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Regional-scale Identification of Three-dimensional Pattern of Vegetation Landscapes

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Abstract: The altitudinal pattern of vegetation is usually identified by field surveys, however, these can only provide discrete data on a local mountain. Few studies identifying and analyzing the altitudinal vegetation pattern on a regional scale are available. This study selected central Inner Mongolia as the study area, presented a method for extracting vegetation patterns in altitudinal and horizontal directions. The data included a vegetation map at a 1∶1 000 000 scale and a digital elevation model at a 1∶250 000 scale. The three-dimensional vegetation pattern indicated the distribution probability for each vegetation type and the transition zones between different vegetation landscapes. From low to high elevations, there were five vegetation types in the southern mountain flanks, including the montane steppe, broad-leaved forest, coniferous mixed forest, montane dwarf-scrub and sub-alpine shrub-meadow. Correspondingly, only four vegetation types were found in the northern flanks, except for the montane steppe. This study could provide a general model for understanding the complexity and diversity of mountain environment and landscape.

Keywords: landscape pattern; vegetation pattern; altitudinal zone; landscape identification; mountain landscape

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1 Introduction

Approximately 25% of the land surface of the earth is covered by mountains which hold at least a third of terrestrial plant species (Hagen *et al.*, 2007; Körner, 2007). Mountainous areas are characterized by various types of vegetation which are found at different elevations and mountain flanks (Kitayama, 1992; Hemp, 2006). These different types of vegetation form a three-dimensional pattern in horizontal and altitudinal gradients. Most biogeographic zones on the earth are packed into a mountain range of 10-km or less, which is one of the reasons that the research on mountain is important and valuable (Lauer, 1993).

The three-dimensional pattern of vegetation landscapes is significant in landscape ecology and geographical studies due to the extremely complex environment and diverse vegetation types in mountainous areas. As early as 1807, von Humboldt, a geographer, naturalist, and explorer, investigated arranged altitudinal vegetation sequences in tropical mountains. He found that the vegetation landscape had a similar pattern to that in the latitudinal zone extending from the tropic to the pole (Sachs, 2003). Many studies have investigated vegetation types and patterns along altitudinal gradients in the mountains (Kitayama, 1992; Lovett, 1996; Kessler, 2000; Hemp, 2006). The three-dimensional pattern of vegetation landscapes are usually been related to the species diversity and distribution (Körner, 2000; Kitayama and Aiba, 2002; Wang *el al.*, 2002; Bhattarai

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and Vetaas, 2003; Wang *et al.*, 2007; Batllori *et al.*, 2009; Sang, 2009). Recent studies have quantified environmental factors along altitudinal gradients, as well as vegetation responses on climate changes (Daniels and Veblen, 2003; Gian-Reto *et al.*, 2005; Walther *et al.*, 2005; Erschbamer *et al.*, 2009; Odland, 2009; Wang *et al.*, 2009).

Identifying the three-dimensional pattern of vegetation landscapes could improve their ecological interpretation (Kitayama, 1992; Miehe, 1994; Fang *et al.*, 1996; Tang and Ohsawa, 1997; Leuschner, 2000; Hörsch, 2003; Tang, 2006; Proctor *et al.*, 2007). It was found that the same type of vegetation might have different spatial distribution and elevations in different mountains or mountain flanks, such as different flanks of the Karakorum (Miehe, 1994) and some African mountains (Bussmann, 2006). Field investigations could provide the quantitative information on the three-dimensional pattern of vegetation landscapes at the local scale. For example, about nine types of mountain vegetation were identified in the Namjagbarwa Mountain, located in the eastern end of the Himalayas (Peng, 1986), and three types were found in the northern Qinghai-Tibet Plateau (Zhang, 1995; Zhang *et al.*, 2006). However, only discrete data could be derived from the field survey due to the limited time and budget. Moreover, the three-dimensional pattern of vegetation landscapes is usually expressed by free-hand mapping (Liu, 1981; Peng, 1986; Frahm and Gradstein, 1991; Hemp, 2002; 2006; Da *et al.*, 2009). These methods of investigation and mapping may be available in one or several sections of certain mountains on a local scale (Troll, 1973; Miehe, 1994; Miehe *et al.*, 2007). However, when they are used at the regional scale, such as with a group of mountains, it is difficult to find general information on the three-dimensional pattern of vegetation landscapes. There is currently a lot of spatial data available on mountain areas, including vegetation and topographic data. Therefore, it is necessary to develop a method to identify the vegetation pattern from available spatial data.

This study presents a feasible method for identifying the continuous distribution of mountain vegetation by using the digital elevation model (DEM) and vegetation map at a regional scale. The identified three-dimensional pattern included horizontal and altitudinal vegetation information in all mountain flanks in the central Inner Mongolia, and can promote an understanding of the complexity and diversity of mountain environment and landscape.

2 Materials and Methods

2.1 Study area

This study was conducted on a regional scale including parts of the Hetao Plain, Inner Mongolia Plateau, and the Daqing Mountains. The study area (40°30′–41°20′N, 109°30′–111°30′E) lies in the center of the Inner Mongolia Autonomous Region, covering an area of 9336 km^2. The altitude of this region ranges from 990 m to nearly 2340 m above sea level (Fig. 1). The climate alternates between hot, humid summer and cold, dry winter. The average annual precipitation is 336 mm and decreases from the southeast to the northwest (Sun *et al.*, 2008). The study area serves as the dividing line between warm-temperate and middle-temperate zones in the northern China. As a result, the vegetation and soil patterns significantly change in horizontal and altitudinal directions. There are different soil types at low and high elevations, such as the chestnut soil, chernozem soil, and meadow soil on the sunny flanks, and the chestnut soil, cinnamon soil, brown soil, and meadow soil on the shadow flanks.

The core region of the study area is located in the Daqingshan Nature Reserve in China. The landscapes mainly consist of the natural vegetation of the Daqing Mountains, and cultivated vegetation and pastures in the Hetao Plain and Inner Mongolia Plateau. The vegetation pattern was recorded from field surveys in previous studies (Li, 1962; Liu, 1992). The broad-leaved forests, such as the *Populus davidiana* and *Betula platyphylla*, were sparse from 1300 m to 1700 m elevation. The juniper and coniferous populations (e.g., *Picea asperata*, *Juniperus rigida*, *Pinus tabulaeformis*, *Biota orientalis*) also appeared at this altitudinal zone, especially above 1600 m. The coniferous forests dominated at approximately 1700 m, and patches of coniferous forests were sparsely found in shadow flanks as a result of the relatively lower solar radiation and higher humidity than that found in the sunny flanks. The forests were gradually replaced by *Ostryopsis davidiana*, and a scrub belt was well-developed above 1900 m. Above a small transition zone of about 2000 m, the sub-alpine shrub-meadow was characterized by such plants as *Bromus inermis*, genus *Delphinium*, and *Carex* sp., in all moun-

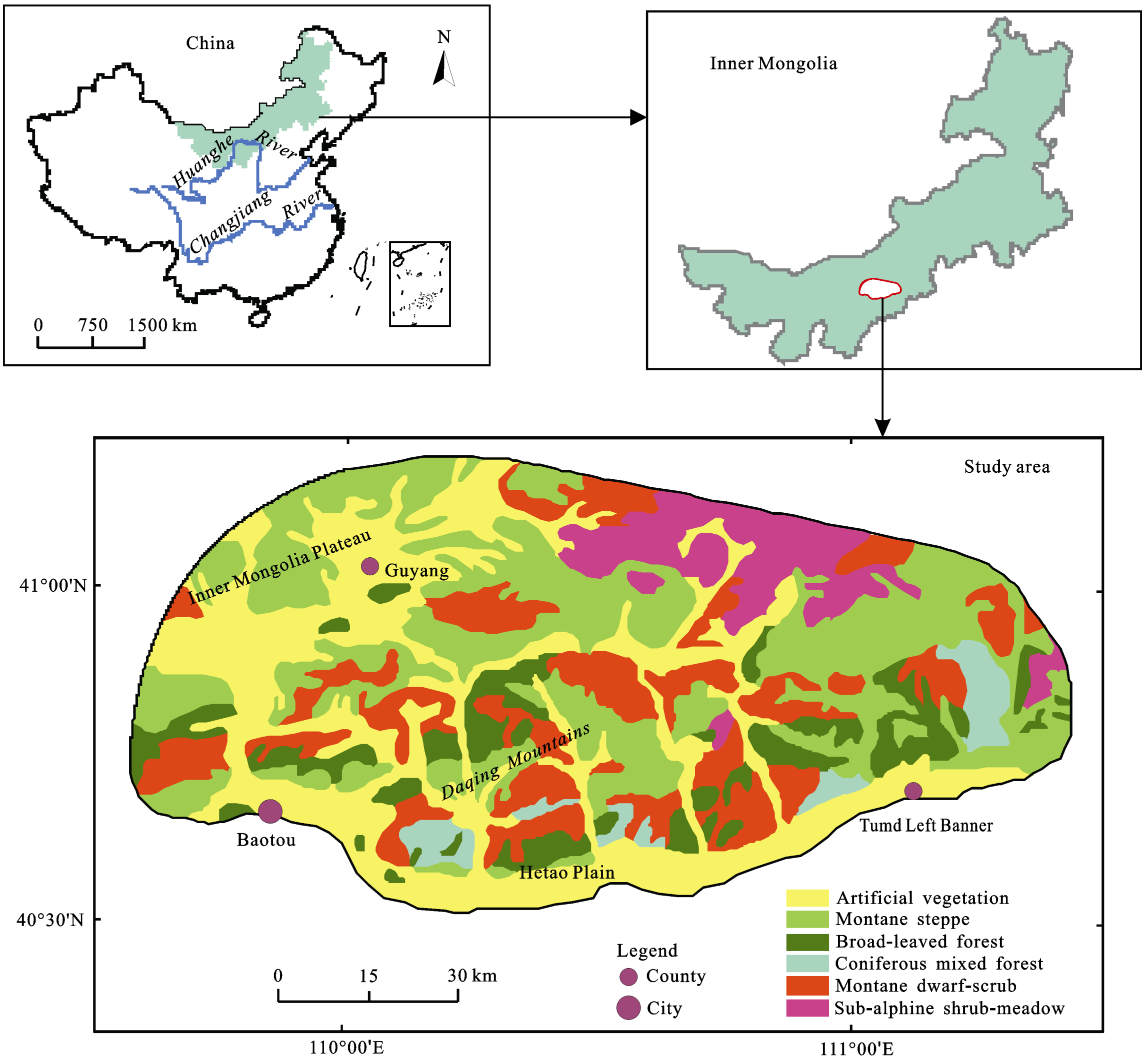

Fig. 1 Study area and spatial pattern of vegetation landscapes

tain flanks. Based on these studies, five types of mountain vegetation were found in the Daqing Mountains. The average altitude of the vegetation boundary was 1300 m between montane steppe and broad-leaved forests, 1700 m between broad-leaved forests and coniferous mixed forests, 1900 m between coniferous mixed forests and montane dwarf-scrubs, and 2000 m between dwarf-scrubs and sub-alpine shrub-meadows.

2.2 Methods

The three-dimensional vegetation pattern presents the distribution and proportion of different vegetation landscapes in horizontal and altitudinal gradients. The main procedure was as follows:

(1) The horizontal and altitudinal ranges of the vegetation pattern were defined. The central peak was identified as the highest elevation in the region, and served as the initial point in developing the vegetation pattern. The mountain flank (*F*) was defined in relation to the central peak, 0° to the north, increasing clockwise, and 180° to the south. The horizontal range of the three-dimensional vegetation pattern was designated as the mountain flank, and the altitudinal range was designated as the elevation (*E*).

(2) The vegetation proportion was calculated according to the horizontal and altitudinal range. Specifically, the total amount of vegetation cells was calculated at each horizontal and altitudinal range. The vegetation proportion was then calculated for each vegetation type at this horizontal and altitudinal range. The weighted vegetation proportion was recalculated after considering the cell size and their weighted values in each cell. The weighted value (*w*) was calculated by the cell size (*A*) and its surface slope (*S*) (Equation 1):

$$w = A/\cos(S) \quad (1)$$

The weighted vegetation proportion can reflect the magnitude of vegetation information in the real land surface rather than the projection surface. For example, there were *n* cells in a cell group with the same elevation and mountain flank. The weighted proportion of a vegetation type (P_k) was calculated as Equation 2, and the dominant vegetation type (P_x) was defined as the maximum value of P_k (Equation 3).

$$P_k = \sum_{i=1}^{m} w_i / \sum_{j=1}^{n} w_j \times 100\% \quad (2)$$

$$P_x = \max(P_k) \quad (3)$$

where P_k is the weighted proportion of vegetation type *k* in the cell group; w_i is the weighted value of cell *i* of vegetation type *k* in the cell group; w_j is the weighted value of cell *j* of all vegetation types in the cell group. P_x is the proportion of the dominant vegetation type.

(3) Vegetation patterns were plotted according to the vegetation proportion and dominant vegetation type. The above mentioned algorithms were implemented in ArcGIS and Matlab software. Then, all algorithms were compiled into a dynamically linked library and a component object model. We packaged these algorithms into an object-oriented programming platform (Visual Basic Language), which included several modules, such as selecting spatial data, defining mountain flanks, calculating vegetation proportion, and outputting the results.

(4) The transition zone of different vegetation landscapes was identified. The upper and lower boundaries of each vegetation type were defined from the dominant vegetation pattern, and the location and width of the transition zone were manually identified in horizontal and altitudinal ranges.

The method of this study is designed to be used at a regional scale. The vegetation data were digitized from the 1∶1 000 000 vegetation map. Topographic parameters were obtained from DEM of 1∶250 000. These vegetation and topographic data were interpolated at a 100-m resolution.

3 Results and Analyses

3.1 Three-dimensional pattern according to proportion of each vegetation type

The proportion of each vegetation type was plotted according to the continuous ranges at different mountain flanks and elevations. Figure 2 showed the probability of the three-dimensional distribution for each vegetation type. The montane steppe was mainly distributed on the sunny flanks (average flank was 90°–300°), with the probability of occurrence decreasing from low elevation (1000 m) to high elevation (1500 m) (Fig. 2a). The broad-leaved forest was distributed on the mountain flanks from 80° to 320°, and at an elevation ranging from 1200 m to 1700 m (Fig. 2b). The coniferous mixed forest was distributed on the flanks from 60° to 330°, at a range from 1500 m to 2000 m (Fig. 2c). The montane dwarf-scrub and sub-alpine shrub-meadow were distributed on all of the mountain flanks (Fig. 2d and Fig. 2e). The montane dwarf-scrub ranged from 1700 m to 2100 m, while the sub-alpine shrub-meadow was distributed above 2000 m. The vegetation patterns identified from DEM and vegetation maps were in accordance with the descriptions from previous studies (Li, 1962; Liu, 1992). The continuous vegetation patterns showed more details in the three-dimensional ranges, and presented a general sketch map for the use of a qualitative assessment and further quantitative analysis.

3.2 Three-dimensional pattern according to dominant vegetation

The three-dimensional pattern of dominant vegetation types was plotted according to their maximum probability in comparison to other vegetation types (Fig. 3). It showed that the montane dwarf-scrub and sub-alpine shrub-meadow appeared on all flanks. The montane steppe, broad-leaved forest, and coniferous mixed forest were dominant on the sunny flanks, but were replaced gradually by the dwarf-scrub and sub-alpine shrub-meadow as the ground level increasing from sunny to shady flanks. From low to high elevations, there were five vegetation types on the southern flanks (i.e., montane steppe, broad-leaved forest, coniferous mixed forest, montane dwarf-scrub and sub-alpine shrub-meadow). Correspondingly, only four vegetation types (no montane steppe) were found on the northern flanks.

3.3 Transition zones between different vegetation landscapes

The upper and lower boundaries of the vegetation landscapes were extracted from the three-dimensional pattern of dominant vegetation types. These boundaries

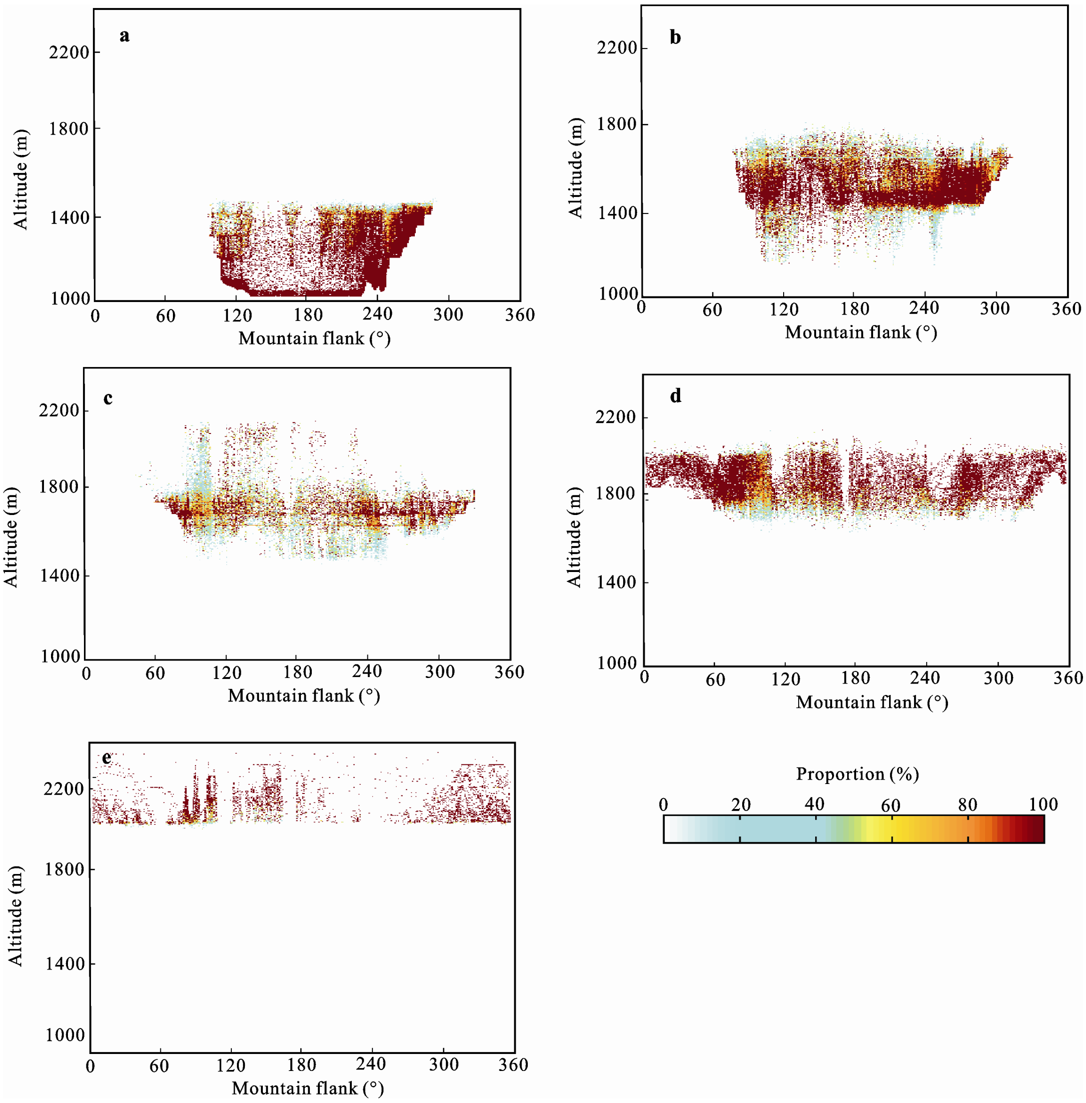

Fig. 2 Proportion of different vegetation types in three-dimensional ranges. a, montane steppe; b, broad-leaved forest; c, coniferous mixed forest; d, montane dwarf-scrub; e, sub-alpine shrub-meadow

formed several narrow and obvious transition zones between the montane steppe and broad-leaved forest, the broad-leaved forest and montane dwarf-scrub, and the dwarf-scrub and sub-alpine shrub-meadow (Fig. 4). The transition zone between the montane steppe and the broad-leaved forest ranged between 1200 m and 1300 m (approximately NE to SW exposures), with a width of about 100 m. The transition zone between the broad-leaved forest and coniferous mixed forest descended from 1500 m to 1700 m. The transition zone between the coniferous mixed forests andmontane dwarf-scrub ranged from 1700 m to 2000 m. The montane dwarf-scrub was a gradual change of arbor species. These arbour species maintained its scapose life form, but the height of these plants decreased until it attained a creeping form or dwarf scrub habit. Although the transition zone between the broad-leaved forest and montane dwarf-scrub was apparent, the upper boundary of forests could reach 2000 m on the northern flanks due to dispersed patches of coniferous forests. The coniferous forests were approximately distributed around the transition between the broad-leaved forest and montane dwarf-scrub, although their precise spatial positions need to be validated by further field surveys. There was a narrow transition zone of about 2000 m between the montane dwarf-scrub and sub-alpine shrub-meadow. Above the transition zone, the sub-alpine shrub-meadow was dominant on all mountain flanks.

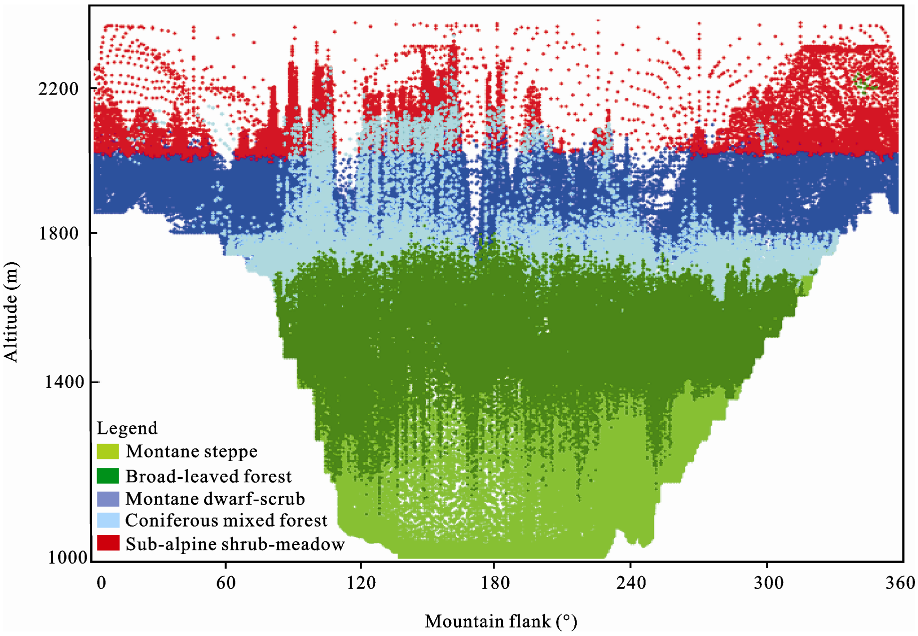

Fig. 3 Three-dimensional pattern of dominant vegetation types

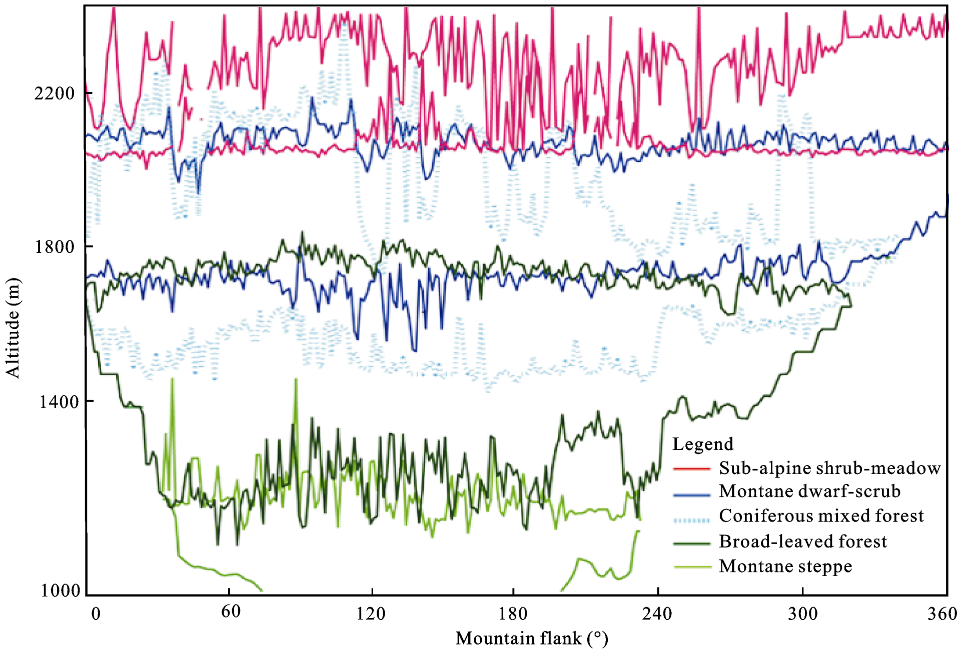

Fig. 4 Transition zones of different vegetation types

4 Discussion

4.1 Implications for mountain research and management

More attention has been paid to the three-dimensional vegetation pattern in complex mountain areas (Erschbamer *et al.*, 2009; Smith *et al.*, 2009). Climatic factors are often correlated with the altitudinal boundaries of vegetation landscapes observed at limited sampling spots (Takyu *et al.*, 2005; Wieser *et al.*, 2009). These altitudinal patterns of vegetation landscapes are usually derived from field surveys at a local scale, such as in Mount Elgon (Hamilton and Perrott, 1981), Mount Namjagbarwa (Peng, 1986), Mount Kinabalu (Kitayama, 1992), Mount Emei (Tang and Ohsawa, 1997), Mount Kilimanjaro (Hemp, 2006), Mount Cameroon (Proctor *et al.*, 2007), and the Tianmu Mountains (Da *et al.*, 2009). In addition, these vegetation patterns are usually illustrated by hand-drawn diagrams.

The traditional vegetation pattern is not suitable for use at a regional scale. The three-dimensional vegetation pattern is useful to investigate the vegetation-climate relationship by integrating more regional factors. This study provides an economically sound and feasible method for extracting and expressing the three-dimensional patterns of vegetation landscapes at a regional scale. The vegetation patterns show detailed information of the specific probability for different vegetation types in altitudinal and horizontal ranges. This method is easily implemented by using DEM and vegetation data. The impact of environmental factors on the shift of vegetation landscapes may be quantified at a regional scale. Then, the sensitivity and adaptability of vegetation landscapes can be quantified under the scenarios of regional climate changes.

The three-dimensional vegetation pattern can be used to guide the vegetation restoration and land use planning. Together, natural and human factors contribute to the formation of a mosaic of humanized mountain landscapes (Lauer, 1993). The physiological needs of different vegetation types in an altitudinal gradient have been revealed in many studies (Zimmerer, 1999; Mekbib, 2008). Nevertheless, we often need to know the horizontal and altitudinal distribution of a specific vegetation type at the regional scale. The three-dimensional vegetation patterns can be used as a general sketch map of potential land use. The three-dimensional patterns of vegetation landscapes could be constructed from existing vegetation data to timely reflect the dynamic changes of vegetation landscapes. The results of previous study showed that the seasonal transfer of pastoral farms is widespread between different altitudes and flanks in mountain areas (Mysterud *et al.*, 2007). Appropriate management strategies can be made by using the three-dimensional vegetation pattern.

4.2 Applicability and limitation of this study

The method in this study can be used to identify the three-dimensional vegetation pattern at a regional scale, and might provide useful information on research and management of the mountain. However, there is some limitation. First, the identification method is only a way of data integration; and the final accuracy of vegetation pattern is controlled by the precision of source data, including vegetation and DEM data, which might influence the results. Second, the vegetation information of three-dimensional patterns is generalized to the same altitude and mountain flank. Therefore, the vegetation patterns are suitable for mountain research at a regional scale. Finally, the method is mainly used to identify the existing vegetation landscapes. We have not enough data to identify potential climax vegetation compared to humanized vegetation landscapes. Further studies need to be conducted on more data sources to meet a specific research objective.

5 Conclusions

This study presents a method to identify the three-dimensional patterns of vegetation landscapes at a regional scale. The three-dimensional pattern of vegetation landscapes was identified according to the probability of each vegetation type and the transition zones between different vegetation landscapes in the central Inner Mongolia. The method only needs existing DEM and vegetation data, and can easily be applied in other regions. It is noted that this study is only a first step towards integrating multi-source data, and can be improved if more accurate data become available. This method provides a general model for understanding the complexity and diversity of mountain environments, and can be used to enhance the spatial database for landscape ecology and mountain geography.

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