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Evaluating the sustainability of rural complex ecosystems during the development of traditional farming villages into tourism destinations: A diachronic emergy approach

Jinxin Zhu [a,b], Xiaomei Yuan [a,b,*], Xingzhong Yuan [c,d,**], Siman Liu [a,b], Beiting Guan [a,b], Jinfang Sun [c], Hongfei Chen [c,d]

[a] School of Architecture, South China University of Technology, Guangzhou, 510641, China
[b] State Key Laboratory of Subtropical Building Science, Guangzhou, 510641, China
[c] Faculty of Architecture and Urban Planning, Chongqing University, Chongqing, 400030, China
[d] Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing, 400030, China

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ABSTRACT

Many villages that have transformed from traditional agricultural communities into tourism destinations to eliminate poverty are encountering ecological and social crises that threaten sustainable development. The dilemmas of rural complex ecosystems are the cumulative results of historical material and energy exchange between humans and nature in the social-ecological dimension. A tool for evaluating sustainability, emergy theory, measures different resource flow qualities. To conserve healthy rural ecosystems, dynamic equilibrium with a coupled interrelation of social development and energy operation must be maintained within system carrying capacities. This raises the question that current emergy studies ignored of how to explore reference indicators for technical solutions and the roots of sustainability change for rural governance systems under social development. This paper proposes a diachronic emergy approach that integrates emergy evaluation into an environmental history research framework with social development models and social-ecological factors to realize system well-being. Considering the village of Hekeng, China, emergy accounting was performed for three typical years (1953, 1990 and 2015) combined with social development models (traditional agriculture, chemical-assisted agriculture and commercial tourism periods). Based on the benchmark year 1953, a diachronic analysis of changes in emergy indicators reconstructed in a social-ecological context and corresponding social-ecological factors was conducted. The results show that the EYR and ELR of 3.16 and 0.53, respectively, for 1953 can be employed as reference indicators of resource utilization in the sustainable development of Hekeng. The potential impacts of resource use changes on the system's well-being were explored, and the findings indicate that technical solutions must be integrated with a governance system based on production relations, forest environments and community culture. Recommendations for sustainable development of ecological agricultural techniques, ecotourism modes, and governance with social-ecological integration are proposed. The diachronic emergy approach provides a new perspective for the implementation of technical solutions in human society and the formation of sustainability strategies for system well-being.

1. Introduction

As the product of human settlements of agrarian age, traditional farming villages are complex ecosystems in which natural, economic and social subsystems are integrated (Wang et al., 2018). Humans carry out material recycling and energy flows with nature through production and lifestyles, a process that operates within the social-ecological dimension. The ancient Chinese philosophy of the "heaven, earth, and mankind" triad indicates that humans cohabit harmoniously with nature, forming a corresponding community culture; these values have

* Corresponding author. School of Architecture, South China University of Technology, State Key Laboratory of Subtropical Building Science, Guangzhou, 510641, China.
** Corresponding author. Faculty of Architecture and Urban Planning, Chongqing University, Chongqing, 400030, China.
E-mail addresses: xmyuan@scut.edu.cn (X. Yuan), 1072000659@qq.com (X. Yuan).

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sustained China's agricultural society for 5000 years (Chen et al., 2018; Zheng et al., 2018). Humans' utilization of natural resources has changed towards the reliance of technological advances embedded in rapid social development and has become market-oriented since industrialization (Liu, 2018; Long et al., 2009). Moreover, commercial tourism development has ascended history to eliminate poverty in many villages (Christensen and Jones, 2020), especially in developing countries (Regmi and Walter, 2017). Because rural areas are heavily dependent on natural inputs and ecosystem processes to fulfil the production functions of land (Falkowski et al., 2015; Pincetl et al., 2012), a large amount of capital from institutions at different governance levels is invested in consuming natural resources, which will ultimately hinder their self-organization and balanced system states, resulting in very prominent natural environmental and social crises that are interconnected and historically accumulated (Agostinho et al., 2010; Li et al., 2019; Takeuchi et al., 2016). The task of achieving sustainable development requires not only that technology be optimized but also that the underlying issues and roots of the sustainability crisis be addressed for the development of long-term holistic strategies.

To assess the cumulative sustainability results of the material recycling and energy flows between humans and nature in rural areas, it is necessary to identify a way to measure the real wealth of both the natural environment and human activity. Emergy theory, which provides a biophysical perspective, was developed in the 1980s and 1990s by H.T. Odum, the father of systems ecology (Odum, 1988, 1996). The theory refers to the conversion of various products (natural or man-made) into solar emjoules (sej) as a unified, self-consistent method for quantifying the relative value of emergy flows of human activity and the environment (Amaral et al., 2016; Hopton et al., 2010). The ability to equally assess energy, material and information makes emergy analysis an attractive tool for assessing the sustainability of various ecosystems (Chen et al., 2017; Xiao et al., 2017). However, emergy analysis at the rural level with more emphasis on a single agricultural ecosystem may produce isolated judgments in the ecological domain. For instance, a sustainable agricultural model with widespread application in southern China, the mulberry plot fish pond, integrates mulberry cultivation, sericulture and fish farming to fully exploit the production potential of an ecosystem. This model has transformed the social development of the Pearl River Delta region with the replacement of paddy rice cultivation while requiring a constant supply of grain from external sources, which has caused the depletion of grain in other regions, such as Guangxi. Although mulberry plot fish ponds are usually regarded as a model of sustainable ecological agriculture by ecologists who are unable to recognize that the system is not closed or isolated, the system is unsustainable unless an increasing number of external resources are input into the system (Marks, 2020). From this case, it is evident that the roots of realistic sustainability crises should be explored in the dynamic context of social development rather than a one-sided focus on technical solutions by regarding rural areas as complex ecosystems that are related to the integration of the natural environment, economic development and social culture. Complex rural ecosystems with high sustainability have the adaptability to adjust to changing social development and energy operation within a certain range of system carrying capacities. Current studies about single agricultural ecosystems, such as farms or specific agricultural systems (Liu et al., 2019; Wang et al., 2017; Zhang et al., 2012), have focused on proposing technical solutions with minimal discussion about providing reference indicators conducive to sustainable development. On the other hand, emergy studies based on sufficient time series have argued the changing trends of indicators and sustainability (Cheng and Cheng, 2018; Wan et al., 2021), and few studies have considered that the different patterns of energy flows might build on the specific dynamic process of social development and focused on the roots of sustainability change for strategies. As the definition of sustainability shows, in addition to balancing the physical relationships between human activity and the natural environment, system well-being should also be addressed (Janker et al., 2019; Morén-Alegret et al., 2018; Rogers et al., 2012). Different from the dynamic analysis of emergy evaluation in general agricultural ecosystems (Ghisellini et al., 2014), the dynamic process of material recycling and energy flow involved in human-nature interactions in rural complex ecosystems operates within a unique social-ecological context. With social transformation from traditional farming to modern societies, the patterns of material and energy use and the well-being of system outputs are changing over time. Thus, attention must be shifted to social-ecological contexts and goals toward achieving system well-being while evaluating the sustainability of a system or region using emergy theory.

As a new disciplinary area that emerged in the 20th century, environmental history explores the changes in human-nature interactions that occur throughout historical processes, including social and ecological dimensions, and provides a useful perspective for formulating long-term strategies (Elvin, 2008; Marks, 2011; Zhang, 2016). Oral history collection, participatory observation and personal interviews can help supplement a lack of available data and specific data with historical depth. Previous research has revealed how complex human-nature interactions develop over time, which can inform policy adaptations (Steen-Adams et al., 2015). However, there has been minimal quantitative analysis of the impact of human-nature interactions on system sustainability. Yuan (2019) mapped material and energy circulation diagrams for the village of Hekeng from the aspects of the natural environment, society and the economy with preliminary restoration of the socioecological status, in order to summarize crises in the agricultural ecosystem and human activities from a historical perspective, covering the farming period, chemical agriculture period and commercial tourism period. It has been effectively established that the deviation of human production and lifestyles from the circulatory system of materials and energy in an agrarian society, which represent social-ecological dimension aspects, can be identified as the main issue. In view of the limitations of emergy studies for providing reference indicators and exploring the roots of sustainability change for strategies in rural areas, this paper provides an innovative method, namely, the diachronic emergy approach. This approach integrates the emergy evaluation method into an environmental history research framework with the introduction of social development models and social-ecological factors to realize system well-being. Selecting the village of Hekeng as a case study, a diachronic analysis is carried out by an emergy assessment of typical years with corresponding social-ecological factors under different patterns of material and energy use and social development models from traditional farming to tourism development. The proposed approach can provide technical solutions based on reference indicators and adapted governance systems for the sustainable development of rural systems. Moreover, this paper provides suggestions for the formation of long-term and holistic strategies for sustainable development and system well-being.

2. Study area

2.1. Hekeng village

The village of Hekeng, which was chosen for this case study, is located in the southwestern part of Fujian Province, China, in the town of Shuyang, Nanjing County, Zhangzhou (Fig. 1). Hekeng is known as the "eight mountains of water as a subfield," which means that it has a scarcity of arable land. In 2015, the village's permanent registered population reached 1413; all residents were Hakka. Harsh environmental conditions and the formation of adaptive production systems and lifestyles pose a great challenge to indigenous people in the area. Residents have continuously transformed material and energy in the natural environment into products to sustain themselves during traditional agricultural periods, thus forming a community culture based on coordinated interactions among heaven, earth, and mankind.

During the Ming Dynasty (1443 AD), the Zhang family migrated to

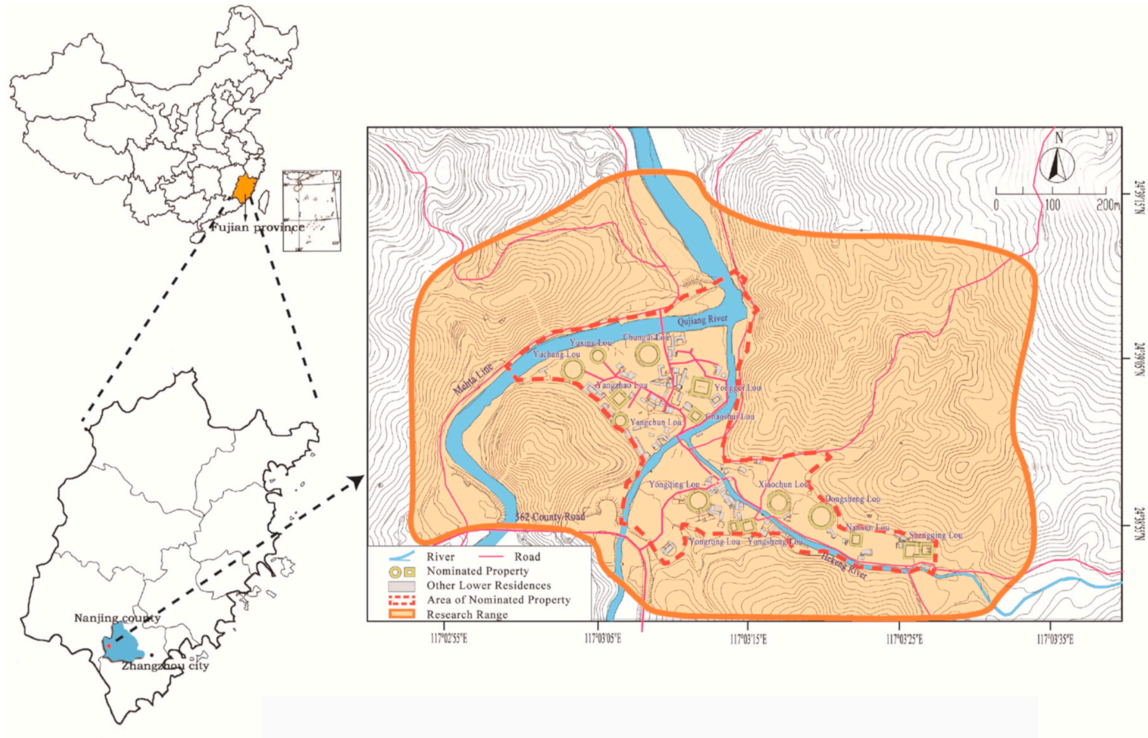

Fig. 1. Location of the study area and research boundaries.

Hekeng and constructed the first Hakka earth building (abbreviated as Tulou). By the Qing Dynasty (1850 AD), seven square Tulous and some religious spaces had been built, forming a settlement space combined with an agricultural ecosystem (Fig. 2a). The land was privately owned during this period, and the clan managed many affairs as an autonomous organization in the village. Villagers were accustomed to recycling nutrients from plants and animals back into the soil and carefully maintaining the regeneration and balancing of the material energy circulation system using traditional ecological knowledge. During the land reforms after the founding of New China (1949), the trend toward collectivization changed the village from a family community into a new collective economic community. Although the social development and management modes adopted in 1953 were somewhat different from those adopted by a traditional society, the state of material and energy flows in 1953 reflected that of a traditional society. Based on its proximity to contemporary times and the data availability that can be supplemented by oral history collections, 1953 was chosen as a representative year.

Due to the heavy endowment of resources reflecting the human-land relationship, China's modern agricultural revolution was delayed until the 1980s (Huang, 2016), with the second leap of the rural economy after 1978. The household contract responsibility system and market economic system were established in the early 1990s in the village of Hekeng. The policy of dividing farmland into households was embraced with enthusiasm by the villagers, and the stable settlement pattern changed (Fig. 2b). In the 1990s, religious spaces and forest vegetation began to be rebuilt and restored (The State Administration of Cultural Heritage of China, 2008) (Fig. 3a and b). Coupled with the increasing outflow of young adults after 1978, the villagers' lifestyles in Hekeng underwent tremendous changes. In 1990, faced with the popularization of modern agricultural production technologies, the self-organization and balancing of agricultural ecosystems were seriously undermined.

In 2008, Hekeng successfully applied for World Heritage status to conserve the Tulou. One of the goals of heritage protection is to promote the development of the local economy, which undoubtedly brings about the rapid development of commercial tourism. The village lost its recycling mechanism for regeneration, and it became a tourist attraction with energy consumption and emissions. According to the protection plan, which was revised in January 2009, the government removed buildings attached to the Tulou, including pigpens, aquaprivies and tea

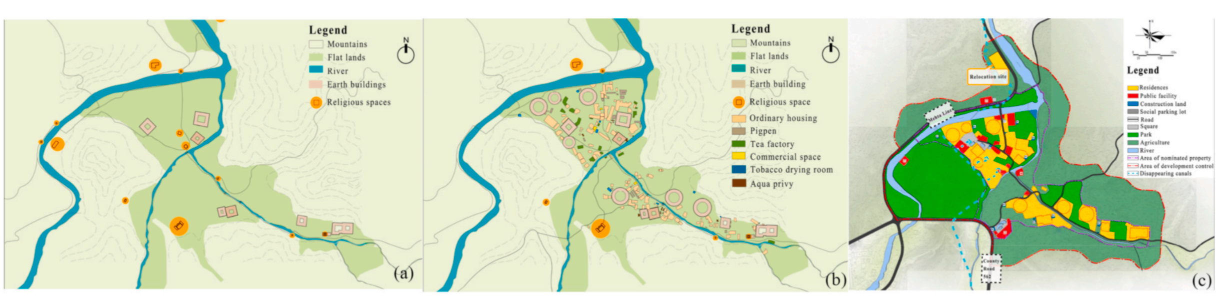

Fig. 2. Schematic of settlement space evolution in the village of Hekeng. (a: Qianlong period of the Qing Dynasty, drawn according to the present topographic map of Hekeng provided by the Hakka Earth Building Management Committee of Nanjing County, combined with genealogy records and investigation results. b: Before applying for World Heritage status. c: Planning map of Hekeng. The maps in b and c were redrawn from "Protection Planning of the Village of Hekeng in the Town of Shuyang, Nanjing County (revised in January 2015)."

Fig. 3. Photos of settlement evolution in Hekeng in different years (a: 1990; b: 2017).

factories. Moreover, the nature of the land around the settlement has changed (Fig. 2c). Currently, Hekeng is in a period of tourism stagnation in terms of management and maintenance. As a village that relies on World Heritage status and the Tulou to develop tourism in the face of many predicaments relating to protection and development (Yuan, 2019), Hekeng can be representative of villages that have transitioned from traditional farming villages to tourism destinations. This paper can provide some predictive and strategic guidance for future development.

Excluding the special period in China and based on the availability of statistical data, this study employed 1953, 1990 and 2015 as representative years when the settlement space form and the resource utilization mode were relatively stable (Fig. 2). Moreover, 1953, 1990 and 2015 represent the typical patterns of social development and accumulated material and energy use for the periods of traditional agriculture (1443 AD-1978), chemical-assisted agriculture (1978–2008) and commercial tourism (2008–2020), respectively.

2.2. Study site

Regarding long-term holistic strategies for sustainable development in rural China, especially for heritage conservation under the background of commercial tourism, we must seek successful prototypes in the social-ecological context with the integration of humans and nature in a manner that is beneficial to both humans and nature (Takeuchi et al., 2012). According to the planning text revised in January 2009, Hekeng demarcated the core protection area to 50 m outside the village boundary. The research area of this study is limited to the village area (Fig. 1), which is within the scope of human-nature interactions centered on the daily lives and production of villagers in Hekeng, as determined by field investigations, including the core area of the 2009 Hekeng Village Plan (17.40 ha). The study site covers 78.03 ha, representative of a typical rural complex ecosystem in Hekeng.

3. Methodology of the diachronic emergy approach

3.1. Research framework

As shown in Fig. 4, we performed a case study of Hekeng by employing a literature review and field investigation. Corresponding to an understanding of the social development models in three historical periods, emergy accounting for three typical years was conducted to identify the benchmark year with a harmonious relationship between the system's energy performance and social development. The emergy indicators of the system over three years were synchronously analyzed with the corresponding social-ecological factors of different historical periods, and other regions were selected for a synchronic comparison of each year to clarify resource utilization statuses and their social-ecological backgrounds. Based on data from the benchmark year, a diachronic analysis of changes in the emergy indicators and social-ecological factors was conducted to identify reference indicators, to explore the roots of sustainability changes in the dynamic context of social development and to propose corresponding technical solutions and governance systems suitable for sustainable development. Suggestions for long-term strategies for the well-being of the system were proposed.

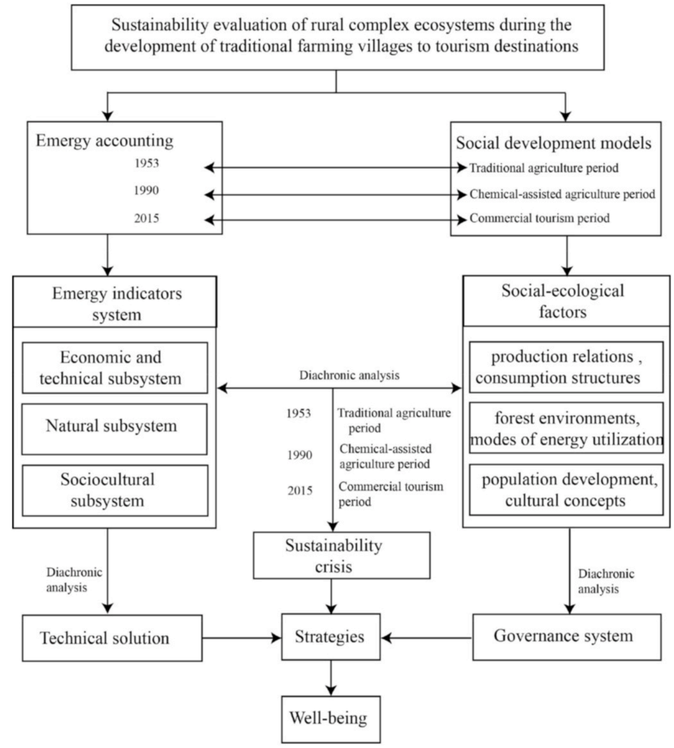

Fig. 4. Research framework for the diachronic emergy approach for rural complex ecosystems.

Within the framework of environmental history, analytical and interpretative models mainly highlight the integration of social and ecological factors (Agnoletti and Neri Serneri, 2014). The crisis of sustainable development faced by many villages, as represented by the village of Hekeng, has been the result of the historical accumulation of interactions between humans and nature (Yuan, 2019). Thus, in this social-ecological context, integrating emergy accounting for typical years into the framework of environmental history can privilege the introduction of a social development model, which was illustrated with human-nature interactions focused on the production and lifestyles of villagers in different historical periods. As the primary actors in a village, villagers participate in the operation of the natural ecosystem through their cultural existence and influence the village's material recycling and energy flow process through specific production and lifestyle practices. After identifying the benchmark years, the diachronic emergy analysis was integrated into the dynamic context of social development and accompanied by the introduction of social-ecological factors. The social-ecological factors covered by the framework of environmental history with the greatest influence on the patterns of material recycling and energy flow of the system were identified through a literature review and field investigation (Takeuchi et al., 2016), including production relations and consumption structures, forest environments and modes of energy utilization, cultural concepts and population development related to the economic aspect, natural aspect and social aspect, respectively, of system sustainability (Fig. 4). Under these circumstances, the emergy indicator system in diachronic emergy analysis needs to be reconstructed. The indicators of the economic and technical subsystems, natural subsystem, and sociocultural subsystem are represented by the intensity of economic development and output efficiency, utilization of natural resources and pressure on the natural environment, population living standards and comprehensive sustainability of the system, respectively. Beyond the standard measure of money, the components of well-being usually include three parts, namely, material concerns, relational concerns and subjective concerns (Coulthard et al., 2011). In this paper, sustainability is defined by the emergy assessment results, and the factors of a system's well-being include physical health, environmental quality, social relations and life satisfaction.

This paper proposes a diachronic emergy approach that applies to a rural complex ecosystem transforming from a traditional farming village to a tourism destination. The integration of an emergy evaluation method in the research framework of environmental history contributes to the introduction of social development models and social-ecological factors that can correspond to emergy accounting and emergy indicators in the diachronic emergy approach. Technical solutions based on reference indicators and governance systems in social-ecological contexts to achieve system well-being can then be explored. This method is conducive to providing sustainable development strategies for the well-being of a system as a new perspective and an operational means for the actual implementation of technical solutions in a real social environment.

3.2. Data sources

3.2.1. Literature research

Considering the availability of data, a review of the existing literature through archival and press research and a field investigation by oral history collections were conducted. Regarding the former, we consulted three types of primary documentary materials: (1) local chronicles, (2) statistical yearbooks and annals published by county governments, and (3) genealogy and statistical data compiled by the villagers' committee. Since the economic development level of Hekeng in 1953 and 1990 was near the average economic development level of Nanjing County, the raw data of these two periods were primarily derived from statistical yearbooks, published papers and governmental reports referring to the average value of Nanjing County (Forestry Bureau of Nanjing County, 1999; Local Chronicles Compilation Committee of Nanjing County, 1997; Statistics Bureau of Nanjing County of Fujian Province, 1979, 1991; Water Conservancy And Hydropower Bureau of Nanjing County, 1999). The consumption structure data for 1991 to 2014 refer to the national economic statistics yearbook of Nanjing County. Considering that many tourism projects in Hekeng have not been fully implemented, some data on the tourism development period were primarily obtained from field investigations with local villagers and stakeholders and supplemented with the 2015 Nanjing Statistical Yearbook and 2015 Hekeng planning text. The cultivated land data were obtained from the General List of Resource Assets Inventory and Registration of Hekeng in 2018, and the results of the field investigation were employed to deduce these data in reverse.

3.2.2. Field investigation

From August 10th, 2017, to January 6th, 2020, a total of four systematic quantitative surveys and several qualitative supplementary surveys were performed. The average duration of each survey was 20 days. In addition, this study follows oral history collections, semi-structured interviews and participant observations with village cadres, remaining villagers and migrant workers, especially elderly people with extensive local knowledge. The interviewees were chosen based on their trajectory and experience of having lived in Hekeng for at least 5 decades and having witnessed potential changes in land use. The events that triggered changes in the village, the years in which these changes occurred and the biophysical and/or socioeconomic reasons for any changes were identified. The interviewees were asked to reconstruct their histories in terms of lifestyle and agricultural practices, to describe their current situation in terms of well-being (i.e., social relationships and life satisfaction) and to provide supplementary data for emergy calculations (i.e., information on the amount of time, money, pesticides and fertilizers required for farming; the village population; the amount of arable land; the division of labor; and the prices of specific cash crops and products). In addition, physical health data were drawn from the Shuyang Health Institute, and environmental quality information was obtained through onsite observations and interviews. These data were further validated by local stakeholders via informal meetings.

4. Emergy accounting of typical years in different social development models

The emergy evaluations of Hekeng's complex ecosystem were conducted as follows:

(1) After the system boundary is identified, we draw a system diagram (Fig. 5) for each period according to the results of the field investigation to describe the emergy input and output across the boundary.
(2) The related emergy flows are classified into six categories: renewable natural resources (R), nonrenewable natural resources (N), renewable purchased emergy input (F_R), nonrenewable purchased emergy input (F_N), total purchased emery input (F) and yields (Y).
(3) Emergy is expressed in sej by multiplying the available energy by an appropriate solar transformity, which is a conversion factor for converting available energy into emergy. Thereafter, we can create an emergy analysis table and establish emergy-based indicator systems according to the calculation results. These indicators can also be compared to the corresponding indicators of other regions so that the development and utilization of resources in Hekeng can be better understood. Since few researchers have conducted emergy analyses of entire villages, the scale of the synchronous comparison area utilized in this study covers the country, province, and village of China. Thus, the calculated results are intended to reflect the relative development level over three years.

Transformity represents the unit emergy of a product or energy flow; it is expressed in sej/unit. Transformity is an indicator of the energy quality scale. Larger transformity values correspond to better energy quality, higher placement on the energy hierarchy in the energy system and a greater need for environmental support for the process and product (Cavalett et al., 2006; Odum, 1996). When comparing two or more processes that produce the same output, a lower transformity value can be regarded as a measure of higher efficiency, i.e., fewer resources are required to produce the same number of products or more products can be obtained with the same emergy input (Mu et al., 2013; Zhang et al., 2012). In this study, all of the transformities of emergy input were obtained from papers published in international peer-reviewed journals and from the National Environmental Accounting Database (NEAD), and the transformities of emergy output were calculated according to the characteristics of the total inheritance of the emergy algebra. Detailed information on the raw data and corresponding transformities are shown in Table 1.

To avoid double calculation, the same emergy inputs consider only the maximum value according to emergy theory, and wind, rain geopotential, rain chemicals and earth cycle energy are defined as forms of solar energy conversion. In addition, we applied the new global emergy baseline (12.00 E+24 sej. yr^{-1}) calculated by (Brown et al., 2016). Therefore, the previously calculated transformities and emergy-based indicators of the compared regions were converted to the baseline of 12.00 E+24 sej. yr^{-1} by multiplying the factor of (12/9.44) (from a baseline of 9.44 E+24 sej. yr^{-1}) and (12/15.83) (from a baseline of 15.83 E+24 sej. yr^{-1}).

Although the collected data were derived from both previous

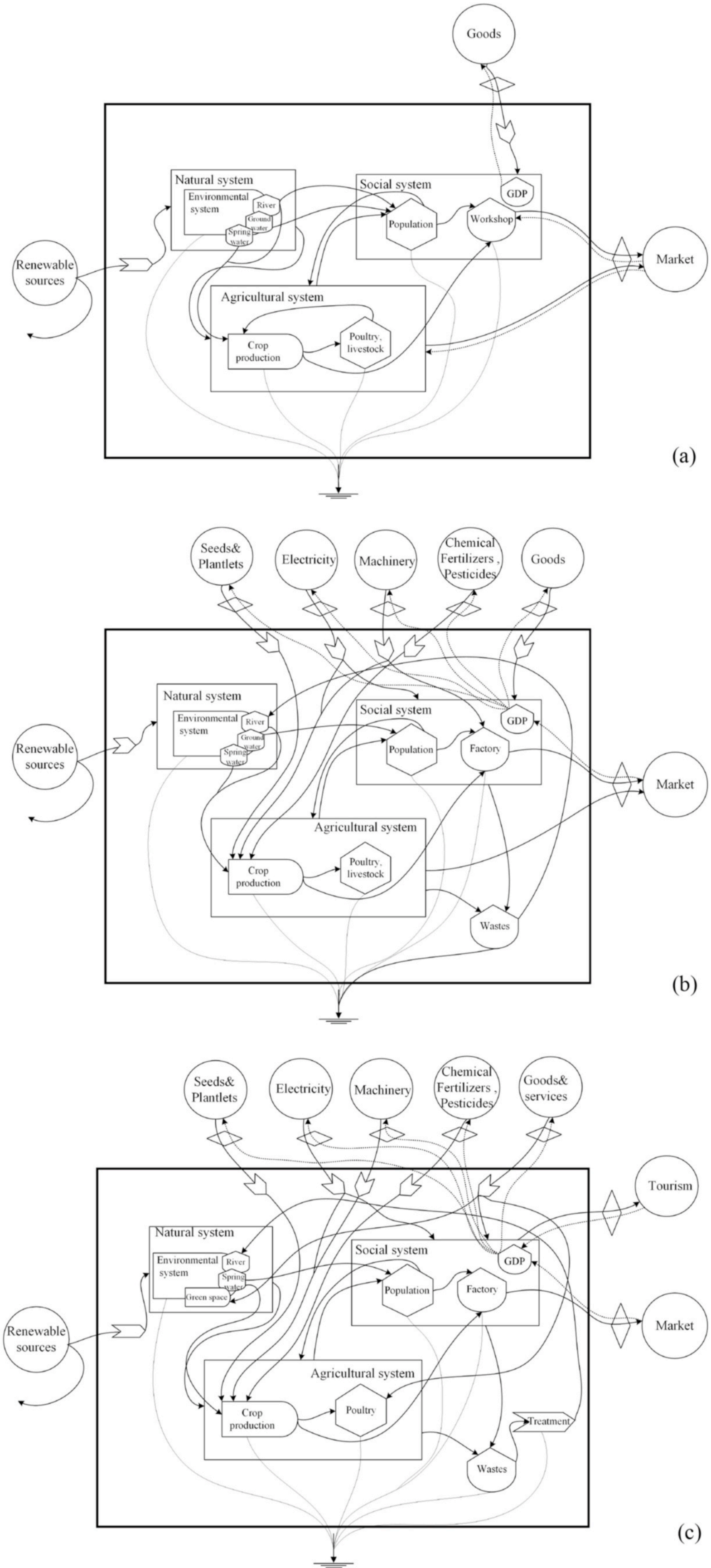

Fig. 5. Emergy diagram of the social development models transforming from traditional agriculture (a) to chemical-assisted agriculture (b), and then to tourism development periods (c).

Table 1
Data employed for an emergy-based sustainability evaluation, and major emergy flows of Hekeng during typical years for different periods of social development models.

Note	Item	Raw data			Unit	UEV (sej/unit)	Reference	Solar emergy (sej/yr)		
		1953	1990	2015				1953	1990	2015
Renewable natural resources (R)										
1	Solar	2.75 E+07	2.75 E+07	2.75 E+07	J	1.00 E+00a	Odum (1996)	2.75 E+07	2.75 E+07	2.75 E+07
2	Wind	1.87 E+11	1.87 E+11	1.87 E+11	J	1.90 E+03a	Odum (1996)	3.55 E+14	3.55 E+14	3.55 E+14
3	Rain, geopotential, land	2.86 E+11	2.91 E+11	2.75 E+11	J	1.33 E+04a	Odum (1996)	3.82 E+15	3.88 E+15	3.66 E+15
4	Rain, chemical	6.84 E+12	6.94 E+12	6.55 E+12	J	2.31 E+04a	Odum (1996)	1.58 E+17	1.61 E+17	1.52 E+17
5	Earth cycle	7.80 E+11	7.80 E+11	7.80 E+11	J	4.37 E+04a	Odum (1996)	3.41 E+16	3.41 E+16	3.41 E+16
Sum of R (maximum of line items 1 to 5)								1.58 E+17	1.61 E+17	1.52 E+17
Nonrenewable natural resources (N)										
6	Topsoil losses	7.69 E+10	1.14 E+11	5.85 E+10	J	9.40 E+04 b	Wang et al. (2017)	7.23 E+15	1.08 E+16	5.50 E+15
Renewable purchased emergy input (F_R)										
8	Seeds		2.69 E+11	1.38 E+11	J	8.41 E+04c	Odum et al. (2000)		2.27 E+16	1.16 E+16
9	Plantlets		1.48 E+12	8.95 E+11	J	8.41 E+04c	Odum et al. (2000)		1.24 E+17	7.53 E+16
10	Labor for tourism			1.68 E+11	J	5.73 E+06 d	Brandt-Williams (2002)			9.65 E+17
Sum of F_R (sum of line items 7 to 10)									1.47 E+17	1.05 E+18
Nonrenewable purchased emergy input (F_N)										
11	Goods	4.03 E+03			$	1.90 E+13	NEAD (2000)	7.65 E+16		
12	Goods		3.82 E+05		$	1.70 E+13	NEAD (2004)		6.50 E+18	
13	Goods			1.82 E+06	$	1.10 E+13	NEAD (2008)			2.00 E+19
	Fertilizers									
14	Nitrogen(N)		2.95 E+07	1.51 E+07	g	4.84 E+09 b	Wang et al. (2017)		1.42 E+17	7.28 E+16
15	Phosphate (P_2O_5)		1.07 E+07	5.45 E+06	g	4.97 E+09 b	Wang et al. (2017)		5.29 E+16	2.71 E+16
16	Potash (K_2O)		9.83 E+05	5.02 E+05	g	1.40 E+09 b	Wang et al. (2017)		1.38 E+15	7.04 E+14
17	Compound fertilizer		4.91 E+06	2.51 E+06	g	3.56 E+09a	Odum (1996)		1.75 E+16	8.94 E+15
18	Pesticides		2.50 E+06	1.28 E+06	g	2.03 E+09e	Lan et al. (2002)		5.08 E+15	2.60 E+15
19	Agricultural film		1.45 E+06		g	4.83 E+08e	Lan et al. (2002)		7.01 E+14	
20	Mechanical power		7.05 E+10	1.06 E+11	J	7.50 E+07f	Wang et al. (2019)		5.29 E+18	7.95 E+18
21	Electricity		9.97 E+10	2.11 E+12	J	2.18 E+05 b	Wang et al. (2017)		2.17 E+16	4.58 E+17
22	Maintenance			6.39 E+05	$	1.10 E+13	NEAD (2008)			7.03 E+18
23	Pollution abatement			1.22 E+04	$	1.10 E+13	NEAD (2008)			1.34 E+17
Sum of F_N (sum of line items 11 to 23)								7.65 E+16	1.20 E+19	3.57 E+19
Sum of F (sum of F_R and F_N)								7.65 E+16	1.22 E+19	3.67 E+19
Total emergy used (U) *(sum of R, N and F)*								2.42 E+17	1.23 E+19	3.69 E+19
Yields (Y)										
24	Paddy rice	1.36 E+04	4.15 E+04		$					
25	Tobacco	1.78 E+01	1.24 E+05		$					
26	Meat	3.13 E+04	3.72 E+04		$					
27	Egg	1.93 E+04	3.49 E+04		$					
28	Bamboo	1.24 E+03	1.79 E+04		$					
29	Wood	2.55 E+03	3.33 E+03		$					
30	Handmade paper	9.58 E+02			$					
31	Tea-leaf		5.12 E+03	8.69 E+04	$					
32	Fruit		2.35 E+03		$					
33	Tourist income			7.84 E+05	$					

Note: a Odum, 1996 (converted to 12.00 E+24 $sej.yr^{-1}$ baseline from 9.44 E+24 $sej.yr^{-1}$ baseline); b Wang et al., 2017 (converted to 12.00 E+24 $sej.yr^{-1}$ baseline from 15.83 E+24 $sej.yr^{-1}$ baseline); c Odum et al., 2000 (converted to 12.00 E+24 $sej.yr^{-1}$ baseline from 15.83 E+24 $sej.yr^{-1}$ baseline); d Brandt-Williams, 2002 (converted to 12.00 E+24 $sej.yr^{-1}$ baseline from 15.83 E+24 $sej.yr^{-1}$ baseline); e Lan et al., 2002 (converted to 12.00 E+24 $sej.yr^{-1}$ baseline from 9.44 E+24 $sej.yr^{-1}$ baseline); f Wang et al., 2019 (no need to convert). Refer to Appendix A for calculation details and sources of emergy flow data.

documentation and in-depth interview sources, we attempt to holistically explore emergy flows for different social development periods to support the sustainable development of the complex ecosystem in Hekeng. The emergy values may suffer from uncertainty and approximation. However, these factors do not have significant effects on the final results because the degree of uncertainty is very marginal, and this study highlights comparisons of the temporal dynamics of emergy changes across typical years.

The historical accumulation of the completely different states of material and energy operation under the dynamics of human-nature interactions can be performed by combining the cumulative results of emergy accounting for typical years with the corresponding analysis of social development models for different historical periods.

4.1. *Traditional agriculture period (1443 AD-1978)*

During the traditional agriculture period, the villagers of Hekeng depended on local natural resources for production and life. Rich spring water and rivers are diverted to irrigate paddy fields, and river water is directly utilized as drinking water in daily life. Other production activities comprised planting dryland crops, including sweet potatoes, corn, and potatoes, and managing forests. Crop residue as fodder for livestock and manure as organic fertilizer returned to the farmland form an agricultural structure that centers on food production, livestock and forest production. As previously stated, the total emergy invested to support each of the four output sectors reached 2.42 E+17 sej in 1953 (Table 1). In concert with the economy primarily relying on selling tobacco and handmade paper with small workshops, the transformity of tobacco and handmade paper contributed the largest shares (1.36 E+16 sej/$ and 2.53 E+14 sej/$, respectively). As Hekeng gradually became a transfer station for transferring mountain goods from Yongding County to the town of Shuyang during the Republic of China period, rural markets and courier stations were constructed for trade and commerce, and people began to exchange daily goods through markets to meet their material needs. The purchased emergy input accounted for 31.62% of the total emergy input in 1953. Therefore, the energy operation of the system during this period focused on the internal cycle of local resources, as natural resources represented 68.38% of the total emergy input, the state of relative harmony and stability was inherent in social development and the villagers coexisted with nature in a close and harmonious relationship.

4.2. Chemical-assisted agriculture period (1978–2008)

During the period of chemical-assisted agriculture, accompanied by improvements in production technology, the reform of the economic system and an increase in population, the relationship between villagers and land weakened and became more indirect, and the material recycling and energy flows of Hekeng underwent substantial changes. The need for a planned economy led to road development to transport bamboo and wood directly out of the forests, and the transformity of wood and bamboo in 1990 increased relative to that in 1953, showing that the natural ecosystem dominated by forest was destroyed during this period. With the development of the market economy in the 1980s, the transformity of tobacco in 1990 reached 9.92 E+13 sej/$, which is lower than that recorded in 1953, showing that villagers began to depend on mechanized production during this period. After the 1980s, cash crops such as tea and fruit trees were cultivated for economic benefits, which occupied paddy fields and required more external inputs (such as chemical fertilizers and pesticides) and careful management. In 1990, the emergy input of goods, machinery and all pesticides and chemical fertilizers contributed to 52.63%, 42.83% and 1.78%, respectively, of the total emergy inputs. Thus, until 1990, changes in villagers' ways of life resulted in a preference for purchased external resources, as shown in Table 1. The total emergy input in 1990 was 1.23 E+19 sej, of which natural and purchased emergy inputs accounted for 1.39% and 98.61%, respectively. Social development was in a state of turbulence between the pursuit of economic growth and the self-balanced state of energy flow in the system.

4.3. Commercial tourism period (2008–2020)

With World Heritage conservation of the Tulou, along and the goal of continuous economic development, the village of Hekeng has transformed into a scenic commercial hub that is reliant on cash, which has affected the social development model and completely changed the village's emergy flow system. Green spaces, such as parks, brought by tourism development have replaced some farmland, followed by increased additional inputs of labor and maintenance. As stated in the survey data, with the loss of workforce and the abolition of livestock, grain and meat once produced self-sufficiently have been gained by purchasing. The purchased emergy input accounted for 99.57% of the total emergy input in 2015, which is substantially greater than that in 1953 (accounting for 31.62%), as shown in Table 1; these inputs, goods, machinery and maintenance accounted for the largest proportions (54.43%, 21.64% and 19.15%, respectively). The system output in the commercial tourism period relies mainly on tea and tourism. As the community has transformed from a self-sufficient traditional agricultural system to a chemical-assisted agricultural system reliant on economic benefits and then to a tourism destination separated from agricultural production, the accumulated external emergy inputs have caused the energy operation of the system to lose its recycling mechanisms of regeneration.

According to this analysis, as a representative year of China's first economic boom and increased productivity with land reform, 1953 can be regarded as the benchmark year for a state of relatively dynamic equilibrium of the system under the coupled interrelation of social development and energy operation. Based on the designation of 1953 as a benchmark year, a diachronic analysis was conducted by combining social-ecological factors with the emergy indicator system.

5. Diachronic emergy analysis of the social-ecological context

5.1. Economic and technical subsystem influenced by production relations and consumption structure

In Hekeng, as production relations changed from a focus on private land ownership to a focus on collective production after 1949 and then to a household contract responsibility system after 1978, many paddy fields were covered with flats, and irrigation canals disappeared. Most of the terraced fields have been converted to plant cash crops, especially tea, and the village's agricultural ecosystem has fundamentally changed, resulting in increasingly weakened connections between villagers and the land. The consumption structure of villagers began to become diversified after 1978, and per capita food consumption accounted for 62% of total expenditures, of which staple foods accounted for 29.7% in 1991. Over the next few years, per capita consumption in the medical, transportation and entertainment sectors increased (Fig. 6). The empower density (ED) is a measure of the spatial concentration of emergy flows in a process or system and indicates the intensity of economic development and grade of the evaluated system. The emergy yield ratio (EYR) is used to measure the efficiency of system outputs; it is usually large because developing regions must rely on outside materials and energy to develop their economies. Based on tourism investments, Hekeng's ED reached the highest values in 2015 (ED = 4.73 E+13 sej/m^2) at 152.46 times that in 1953 and higher than those of Queshan village in Shanxi province (see Table 2). However, the EYR reached the lowest value in 2015 and was lower than that in Fujian Province and Queshan village (Li et al., 2014; Wan et al., 2021). The intensity of economic development increased more from 1953 to 1990 with the transformation of production relations, but the output efficiency of the system gradually decreased due to the imbalance between system inputs and outputs with excessive purchase of emergy inputs.

5.2. Natural subsystem influenced by forest environment and mode of energy utilization

The forest environment was destroyed as roads developed in the 1960s and 1970s with the country's timber needs, and the exhaustion of local resources required more external resources to maintain the operation of the system (Marks, 2020). Therefore, in the 1980s and 1990s, villagers introduced tea and fruit trees that could produce economic benefits, investing more nonrenewable purchased resources, such as machinery, fertilizers and pesticides. The mode of energy utilization focused on tap water and electricity in the commercial tourism period took the place of natural water (e.g., rivers and wells), and natural energy (e.g., vegetation) adopted in traditional society. These products created for the purpose of consumption are eventually converted into waste (feces, kitchen waste, and sewage) that must be managed by a management committee. The emergy investment ratio (EIR) is an indicator of the extent to which a system consumes natural resources. The lower the value is, the lower the degree of development and the stronger the dependence on the natural environment, and vice versa. The environmental loading ratio (ELR) is characterized as "an indicator of the pressure of the process on the local ecosystem and can be considered a measure of the ecosystem stress due to production activity" (Brown and Ulgiati, 1997). The EIR in 1990 was higher than that in Xiamen (Yang et al., 2014) (Table 3), implying that economic development, which originally relied on the environment, became disconnected from the land. The EIR reached the highest value in 2015, at 505.55 times that of 1953. As villagers became more dependent on external resources, especially for the purchase of daily necessities and machinery, Hekeng had the highest ELR (242.30) in 2015, 457.84 times that of 1953. Production activities accompanied by changes in the forest environment in the 1980s triggered excessive dependence on external resources, which placed potential pressures on the natural environment.

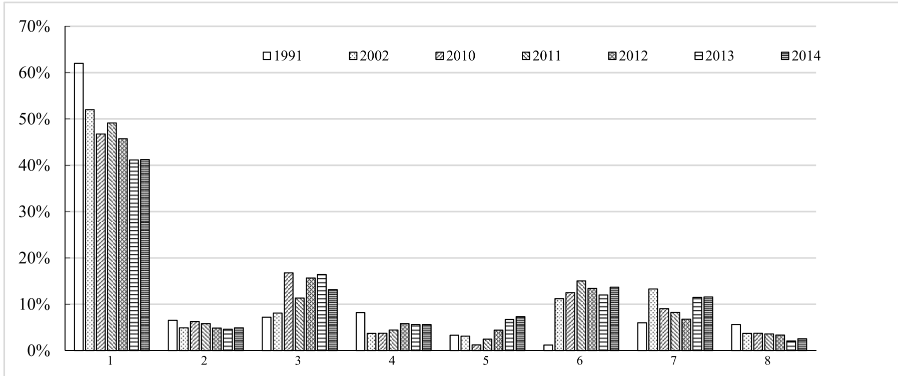

Fig. 6. Per capita living expenditure of villagers in Nanjing County from 1991 to 2014. (1: Food; 2: Clothes; 3: Living; 4: Household products; 5: Medical treatment; 6: Transportation and communications; 7: Culture, education and entertainment; 8: Other).

Table 2
Diachronic analysis of emergy indicators of the economic and technical subsystem and comparisons to other regions.

Item	ED (sej/ m^2)	Reference	Item	EYR	Reference
Expression	U/A		Expression	U/F	
Hekeng (1953)	3.10 E+11	This study	Hekeng (1953)	3.16	This study
China (1990)a	9.11 E+11	Yang et al. (2010)	Hekeng (1990)	1.01	This study
Hekeng (1990)	1.58 E+13	This study	Fujian (2011)	1.75	Li et al. (2014)
Queshan village (2015)	3.07 E+13	Wan et al. (2021)	Queshan village (2015)	1.03	Wan et al. (2021)
Hekeng (2015)	4.73 E+13	This study	Hekeng (2015)	1.00	This study

Note: $U = R + N + F_R + F_N$, survey area (A); a was converted to 12.00 E+24 sej.yr-1 baseline from 9.44 E+24 sej.yr-1 baseline.

Table 3
Diachronic analysis of emergy indicators of the natural subsystem and comparisons to other regions.

Item	EIR	Reference	Item	ELR	Reference
Expression	F/(R + N)		Expression	(F + N)/R	
Hekeng (1953)	0.46	This study	Hekeng (1953)	0.53	This study
Hekeng (1990)	71.08	This study	China (1990)	3.03	Yang et al. (2010)
Xiamen (1992)	47.9	Yang et al. (2014)	Hekeng (1990)	75.91	This study
Fujian (2011)	1.34	Li et al. (2014)	Queshan village (2015)	35.00	Wan et al. (2021)
Hekeng (2015)	233.79	This study	Hekeng (2015)	242.30	This study

5.3. Sociocultural subsystem accompanied by the development of population and cultural concepts

During the traditional agriculture period, the remote and inward-looking development of the mountainous area of Hekeng, with a moderate population and harmonious community culture, allowed the social, ecological, and economic situation of the system to experience a period of stability. Traditional societies in rural China have a strong affinity for human-nature nexuses, which are perceived as carrying symbolism and metaphor. This worldview facilitates locals to form close and united social clan structures adapted to this perception (Zhang, 2020). An emphasis on Feng Shui among the villagers of Hekeng and their belief in the power of interior Tulou spaces reflect this idea. Since the era of industrialization, the population increased from 550 in 1953 to 1200 in 1990, and an increasing number of young adults began to leave the village to pursue a living meanwhile. The human-nature relationship transformed from the emotional induction of traditional society to the market-oriented linkages of modern society.

The per capita emergy used (U_{cap}) reflects the material living standards of a population, including both per capita renewable emergy (R_{cap}) and per capita nonrenewable emergy (N_{cap}). The emergy sustainability index (ESI) is a composite evaluation indicator, and high values indicate more renewable emergy being used by the system and a high level of system sustainability (Yu et al., 2016). In 1953, R_{cap} was higher than N_{cap}, and Hekeng villagers' material standard of living was very low (U_{cap} = 4.40 E+14 sej/person); however, the ESI was highest in 1953 (5.975). U_{cap} reached the average value for China in 1990 (Yang et al., 2010), 23.39 times that of 1953 (see Table 4). Based on tourism investments, Hekeng's U_{cap} reached the highest values in 2015 (U_{cap} = 2.61 E+16 sej/person), while the ESI was the lowest in 2015 (ESI = 0.004). In comparison, Cheng and Cheng (2018) reported that Hakka villages showed high levels of environmental sustainability in the Liu-Tui area of Taiwan from the 1920s–2010s, when Taiwan's settlements were not highly urbanized and industrialized relative to non-Hakka villages. Moreover, in 2010, the average ESI values of Hakka

Table 4
Diachronic analysis of emergy indicators of the sociocultural subsystem and comparisons to other regions.

Item	Per capita emergy (U_{cap}) (sej/person)	Reference	Item	ESI	Reference
Expression	U/P		Expression	EYR/ELR	
Hekeng (1953)	4.40 E+14	This study	Hekeng (1953)	5.975	This study
China (1990)a	7.65 E+15	Yang et al. (2010)	Hekeng (1990)	0.013	This study
Hekeng (1990)	1.03 E+16	This study	Fujian (2011)	0.191	Li et al. (2014)
Fujian (2011)b	1.86 E+16	Li et al. (2014)	Queshan village (2015)	0.030	Wan et al. (2021)
Hekeng (2015)	2.61 E+16	This study	Hekeng (2015)	0.004	This study

Note: $U = R + N + F_R + F_N$, total population (P); a and b were converted to 12.0E24 sej.yr-1 baseline from 9.44 E24 sej.yr-1 baseline and 15.20 E+24 sej.yr^{-1} baseline, respectively.

villages and non-Hakka villages were 0.135 and 0.030, respectively, and thus, the modernization process developed rapidly in Hekeng. The human-nature relationship regulated by community culture has an important role in maintaining the comprehensive sustainability of a system.

5.4. Sustainability crises in hekeng

As many studies have shown, the roots of ecosystem sustainability crises often do not lie in the ecosystem but in human society (Tello-Aragay and Jover-Avellà, 2014; Wang et al., 2013). The establishment of a strategy requires comprehensive consideration of the consequences of sustainability changes for the system in human society. The ultimate goal of sustainable development is to improve well-being (Daly and Cobb Jr., 2015) with particular attention given to meeting human emotional and social needs (Gautam and Andersen, 2016; Rogers et al., 2012). Therefore, research that considers the sustainability crisis with changes in emergy indicators allows us to show the impact of changes in resource utilization on well-being, which is conducive to the formation of long-term sustainable strategies for the system well-being.

As indicated by a previous study, a high dependence on tourism and the loss of traditional livelihoods may increase long-term risks (Su et al., 2016). After settlement patterns changed in 2008, Hekeng villagers' basic source of income was lost. The nonagricultural population currently accounts for 64.61% of the total population. Based on the registered population of Hekeng in 2015, the villagers' material living standards have improved. However, the rate of increase in the ELR was faster than that of the U_{cap}, indicating that the natural environment was under great pressure with the improvement of material standards of living, and the nonrenewable emergy input was increasing at an excessive rate. While the natural environment might seem to be well protected, the sustainability of the system is decreasing exponentially underneath the surface.

The abandonment of traditional agricultural production styles was followed by substantial input into nonrenewable emergy and losses in labor (Fig. 7a), leading to environmental pressure and social crises. Excessive investment in chemical fertilizers and herbicides resulted in soil compaction and a decrease in soil water content (Fig. 7b). The popularization of chemical fertilizers and pesticides has created household waste, causing human and animal excreta to lose their regeneration mechanisms and produce redundant waste. Due to insufficient rural infrastructure, waste and chemicals penetrate the ground through the soil or enter the river, which is being polluted, and river water in Hekeng is not directly drinkable with the advent of industrialization. Villagers' health has also been adversely affected by changes in production and lifestyle. The number of villagers in Hekeng suffering from chronic diseases, such as hypertension and diabetes, increased from 5.61% of all villagers in 2010 to 9.55% of all villagers in 2019. Traditional social relations focused on culture and family clanship have been seriously threatened, and the villagers' sense of clanship and unity have gradually waned. While Hekeng is being planned as a market-oriented tourist attraction that relies heavily on economic input, the lives of villagers have not been prioritized, for instance, housing shortage problems accounting for 21% of households in the village, construction problems of resettlement housing delayed by the stagnation of tourism development (Fig. 7c), a lack of comprehensive medical and educational resources, and inconvenient transportation. Thus, villagers' life satisfaction is also declining.

In summary, the system increasingly privileges the utilization of external resources in the specific social-ecological background driven by the change in production relations, destruction of forest environments and disappearance of the community culture. As Hekeng transforms toward tourism development with improved material living standards, nonrenewable emergy inputs present an increase with excessive speed, and the well-being and sustainability of the system are being undermined. The natural environment is under potential pressure, and the physical health, social relations and life satisfaction of the villagers have been negatively impacted. These factors are not easy to identify in the findings of an economically oriented development evaluation. The excessive commercial development of Tianluokeng earth buildings and the ancient village of Yunshuiyao around Hekeng serve as examples. In addition, the ESI is affected by the EYR and ELR, and as the benchmark year for the coordination between the energy operation and social development, the ELR and EYR of 1953 can serve as reference indicators of the future development of Hekeng.

6. Conclusions and recommendations

This paper proposes a diachronic emergy approach that integrates the emergy evaluation method into the research framework of environmental history by regarding rural areas as complex ecosystems. Hekeng, which represents a key example of villages transforming from traditional farming villages into tourism destinations, was chosen as a case study. The results of this study can be summarized as follows:

Through emergy accounting of three typical years in different social development models, it can be revealed that as the social development model changed, the purchased emergy input into the total emergy input increased from 31.62% in 1953 to 98.61% in 1990 and then to 99.57% in 2015, of which goods and machinery input accounted for the largest proportion. The benchmark year of 1953 can be identified for the village of Hekeng, maintaining dynamic equilibrium under the coupled interrelation of social development and energy operation. Combined with social-ecological factors and emergy indicators, the results of the diachronic comparison to the benchmark year show that the EYR and ELR of 3.16 and 0.53, respectively, for 1953 can serve as reference indicators of resource utilization in the sustainable development of Hekeng.

Moreover, it is clear that the implementation of technical solutions must extend beyond the consideration of pure technology to the interaction between social and ecological systems by integrating the material and energy circulation of the local agricultural ecosystem with a governance system based on production relations, forest environments and community culture for village of Hekeng. The potential impacts on system well-being, such as the physical health, social relations and life satisfaction of villagers and environmental quality, must be taken into account in future strategies.

Fig. 7. Problems facing Hekeng: a: empty Yongsheng Lou; b: tea garden grown with herbicides; and c: unfinished rehousing development.

The diachronic emergy approach introduces social development models and social-ecological factors corresponding to emergy evaluation in the dynamic context of social development, such that technical solutions based on reference indicators and adapted governance systems can be determined. Suggestions for the formation of long-term, holistic strategies for sustainable development in Hekeng are presented as follows:

1) The quantitative assessment results of this study contribute to predicting future development patterns more clearly regarding the adjustment of development strategies and the supplementation of rural sustainability research with a new emergy baseline. Hekeng must develop ecological agricultural techniques with local renewable resources at their core based on the ecological wisdom of the traditional agriculture period and form a diversified ecological industry development mode. The current study has revealed that the renewability of an organic production system is 2.27 times that of a conventional production system that uses chemical fertilizers and lacks a composting process, while the renewability of a production system of a complex agroecological farm is 3.25 times that of an exclusively conventional production system (Nakajima and Ortega, 2015).
2) To form a long-term sustainable development strategy, Hekeng needs to change its existing mode of tourism development and promote a more ecological and environmentally friendly tourism mode based on optimized local agricultural production and corresponding culture. For instance, preserving knowledge transfer systems that generate traditional ecological knowledge and develop hands-on educational systems that rely on the natural world as the primary classroom have been suggested to be important for sustainability, especially for indigenous communities experiencing an influx of tourist money (Falkowski et al., 2015).
3) Furthermore, the focus of Hekeng's protection should shift attention from a single Tulou to the total agricultural ecosystem and its culture; the management mode of this scenic area must enable transformational change through community-based participatory governance; and the damaged local agricultural ecosystem and social operation mechanisms need to be repaired in terms of interactive integration of social and ecological aspects. In response to a series of social and ecological crises caused by the top-down scenic management model, we can learn from the management model of Historic Villages of Shirakawa-go and Gokayama in Japan, which revolves around villager autonomy. The villagers have spontaneously established landscape protection criteria with the help of local and national governments, which has been conducive to the preservation of the total appearance of the village and the inheritance of local culture.

The diachronic emergy approach is a novel approach for rural sustainability studies. The reference indicators for Hekeng's sustainability proposed in this article must be further tested in the context of future development. While this article addresses only Hekeng as a case study, it conducts a preliminary and long-term study from a social-ecological perspective. To generalize and improve this approach and promote an understanding and interpretation of rural sustainable development, there is a need for future research on the application of additional cases, expanding the time scale, and integrating more specific social-ecological factors for consideration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jrurstud.2021.07.010.

Credit author statement

Jinxin Zhu: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. Xiaomei Yuan: Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration. Xingzhong Yuan: Methodology, Writing – review & editing. Siman Liu: Formal analysis, Investigation, Data curation, Visualization. Beiting Guan: Formal analysis, Investigation, Data curation, Visualization. Jinfang Sun: Formal analysis, Data curation. Hongfei Chen: Investigation, Data curation.

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