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Introduction

The karst mountain region of Southwest China is one of the largest karst areas in the world. This karst geomorphology covers about 620,000 km², and the ecological environment is extremely fragile (Wang and Liu 2004; Zhang et al 2006). This has led to serious land degradation in the form of desertification: soil is severely or even completely eroded, so that bedrock is exposed over large areas, the carrying capacity of land declines severely, and the landscape resembles a rocky desert because of severe human impacts on the vulnerable eco-environment (La Moreaux et al 1997).

Monitoring and assessing karst rock is important for policy-makers and academic researchers. Traditional methods of mapping karst rock, such as manual interpretation and computer-assisted digital processing of aerial photographs and satellite images, have limitations. Manual interpretation is expensive and laborious and can be used only for a small region. With computer-assisted digital processing, results vary depending on the characteristics of the training samples selected by the analyst, because different analysts do not interpret images in the same manner.

Many techniques have been attempted to map land cover, such as using indices derived from the RS images. A commonly used index is the Normalized Difference Vegetation Index (NDVI), calculated as the difference between the near-infrared and red reflectance values normalized with their sum. For example, Achard and Estréguil (1995) used multitemporal AVHRR mosaics for tropical forest discrimination and mapping, and Fernandez et al (1997) mapped the surfaces affected by large forest fires using NDVI data.

The Normalized Difference Snow Index (NDSI), derived from Landsat Thematic Mapper (TM) bands 2 and 5, (TM2 − TM5) / (TM2 + TM5), has been successfully used to map glaciers in the Illecillewaet Icefield, British Columbia, Canada (Sidjak and Wheate 1999). This index is based on the difference between strong reflection of visible radiation and near total absorption of middle infrared wavelengths by snow (Hall et al 1995a, 1995b). It is effective in distinguishing snow from similarly bright soil, vegetation, and rock, as well as from clouds (Dozier 1989).

The Normalized Difference Water Index (NDWI), calculated as (GREEN − NIR) / (GREEN + NIR), was developed to delineate open water features and enhance their presence in remotely sensed imagery based on reflected near-infrared radiation and visible green light (McFeeters 1996). The selection of wavelengths was done to maximize the typical reflectance of water features by using light wavelengths to minimize the low reflectance of NIR by water features. NDWI may allow turbidity of water bodies to be estimated from remotely sensed data. NDWI is sensitive to changes in the liquid water content of vegetation canopies. It is complementary to but not a substitute for NDVI (Gao 1996).

Few papers focus on methods of mapping barren areas (Jiang et al 2005; Zhao and Chen 2005). Zhao and Chen (2005) used the Normalized Difference Bareness Index (NDBaI, calculated as [TM5 − TM6] / [TM5 + TM6]) to map bare areas. Although the method has good accuracy, it is limited by the use of TM6 (thermal infrared band), which makes it difficult to distinguish barren and built-up areas in the suburban areas where urban heat islands exist.
The objective of the present paper is to offer a new and simple method for mapping karst rock rapidly and accurately. This method is based on the unique spectral response of karst rock and other land cover. The mapping is accomplished through trials using different input bands (Landsat TM band 3–5, NDVI and NDRI derived from TM imagery). The effectiveness of this method was tested by mapping karst rock in Bijie County, Southwest China. Comparison of the results obtained using this method with an existing land use map (2000) demonstrates that it is highly reliable. This method also produces very accurate results more efficiently than supervised classification using only Landsat TM bands.

**Study area**

Bijie County is in Southwest China (ranging from 104°52' to 106°6'E and from 26°49' to 27°46'N) with an estimated area of 6900 km². Karst areas account for 61.9% of the land area (Figure 1; Cai 1990). It is a typical karst rock area with rather severe desertification, the spatial extent of which has drastically expanded during the last decade. The Chinese Academy of Science submitted two reports to the China central government in 1994 and 2003, proposing comprehensive rehabilitation. Limited by local biophysical conditions and low population density, farmland is scarce and can be ignored. The main land cover areas are needleleaf forest, broadleaf forest, grasslands, and barren karst rock, which account for about 90% of the total surface. Other forms of land cover are a water body and built-up area (mainly the national-level road; Huang and Cai 2007).

**Data and methodology**

**Data sources**

A Landsat ETM recorded on 22 May 2001 was acquired from the Global Land Cover Facility at the Institute of Geographic Sciences and Natural Resources Research (http://glcf.geodata.cn). The land use map for the year 2000 at a scale of 1:50,000 was acquired from local Land Management Bureaus.

**Methodology**

Figure 2 shows the Landsat TM image of the study area on which various surface covers (e.g., broadleaf forest,
needleleaf forest, grassland, and karst rock) are distinguishable. By repeatedly using the representative pixels of each of these covers (on average 10–15 pixels were groundtruthed), their Digital Number (DN) values in 7 bands were averaged and displayed graphically in Figure 3. This profile illustrates that their spectral disparity is greatest in bands 3, 4, and 5. These values are distinctive from one another. Therefore, they are the most useful bands from which land cover may be potentially differentiated.

A close scrutiny of Figure 3 reveals that except for karst and built-up areas, vegetation (broadleaf forest, needleleaf forest, grassland) has a higher reflectance on band 4. Band 4 exceeds those on band 3. By comparison, all the nonvegetative categories have a smaller pixel value on band 4 than band 3. Therefore, the commonly used index, NDVI (Equation 1), referred to as subtraction of band 3 from band 4, results in positive pixel values for vegetation pixels:

$$\text{NDVI} = \frac{\text{band } 4 - \text{band } 3}{\text{band } 4 + \text{band } 3}. \quad (1)$$

To facilitate subsequent processing, the NDVI image was derived for further analysis.

Vegetation types, karst rock, and built-up areas experience a drastic increase in their reflectance from band 3 to band 5. Water has a slightly smaller pixel value
on band 5 than on band 3 (Figure 3). The derived index—the Normalized Difference Rock Index (NDRI)—is a standardized differentiation of these two bands (Equation 2); it was derived using principles similar to those used to derive the NDVI. The NDRI results in negative pixel values for water bodies but positive pixel values for all other land cover classes. The pixel values for water bodies are markedly lower in the fourth and fifth bands, based on the difference between strong reflection of visible radiation and near total absorption of middle infrared wavelengths by water (Hall et al. 1995b):

\[
\text{NDRI} = \frac{(\text{band 5} - \text{band 3})}{(\text{band 5} + \text{band 3})}.
\]

In order to facilitate subsequent processing, the NDVI image was derived for further analysis.

Based on the two indices (NDVI and NDRI), supervised maximum likelihood classification trials were conducted using different combinations of input bands. Preliminary qualitative assessment of classification results was guided by a visual interpretation of the image. Training areas were established for 6 separate classes: needleleaf forest, broadleaf forest, grassland, water, built-up areas, and karst rock. Classification trials were performed with the following band combinations:

1. TM bands 3, 4, and 5
2. NDVI and NDRI
3. TM bands 3–5 and NDRI
4. TM bands 3–5 + NDVI + NDRI.

In the final classification result, dispersed and continuous karst rock (indicating slight and severe desertification) were combined into one category: karst rock.

The classification method of automatic mapping suggested by Zha et al. (2003), a binary assessment method, was also used to judge extracting built-up areas and barren lands (such as karst rock) according to the different positive or negative values of each index map. According to this method, the true value of each pixel is recoded to 254 if the NDVI (NDRI) value is positive (+) or to 0 if the NDVI (NDRI) value is negative (−). Table 1 shows that the NDVI and NDRI values for needleleaf forest, broadleaf forest, grassland, and water are all identical (the first three are positive, the last, water, is negative), but the NDVI and NDRI values for built-up areas and karst rock are quite different. Thus, after subtraction of NDVI from NDRI, the pixels with a value of 254 indicate the area with karst rock. (Because built-up areas in this area are quite limited, they may be counted as karst rock using this method.)

Finally, these classification results were compared with the actual land use map for 2000. Operations to derive NDVI and NDRI, guided maximum likelihood classifications, and recording pixel values were done using the ERDAS software.

**Results**

Table 2 shows the results of the different land cover classifications using supervised maximum likelihood classification by various band combinations. In this table Trials 1–4 were used to determine maximum likelihood classification by various band combinations. Trial 5 was used with binary judging, and the land cover types were classified into vegetation (including forest and grassland), water, and karst rock (including built-up areas).

Spatial accuracy from spatial pattern was performed in the ArcGIS environment using different band combinations compared with land use in 2000. Several methods exist to assess spatial accuracy in current practice. One is the Kappa statistic (Munroe et al. 2002; Pontius 2002); another the Receiver Operating Characteristic (ROC) curve (Pontius and Schneider 2001). In this study we overlaid the different trial maps on the 2000 land use map; then a cell-by-cell comparison of the accuracy of the method was performed to evaluate the predicted versus actual karst rock spatial pattern. This spatial assessment method was also used widely (Pereira and Itami 1991; Bian and West 1997; Narumalani et al. 1997). The result is shown in Table 3. Trial 2 shows better performance than other trials for mapping karst rock. The result shows that about 77% of non-karst rock and 82% of karst rock was classified correctly, corresponding to their spatial locations. Figure 4 shows the spatial pattern of actual karst rock using the NDVI and NDRI indices in Bijie County. The results were satisfactory.

**TABLE 1** Positive and negative values of each representative land cover class in NDVI and NDRI maps.

<table>
<thead>
<tr>
<th>Index</th>
<th>Needleleaf forest</th>
<th>Broadleaf forest</th>
<th>Grassland</th>
<th>Water</th>
<th>Built-up area</th>
<th>Karst rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI</td>
<td>+(254)</td>
<td>+(254)</td>
<td>+(254)</td>
<td>−(0)</td>
<td>−(0)</td>
<td>−(0)</td>
</tr>
<tr>
<td>NDRI</td>
<td>+(254)</td>
<td>+(254)</td>
<td>+(254)</td>
<td>−(0)</td>
<td>+(254)</td>
<td>+(254)</td>
</tr>
<tr>
<td>NDRI–NDVI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>254</td>
<td>254</td>
</tr>
</tbody>
</table>
**TABLE 2** Results of different land cover classifications.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Forest (%)</th>
<th>Grassland (%)</th>
<th>Water (%)</th>
<th>Built-up area (%)</th>
<th>Karst rock (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1 (TM 3–5)</td>
<td>28.23</td>
<td>6.53</td>
<td>0.08</td>
<td>6.12</td>
<td>59.04</td>
</tr>
<tr>
<td>Trial 2 (NDVI + NDRI)</td>
<td>45.33</td>
<td>7.26</td>
<td>0.07</td>
<td>9.45</td>
<td>37.88</td>
</tr>
<tr>
<td>Trial 3 (TM 3–5 + NDRI)</td>
<td>36.55</td>
<td>8.75</td>
<td>0.29</td>
<td>0.75</td>
<td>53.66</td>
</tr>
<tr>
<td>Trial 4 (TM 3–5 + NDVI + NDRI)</td>
<td>43.83</td>
<td>0</td>
<td>0.10</td>
<td>0</td>
<td>42.48</td>
</tr>
<tr>
<td>Trial 5 (NDRI – NDVI)</td>
<td>62.4</td>
<td>—</td>
<td>1.30</td>
<td>—</td>
<td>36.30</td>
</tr>
<tr>
<td>Land use map (2000)</td>
<td>44.63</td>
<td>9.15</td>
<td>0.08</td>
<td>3.13</td>
<td>43.02</td>
</tr>
</tbody>
</table>

**TABLE 3** Spatial accuracy of karst rock mapping using different band combinations.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Actual land cover classes</th>
<th>Classified land cover classes (km²)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non-karst rock</td>
<td>Karst rock</td>
</tr>
<tr>
<td>1</td>
<td>Non-karst rock</td>
<td>1267</td>
<td>1024</td>
</tr>
<tr>
<td></td>
<td>Karst rock</td>
<td>377</td>
<td>1348</td>
</tr>
<tr>
<td>2</td>
<td>Non-karst rock</td>
<td>1967</td>
<td>581</td>
</tr>
<tr>
<td></td>
<td>Karst rock</td>
<td>378</td>
<td>1684</td>
</tr>
<tr>
<td>3</td>
<td>Non-karst rock</td>
<td>1589</td>
<td>1040</td>
</tr>
<tr>
<td></td>
<td>Karst rock</td>
<td>547</td>
<td>1433</td>
</tr>
<tr>
<td>4</td>
<td>Non-karst rock</td>
<td>1536</td>
<td>1094</td>
</tr>
<tr>
<td></td>
<td>Karst rock</td>
<td>490</td>
<td>1490</td>
</tr>
<tr>
<td>5</td>
<td>Non-karst rock</td>
<td>2002</td>
<td>627</td>
</tr>
<tr>
<td></td>
<td>Karst rock</td>
<td>936</td>
<td>1044</td>
</tr>
</tbody>
</table>

**Discussion**

The study area is located in the karst mountain regions of Southwest China, where land degradation is most serious, land surface is uneven, and topographic conditions are complicated. All these factors increase the difficulty of mapping land use precisely. Even the Chinese Academy of Science uses the TM/ETM image to interpret the land use map. The accuracy is merely about 75% before manual adjustment; only after the manual adjustment might the accuracy reach about 85% (Xiong 2002). The new combination of NDVI and NDRI exemplified in this paper can map karst rock at an accuracy level of 80% using supervised classification, and the method is greatly superior to that with TM band supervised classification or the binary judging method. In comparison with combination of TM band supervised classification, the new method enables karst rock areas to be mapped at a higher degree of accuracy. Therefore it could be concluded that the proposed combination of NDVI and NDRI is much more effective and advantageous in mapping karst rock area than Landsat TM bands when performing maximum likelihood classification. By comparison with the binary judging method, it could distinguish between built-up areas and karst rock. So the method can serve as a worthwhile alternative for quickly mapping karst rock area.

However, it is also important to know the limitations of this method. Sidjak and Wheate (1999) successfully classified iceberg cover with other land cover using NDSI; Zha et al (2003) mapped the built-up area of Nanjing, China, using the NDBI with an accuracy of 94%. In this research, using the derived NDRI, the highest accuracy is only about 80%. Several reasons contribute to incorrect classification of the karst rock, including the following: (1) the pixel values of karst rock and built-up areas are rather close, and it is not easy to differentiate them just through maximum likelihood classification, and (2) Landsat image errors are induced by the sensor system and data...
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