative models, thereby providing stronger support for decision-making. Future studies will be able to use quantitative adaptive cycle models to analyze socio-ecological feedback changes, identify key barriers and leverage points in the ACR, and evaluate the outcomes of socio-ecological transformations [62,63].

5. Conclusion

This study comprehensively analyzes the adaptive cycle resilience of SESs in the TRB over the past two millennia. It identifies different phases of SESs evolution, crucial for understanding the complex interactions between human activities and environmental changes. SESs in the TRB have undergone significant regime shifts due to external pressures such as climate change and human interventions. The ACR framework plays an important role in elucidating these transitions. Climate change and human activities have exacerbated ecological degradation and desertification, leading to key transitions within SESs. This study uses PLR to identify breakpoints in socio-ecological system interactions, which are critical in defining the stages of the ACR. The historical evolution of SESs in the TRB can be categorized into three distinct stages through PLR.

The findings reveal that the 7th century and 1850s were the critical points of regime shift in ACR. The periods 200s BC-350s AD and 700s AD-900s AD were in the forward loop (r-K) phase of the ACR. The periods 350s AD-700s AD and 900s AD-1850s AD were the adaptive resilience backward loop (Ω-α) phase. The warm and humid climate, low frequency of wars and stable river channels play a decisive role in the renewal and restoration of the system. This enhances the socio-ecological system's resilience, making them enter the forward loop (r-K) phase. Conversely, dry and cold climates, frequent wars, and significant river channel migrations will reduce SES's resilience. This makes SHSs more likely to enter the rapid backward loop phase (Ω-α) of ACR. After the 1850s, human factors became the dominant influence on socio-ecological system resilience driven by advancements in science, technology and the development of industrial and agricultural production. The advantage of this method is its ability to capture nonlinear dynamics within SESs, while its limitation is the reliance on historical data that may not fully represent the complexity of past environmental conditions. Future research needs to undertake interdisciplinary studies to gain a more comprehensive understanding of historical environmental changes in the basin. Additionally, enhancing the excavation and validation of historical data is necessary to improve the accuracy of environmental reconstructions and refine the semi-quantitative models used in this study, thereby providing stronger support for the decision-making.

Data availability

The datasets used for this study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Shunke Wang: Writing – original draft, Data curation. **Jie Xue:** Formal analysis, Conceptualization. **Zhiwei Zhang:** Software. **Huaiwei Sun:** Methodology. **Xinxin Li:** Methodology, Investigation. **Jingjing Chang:** Visualization, Data curation. **Xin Liu:** Investigation, Data curation. **Luchen Yao:** Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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