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Multifunctional landscapes identification and associated development zoning in mountainous area

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ABSTRACT

Multifunctional landscape has become a new discipline growth point in landscape ecology. Globally mountainous areas occupy about one fifth of Earth's surface. However, few studies focused on landscape multifunctionality in mountainous areas. Taking Dali Bai Autonomous Prefecture, China, as a case study area, five typical landscape functions (net primary productivity, soil retention, water yield, crop production, and residential support) were quantified and mapped. Hotspots of multiple landscape functions were identified using spatial overlap tools, interaction between each landscape function pair was discussed through Spearman's rank correlation analysis, and development zoning was conducted based on landscape function bundle. The results showed that, about 61% of the study area had at least one kind of landscape function hotspot, with only 2.7% covering three or more kinds of landscape function hotspots. Significant trade-offs or synergies existed between all pairs of landscape functions, except the pair of net primary productivity and residential support. With the application of Self-Organizing Feature Maps (SOFM) method, the study area was divided into four types of development zones (i.e. ecological shelter area, ecological transition area, suburban development area, and urban agglomeration area) which were all corresponding to different landscape function bundles. This study could provide spatial guidance for differentiated sustainable developing in mountainous areas according to local conditions of landscape multifunctionality.

Keywords: Multifunctional landscape; Synergies and trade-offs; Development zoning; Northwestern

Yunnan

1. Introduction

A landscape is a geographic entity with obvious visual features composing a mix of local ecosystem land use types Forman, 1995 Noss, 1991). Landscape function can be described as the interaction between landscape structure and ecological processes or between landscape components (Wu, 2007). Similar to ecosystem service, landscape function refers to the capacity of a landscape to provide goods and services to human beings (Willemen et al., 2010). A wide range of landscape functions can be divided into four major groups: (i) production functions; (ii) regulation functions; (iii) habitat functions for maintaining ecological structures and processes; and (iv) information functions (Bolliger et al., 2011), indicating multiple attributes of coupled human and nature system. The functions that are or can benefit humans in economic, social or ecological dimensions, are further defined as landscape services (Bastian et al., 2014; Termorshuizen and Opdam, 2009). With the intense growth of anthropogenic activities, the combination of different functions is increasingly repeating in the same landscape. These combined functions can be defined as landscape function bundles, a specific attribute of a multifunctional landscape (Peng et al., 2016). Multifunctional landscapes are regarded as the inevitable result of the trade-offs of multiple landscape functions determined by the interaction between human and nature, with the original studies on multifunctional agricultural systems (Vejre et al., 2007; Wilson, 2007). By integrating multiple ecological, economic and/or social functions in the same landscape, the concept of multifunctional landscapes have provided an important approach to bridging the gap between human and nature (Brandt and Vejre, 2004). In contrast to the concept of multifunctional land use, multifunctional landscape focuses on combining multiple ecological functions rather than land cover types as such (Vreeker et al., 2004; Liu et al., 2018). Thus, multifunctional landscape has become a new discipline growth point in the field of landscape ecology (Fu et al., 2008).

Multifunctional landscapes studies originated from The International Conference of Multifunctional Landscape: Interdisciplinary Approaches to Landscape Research and Management held in 2000. Subsequently series of theoretical, methodological and case studies have been conducted. Focusing on the three kinds of multifunctionality defined by Brandt and Vejre (2004) (i.e. spatial segregation, time segregation and spatial integration), the topics of these studies mainly included the concept and significance (Bolliger et al., 2011; Fry, 2001; Lovell and Johnston, 2008; Naveh, 2001), formation mechanism and comprehensive assessment (Sal and Garcia, 2007; Maes et al., 2012; Willemen et al., 2008), and planning and management (Bastian et al., 2012; Groot et al., 2010; Li et al., 2013; White et al., 2012), of multifunctional landscapes. Among these studies, approaches to quantifying landscape multifunctionality are always highly focused on. For example, Vatn (2002) developed an economic approach to analyzing the impact of trade policy on multifunctional agriculture considering both private and public goods as well as transaction costs. Cassatella and Seardo (2014) proposed the methodology to assess scenic landscape with the flows of characteristics identification by means of indoor study and field survey, visual analysis, and indicators integrating and assessment. However, for geographers and landscape ecologists, who highlight the interaction between spatial patterns and ecological processes, the spatially explicit interaction between landscape functions, ecosystem services and social benefits is crucial. For example, Willemen et al. (2010) quantified seven landscape functions in a Dutch rural region, and then identified multifunctionality hot spots and cold spots by means of spatial overlay tools and correlation analysis.

The multifunctional landscape has become one of the response pathways to achieve the goal of Land Degradation Neutrality, as pointed out in 2017 by the First Edition of Global Land Outlook published by United Nations Convention to Combat Desertification. To plan and manage multifunctional landscapes rationally, it is necessary to identify and quantify landscape functions according to the specific natural and social conditions. Trade-offs and synergies among landscape functions, which further form specific spatial bundles (Bai et al., 2011; Bennett et al., 2009; Queiroz et al., 2015; Yang et al., 2015), can characterize the integrality of multifunctional landscapes as well as the independence of individual landscape functions (Naveh, 2001). As a result, interactions among landscape functions should be further explored, especially in different landscape types. Related studies have been well conducted across a wide range of landscape, such as agriculture landscape (Bernues et al., 2015), agroforestry landscape (Jose, 2009), and urban landscape (Peng et al., 2016; Gao et al., 2014). However, little attention has been paid to mountainous areas where low-slope hilly landscapes are widely distributed with more complex conflicts between key landscape functions.

Mountainous areas represent a unique and fragile geographical environment with important ecological functions, where natural disasters are frequent and the landscape changes with increasing altitude. Along with the rapid urbanization in southwestern China, mountainous areas are characterized by an increasing food demand due to the significant population increases and dietary shifts. Hence, there exists a great challenge to provide increasing social functions while maintaining their ecological functions. Multifunctional landscapes can be a viable approach to facing the challenge. It can coordinate multiple landscape functions which are usually characterized as the conflicts between social development and ecosystem conservation, such as the serious environmental issues of soil erosion, seasonal drought and limited development space.

As a typical minority area with the fragile mountain environment and low economic development, the Dali Bai Autonomous Prefecture (hereinafter referred to as Dali Prefecture) is located in Northwestern Yunnan Province, China. It is one of the world hotspots in both biological and cultural diversity (Wang et al., 2017), and has become an internationally renowned destination for travelers, providing an appropriate case study for investigating multifunctional landscapes in mountainous areas. However, with the large-scale development of tourism over the past two decades, the rapid increase in the local economy and anthropogenic activities pose a huge threat to its fragile eco-environment. Thus, it is significant to coordinate the multiple functions of landscapes rationally and effectively to ensure sustainable development in this region. Correlation analysis among multiple ecological and social landscape functions in this region can provide the theoretical basis to guide the process of urbanization for policymakers in mountainous areas. In this study, taking Dali Prefecture as the study area, we quantified several landscape functions, identified their interactions, and classified the development zones at the township level. In details, the following questions were focused: (i) what were spatial patterns of individual landscape functions? (ii) what were the interactions between different landscape functions, and in which pair(s) of landscape functions did the trade-offs and synergies exist? And (iii) how to divide the region into different development zones according to the combinations of landscape functions?

2. Materials and methods

2.1. Study area

Dali Prefecture is situated in an ecologically fragile transition zone extending from the low altitudes of the Yunnan Plateau to the high altitude of the Qinghai-Tibet Plateau, in Northwestern Yunnan Province, China (98°52'–101°03'E, 24°41'–26°42'N) (Fig. 1). The total area of the region is 29,459km^2 with the 320 km length from east to west and the 270 km width from north to south. It has a variety of topographical types with higher lands in the west and lower lands in the east. The study area has a subtropical plateau southwest monsoon climate, characterized by an average annual temperature of approximately 15°C and mean annual precipitation of 800–1000 mm. However, there is great seasonal variability, such as a seasonal drought. Water resources are relatively abundant with 13.44 billion m^3 which are mostly present in the Northwest. The overall eco-environment is fragile, and hence intensified human activity results in an increase in land degradation and soil erosion, in particular in topographically more complex terrain

Natural land covers (i.e. forest land, grassland, water body, and wetland) dominate the landscape of the Dali Prefecture, equal to 76.1% of the total land area. The study area is also an agricultural prefecture. The distinctive mountain agriculture has been developed under the topographical limitation where mountain areas account for 93.4% of the total land area. The limited cultivated land in Dali Prefecture showed a decreasing trend from 375260 hm^2 in 2009 to 370628 hm^2 in 2016. The construction land accounted for about 2.23% of the total land area. However, along with rapid urbanization and economic growth in China, the increasing demand for construction land is expected to occupy cultivated land and natural land, which poses great challenges to maintain the local agriculture production and ecological functions.

The newest version of Dali Prefecture Land Use Planning (2016-2020) underlines the importance to apply the most strict cultivated land protection regulation in order to improve regional crop production and enhance local food security. This official planning guidance also mentioned to promote new urban development and rural revitalization strategy for mountainous areas under the premise of natural resources and eco-environmental protection. Therefore, crop production, urban and rural settlement construction as well as ecological functions conservation are all important regional sustainable development goals.

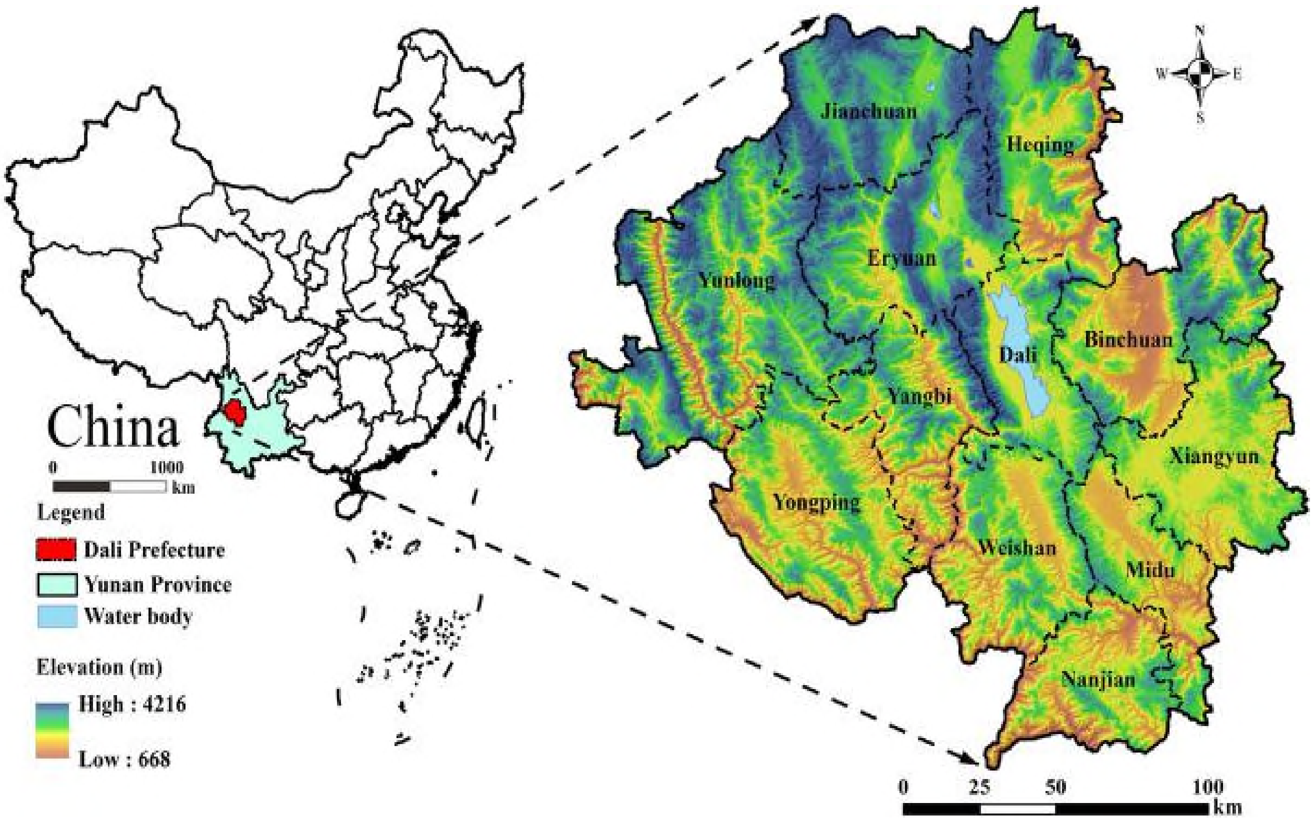

Fig.1. Location of the study area.

2.2. Methodology

This study was conducted in four steps. Firstly, five key landscape functions (net primary productivity, soil retention, water yield, crop production, and residential support) were identified from both eco-environmental and socio-economic perspectives, and were quantified spatial explicitly through applying specific models. Secondly, hotspots were identified with multiple landscape functions. Thirdly, correlations across different pairs of landscape functions were investigated by means of overlay analysis and Spearman's rank correlation. Finally, development zoning was conducted using the method of Self-Organizing Feature Maps (SOFM).

2.2.1 Mapping landscape functions

(1) Net primary productivity

The high level of vegetation coverage in the study area plays an essential role in regional ecological security, and hence the vegetation growth status can influence the quantity and quality of ecosystem services and biodiversity. Net primary productivity (NPP) is one of the important parameters measuring plant photosynthesis which can represent the quality of terrestrial ecosystems

(Field et al., 1998). CASA (Carnegie-Ames-Stanford Approach) was employed, which had been widely used in NPP estimation (Potter et al., 1993). The model can be expressed as following:

$$NPP(x,t) = APAR(x,t) \times \xi(x,t) \tag{1}$$

where $APAR(x, t)$ is the photosynthetically active radiation absorbed at the pixel x in the month t that is influenced by total solar radiation and absorption ratio of active radiation based on the results of NDVI (normalized difference vegetation index); and $\xi(x, t)$ is the actual light energy utilization at the pixel x in month t which is estimated through temperature stress, water stress and vegetation maximal utilization efficiency of light. Locally specific estimation of $APAR$ and ξ is developed and designed by Zhu et al. (2007a, 2007b).

(2) Soil retention

Due to the combined presence of low-slope hills and larger mountains, abundant rainfalls and anthropogenic activities, soil erosion has become one of the key land degradation issues and has caused the loss of limited farmland. Therefore, soil retention is an important landscape function that should be focused on within the study area. The capacity of soil retention was quantified with Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which has been widely applied in various mountainous landscapes (Wang et al., 2017):

$$A = R \times K \times LS \times (1 - C \times P) \tag{2}$$

where A is the soil retention, R is rainfall erosivity factor, K is soil erodibility factor, LS is slope length and steepness factor, C is land cover and management factor, and P is support practice factor (Jia et al., 2014).

(3) Water yield

The functionality of a given landscape to provide fresh water is of great importance in order to have a healthy landscape and secure social welfare (Caldwell et al., 2016; Zhao et al., 2018). In the study area, the monsoon climate is characterized by great variation in annual precipitation, including seasonal droughts threats. In addition, water resources in the mountainous area are spatially imbalanced due to the complex terrain. Therefore, quantifying and mapping water yield function is of significance for landscape management purposes. Water equilibrium model were used here, which defined annual water yield as the balance between annual precipitation and evapotranspiration (Jia, 2014).

(4) Crop production

Crop production is of great importance in terms of local food security and livelihoods, and also is highlighted in regional land use planning. Thus, crop production is one of essential landscape functions to be identified and mapped. Because NDVI has been proved to have strong linear relationship with crop yields (Groten, 1993), downscaling the county-level crop yield statistics data with this relationship is able to map the function of crop production. More precisely, maximum value of NDVI which reflected the best growth status during June to September of each grid was extracted, and then grain crop production of the whole county was allocated to the farmland grids according to NDVI as following:

$$G_{ij} = \frac{NDVI_{i,j}}{NDVI_{mean,j}} \times G_j \quad (3)$$

Where G_{ij} represents the crop yield of the farmland grid i in the county j, G_j is average yield of the county j, $NDVI_{ij}$ means the $NDVI$ value of the farmland grid i in in the county j, and $NDVI_{mean,j}$ is the average NDVI of the farmland in the county j.

(5) Residential support

Out of the purposes of maintaining ecological and agricultural fun-tions, the construction land has become very limited. In the context of population increasing and limited construction land, residential settlement should be taken into consideration seriously in order to ensure social welfare. Nighttime light intensity has been proved to be strongly related with human settlements (Amaral et al., 2006). Using the equation similar with NDVI, total population of each county obtained from statistic data was assigned to the residential grids within its jurisdiction according to nighttime light intensity differences of the grids.

In detail, the main data sources for mapping landscape functions are as follows. NDVI and land-cover data were obtained from the data set of MOD13Q1 at the 250-m spatial resolution and MCD12Q1 at the 500-m spatial resolution, respectively, which were both produced by the US National Aeronautics and Space Administration (NASA) (http://modis.gsfc.nasa.gov/). The soil constituent distribution map was digitized from the map of soil types in in Dali Prefecture. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data at the 30 m spatial resolution were downloaded from http://www.gdem.aster.ersdac.or.jp/search.jsp. The DMSP/OLS nighttime light data were collected from the US National Geophysical Data Center (NGDC) (http://www.ngdc.noaa.gov/dmsp/global composites v2.html) at the ground resolution of 0.008333 degrees. The annual mean evapotranspiration was obtained from the data set of MOD16A3 at the 1-km spatial resolution (http://wist.echo.nasa.gov/api/). The annual mean precipitation, temperature, and solar radiation data were derived from weather stations within and near Dali Prefecture (http://cdc.cma.gov.cn/home.do). The river course and the boundaries of the study area were obtained from the National Fundamental Geographic Information System of China (http://nfgis.nsdi.gov.cn/). Grain output data were collected from the statistical yearbook, and population data came from the sixth population census of China. Most of the data were collected for the year 2009, except for the DMSP/OLS nighttime light data and population data (for 2010). All the data were unified for the 1-km grid, which was used to make preparations for the subsequent overlay analysis. All the quantification and spatial analysis of landscape functions were performed using ArcGIS 10.1. The data and methods used to quantify landscape functions were listed in Table 1.

Landscape function (abbrev.)	**Description**	**Landscape indicator**	**Main Data**	**Unit**	**Calculation method**
Net primary productivity (NPP)	Benefits from plants in terms of carbon sequestration and oxygen release	Carbon sequestration estimation	MOD13Q1 NDVI products, MODIS IGBP land cover data sets, monthly meteorological data	gC per m^2 per year	CASA Model. It was calculated through ENVI integration module, which was designed and developed by Zhu et al. (2007).
Soil retention (SR)	Preservation of soil quality and control of erosion	Difference between potential and actual soil erosion	MODIS IGBP land cover data sets, soil type chart, DEM data	Ton per hm^2 per year	RUSLE Model. $A = R \times K \times LS \times (1 - C \times P)$, where A is the soil retention, R is rainfall erosivity factor, K is soil erodibility factor, LS is slope length and steepness factor, C is land cover and management factor, and P is support practice factor.
Water yield (WY)	Capacity of vegetation	Balance between PPT and ET	MOD16 evapotranspiration	Mm per year	Water Equilibrium Model. $Q = PPT - ET$, where Q is the annual water yield,

	coverage to conserve water resource		product, precipitation data		*PPT* is precipitation, and *ET* is evapotranspiration (Jia et al., 2014).
Crop production (CP)	Capacity of farmland to provide food	Crop production mapping	County-level grain output, MOD13Q1 NDVI products, MODIS IGBP land cover data sets	10^4 Ton per year	Total crop production of each county was allocated to the farmland grids within its jurisdiction based on NDVI differences of the grids.
Residential support (RS)	Capacity to support human population	Residential population mapping	County population, DMSP/OLS night light data	10^4 Person per km^2	Total population of each county was assigned to the residential grids within its jurisdiction according to nighttime light intensity differences of the grids.

Table 1 Landscape functions and their calculation methods

2.2.2 Identifying multifunctional landscapes

Landscape functions can be overlapped together, which actually means that one spatial grid is possible to provide multiple landscape functions at the same time. These regions can be defined as multifunctional landscapes. Here a new approach to identifying multifunctional landscapes, was developed with consideration of spatial neighboring relationships.

Firstly, the Getis Ord Gi* statistic, one of the most widely used indicators of local spatial autocorrelation (Getis and Ord, 1992), was applied to detect spatial aggregation of each landscape function, by identifying specific geographical areas with values significantly higher than others as hotspots according to spatial weight matrix. It is an effective way of measuring spatial patterns of grids with high or low values in different spatial units. In this case study, spatial distribution of landscape functions and spatial correlation of landscape functions within the neighboring regions were characterized using Getis Ord Gi* statistic with the 1-km grid :

$$G_i^*(d) = \sum_{i=1}^{n} w_{ij}(d) x_j \Big/ \sum_{j=1}^{n} x_j \tag{4}$$

where w_{ij} is a symmetric one or zero spatial weight matrix, with one for all grids within a given distance d of cell i including the cell i itself, and zero for the other grids. In this case study, the numerator is the sum of all the values of specific landscape functions associated with the grids within the distance d of cell i, whereas the denominator is the sum of all the values of specific landscape functions associated with all the grids. For the convenience of interpretation, G_i^* can be standardized as following:

$$Z\left(G_i^*\right)=\frac{G_i^*-E\left(G_i^*\right)}{\sqrt{Var\left(G_i^*\right)}} \tag{5}$$

where $E\left(G_i^*\right)$ and $Var\left(G_i^*\right)$ are the mathematical expectation and variable coefficient of G_i^*, respectively. A significantly high positive Z score for a grid indicates that the values of its neighborhood grids within a certain distance are higher than the average with an apparent spatial concentration. A Z score near zero refers to spatial dispersing.

The second step was to identify the hotspots of each landscape function according to the Z score. Then, these hotspots of all landscape functions were overlaid, and the number of total hotspots of landscape functions for each grid was calculated. Areas with three or more types of landscape function hotspot could be defined as multifunctional landscape hotspots. In other words, these grids had three or more landscape function hotspots and spatially formed a range of high-value clusters of landscape functions.

2.2.3 Quantifying interactions among landscape functions

Spatial overlay analysis is an effective means of identifying hotspots where the values of a range of landscape functions are at high level simultaneously, although it cannot quantitatively describe the complex interactions between landscape functions. An enhanced understanding of trade-offs and synergies among multiple landscape functions can provide the scientific basis for integratively managing multifunctional landscapes to better contribute to human and ecosystem well-being. More specifically, interactions between different landscape functions can be divided into three types (Willemen et al., 2010): (i) conflicts, the combination of landscape functions reduces a certain landscape function in its provision of goods and services; if the coefficient of the Spearman's rank correlation is negative, conflicts might exist between the landscape function pair, which refers to the trade-off between the two landscape functions; (ii) synergies, the combination of landscape functions enhances a certain landscape function; if the coefficient is positive, potential synergies might occur; and (iii) compatibility, landscape functions co-exist without reducing or enhancing one another; landscape functions might be compatible with each other when the coefficient is zero or the correlation between landscape functions is not significant. To test and quantify relations between each pair of landscape function, Spearman's rank correlation were conducted at grid level using SPSS20.0.

2.2.4 Classifying landscape function bundles

Specific combinations of landscape functions are the key characteristics of landscape function bundles, which shape the production and consumption of landscape functions. Bridging the gap between natural ecosystem and human society, landscape functional bundles can represent different development types. Furthermore, the use of socially defined boundaries makes it possible to efficiently combine multifunctional landscape management with local development planning, such as the establishment of key ecological protection areas (Raudsepp-Hearne et al., 2010). In this study, development zoning associated with multifunctional landscapes could be used to perform a comprehensive analysis of inter-related landscape functions, thus avoiding treating them as separate and unrelated entities (Rodríguez et al., 2006; Turner et al., 2014). The potential linkages between landscape functions revealed by cluster analysis and the clusters' spatial distributions, indicate not only the integrity of the multifunctional landscape, but also the independence of each specific landscape function.

SOFM is an unsupervised artificial neural network model with the characteristics of being self-adaptive, self-organization and self-learning. It has been wildly applied to classification studies in geography and land system science (Foody, 1999; Peng et al., 2016). The structure of SOFM consists of an input layer, interconnecting weights, and competitive layer. The interconnection weights are identified by the training process based on the feature and topological structure (Gao et al., 2014). Therefore, the SOFM is a non-parametric method with the advantages of being objective, high tolerance of error, and robustness (Park et al., 2003). To explore spatial combination regularities of multiple landscape functions, landscape function bundles at the township level were identified using SOFM neural network.

The input layer in this study consisted of five landscape functions which were recalculated at the township level and the training epochs were limited to 1000. MATLAB R2014a was used for SOFM neural network cluster. The classification number was set to 4 to guarantee the differences among multiple bundles and spatial continuity of each bundle simultaneously. The four development zones were named according to the different combinations of landscape functions.

3. Results

3.1 Spatial patterns of multiple landscape functions

Spatial patterns of the five individual landscape functions were shown in Fig. 2. It could be concluded that, the functions varied substantially across the study area, and their spatial heterogeneity was conspicuous, with significant spatial clustering for each landscape function. Also, it was hard to maintain all landscape functions at high levels in a particular area.

In details, net primary productivity in Dali prefecture decreased from the southwest to northeast and the high-value regions were distributed mainly in the southern part of the study area, covering the counties of Yongping, Weishan and Nanjian. Soil retention was affected by land use, elevation and slope. Among all land use types, soil retention was the highest in forest land. Areas with high water yield capacity clustered around northeastern Erhai Lake because of primarily determined by rainfall and evapotranspiration on water yield. Crop production was more spatially concentrated, with high-value areas mainly located in central and eastern plains. High-value areas of residential support function presented a polycentric scattered pattern, distributed around the centers of counties and towns in the study area.

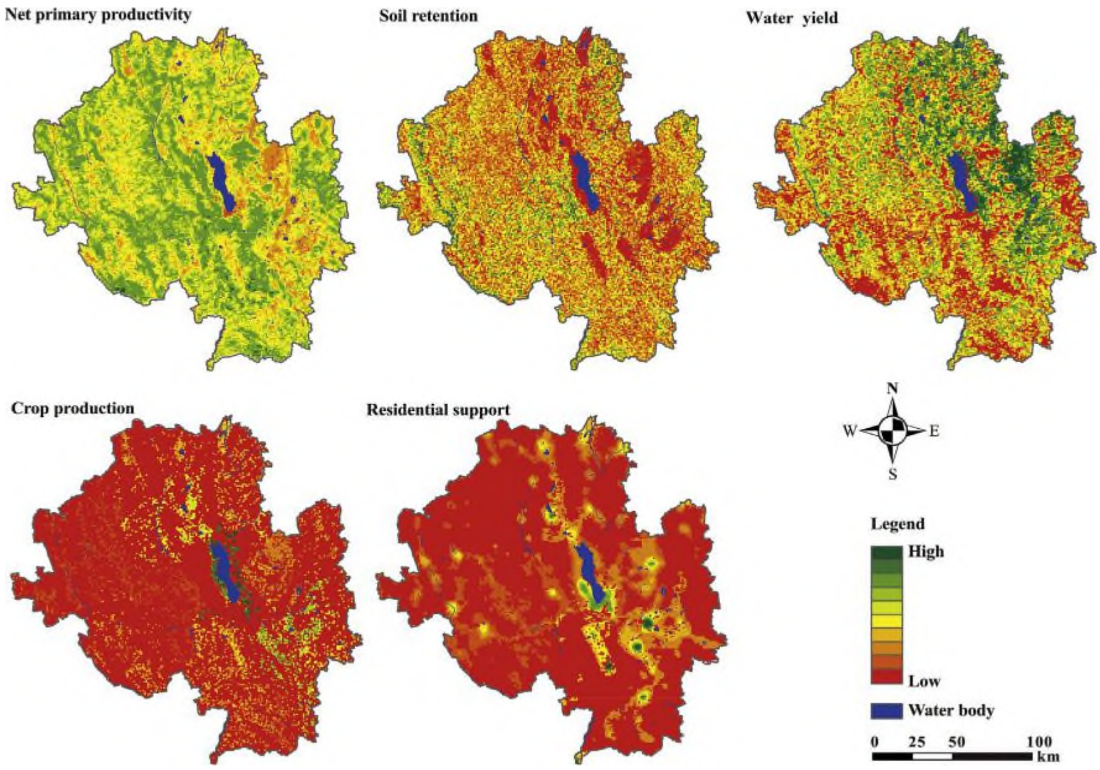

Fig. 2. Spatial distributions of landscape functions in Dali Prefecture, China.

3.2 Hotspots of multifunctional landscapes

Detecting multifunctional landscape hotspots means to identify the areas maintaining multiple landscape functions at high level, and to understand the combination way of multiple landscape functions in the hotspots. As shown in Table 2, the overlapped areas between every two hotspots of the five landscape functions were all small, which indicated that it was rare to maintain two or more landscape functions at high level simultaneously. The top three combinations of multiple landscape functions, in terms of area proportion of the overlapped hotspots in the study area, were water yield and crop production (5.95%), water yield and residential support (4.8%), and net primary productivity and soil retention (4.08%).

Landscape function	**Overlapped area proportion of hotspots (%)**			
	SR	WY	CP	RS
NPP	4.08	0.41	0.53	0.53
SR	-	1.43	0.32	0.65
WY	-	-	5.95	4.80
CP	-	-	-	3.98

Table 2 Overlapped area proportion of multiple landscape function hotspots

Landscape multifunctionality, measured as the Hotspot number of multiple landscape functions, were shown in Fig. 3. In sum, 61.0% of the total area in Dali Prefecture had at least one kind of landscape function hotspot, indicating that, among all the five landscape functions provided by these areas, at least one kind of landscape function was significantly higher than the average of the whole prefecture. Furthermore, areas with only one kind of landscape function hotspot accounted for 44.2% of the total area and the main land-use types were grassland and forest land. Areas with two landscape function hotspots were primarily farmlands, comprising 14.1% of the total area. Areas defined as multifunctional landscape hotspots, which were able to keep three or more types of landscape functions at high level accounted for only 2.7% of the total area.

Accordingly, 39% of the whole prefecture didn't have any landscape function hotspots. That was to say, none of the five landscape functions in these areas were higher than the average for the whole study area. This indicated that most parts of the region could provide landscape functions, but areas with high values for multiple landscape functions were limited to a small part of the prefecture. It should also be noted that, all the five landscape functions could not be kept at high level in the study area, which suggested that trade-offs existed among multiple landscape functions and the provision of specific landscape function was likely to weaken one or more of the other landscape functions.

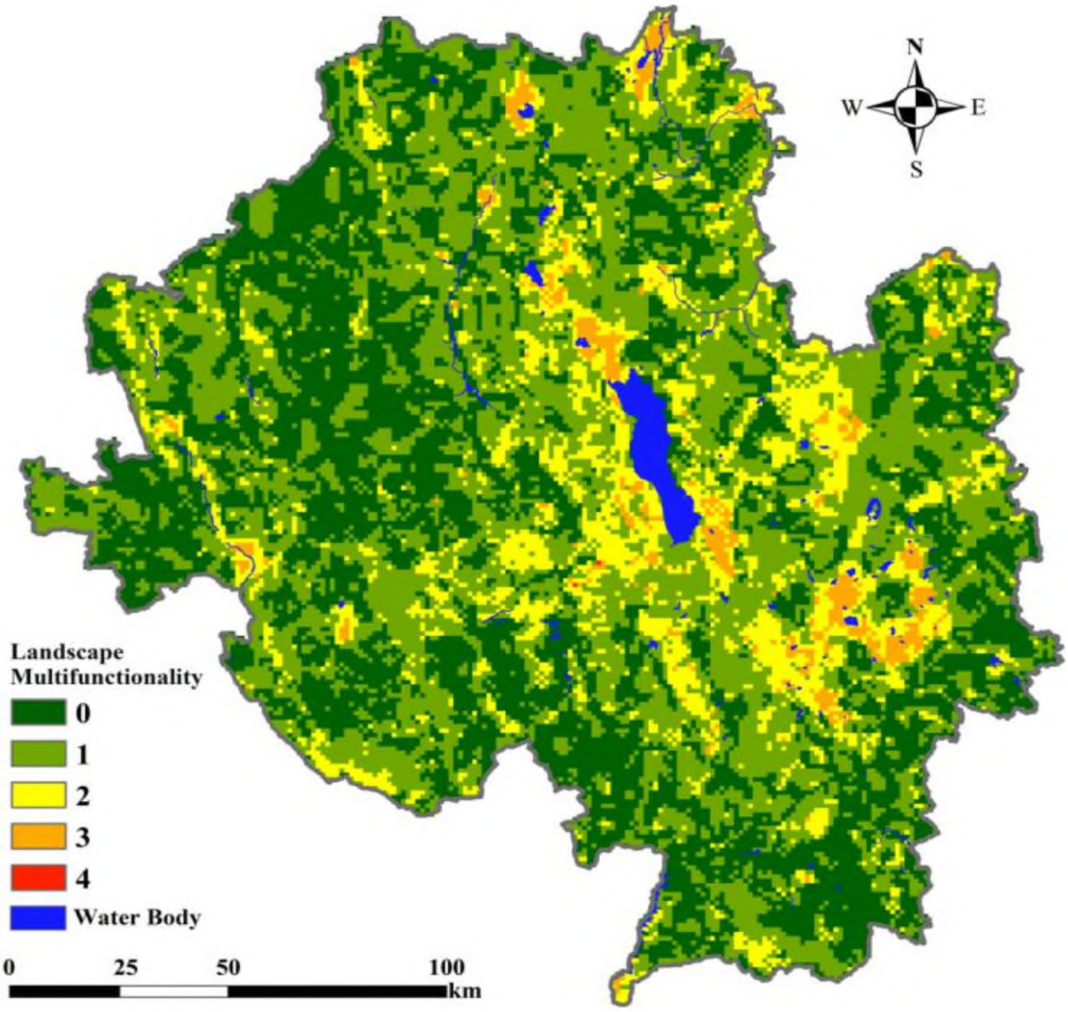

Fig. 3. Spatial distribution of landscape multifunctionality in Dali Prefecture, China.

3.3 Synergies and trade-offs among multiple landscape functions

Spearman's rank correlation coefficient for each pair of landscape functions in Dali Prefecture was calculated using SPSS20.0. As shown in Table 3, significantly negative correlations occurred in half of the ten pairs of landscape functions, i.e. NPP-WY, NPP-CP, SR-WY, SR-CP, and SR-RS. For another four pairs of landscape functions, i.e. WY-CP, NPP-SR, WY-RS, and CP-RS, significantly positive correlations existed.

In details, WY and NPP had the highest correlation among all the landscape functions. The negative coefficient meant that at locations with high capacity of net primary productivity, there would be low water yield. This result was consistent with that of Jia et al. (2014) and Su and Fu (2013), and was to be expected, given that, as a major land-cover type providing net primary productivity, forested areas had higher levels of evaporation and infiltration. Therefore, the amount of water yield in forested area was relatively small, given stable precipitation and ignoring run-offs. By contrast, the water yield capacity of farmland was higher owing to less evaporation, although its net primary productivity was less than that of forest land. Those two factors contributed to spatial pattern of conflicts between WY and NPP.

A positive correlation was found between NPP and SR, referring to the synergy between NPP and SR which was consistent with the result for tea plantations in China (Xue et al., 2015).
374 However, the coefficient of NPP and CP was negative, representing the well-accepted trade-off relationship between provisioning and regulating functions in landscapes. This was because forest had a leading role both in providing the function of net primary productivity and soil retention (Zhou et al., 2011); thus, these two landscape functions were likely to have the same tendency in spatial differentiation and to be positively correlated. The main land-cover type that provided crops was farmland, whose capacity of net primary productivity was weak; and thus, these two landscape functions tended to change in the opposite direction and had a negative relationship.

SR was negatively correlated to CP, RS and WY, suggesting that SR was in conflicts with these three landscape functions. On the one hand, frequently anthropogenic interferences, such as mechanized farming and intensive residential area construction, could significantly alter the land-cover types, damage soil structure, and even reduce existing soil nutrients, resulting in acceleration of soil erosion. That was the reason forthe trade-offs of SR-CP and SR-RS (Pilgrim et al., 2010; Zheng et al., 2008). On the other hand, farmlands tended to have weak capacity for soil retention but a strong capacity for water yield, which gave rise to trade-offs of SR-WY across the study area. Furthermore, WY, CP and RS were positively correlated to each other, which might be because farmlands tended to have strong capacity for water yield and crop production, and were mostly distributed around residential areas.

The correlation between NPP and RS was nonsignificant, indicating that they were mutually compatible in the study area. As we knew, in densely populated areas where the vegetation coverage was likely to be low, it was difficult to keep NPP and RS both at high level. However, suburban areas with high forest vegetation coverage could not only provide high-level net primary productivity, but also meet human demanding for high-quality residential environment.

	SR	WY	CP	RS
NPP	0.279	-0.447	-0.302	-0.368
SR	-	-0.181	-0.225	-0.226
WY	-	-	0.148	0.252
CP	-	-	-	0.208

Table 3 Spearman's rank correlation coefficients of landscape functions ($p<0.01$ except NPP-RS)

3.4 Development zoning at the township level

Through landscape function bundle identification using the method of SOFM, the development zoning of the study area was conducted at the township level. As shown in Fig. 4, four kinds of development zones were classified, i.e. ecological shelter area, ecological transition area, suburban development area, and urban agglomeration area. The flower diagrams characterized the difference in average value combination of each landscape function among the four development zones, with the standardized value from -2 to 2 and 0 for the mean value of each landscape function.

In details, the ecological shelter area had the largest area (43.15% of the total area), including most of the western townships in Dai Prefecture. The main land-cover type in this development zone was forest land with high vegetation coverage and strong capacities for NPP and SR. The ecological transition area was mostly located in the north with higher elevation and rugged topography, where forest land and grassland were the main land-cover types. This kind of development zone occupied approximately 25.59% of the total area, and their capacities for NPP, SR and WY were above average in Dali Prefecture. The suburban development area had the smallest area, covering only 11.98% of the total area. This kind of development zone had higher function of crop production, but weak ecological functions with large populations and convenient traffic conditions. Occupying 19.28% of the total area, the urban agglomeration area was mostly located with flat topography and fertile farmland; and thus, it was the main agricultural supply area in Dali Prefecture. This development zone also contained numerous townships with large populations and high level of economic development.

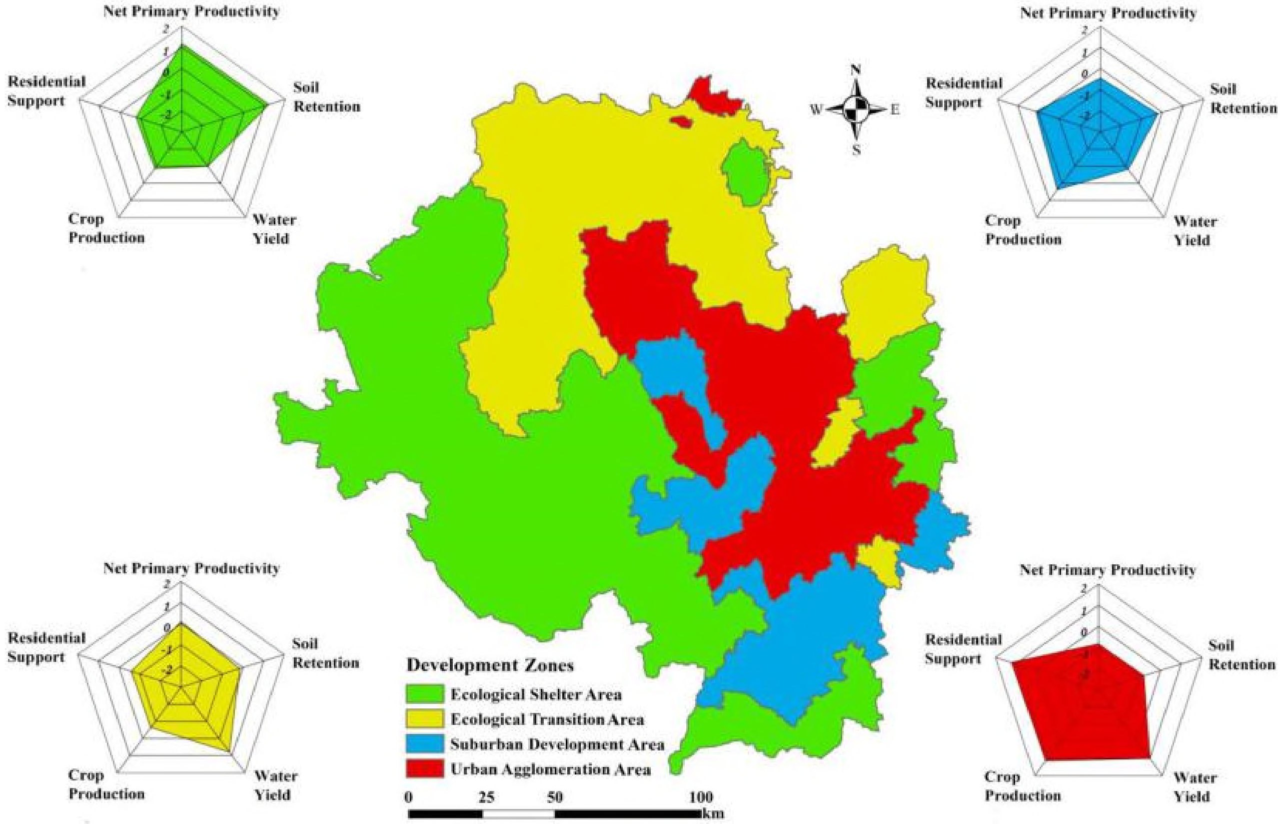

Fig. 4. Development zoning at the township level in Dali Prefecture.

4. Discussions

4.1 Advantages in identifying multifunctional landscape and classifying development zones

This study presented an integrated framework to investigate landscape multifunctionality in mountainous areas with a special focus on quantifying and mapping multiple landscape functions, assessing interaction relationships, and classifying development zones. The key landscape functions were processed from the perspective of both natural ecosystems (i.e. water, climate, terrain, soil and vegetation) and social welfare (i.e. agricultural and residential demanding). The estimation methods for holistically quantifying landscape functions were widely accepted models and approaches, and could map the functions spatial explicitly. Data used in this study were all readily obtained including remote sensing index, environmental variables and social statistics. As for the approach to identify multifunctional landscapes, spatial neighborhood relations were taken into consideration rather than directly overlying the function performance. This approach could contribute to identify the spatially aggregated multifunctional areas instead of isolated grid cells with high values of landscape functions, as conducted by Peng et al. (2016). Furthermore, quantitative assessment of the interactions among multiple landscape functions was still rare. Apart from the accepted root mean square deviation (RMSD) (Lu et al., 2014), the Spearman's rank correlation coefficients, a simple but effective method, was used to measure the degree of correlations between landscape functions.

When comparing the results of different cluster numbers through SOFM method, it could be found that there was the highest integrity of each kind of development zone with notable spatial variation for the cluster number of 4. By contrast, there was no obvious difference among multiple development zones with the cluster number of 3 or lower. When the cluster number was 5 or more, the fragmentation of each kind of development zones began to increase. Moreover, the five landscape functions in the four individual development zones were calculated and then the chi-square test was applied to determine whether the difference among these four development zones was significant. The chi-square values of net primary productivity, soil retention, water yield, crop production, and residential support were 39.23, 102.47, 112.25, 94.9 and 72.88, respectively, which were all greater than the threshold ($P<0.05$), and indicated that the classification of these four development zones in Dali Prefecture passed the chi-square test. The effectiveness of SOFM in spatial zoning was also proved by Gao et al. (2014), through comparing SOFM with traditional methods such as K-means.

Landscape functions are produced and consumed in social processes restricted to the administrative boundaries, which are demarcated for the convenience of social-economic development and management (De Groot et al., 2002). The township was chosen as the spatial unit for cluster analysis in this study, which differed from that of quantitative assessment and hotspot identification i.e. the grid, with the aim of effectively combining landscape function management with administrative management for overall planning of social-economic development and environmental protection. Spatial heterogeneity of development zones indicates that local-scale landscape function management should not be overlooked (O'Farrell et al., 2010). It is important for the local government to develop specific functional planning according to geographical locations and spatial neighboring of multiple landscape functions for improving landscape multifunctionality (Nassauer and Opdam, 2008). Therefore, administrative unit based approach is the key to understanding how multifunctional landscapes interact directly with land users and land managers within social processes (Opdam, 2013). Furthermore, the integrity of landscape function is an important guarantee for ecological security and sustainable development (Ahern, 1991; Roth et al., 1996), and it is necessary to manage the correlations among multiple landscape functions for sustainable landscape management through reducing trade-offs and enhancing synergies.

4.2 Implications for development policy in mountainous areas

Mountainous areas play great important roles in maintaining regional ecological security because of unique terrain and associated natural conditions, while these areas are also under less developed in social and economic dimensions due to the limited plain land. It poses challenges for policy makers on how to trade-off across multiple ecological benefits and socio-economic development demanding. The concept of multifunctional landscapes provides an effective pathway to achieve regional sustainable development comprehensively. The combinations of key landscape functions and their interactions are diverse in different regions because of various natural and social conditions. It is important to understand the interactions among landscape functions and formation mechanism of multifunctional landscapes for sustainable ecosystem management.

The interactions among multiple landscape functions are very complex but useful and necessary for policy makers. Focusing on the interactions, this study in Dali Prefecture was compared with a former study in Beijing-Tianjin-Hebei region (Peng et al., 2016). There was no compatible relationship in Beijing-Tianjin-Hebei region, while in this case study RS and NPP performed such kind of interaction. This difference might result from land competition between construction land and ecological land in the context of high urbanization in Beijing-Tianjin-Hebei region. In addition, the interactions among landscape function pairs of NPP and WY, NPP and CP, and SR and WY, were quite different in these two regions. These three pairs of landscape functions were characterized as trade-off relationship in this study, while synergy relationship in Beijing-Tianjin-Hebei region. This might result from different land use/cover types in two regions. In mountainous area of this study, the abundant rainfall was one of the reasons for soil erosion resulting in trade-off between water yield and soil retention, but in Beijing-Tianjin-Hebei region without widespread slopes, water and soil were distributed with coherence. The area proportion of construction land in Dali Prefecture was less than 3%, whereas the main land competition is between forest and agriculture, and the areas unsuitable to farmland would be covered with forests. However, in Beijing-Tianjin-Hebei region with sparse natural vegetation, NPP was highly influenced by crops, which led to the synergy between NPP and crop production. Therefore, land use and land cover would influence not only the provision of landscape functions, but also their interactions.

According to different combinations of key landscape functions, there were four kinds of development zones using SOFM method. The ecological shelter area and ecological transition area were mostly located in the west, north and east of the study area, and the other two development zones related to urbanization was mainly distributed in the central part of Dali Prefecture. Spatial distribution of different development zones was concerned with regional elevation and terrain, which meant that mountain development was influenced and controlled by geographical conditions. The study conducted in Beijing-Tianjin-Hebei region located on the North China Plain, indicated that in the high urbanization area, development zones resulted from combinations of similar landscape functions and economic conditions were mainly controlled by regional population density (Peng et al., 2016). Thus, to realize integrated and sustainable development in the mountainous areas, environmental protection should be emphasized to maintain regional ecological functions, and agricultural and constructive activities should be strictly restricted in the ecological shelter area and ecological transition area. Suburban development area and urban agglomeration area located in the relatively flat area were able to undertake more social and economic functions due to high level of residential support and crop production.

The overall urban planning of Dali Prefecture showed that the central and eastern areas, including Dali City, Midu County, Xiangyun County, and Binchuan County, were planned for suitable construction area. This was substantially accordance with the development zoning in this study. The western, northern and southern part of the prefecture were set as ecological conservation areas where construction would be forbidden or restricted, which were also highly overlaid with ecological shelter area and ecological transition area identified in this study. Overall, the zoning results were basically consistent with the spatial planning in practice, which proved the robustness of multifunctional landscape based development zoning. The development strategies proposed by local government in 2018 gave high political priority to protect water quality of the Erhai Lake located in Dali City, which was mainly recognized as urban agglomeration area and suburban development area in this study. There was the conflict between key landscape functions provision based on development zoning and practical function demanding of local development policy. In temporal dimension, the function provision was assessed at present, while the function demanding was targeted for the future. Thus, trade-offs between present and future should be focused in the overall urban planning of the study area.

4.3 Limitations and future research directions

In this study, five landscape functions, i.e. net primary productivity, soil retention, water yield, crop production, and residential support, were calculated using a range of quantitative models. Hotspots analysis was used to identify multifunctional landscapes, relationships among landscape functions were explored through Spearman's rank correlation analysis, and development zoning was conducted in view of landscape function bundles. This framework has been used in several previous studies (Anderson et al., 2009; Bai et al., 2011; O'Farrell et al., 2010; Swallow et al, 2009), although there are still some limitations.

Firstly, considering the limitation of data availability and imperfect models, there are uncertainties in the quantification of landscape functions. The number and type of the focused landscape functions will affect the final results, such as spatial pattern of multifunctional landscapes, correlations among landscape functions, and development zoning. Moreover, although the widely used models are selected to quantify landscape functions, the uncertainty of these models is a thorny problem in the quantitative assessment of multifunctional landscapes or ecosystem services.

Generally speaking, uncertainties derive from numerous causes, including data sources, quantification indicators, basic spatial units, and tempral scale, which can have potential but considerable impacts on the results. In this study, the uncertainties related to the detailed models might occur as follows: (1) The accuracy of NPP estimation using CASA model depends on the input data. Spatial resolution of these data has been unified to 1 km, which may result in mechanism differences between the model and related ecological processes although CASA is well established in great detail (Jia et al., 2014). (2) RUSLE based soil retention may be overestimated on slopes steeper up to 30%, especially in those areas characterized by large gully-systems (Beskow et al., 2005; Liu et al., 1994). For the low-slope hilly study area, gully erosion is not common which reduces this kind of uncertainty. (3) Water storage change is negligible at regional scale and over the long term in the water equilibrium model used for calculating water yield, resulting in slight difference with the actual situations. Although previous studies have proved the usefulness of this model (Jia et al., 2014; Zhang et al., 2008), whether ignoring runoff in quantifying water yield should depend on local hydrological conditions. (4) NDVI and nighttime light show strong linear relationship with crop production and residential support respectively. However both are often hard to map precisely, such as the influence of overflow effect and saturation effect in quantifying nighttime light intensity. (5) Although the SOFM clustering method is effective to detect multiple landscape function zones, the black box mechanism of this method makes it difficult to find how the automatically clustering model combined these landscape functions (Gao et al., 2014).

Secondly, trade-offs and synergies among landscape functions or ecosystem services are strongly scale dependent (Rodríguez et al., 2006). There is no doubt that the results are likely to vary with the change of spatial unit (De Groot and Hein, 2007; Qiu and Turner, 2013). The correlations between different landscape function pairs might only be applicable to the specific temporal or spatial scale which is followed in this study. Comparative analysis at multiple spatial scales is likely to be one of the key topics in further multifunctional landscapes study; and thus local-scale, regional-scale, and global-scale assessment of landscape multifunctionality could be incorporated together with the perception of both ecological and social processes simultaneously (Cowling et al., 2008). The mechanisms of the nonlinear correlations among multiple landscape functions at different scales should also be compared and integrated (Bennett et al., 2009).

Finally, hotspots identification of multifunctional landscapes provides an effective approach to locating the key areas of conservation priorities; however, it could result in neglecting the secondary or none hotspots, underplaying local dependence on particular landscape functions or specific areas that should not be overlooked (O'Farrell, 2010). The preferences of different stakeholders are not taken into consideration to give weights to landscape functions, or to discuss the superiority of specific landscape function versus multifunctionality. For instance, the demand for the function of water yield from upstream and downstream residents are different; and thus, ecological compensation has become an effective measure to solve the conflict between the upstream and downstream (Zheng et al., 2013). Furthermore, in fragile and less developed regions, subtle change of particular landscape functions in non-hotspots of multifunctinal landscapes might have greater unpredictable impacts on social welfare; whether an increase in landscape multifunctionality is appropriate, is still a matter for deep debate.

5. Conclusions

Multifunctional landscapes are one of the key research topics in landscape ecology. Taking Dali

Prefecture as the case study area, and focusing on five typical landscape functions in mountainous area, this study proposed a hotspot based approach to identify multifunctional landscapes. The results showed that multifunctional landscape hotspots only covered 2.7% of the study area, with 14.1% of these areas representing two kinds of landscape function hotspots, indicating the dominance of mono-functionality in mountain landscape. Moreover, all pairs of landscape functions had significant correlations, except NPP and RS, and thus mountain landscape management should focus on the trade-offs and synergies among landscape functions. The development zoning based on landscape function bundles was such a kind of landscape management.

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