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Case Study

How to assess urban development potential in mountain areas? An approach of ecological carrying capacity in the view of coupled human and natural systems

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ABSTRACT

How to assort with the relationship between mountain development and ecological protection is a key issue during the process of mountainous urban construction. Ecological carrying capacity (ECC), as the key to measuring regional sustainable development in terms of society, economy and ecology, provides an approach to assess urban development potential in mountain areas. Taking Dali Bai Autonomous Prefecture in Yunnan Province, China as a study area, this study has explored the conceptual framework for ECC in view of coupled human and natural systems (CHANS), and has constructed an index system using aspects of ecosystem vigor (EV), resources and environmental carrying capacity (RECC), and social development ability (SDA). The results at the county level showed that: (1) Dali City had the highest EV and SDA, with a relatively good ecological background, stable geological environment, and more concentrated population and flourishing urbanization. Yunlong County occupied the best RECC for its relatively abundant stock of water and land resources. Due to well-balanced ecosystem stability maintenance, resource utilization, and human development, Yunlong County possessed the highest ECC all over the prefecture; (2) the study area can be grouped into five categories considering trade-offs between mountain development and ecological protection. That is, priority areas for conservation, priority areas for development, areas suitable for short-term conservation but long-term development, areas suitable for short-term development but long-term conversation, and areas reserved for future appropriate development. This research could help to identify the approach to sustainable mountain development from the perspective of CHANS, and to make effective contribution to urban development decision-making in mountainous areas.

1. Introduction

China has been experiencing its urban expansion at an unprecedented speed in the process of economic development (Bai et al., 2014; Li et al., 2014a; Liu and Li, 2014). The Central Economic Work Conference that met in Beijing from December 10 to 13 in 2014 clearly pinpointed that the environmental carrying capacity in China already neared its upper limit during the urban sprawl. The natural resources, energy, and ecological environment turned to experience rigid constraints day by day, and shortage of land in developable conditions is no doubt one of the manifestations. With the most widely distributed mountainous areas around the world, 65% of China's territory is covered by mountains, plateaus, and hills (Editorial Board of Chinese Academy of Sciences, 1985). However, large-scale land use in upland and hilly regions is usually at a low level for the landform restriction and eco-protection requirement. A low-slope hilly region, one hilly terrain with a relative height difference less than 500 m and a slope within 6–25° includes several kinds of reserved land resources like grasslands, bare lands, abandoned gardens, and inefficient woodland. It poses a potential for exploitation and can become the focal space for future effective development.

Considering both the facts that China has a large population but scarce land resources (especially for arable land), and that most counties are located in upland and hilly regions, the Ministry of Land and Resources of the People's Republic of China proposes to carry out pilot programs in Yunnan and other provinces from 2012. Further, its aim is to develop the unused low-slope hilly wasteland and promote mountain urban construction. However, compared to the flatland, the low-slope hilly land is always difficult to develop because of the complex topography, vulnerable eco-environment, and the geological disaster risk. Thus, in order

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to balance the mountain development and ecological protection, it has become an important issue to make scientific and reasonable decisions about the development usage, scale, schedule, and layout when developing the low-slope hilly region.

Ecological carrying capacity (ECC), the key indicator to measure the sustainable development of regional economy, society, and ecology (Costanza, 1995), has become a research hot spot (Arrow et al., 1995; Seidl and Tisdell, 1999). This concept was born under the background of ecological disruption, resource shortages, and environmental pollution with the evolution of several conceptions such as the population carrying capacity, grazing capacity, land carrying capacity, and the environmental carrying capacity. ECC was once the first ecological discipline (Hardin, 1986) and one of the most important notions of bioscience (Mayr, 1997). Currently, it is becoming more and more mature, from researches of biotic population growth law to practical problem studies serving for human economic development, from carrying capacity restricted by a single factor like food, water, or land to systematic capacity involving multi-factor constraints. With sustainable development pursued by nations all over the world, ECC is widely employed in urban planning, resource and environmental management, regional development, and other macro-social economic activities. Mountain urban construction or low-slope hilly land exploitation acts as a typical social practice for which ecological carrying capacity theories can potentially provide huge guidance.

The evaluation methods of ECC can be roughly summarized as three types according to their different emphases. The first one is the resource supply and demand balance method that focuses on ecosystem function and characterizes the absolute size of ECC through comparing resource supply and demand from the carrier and the carrying target. The ecological footprint method (Peng et al., 2015; Wackernagel and Rees, 1996), energy analysis (Lou et al., 2015), and net primary productivity method (NPP) (Sutton et al., 2012; Thebault et al., 2008) all belong to this category. The second one is the index system method which reifies ecosystem information based on several theoretical frameworks such as "pressure-state-response" (PSR) (Wei et al., 2014; Zheng et al., 2015), "pressure-state-impact-response" (PSIR) (Lockie et al., 2005), and "driving force-pressure-state-impact-response" (DPSIR) (de Jonge et al., 2012). The third one is the system model method that uses models to simulate and reflect the current situation and possible changes of the ecosystem's carrying capacity, such as system dynamics (SD) (Wang et al., 2013), multi-objective programming model (MOP) (Wang and Zeng, 2013), and artificial neutral network (ANN) (Wang et al., 2013).

Although differences in research focuses or methods exist, and a unified paradigm has not yet been formed, studies on ECC appear to have a common trend. That is to say, related literatures are apt to aim at promoting a harmonious coexistence between human and nature, analyze questions from the view of coupled human and natural systems, and to pay attention to multi-factor coordination and holistic approaches instead of stressing a sole human or nature object. However, although the research object is explicit, the structure of ECC is vague, relations among the elements still need a deeper interpretation, with the concept and connotation of ECC for further detailing. Moreover, previous studies mainly emphasize the carrying capacity threshold identification of a single study area based on indicators like GDP or population, while lacking a carrying potential comparison among regions based on more information-rich indices. Furthermore, as to the design of evaluation systems, most of the previous work focuses on simple superposition of many statistical indicators, falling short of in-depth mechanism exploration. In addition, the interaction between natural ecosystems and socio-economic systems urgently requires an all-around description relying on eco-geographical processes.

Coupled human and natural systems (CHANS) are complex systems in which components of human systems and natural systems link with each other closely (Alberti et al., 2011; Liu et al., 2007a,b). CHANS pay close attention to the modes and processes that the subsystems are inter-related, inter-linked and inter-dependent. This conjunction appears in the form of material, energy and information flows and develops from simple to complex, from direct to indirect impacts. This conjunction also emphasizes interplay and feedback between two subsystems across space, time, and organizational units, as well as the interaction under a certain scale or across different scales. The approach of CHANS is significant to system management and control, as well as socioeconomic and environmental decision-making. ECC is discussed based on complex systems containing ecology, resources, environment, human societies and economy, and is directly associated with sustainable development (Costanza and Cornwell, 1992; Arrow et al., 1995; Kang and Xu, 2010), which determines its basic research approach of CHANS. Moreover, humans and nature currently penetrate into each other more and more deeply (Li et al., 2010a, 2012, 2014b; Liu et al., 2014b), and human factors have replaced the role of natural factors to dominantly affect the regional balance and environmental change (Messerli et al., 2000; Rediscovering Geography Committee, 1997). All these facts further emphasize the necessity of assessing ECC based on the angle of CHANS rather than solely through nature or humans. Additionally, features that CHANS exhibit such as thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises (Alberti et al., 2011) again supply theoretical supports for ECC studies on inherent issues like ecosystem stability and human–nature interaction.

Taking Dali Bai Autonomous Prefecture in Yunnan Province as the example, as it is one key area of low-slope hilly land development, this paper studies the ECC and mountain exploitation potential at the county level from the perspective of coupled human and natural systems. Furthermore, this paper investigates future potential applications of the ECC model on quantifying resilient space of ongoing population agglomeration, urbanization, and industrialization. The specific goals are as follows: (1) to establish a multidimensional conceptual framework for the ECC of coupled human and natural systems, and then apply it to evaluate the ECC of the low-slope hilly region and (2) to make the trade-off between mountain development and ecological conservation based on a single dimensional ECC and their combinations.

2. Materials and methods

2.1. Study area

Dali Bai Autonomous Prefecture (24°41′–26°42′N, 98°52′–101°03′E) (hereafter called Dali Prefecture), is located in western Yunnan Province. It borders Chuxiong Prefecture in the east, Pu'er City and Lincang City in the south, Baoshan City and Nujiang Prefecture in the west, and Lijiang City in the north. Dali Prefecture, a representative southwestern mountainous region, has an area of 29,459 square kilometers, and mountainous areas cover around more than 90% of the territory. The terrain of Dali Prefecture declines from northwest to southeast. With a complex and varied topography, geological disasters such as earthquakes and landslides occur frequently, and in certain areas, soil erosion and rocky desertification are simultaneously serious, which brings about the relatively fragile ecological environment throughout the prefecture. Moreover, the plateau lakes there are primarily rift lakes of tectonic evolution distributed in the upstream regions. The water bodies always have small catchment areas and long natural renewal periods, so water quality restoration is difficult to control once polluted. Furthermore, Dali Prefecture, one of the world's biodiversity hot spots (Xu and Wilkes, 2004), is rich in wild fauna and flora, having a unique advantage in species germ plasm conversation and utilization. In the viewpoint of landscape, the natural ecosystem is the dominating background all over the prefecture, and manual or semi-artificial ecosystems are embedded in the former as patches. The natural ecosystems such as forests, grasslands, waters, and wetlands cover around 76.06% of the territory of Dali Prefecture, among which the proportion of forests is as high as 67.47%. However, in recent years, with land use changes caused by human settlement and economic growth, a trend of vegetation cover reduction and environmental quality degradation comes along in certain regions faced with strong human interference (Peng et al., 2008, 2012).

As one of the early developed border areas of southwestern China, Dali Prefecture has jurisdiction over the county-level city of Dali and the 11 other counties, namely Yangbi Yi Autonomous County, Nanjian Yi Autonomous County, Weishan Yi and Hui Autonomous County, Binchuan County, Xiangyun County, Midu County, Yongping County, Yunlong County, Er'yuan County, Jianchuan County, and Heqing County. By the end of 2012, Dali Prefecture had a total population of 3.56 million people, made up of ethnic minorities numbering 1.83 million and accounting for 51.31%, and the agricultural population numbering 2.17 million and accounting for 60.85%. Further, the GDP per capita of Dali Prefecture is about 19,000 yuan, approximately 50.19% of the national average; moreover, the proportion of primary industry, secondary industry and tertiary industry is 21.73%, 41.93%, and 36.34%, respectively.

Considering that Yunnan has large mountainous areas but small flatland areas, in 2011, Yunnan Province put forward the strategy of propelling the urbanization to gentle rolling hills and aimed at the goal of constructing towns toward hillside and leaving fertile farmland to descendants. In the future, mountains over 25° are prohibited to exploitation, and low-slope hilly lands within 6° and 25° will become the key development zones. As an important hub for the opening up of southwestern China, Dali Prefecture is an important pilot zone for the mountain-area urban construction policy in Yunnan Province. Meanwhile, it should be known that Dali Prefecture is a typical agricultural prefecture where fertile farmlands are mainly concentrated in Bazi (Bazi is a flat area of the Yunnan-Guizhou Plateau, which mainly consists of mountain basins, valleys, and piedmonts). These farmlands are easily degraded during the traditional urban sprawl occurring in the Bazi region (Liu et al., 2014a). Besides the demand for farmland protection, natural ecosystems like Cangshan Mountain and Erhai Lake also put high ecological protection pressures on urban construction. Therefore, low-slope hilly region development becomes an effective way to reduce the potential threat to food security to some degree. Further, it is significant to focus on ecological conservation, Bazi farmland protection, disaster risk aversion, and regional economic development during the mountainous urban construction in Dali Prefecture, based on the specific geological environment, ecological background, and social status of the study area (Fig. 1).

2.2. Data source

This study involves datasets on land use, topography, vegetation types, soil, geological disasters, social economic statistic data, and other data standards regarding ecological function zoning and environmental protection. Land-use data with a resolution of 30 m are available from the International Scientific Data Service Platform (http://datamirror.csdb.cn/), and are interpreted from remote-sensing images taken by Landsat7 ETM+ in Spring 2010. Digital elevation data (DEM) with a resolution of 90 m are available from the GDEM dataset provided by the Computer Network Information Center (CNIC) attached to the Chinese Academy, and from these data, gradient data could be generated. Vegetation types are obtained from Yunnan Province vegetation maps on a scale of 1:250,000 compiled by the Institute of Ecology and Geobotany (IEG) of Yunnan University, and relevant forest resource data from the China Forestry Science Data Center (CFSDC). Locations of earthquakes as well as geological disasters and the spatial distribution of fracture zones are digitized from related geological disaster prevention maps in Dali Prefecture. Soil data were digitized from soil type maps from the *Ecological State Construction Plan of Dali Prefecture*. Socioeconomic data comes from statistical yearbooks of Dali Prefecture and all concerned counties. Other data standards refer to government notices such as *Chinese Ecological Function Zoning Interim Provisions*, *Provincial Development Priority Zoning Technical Specification*, *Ecological Environment Evaluation Technical Specification 2006*, *GB2011 Standards of City Land-use Classification and Constructive Land Planning*, *GB2012 Standards of Ambient Air Quality*, and the *GB1996 Technical Specification of Water and Soil Conservation*.

2.3. Methods

2.3.1. Conceptual framework for ECC of CHANS

Currently, large tasks faced by the study of ECC include the establishment of common conceptual frameworks and feasible index systems for ECC evaluation, and the standardization of its research paradigm based on coupled human and natural systems. The ECC of coupled human and natural systems (hereafter called the ECC of CHANS) is the capability of the coupled systems to support human sustainable development. Therefore, the ECC of CHANS focuses on the feedback and adjustment of humans to nature, with tangible products and intangible ecological services supplied from nature at its core (Gao et al., 2014).

As shown in Fig. 2, CHANS consists of two subsystems: a natural ecosystem acting as the carrying subject, and a social economic system as the carrying object. It is their coupling and interaction that finally determine the ECC (Wei et al., 2015). According to these subsystems, a natural ecosystem supports a social economic system through outputting ecosystem services such as natural resource supply or pollutant absorption. Undoubtedly, a natural ecosystem should also keep its structure and function robust. Humans have been playing a dual role of both positive and negative interveners. On the one hand, strong human activities and excessive utilization may destroy the natural ecosystem's initial state to some degree. On the other hand, certain technologies and policies may promote the natural ecosystem's benign development (Kang and Xu, 2010; Graymore et al., 2010; Liu and Borthwick, 2011; Li et al., 2010a; Salerno et al., 2013; Tehrani and Makhdoum, 2013). Finally, the development of human society affects its own active adaption ability as well as the whole CHANS's stability.

Therefore, the ECC of CHANS reflecting the man–earth relationship can be decomposed into three parts as follows: (1) ecosystem vigor (EV). This corresponds to the natural system's self-renewal, self-maintaining, and self-regulation, and is the vital foundation of ECC of CHANS. EV mainly focuses on the quality of ecological background, the stability of ecosystem structure and function, and the ecosystem vulnerability related to its stability. (2) Resources and environmental carrying capacity (RECC). This corresponds to the outward manifestation of the carrying subject acting on the carrying object, namely the resource bases and environmental constraints, which are always bottlenecks for the coupled systems to keep growing (Abernethy, 2001; Liu and Borthwick, 2011; Lane et al., 2014). (3) Social development ability (SDA). This corresponds to the "double-edged sword" impact of the social economic system on the natural ecosystem, and is related to the social economic system's self-development as well. Simply put, SDA pays attention to the action and the state of humans in the coupled systems as a role of the impeller, consumer or administrator (Kang and Xu, 2010;

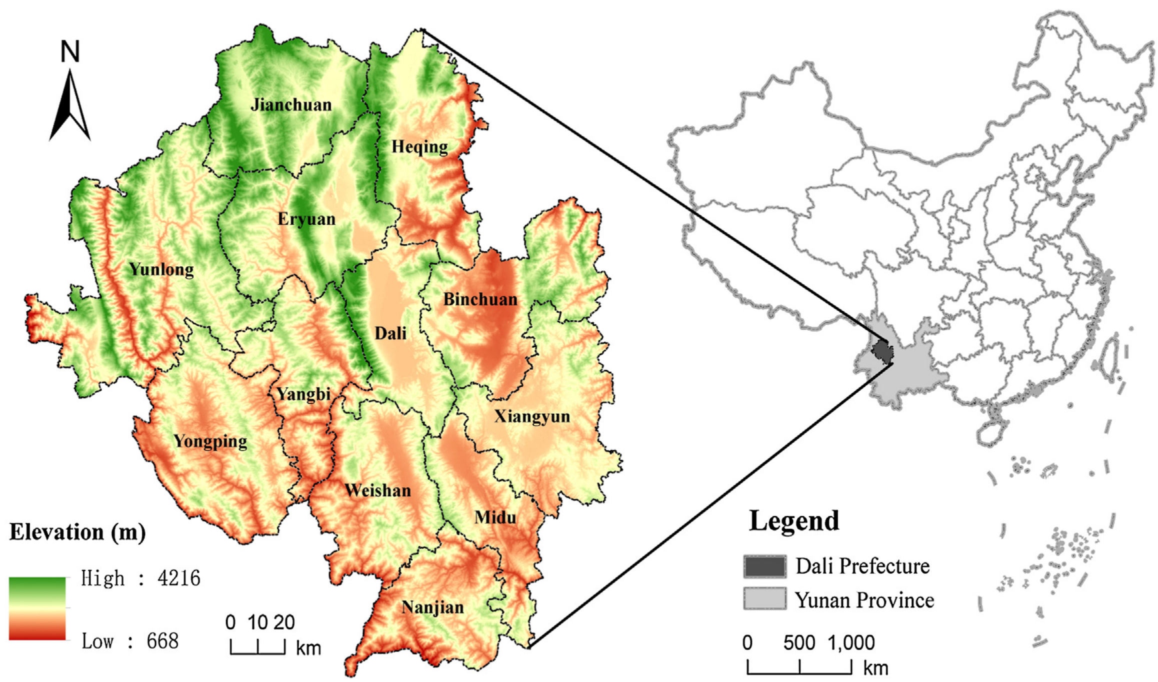

Fig. 1. Location of Dali Bai Autonomous Prefecture.

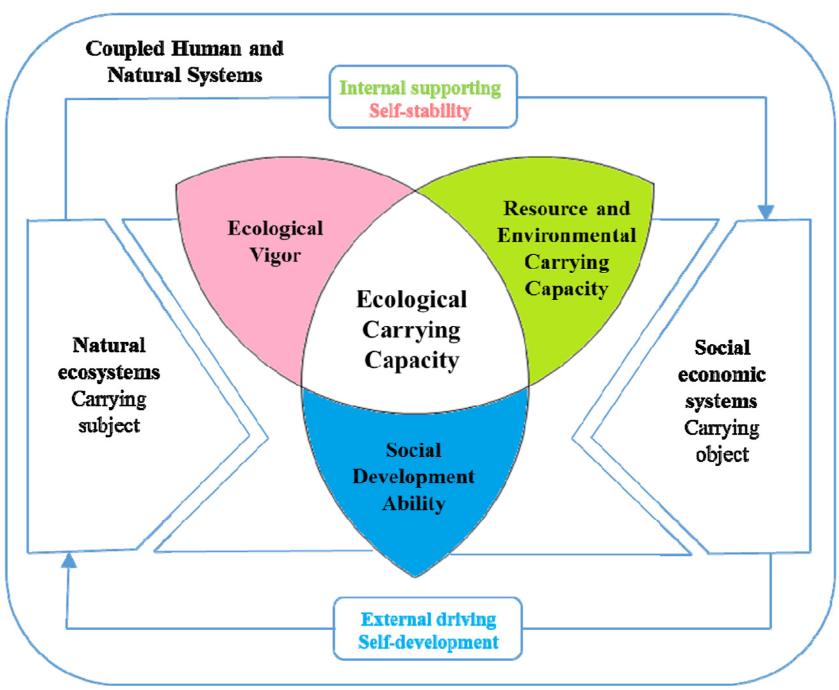

Fig. 2. Conceptual framework for ECC of coupled human and natural systems.

Graymore et al., 2010; Liu and Borthwick, 2011; Salerno et al., 2013; Tehrani and Makhdoum, 2013).

2.3.2. Evaluation model for ECC of CHANS

According to the above definition, this paper evaluates ECC of CHANS from aspects of EV, RECC, and SDA, taking Dali Prefecture's 12 counties as targets. Considering key issues during mountainous urban construction and actual characteristics of the study area, the ECC assessment index system is established in Table 1. The final indices take into account several important points such as the ecological protection necessity, the geo-hazard susceptibility, and the objective requirements that land resources over 25° are not allowed to be developed, and arable land in the Bazi region is forbidden to be occupied. The specific formula of ECC is as follows, where W is the index weight, and ECC, EV, RECC, and SDA respectively represent the ecological carrying capacity, ecosystem vigor, resource and environmental carrying capacity, and social development ability:

$$ECC = W_{EV} \times EV + W_{RECC} \times RECC + W_{SDA} \times SDA \quad (1)$$

Considering that for the whole CHANS, subsystems are interdependent and various functions work jointly, this paper adopts to calculate the ECC of CHANS through equally weighting,

Table 1
Index system for ECC of CHANS in low-slope hilly area.

Target layer	Criteria layer	Index layer[a]	Sub-index layer	Index purposes
ECC of CHANS	EV	Ecological importance (0.250)	Biological resources protection importance Water security importance Nutrients preserving importance	To assess the quality of ecological conditions and the effectiveness of ecosystem structure and function
		Ecological sensitivity (0.083)	Rock desertification sensitivity Geological disaster sensitivity Soil erosion sensitivity	To assess the ecosystem vulnerability and possibility of ecological unbalance
	RECC	Potential resource supply (0.222)	Available land resource Available water resource	To assess the carrying capacity of potential land or water resources to support future population agglomeration, urbanization and industrialization on the premise of protecting farmland
		Remainder environmental capacity (0.111)	Remainder atmospheric environmental capacity Remainder water environmental capacity	To assess the pollutant assimilative capacity of air and water on the premise of not harming ecological environment and human health
	SDA	Human activity effects (0.067)	Production mode and resident living style Scientific and technological progress	To assess the negative interference and positive promotion from social economic systems on natural ecosystems
		Social development degree (0.266)	Economic level Educational level	To assess the human development situation under the support of natural ecosystems

[a] It should be explained that since the weight of criteria layer is aliquant ($W_{EV} = W_{RECC} = W_{SDA} = 1/3$), the weight sum of index layer is not equal to 1 strictly.

adding up all three individual sub-ECCs. That is so say, $W_{EV} = W_{RECC} = W_{SDA} = 1/3$.

2.3.2.1. Ecosystem vigor assessment. Vigor refers to system activity, metabolic ability, and primary productive capacity. Generally, ecosystem vigor is depicted by vegetation production such as NPP (Costanza and Mageau, 1999). This paper regards sustainable development as the theoretical foundation of ECC study, and analyses the connotation of "vigor" from the perspective of ecological sustainability. We argue that EV is closely connected with ecosystem elements, structures, and functions. "Metabolism" within the concept of "vigor" focuses on not only the visible annual renewal of biological resources but also the invisible flow of ecosystem services, or not only the metabolic process itself but also the inertia and resilience to keep an efficient metabolism. Therefore, EV involving self-renewal, self-maintaining and self-regulation of natural ecosystems can be divided into two aspects of the ecological importance and sensitivity. The former is based on ecosystem elements, measuring the output of ecosystem services and the maintenance of ecological processes (Xie et al., 2015). The latter refers to the degree of ecosystem response to environmental change (Li et al., 2014b), showing the ecosystem vulnerability and eco-imbalance possibility (Pan et al., 2012). The EV score is the weighted sum of a normalized ecological importance index and ecological sensitivity index, and the weighting coefficients are obtained by the analytic hierarchy process (AHP).

The next step is to evaluate ecological importance and sensitivity separately. On the one hand, Dali Prefecture has rich biodiversity, so individuals should not militate against the quantity and quality of its initial habitats during the development process. On the other hand, faced with the study area's mountainous and rainy eco-background, relatively abundant water resources, and continuously increasing human disturbance, there is growing concern about other issues like flood discharge, water source conservation, non-point source pollution, and eutrophication. Therefore, this paper comprehensively evaluates the ecological importance by choosing biological resources protection importance ($w = 0.5$), water security importance ($w = 0.3$) and nutrition preserving importance ($w = 0.2$). To be specific, biological resources protection importance aims at exploring the capacity of different land-use types to maintain biotic resources. Water security means we should set apart wetlands and river buffers to adjust and restore floods and meanwhile protect water-source areas at the whole valley level. Nutrition preserving importance considers the consequence of water eutrophication resulting from nitrogen and phosphorus losses. Detailed indices are shown in Table 2. The ecological importance score is obtained by weighted summation of all sub-layers, and then the evaluation results are classified into four levels through a natural breakpoint method. The numbers 4, 3, 2, and 1 are separately assigned for very important areas, important areas, less important areas, and the least important areas, respectively. Furthermore, ecological importance value of each administrative area is the arithmetic mean of all grids included in a certain county.

The ecological sensitivity is evaluated based on the Chinese Ecological Function Zoning Interim Provisions (2003), Chinese Ecological Function Zoning (2008), and Technical Guide of Chinese Ecological Protection Red Line – Ecological Function Baseline (A trial Version) (2014). Considering natural environment conditions of Dali Prefecture, the evaluation is conducted from aspects of rock desertification sensitivity, geological disaster sensitivity, and soil erosion sensitivity. The soil erosion sensitivity is assessed based on Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991; Toumi et al., 2013). First, we obtain several parameters of RUSLE including the soil erosion factor K, rainfall erosion force factor R, terrain factor LS, and vegetation coverage factor C based on datasets on soil, rain distribution, terrain, and vegetation coverage. The next step is to calculate the actual soil erosion modulus of each grid using RUSLE, and then identify the sensitivity level through comparing erosion amounts to grading standard values. The bigger soil erosion modulus shows the more serious erosion status relevant to higher levels of soil erosion sensitivity. In addition, the grading standards here refer to the Soil Erosion Classification and Grading Standards (SL190-2007) from the Ministry of Water Resources (MWR), considering local soil erosion spatial distribution. The final threshold of five levels (i.e., insensitive, mild sensitive, moderate sensitive, severe sensitive, and very severe sensitive) is respectively 10, 25, 80, and 150 $t\,hm^{-2}\,a^{-1}$.

Geological disaster sensitivity is obtained through identifying the potential geological disaster extent and classifying its effect based on several indicators about geological disaster susceptibility. These indicators mainly involve soil erosion modulus, crown density, slope, formation lithology, and geological structure of geological hazard points. Geological hazards here refer to landslides, collapses, debris flow, ground fissures, ground subsidence and unstable slopes.

Rocky desertification sensitivity is found by estimating and classifying relevant factors such as terrain (divided into four levels by

Table 2
Index system of ecological importance.

Factor layer	Indicator layer	Assignment rules			
		Very important (4)	Important (3)	Less important (2)	Least important (1)
Biological resources protection importance	Land-use type	Forest Lake Wetland	Shrubbery Reservoir	Farmland Grassland Orchard land	Other land-use types
	Habitat importance[a]	5.95–7.89	3.67–5.95	1.85–3.67	0–1.85
Water security importance	Distance to river systems[b]	1 km around first-order rivers 400 m around second-order rivers	2 km around first-order rivers 600 m around second-order rivers	3 km around first-order rivers 800 m around second-order rivers	Other areas
	Areas adjusting and restoring floodwater	Wetland for floodwater storage and drainage			Other areas
	Woodland type	Water source conservation forest	Soil and water conservation forests	Natural forest reserve	Others
	Water-source protection areas	Lake Reservoir			Others
Nutrition preserving importance	Significance, locality, and river level of catchments	Important lakes and wetlands in upper reaches of first-order, second-order or third-order rivers	Less important lakes and wetlands in upper reaches of first-order, second-order or third-order rivers Important lakes and wetlands in middle reaches of first-order, second-order or third-order rivers Important lakes and wetlands in upper reaches of fourth-order or fifth-order rivers	Less important lakes and wetlands in middle reaches of first-order, second-order or third-order rivers Important lakes and wetlands in lower reaches of first-order, second-order or third-order rivers Less important lakes and wetlands in upper reaches of fourth-order or fifth-order rivers Important lakes and wetlands in middle reaches of fourth-order or fifth-order rivers	Less important lakes and wetlands in lower reaches of first-order, second-order or third-order rivers Less important lakes and wetlands in middle reaches of fourth-order or fifth-order rivers Important lakes and wetlands in lower reaches of fourth-order or fifth-order rivers Less important lakes and wetlands in lower reaches of fourth-order or fifth-order rivers Other areas

[a] Calculated according to biodiversity service equivalents based on land use type (Xie et al., 2008), and further divided into four levels through standard deviation classification method.

[b] Realized through multiple ring buffers at specified distances in ArcGIS. Different buffer values are set to create non-overlapping buffers.

breaks of 15°, 25°, and 35°), landform (whether to be karst landform or not), and vegetation coverage ratio (divided into four levels by breaks of 20%, 50%, and 70%). The final score of rocky desertification sensitivity depends on the most sensitive factor mentioned above.

Following the "cask principle" and integrating evaluations of soil erosion sensitivity, geological disaster sensitivity, and rocky desertification sensitivity, the final ecological sensitivity corresponds to the most sensitive layer. Extreme sensitivity, high sensitivity, medium sensitivity, light sensitivity and non-sensitivity are assigned the values of 5, 4, 3, 2, and 1, respectively. Furthermore, the ecological sensitivity value of each administrative area is the arithmetic mean of all grids included in a certain county.

2.3.2.2. Resource and environmental carrying capacity assessment. RECC can be divided into two aspects of resources supply and pollutant absorption (Wei et al., 2015; Liu and Borthwick, 2011). Natural resources especially water and land resources, are the basis of ECC, which determine population growth limits and the urban expansion threshold. The pollutant absorption ability, which can also be regarded as the environmental carrying capacity, is the constraint of ECC, which means human outpouring of waste should be under the capacity of environmental self-cleaning.

The RECC assessment in the study area attempts to explore the development possibility of future mountainous urbanization under anthropogenic influence. Referring to the *Provincial Development Priority Zoning Technical Specification* (2008) and previous practical literatures about Yunnan Province (Ma et al., 2011), this paper first assesses the carrying capacity of land and water resources which still remain available to support future population agglomeration, urbanization, and industrialization. Considering the urgent demand for built-up land during mountainous urban construction, the remaining land here actually means potential built-up land excluding basic farmland, water areas, and ecologically sensitive areas.

To evaluate RECC, this paper then assesses the pollutant absorption ability of atmosphere and waters provided that ecological environment and human health are free of harm (Gong and Jin, 2009; Goyal and Chalapati Rao, 2007) (Table 3). It should be added that absorbing targets just refer to SO_2 and COD when evaluating environmental carrying capacity, drawing lessons from the treatments of *National Development Priority Zoning Technical Plan* (2011). The RECC score is the weighted sum of normalized indices of potential resource supply and remainder environmental capacity.

2.3.2.3. Social development ability assessment. Social development ability (SDA) focuses on the status and function of the social economic system dominated by humans in the entire coupled human and natural system. SDA considers both negative interference and positive effects of human activities on the ecological system, and estimates the development level of the social economic system itself as well. SDA is the weighted sum of normalized indices of human activity effects (HAE) and social development degree (SDD), and the weights are confirmed according to the AHP law (Table 1).

HAE is analyzed from two aspects: production mode and resident living style, and scientific and technological progress. For the first part, an ecological footprint is reckoned as an appropriate indicator to present human negative disturbance. An ecological footprint includes a biological resources account and an energy consumption account, and measures natural capital consumed in

Table 3
Index system of RECC.

Factor layer	Indicator layer	Calculation method and basis
Potential resource supply	Available land resource[a]	[available land area] = [area of land suitable for construction] – [area of existing built-up land]; [area of land suitable for construction] = [land area whose slope is within 25°] – [water area] – [area of farmland in the Bazi region];
	Available water resource[b]	[available water volume] = [local usable water volume] – [local water volume which has been developed]; [local usable water volume] = [regional multi-year mean water volume] * α (α = 0.4, the parameter value is an internationally recognized water utilization precaution); [local water volume which has been developed] = [the total quota of water use per capita] * [regional total population]
Remainder environmental capacity	Relative surplus of atmospheric environmental capacity[c]	[relative surplus of atmospheric environmental capacity] = 1 – [SO_2 emission amount/atmospheric environmental capacity]
	Relative surplus of water environmental capacity[d]	[relative surplus of water environmental capacity] = 1 – [COD discharge amount/water environmental capacity of COD]; [water environmental capacity of COD] = [COD target concentration of water environment functional region] * [regional COD discharge amount] * [regional multi-year mean water volume] * [water resource utilization coefficient] * [waste degradation coefficient]

[a] Land-use data were interpreted from remote-sensing images taken by Landsat7 ETM+ in Spring 2010 and converted to a vector format referencing Google Earth through manual correction and verification.
[b] Regional multi-year mean water resource volume comes from *Water Chorography of Dali Prefecture*; the total quota of water use per capita comes from *Water Resources Bulletin of Dali Prefecture in 2010*.
[c] SO_2 emission amount comes from a document in 2009 entitled *Technical Report on First Pollution Sources Census of Dali Prefecture*; atmospheric environmental capacity calculation refers to A Value Method Model in *GB/T13201-91*.
[d] COD discharge amount is from a document in 2009 entitled Technical Report on First Pollution Sources Census of Dali Prefecture.

both industrial activity and residents' daily lives. The bigger the ecological footprint is, the stronger the ecological appropriation will be, and thus the more negative disturbance would form. To describe the second part of HAE, indicators like "water consumption per ten thousand GDP" and "waste outpouring density per thousand GDP" are selected to represent a positive drive of human systems to ecological systems. The greater these two indicators are, the less intensive the economic growth style is, and the easier resource overload and environmental deterioration will take place. The formula of HAE is shown as follows, in which HAE represents human activity effects index; a, b, c respectively represent ecological footprint, water consumption per ten thousand GDP, and waste outpouring density per thousand GDP:

$$\mathrm{HAE} = \sqrt{\frac{1}{3}\left[\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2 + \left(\frac{1}{c}\right)^2\right]} \quad (2)$$

The ecological footprint calculation refers to studies of Wackernagel and Rees (1996). A larger HAE predicts the smaller natural capital occupation scale and the higher capital usage efficiency, and the more sustainable economic growth, which is resource-saving and environmentally friendly.

As previously mentioned, SDA can be assessed from aspects of HAE and SDD. In this context, SDD focuses on the overall level of social economy and civic education. The SDD evaluation is conducted based on indices such as urbanization rate, economic density of built-up areas, GDP per capita, and illiteracy rate, to separately show the urbanization situation, the output efficiency of urban land utilization, people's affluence, and civic educational situation. The calculating formula is:

$$\mathrm{SDD} = \sqrt{\frac{1}{4}[A^2 + B^2 + C^2 + (1 - D)^2]} \quad (3)$$

In this formula, the SDD is the index of social development degree, while *A*, *B*, *C*, and *D* are the normalization values of urbanization rate, economic density of built-up areas, GDP per capita, and illiteracy rate, respectively. A large SDD predicts the relatively good development status of a human society system under the support of the ecological system.

3. Results

We calculated the EV, RECC, SDA and ECC of 12 counties (shown in Fig. 3 and Table 4), and divided the results into four levels by using the natural breakpoint method in ArcGIS10.2. The bigger score is accordant with the higher level (Fig. 4). The EV, RECC and SDA are all dealt with a "range standardization method" and range from 0 to 1. The normalization result presents the relative condition of a certain index in one county compared with the other 11 counties. In addition, all indices are kept in a consistent direction with the final ECC index. For instance, a higher ECC value means the more optimistic ECC. Likewise, when assessing ecological sensitivity, the less sensitive unit will get a higher score, representing the less vulnerable ecosystem.

3.1. Ecosystem vigor

Shown in Table 4 and Fig. 4a, the EV of Dali City is the best, followed by Yangbi County and Yunlong County. The worst EV belongs

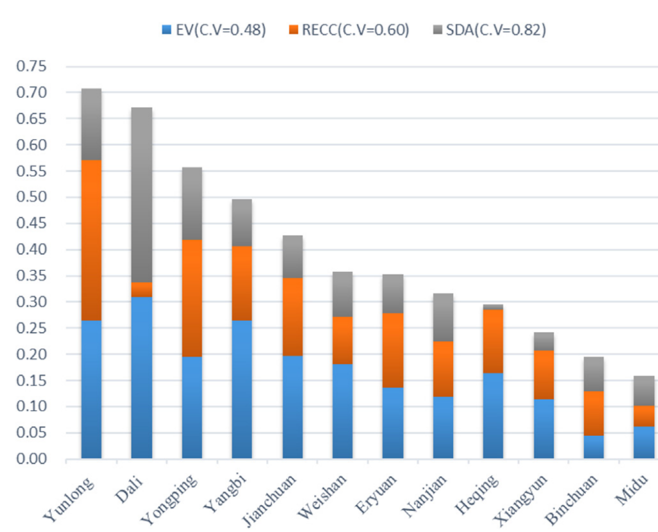

Fig. 3. ECC in Dali Bai Autonomous Prefecture.

Table 4
EV, RECC, and SDA in Dali Bai Autonomous Prefecture (index level).

Counties	EV				RECC				SDA			
	Ecological importance		Ecological sensitivity		Potential resource supply		Remainder environmental capacity		Human activity effects		Social development degree	
	Value	Ranking	Value	Ranking	Value	Ranking	Value	Ranking	Value	Ranking	Value	Ranking
Yunlong	0.93	3	0.38	8	1.00	1	0.77	4	0.73	5	0.33	2
Dali	1.00	1	0.71	3	0.13	10	0.00	12	1.00	1	1.00	1
Yongping	0.49	7	0.89	2	0.50	2	1.00	1	0.90	2	0.29	4
Yangbi	0.93	2	0.38	7	0.22	8	0.83	2	0.84	4	0.13	9
Jianchuan	0.57	5	0.64	4	0.39	4	0.58	5	0.32	6	0.22	6
Weishan	0.58	4	0.43	6	0.25	7	0.33	10	0.00	12	0.32	3
Er'yuan	0.47	8	0.23	10	0.45	3	0.37	6	0.84	3	0.07	10
Nanjian	0.43	9	0.12	11	0.08	11	0.80	3	0.32	7	0.26	5
Heqing	0.57	6	0.27	9	0.37	5	0.35	8	0.17	10	0.00	12
Xiangyun	0.12	11	1.00	1	0.36	6	0.13	11	0.26	8	0.06	11
Binchuan	0.00	12	0.54	5	0.22	9	0.33	9	0.18	9	0.20	8
Midu	0.24	10	0.00	12	0.00	12	0.36	7	0.00	11	0.22	7

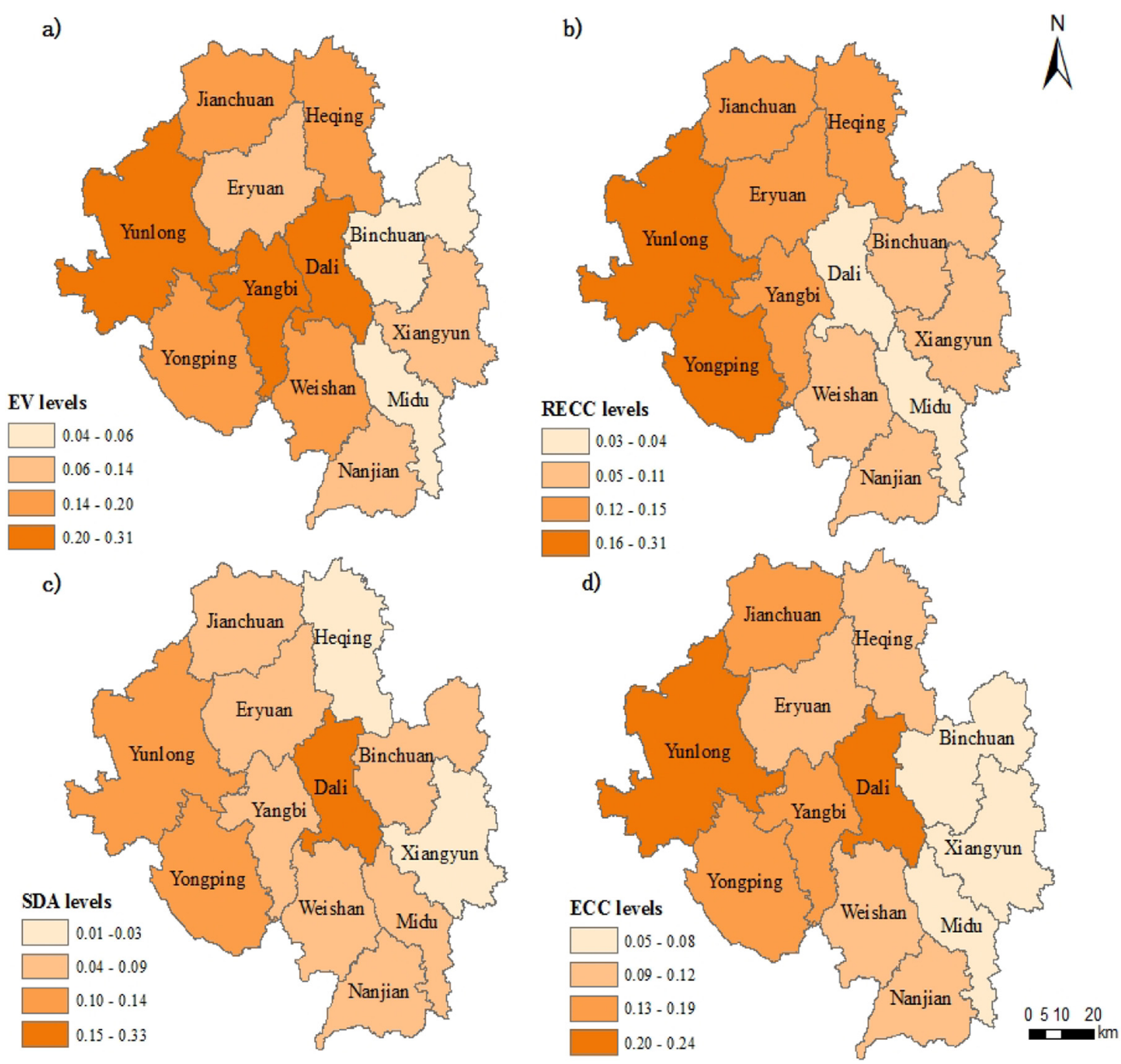

Fig. 4. Spatial patterns of ECC in Dali Bai Autonomous Prefecture.

to Midu County and Binchuan County. Analyzing components of EV (i.e., the ecological importance and ecological sensitivity), it can be seen that each county has its own characteristics. For example, Dali City has an outstanding advantage of ecological importance over the other 11 counties. Midu County occupies the least ecological sensitivity score and becomes the most eco-vulnerable throughout the prefecture. Binchuan County's ecological importance scores the least, and finally its EV index is the overall lowest in Dali Prefecture as well.

Referring to the evaluation index system (Table 1), the outcome (Table 4, Fig. 3) shows that high EV mainly distributes in areas with characteristics of good ecological background, high density of river systems and vegetation coverage, relatively flat terrain, and stable geological environment. For example, Dali City gains the highest scores of EV. Its villages and towns except Taiyi Township are all located in a plateau lake basin where geological disaster is not sensitive at all. Moreover, Dali City owns the National Nature Reserve of Cangshan Mountain and Erhai Lake, which features a large, multi-functioning eco-capacity. It covers 797 square kilometers and occupies 56.84% of whole territory of Dali City. Besides this national-level nature reserve, there are also others on the autonomous prefecture level. All these reserves contain various ecosystem types of forest, inland wetland, and waters, and make a significant contribution to the excellent ecological importance of Dali City, whose ecological importance index and EV both ranks the first.

For another example, Yangbi County, with the second-highest EV, is located in the main tributary valley of Lancang River and has relatively good heat and moisture conditions. Furthermore, the natural vegetation in Yangbi is preserved well overall, especially for the Yunnan pinery and semi-humid evergreen broad-leaved forest. The high vegetation cover conditions help keep a healthy flow of important ecological functions such as water and soil conservation.

As a negative case, Midu County and Binchuan County with low EVs have both commonness and specialty. They are both located on the edge of areas with massive crushing rocks and are prone to geological disasters. Besides having similar geological sensitivity situations, these two counties are both covered with relatively sparse vegetation of prairie, mixed forests, and thickets, which is not robust enough to protect regions from some sudden eco-damages. Objectively speaking, Midu and Binchuan are relatively weak in capacity of biological resource protection, water security keeping, and soil and water conservation. For instance, Midu County just contributes 3.7% to the total water conservation amount and ranks the last of the whole prefecture. Despite similar basic backgrounds, these two counties still have their distinctive EV features. The difference is that the score of Midu's ecological sensitivity ranks the last, while the limitation of Binchuan's ecological importance proves more obvious.

3.2. Resources and environmental potential

Shown in Fig. 4b, Yunlong and Yongping counties occupy the top two RECC, contrasted with the lowest of Midu County and Dali City. Analyzing components of RECC (i.e., potential resource supply and remainder environmental capacity), it can be seen that each county has its own characteristics. Yunlong County's potential resource supply scores the highest while Yongping County's remainder environmental capacity is the best. As counter-examples, Midu County's potential resource supply ranks the last while Dali City's remainder environmental capacity and RECC are both the worst of the whole prefecture.

RECC describes the future potential development capacity under the constraints of resource and environmental background. Considering the study area as a macro-ecosystem and a spatial entity with human management, we can find that RECC differentiation is closely related to both objective and subjective factors, such as underlying surface complexity, natural water renewal capability, environmental function zoning and environmental quality protection goals of water or air. Additionally, it is mainly affected by the land resource endowment, regional development status, and discharge situation of atmospheric or water pollutants. In order to help readers better understand RECC, Yunlong County and Yongping County are taken as examples to be further analyzed through combining the indicators with local reality.

As previously mentioned, RECC involves potential resource supply and remainder environmental capacity. First, available land resource is taken as an example. For Yunlong County and Yongping County with 1st and 2nd RECC respectively, the total land areas are separately 437,014.8 hectares and 278,928 hectares, which are the top two and occupy 25.29% of the whole prefecture. On the other hand, the existing construction land proportion is only 0.79% and 1.11%, respectively. As a result, land resources available for future urban expansion in Yunlong and Yongping are 227.56 and 181.25 hectares, which again ranks the top two highest.

Another example regards the water environmental capacity. The water environment is divided into several function zones according to the water quality target and the actual environmental capacity, and finally three categories are generated in Dali Prefecture, namely Zones for Class II, Zones for Class III and Zones for Class IV. Reaches such as Bijiang River, Caojian River, and Daoliu River distributed in Yunlong County or Yongping County are mainly used for industrial and agricultural water consumption, whose water quality just requires Class IV. Therefore, in these reaches and valleys, the pollutant quantity allowed into the lake is relatively larger (pollutant here refers to COD, ammonia nitrogen, volatile phenol, and so on). Thus, the remainder water-environmental capacity in these two counties is relatively more optimistic. Likewise, similar conclusions for Yunlong and Yongping's remainder air-environmental capacity can also be made, when analyzing their atmosphere environmental function zones and the actual distribution of atmosphere pollutants coming from industry, living, transportation and construction.

3.3. Social development ability

Shown in Fig. 4c, Dali City's SDA scores the highest while Xiangyun County and Heqing County score the lowest. Reverting back to the formation of SDA (i.e., human activity effects and social development degree), it can be seen that both indices of Dali City rank the first of the entire Dali Prefecture. However, both indices of Xiangyun County fall behind: HAE ranks the eighth, SDD ranks the eleventh, and SDA finally ranks the eleventh. As to Heqing County, its HAE ranks 10th, SDD ranks 12th, and the final SDA index ranks the last of the whole prefecture.

SDA is closely related to the present economy and population size as well as their future gathering tendencies, and reflects a kind of initiative adaption of economic activities to ecological feedback. In turn, the feedback information that comes from natural ecosystems is affected by dual human influence. Taking Dali City as example, it deserves the highest SDA in many ways. Its land utilization rate is as high as 86.17%, and industrial enterprises are concentrated. Meanwhile, agriculture modernization here is at a high level and urbanization also appears a leading model.

Tracing SDA evaluation system, it is clear that except for "waste outpouring density per thousand GDP", all other indictors of Dali City are either the highest (positive indicators, the larger value sorting higher) or the lowest (negative indicators, the smaller value sorting higher). This indicates that human activities are intensive and the subsequent ecological effects are obvious. To be specific, from the perspective of HAE, it can be seen that the ecological footprint of Dali City is as high as 983,866.72 hm^2, and its ecological deficit proportion reaches 16.92% leading the whole prefecture, which indicates a big human activity effect. From the perspective of SDD, the following are all the prefecture's leading positive indicators: non-agricultural population accounts for 31.99% of Dali City's total population, which is higher than the average level of Dali Prefecture at 12.72%. The economic density of built-up area is 167.49 yuan per square meters (the average level of the whole prefecture is 77.01 yuan per square meters). GDP per capita is 27,600 yuan per person (the average level of the whole city is 13,400 yuan per person). Other negative indicators are the lowest of the whole prefecture, such as the illiteracy rate of 2.27% (the statewide average level is 4.78%), water consumption per ten thousand GDP of 100 m^3 (the statewide average level is 300 m^3 per ten thousand yuan).

3.4. Ecological carrying capacity

Shown in Fig. 4d, the ECC of Yunlong County is the highest in the whole prefecture, while Midu County ranks the lowest. The final ECC of CHANS is determined by EV, RECC and SDA together. For instance, the three individual sub-ECCs of Yunlong County separately rank 3rd, 1st, and 3rd, and the integrated ECC ranks the best throughout the whole prefecture. As to Midu County, the three individual sub-ECCs separately rank 11th, 11th, and 10th, and the final ECC ranks the worst. At the same time, the spatial differentiation of ECC in Dali Prefecture shows that the ECC of the west region is overall higher than that of the east, and northern parts higher than the south. For example, Dali City and several counties distributed in the west of Cangshan Mountain including Yunlong, Yongping, Yangbi, and Jianchuan have relatively high ECCs. Meanwhile, other counties distributed in the east of Dai Prefecture like Binchuan, Xiangyun, and Midu have relatively low ECCs, and this is generally consistent with the spatial pattern of individual sub-ECCs.

In addition, by comparing the coefficient of variation (CV) of the three individual sub-ECCs, we can find that regional differentiation shows as follows: SDA (CV = 0.82) > RECC (CV = 0.60) > EV (CV = 0.48), which indicates that the SDA among regions varies most distinctly. CV is defined as the ratio of standard deviation to the mean of the individual sub-ECC. What's more, CV of EV, RECC, and SDA are all calculated at the county level. The difference of the three CVs is closely related to the similar geographical conditions within the mountainous Dali Prefecture, as well as the different regional economic development and resource utilization status. To be specific, EV mainly reflects the natural ecosystem's characteristics determined by geographical elements like vegetation, hydrology, and topography as a whole. It is primarily affected by geographical conditions that relatively perform homogeneously in the study area. SDA mainly reflects the feature of social economic systems, while RECC describes the process of human systems interacting with natural systems. Both SDA and RECC tend to perform strong heterogeneity compared with EV, since they are involved with human activity factors, which are more uncertain, discontinuous, and complex than natural ecological factors.

Concerning the local condition of Dali Prefecture, though the geographic environment is complex, partially with various landforms such as hilly canyons, steep slopes, platforms, geo-synclinal fold zones, and lake basins, the general climate and geological background is relatively similar throughout the prefecture. For example, counties are all located in the junction of Yunnan-Guizhou Plateau and Hengduan Mountains, and their climate type is the subtropical monsoon climate of low latitude plateaus, thus it is understandable that the EV among counties is not very different so much. Reflecting on the EV value, from the lower level to the higher level, the number of counties of each category is respectively 2, 3, 4, and 3, which shows a relatively balanced distribution.

In regards to an explanation for SDA variation, taking the social economic characteristic into consideration, we can see that the mountainous Dali Prefecture is a multi-ethnic place, having a population made up of the Han, Bai, Yi, Hui, Lisu, Miao, and Nahsi nationalities, among others. Besides the nationality difference, the large proportion of rural population, complicated geographical environment, various resource endowments, and unique cultural customs all affect the imbalance among county-level development. Moreover, in general, superior resources and administrative dispositions gather intensively in central Dali City. Meanwhile, other small counties and towns are possibly faced with insufficient support for industry development, poor infrastructure, and lagging public services, which aggravates the slow development of these regions. Reflecting on the SDA value, it can be seen that the SDA score of Dali City (0.333) is obviously over the secondary Yongping County (SDA = 0.139). Meanwhile, it highly surpasses the average level of the entire prefecture (SDA = 0.099) and belongs to the first category solely, which directly causes the large fluctuation of SDA throughout the whole prefecture. From the lower level to the higher level of SDA, the number of counties of each category is respectively 2, 7, 2, and 1, and this distribution is obviously less balanced compared with that of EV.

As to the RECC, from the lower level to the higher level, the number of counties of each category is respectively 3, 4, 3, and 2, and the distribution is relatively balanced. Meanwhile, counties with the adjacent RECC level present obvious spatial agglomeration. This phenomenon is probably due to the similar manner of human development influenced by the similar resource endowment, following the principle of "adopting measures suiting local conditions".

To sum up, based on the transition involving human factors replacing the role of natural factors to dominantly affect the regional balance and environmental change (Messerli et al., 2000; Rediscovering Geography Committee, 1997), Dali Prefecture has become the typical CHANS as well as the typical spatial entity complex in the process of urbanization. As a result, natural ecosystems are influenced by geographical background (Wu and Li, 2013) at the large-scale level and present homogeneous features to some degree. Meanwhile, social economic systems involve more nonlinear human factors and present great heterogeneity (Li and Wei, 2010).

4. Discussion

4.1. Trade-offs between mountain development and ecological protection

Comprehensive development of low-slope hilly lands under the background of urbanization objectively requests the scientific developing mode, developing purposes as well as developing schedules on the premise of ecosystem protection. Faced with conflicts among different land usages, we should weigh the county development and ecological protection seriously. At the macro-level of policy-making, this kind of trade-off meets the requirements of the 18th CPC National Congress that placing the construction of ecological civilization in a prominent position and strengthening ecological protection whilst developing the economy to find a balance between development and protection. At the micro-level of local-practice, the trade-off between economic development and ecological protection is advantageous to the making of differentiated administrative plans and appropriate strategies, especially for mountainous western Yunnan and other ecologically sensitive areas.

Based on the ECC model that portrays ecological processes, this study compares different pattern characteristics of diverse sub-ECC combinations, identifies pivotal constraints of each county during short-term or long-term development, and then clears their priority sequences of economic development or ecological protection.

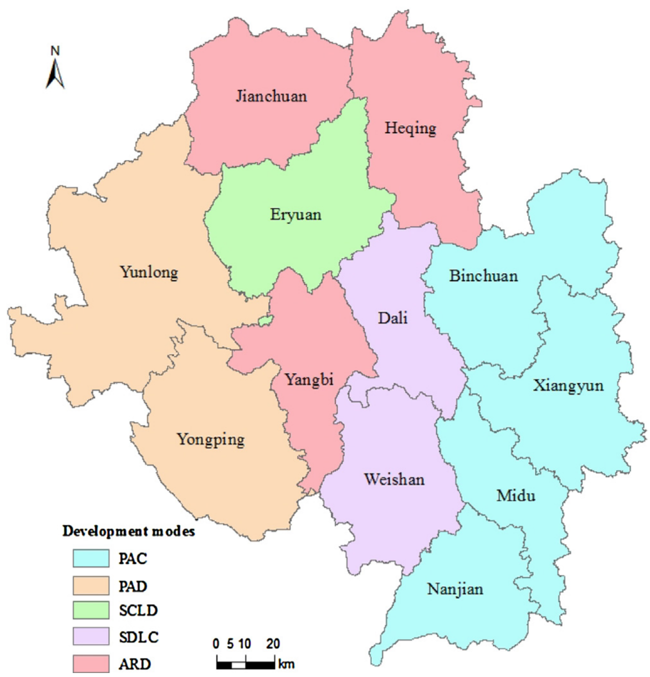

Fig. 5. Trade-offs of urban development at county level in Dali Bai Autonomous Prefecture (PAC, PAD, SCLD, SDLC, and ARD respectively stand for priority areas for conservation, priority areas for development, areas suitable for short-term conservation but long-term development, areas suitable for short-term development but long-term conversation, and areas reserved for future appropriate development).

Considering the popular regulation of most official plans in China as well as the development status of our study area, the short-term here is defined as 10–15 years in the near future, while the long-term refers to the duration of the next 15 years.

In specific, EV, RECC, and SDA scores of each county are divided into low or high levels according to the natural breakpoint method. Then these three layers are overlaid to get four kinds of spatial combinations, namely, three-low type, one-high type, two-high type, and three-high type (Table 5). Finally, development strategies of Dali Prefecture are explored based on this combination (Fig. 5). The study area is grouped into five categories considering trade-offs between mountain development and ecological protection, i.e., priority areas for conservation, priority areas for development, areas suitable for short-term conservation but long-term development, areas suitable for short-term development but long-term conversation, and areas reserved for future appropriate development. Thereinto, for counties falling into the three-high type or "EV-RECC two-high type", the SDA level determines the development schedule: a certain county with a high SDA should be developed at present, while a low SDA is suitable for future development. For counties belonging to three-low type or two-high type, the EV or RECC mainly determines whether they should be developed or not. If the EV and RECC are both at a high level, the county is prone to a development priority. However, if either of the two presents a low level, ecological protection will be encouraged in the late period regardless of whether the county is developed in the early period or not.

More specifically, the ECC hot spots, namely counties of three-high type, include Yongping and Yunlong. With relatively stable ecosystem structure and function, abundant potential resource supply and remainder environmental capacity, and relatively concentrated population and economy, these hot spots can continue to grow fast on their original basis and thus inevitably become the priority development objects. On the contrary, the ECC cold-spots, that is, counties of three-low type, includes Nanjian, Xiangyun, Binchuan, and Midu. With high natural disaster risks, fragile ecological environments and simple ecosystem structures, ecological services sustainability of these regions are usually hard to maintain, so ecological protection should be given priority to these areas. Simply put, "EV-RECC-SDA three-high" counties are priority areas for development, and "EV-RECC-SDA three-low" counties are priority areas for conservation.

As to hybrid areas (i.e., counties that are one-high type or two-high type), when designing their development modes, differentiated characteristics of individual sub-ECCs and an integrated ECC of each county should be focused on first. Then, appropriate development strategies are made in accordance with local conditions, involving the current plan, medium-term plan and long-term plan. For example, EV and SDA are both at a high level in Dali City, whose growth pole advantages guarantee its continual benefits from the expansive development in the near future. However, having experienced long-lasting leading development, Dali City's current resource and environmental conditions have been the most severe of the entire prefecture. The poor remaining environmental capacity and scarce potential water and land resources will undoubtedly be a strong constraint on further development. Allowing for the urgent demand of environmental protection, developing in short-term and protecting in long-term seems to be a moderate development strategy for Dali City.

For another example, Weishan County that is the "EV one-high type" (namely the county with a high EV but relatively low RECC and SDA) is also identified as an area suitable for short-term development but long-term conversation. It is apparent that Weishan County possesses relatively developed economic and cultural levels and remarkable benefits of human exploitative activities with the third highest SDD score. However, the index of HAE just ranks 12th and directly results in a low SDA which is composed of HAE and SDD. Specifically, based on an analysis of the HAE of Weishan County, the ecological footprint is 529,689.01 hm^2 and ranks 8th, water consumption per ten thousand GDP is 432.63 m^3 and ranks 10th, and the waste outpouring density per thousand GDP is 17.03 kg and ranks 11th. All of these poor indicators imply that the immense but inefficient natural capital occupation has put great pressure on the environment. Additionally, it can be concluded that the high profit is based on high cost, and economic development of Weishan County is still in the early extensive period. It is desirable to continuously maintain the momentum of economic growth in Weishan, but we could not ignore the combination of efficiency and effectiveness in pursuit of Green GDP. Furthermore, the unsubstantial resource and environmental conditions may limit the subsequent economic growth. Considering intergenerational equity on natural capital utilization, it's better to classify Weishan County as the type of "developing in short-term and protecting in long-term" in terms of development strategy.

As to areas reserved for future appropriate development, Yangbi, Jianchuan and Heqing counties are good examples. They have a high EV and RECC simultaneously (i.e., counties that are "EV-RECC two-high type"), and are suitable for moderate exploitation within an acceptable bound of resources and environment to meet the needs of local development.

The next example is used to explain "areas suitable for short-term conservation but long-term development". Er'yuan, the county that is a "RECC one-high type", has a strong ecological sensitivity (ranking 10th) but weak ecological importance (ranking 8th). In order to maintain a good ecosystem background, stress should be put on ecosystem protection and ecological risk avoidance. However, for low-slope hilly areas in Er'yuan County, the potential developable land resources are relatively abundant (ranking 3rd), the remaining pollutant absorption capacity is still explorable (ranking 6th), thus the resource and environmental carrying capacity situation remains optimistic on the whole (ranking 4th). With

Table 5
Dominant factors for mountain development strategy balance.

Counties	EV	RECC	SDA	Key constraints
Yunlong	High	High	High	Ecological sensitivity
Dali	High	Low	High	Remainder environmental capacity
Yongping	High	High	High	Ecological importance
Yangbi	High	High	Low	Social development degree
Jianchuan	High	High	Low	Human activity effects/social development degree
Weishan	High	Low	Low	Remainder environmental capacity
Er'yuan	Low	High	Low	Ecological sensitivity/social development degree
Nanjian	Low	Low	Low	Ecological sensitivity
Heqing	High	High	Low	Social development degree
Xiangyun	Low	Low	Low	Social development degree
Binchuan	Low	Low	Low	Ecological importance
Midu	Low	Low	Low	Ecological importance/potential resource supply/remainder environmental capacity

Supplements: Key constraints are identified by the degree of individual sub-ECC falling behind the integrated ECC in each county, and the relative precedence among several detailed indicators of a certain county's individual sub-ECC.

regard to all the aforementioned factors, it is also optional to put Er'yuan County into a coming development status to support the long-dated development scheme, if development in surrounding counties has reached a saturated point and planners have no choice but to find new expansion space.

Simply put, in the short term we should make good use of the present growth pole and give developing priority to counties with good conditions in all three sub-ECC dimensions. We can also disintegrate the overall function of a growth-polar county according to its own features and that of neighbor counties. First, we must deconstruct the original county into several functional parts, and then reorganize each of them with surrounding regions based on their links to form new function groups. In this way, we can realize the trade-off among various dimensions of ECC, and the trade-off between economic development and ecological protection on the town-cluster level, which accords with the trend and prospect of cluster development.

In the long term, the government's support and economic input should be increased in counties with good EV and RECC but poor SDA, to quickly push them toward high-level urbanization. Regions with low EV, high ecological risk and a vulnerable ecological environment should be firstly well-protected by means of biological resource conservation, plateau lake restoration, water and soil loss control, watershed management and natural disaster prevention. Then, moderate development should be approved within the resource and environmental carrying capacity to meet demands of ecosystem-based planning and management (Gao et al., 2014; Li et al., 2014b). Moreover, counties with a vulnerable RECC should take action to use resources economically and protect environment reasonably. For example, it is helpful to curb population, optimize industrial structure and distribution, promote industry with low energy or water consumption and low pollution, encourage enterprises to pay more attention to technological innovation, and so forth. Additionally, stakeholders can attempt to ease the resource shortage and improve externalities resulted from economic entities on the eco-environment according to a price mechanism and eco-compensation method.

4.2. Limitations and future research directions

ECC studies aim at promoting harmony between humans and natures, and realizing sustainable development of coupled human and natural systems. The related work can contribute to the theory development of ECC and sustainability, and also help to identify the way for regional sustainable development. Previous literature has already confirmed that ECC research should not be limited to the sole study object or single perspective of the integrated system. However, despite more and more attention to CHANS, the study of ECC still has a long way to go in respect to revealing interaction and association among subsystems as well as describing internal mechanisms and processes. Furthermore, some questions are still not illustrated clearly in the existing researches, such as the relationship between short-term development and long-term development indicated by ECC from a temporal dimension, and developing focus identification related to regional ECC differentiation from a spatial dimension. In this case study, ECC conceptual framework is built in view of CHANS, focusing on the balance among resource utilization, human development, and ecosystem maintenance, not pursuing the maximum carrying capacity of a certain subsystem. Trade-offs between mountain development and ecological protection are also discussed considering both temporal and spatial dimensions.

However, due to the distinctiveness of low-slope hilly regions and complicated relationships among various sub dimensions of ECC, there are still shortcomings in ECC evaluation aiming at coupled human and natural systems in mountainous areas. Firstly, evaluation itself is subjective; weight setting of indices takes some uncertainty to evaluation results. Nevertheless, quantitative evaluation still provides some objective and intuitive information to understand the ECC status and regional development prospects. Whether the evaluation is scientific or not mainly depends on the logical associations of indicators as well as the comprehensiveness of the designed assessment system. In the future, we can explore weight setting of multiple scenarios based on a multi-targeted development plan to make our schemes more flexible, adaptable and competitive.

Furthermore, the ECC evaluation at county level can help to quickly discover the development weakness of various administrative units, to grasp the comprehensive strategic positioning in regional development and eco-protection, and to do our utmost to promote administrative decision-making. However, the lack of highly precise data has brought about difficulty in figuring out the ecological carrying potential of various villages, towns and non-administrative geographic patches inside counties. Most of all, plenty of researches have verified that the study objects of geography, ecology and other disciplines usually show the feature of scale-dependency in aspects of pattern and process, spatial and temporal distribution, and their interconnection (Levin, 1992; Li et al., 2010b). Under such circumstances, the problem of small spatial grid becomes quite obvious in this paper. Therefore, we should explore methods more appropriate to spatialize social-economic data, and combine it with small watershed management, land-use planning, ecological function zoning, main function zoning, and so forth. In this way, a more detailed research on the spatial distribution of ECC in low-slope hilly areas will be available. Furthermore, based on the existing ECC framework, a more comprehensive indicator system may be put forward, involving more abundant social and economic information such as the developing trend of tertiary industry, urban population structure, and so on. Thus, the ECC assessment could better identify the bottleneck of future population agglomeration, industrialization, and urbanization of Dali Prefecture.

In sum, this paper employs a range standardization method to deal with the three dimensions such as EV, RECC and SDA. A value between zero and one stands for the relative status of a sub-ECC in a certain county compared with other counties. Then, a weighted summation of all indices is conducted, the summation representing the integrated ECC of a region. In the future, we can try a new perspective to understand the ECC based on various interrelations among sub-ECCs, and choose an extremum method or other calculation rules to obtain the final ECC, according to the specific research purpose.

5. Conclusions

The study of mountain ECC is of great significance for estimating development potential and guiding the regional trade-offs. Based on a framework for ECC of CHANS, allowing for the sensitive ecological environment of low-slope hilly regions and its strong development demanding, this study carries out an evaluation of ECC of 12 counties of Dali Prefecture from aspects of ecosystem vigor, resource and environmental carrying capacity, and social development ability. The results show that: (1) focusing on individual sub-ECCs, areas with the highest (lowest) scores of EV, RECC, and SDA are respectively Dali City (Binchuan County), Yunlong County (Dali City), and Dali City (Heqing County); from the viewpoint of comprehensive assessment, the level of ECC in Yunlong County is the highest statewide, while that of Midu County is the lowest. (2) The development and protection of low-slope hilly areas should be based on the differential characteristics of each county's ECC in both single and compound dimensions. Development strategy should be adjusted to local conditions, and different factors should be considered to make short-term or long-term development plans. Binchuan, Xiangyun, Midu, and NanJian counties are priority areas for conservation. Yunlong and Yongping counties are priority areas for development. Er'yuan County belongs to areas suitable for short-term conservation but long-term development. Dali City and Weishan County belong to areas suitable for short-term development but long-term conversation. Yangbi, Heqing and Jianchuan counties are areas reserved for future appropriate development. The results are helpful to identify the sustainable development possibility of regional economy-society-ecology from the perspective of CHANS with an ECC approach, and serves to decision-making on mountainous area construction effectively.

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