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Applicability of longitudinal profiles for glacial cirque classification

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Abstract—**Accurate classification of cirques is essential for studying paleoglacier activities. Longitudinal-profile-based classification has advantages over other methods such as expert classification and the methods that utilize morphometric parameters. Longitudinal profiles method first deploys exponential function to fit the longitudinal profiles of individual cirque samples and then fits a linear classifier based on the exponential coefficient and the cirque height of the cirque sample set to classify cirque candidates as cirques or non-cirques, However, the existing studies have applied and evaluated longitudinal profile based classification using only small number (i.e., several dozens) of cirque sample-set collected within small study areas. In this study we evaluated the applicability of the longitudinal profile method to a larger number of glacial cirques from a larger area. The cirque sample set (256 cirques and 101 non-cirques) of this study was extracted from the southeastern Tibetan Plateau. The original linear classifier fitted in previous studies, and the linear as well as non-linear classifiers fitted from the new sample set were evaluated. The classification accuracy results reveal that the longitudinal profile based classification method was applicable, and that with the non-linear classifiers shows the improved performance than the refitted linear classifier, when both were better than that with original linear classifier.**

I. INTRODUCTION

The cirque is a glacial erosion landform that reflects the glacial imprint on a region as the origin of the mountain glacier. Accurate cirque classification facilitates better understanding and study of the developmental mechanisms of cirques and their coupling with the climate processes [1,2].

Cirque classification methods have slowly evolved from qualitative to quantitative approaches. Qualitative methods, such as expert classification, is based on the experience and knowledge of experts obtained from field observations [3]. However, expert classification is time-consuming, laborious, and difficult to explain and reproduce, making it less suitable for classifying cirques across large areas. Expert classification is descriptive and usually based on qualitative definition, making classification results subjective to different experts' understanding of cirques [4].

Currently there are two types of quantitative cirque classification methods: the morphometric based method, and the longitudinal profile based cirque classification. The former utilizes six morphometric parameters (including length (L), width (W), height (H), L/W, L/H, and area) to cluster cirque candidates. The cluster descriptions are defined by statistics of morphometric parameters that form classification rules [5–7]. However, the morphometric parameters represent insufficiently the spatial structural information of the cirques. The cluster results of the morphometric parameters method do not correspond well to the qualitative expert classification results.

The longitudinal profile based method for cirque classification uses longitudinal profile of cirque to differentiate cirques and non-cirques. Longitudinal profiles of cirques can effectively reflect spatial structures of cirques – that information is useful for understanding the history of development of studied cirques [1,8]. In this classification method, an exponential function shown in Equation (1) is first fitted on the longitudinal profile through the steepest part of the headwall terminated at valley-head point of each individual cirque or non-cirque sample. Then a linear discriminant function based on the fitting parameter of each longitudinal profile, *c*-value in Equation (1), and the height derived from the profile is built and used to classify cirque candidates into cirques or non-cirques [9].

$$y = (1 - x)e^{cx} \tag{1}$$

Currently, this method has been verified only through classifying a total of 55 samples in the Alps and the High Sudetes, and showed reasonable results (overall accuracy is 92.7% and F1 score is 0.91) [9]. To our best knowledge, this method has not been verified neither with a large sample size, nor within other large regions. This study focuses on the assessment of the performance of longitudinal profile-based cirque classification method on large-amount cirque samples across large area, which conducts a preliminary test with both linear and new non-linear classifiers.

II. Experimental Design

The experiment is designed to evaluate the applicability of the longitudinal profile method for cirque classification on large-number of samples in a large test area (Fig. 1).

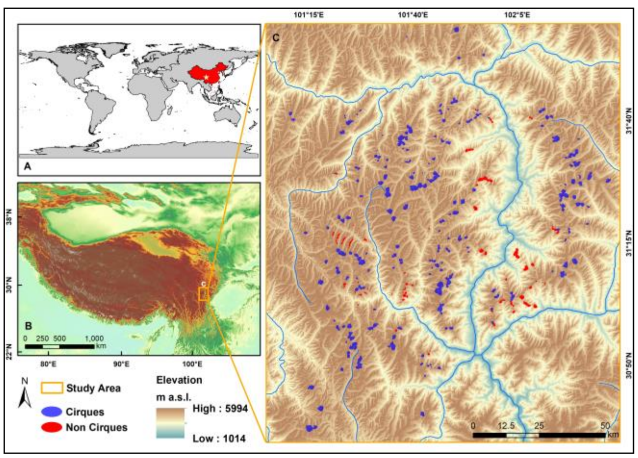

Figure 1. Map of the study area and samples of cirques and non-cirques manually derived in the study area. This area is in the Mt. Daxue and Mt. Qionglai of the Hengduan Range on the southeastern Tibetan Plateau.

A. Study area and data

The study area is in the Mt. Daxue and Mt. Qionglai of the Hengduan Range on the southeastern Tibetan Plateau (Fig. 1). The region is abundant in Quaternary palaeoglacial landforms and has been studied by paleoglacier mapping and reconstruction.

The sample set collected in this area includes 256 typical cirques and 101 non-cirques with cirque-like forms (Fig. 1). It is distinctively larger than the sample set (23 cirques and 32 non-cirques) reported in a related study [9]. The samples were manually delineated based on visual interpretation on Google Earth. ALOS PALSAR RTC (with 12.5-m resolution) was used to derive longitudinal profiles of samples [10].

B. Experimental flow design

The longitudinal profile based cirque classification has two input parameters: the longitudinal profile and the cirque height extracted for each sample or cirque-like object. In this study, the use of longitudinal profile is the median axis of cirque that through the headwall and floor terminated at the cirque threshold. It differs from the Krause et al.'s profile through the steepest part of the headwall terminated at valley-head point that caused by the aims of this study is differentiating cirques and non-cirques rather than differentiating cirque and non-cirque valley head [9]. The longitudinal profile is generated by assigning the elevation of DEM to the median axis of samples that is extracted by an GIS tool in ArcMap named Automated Cirque Metric Extraction (ACME) [11]. The exponential function is fitted to the longitudinal profiles of training samples of cirques. The *c*-value of the fitted exponential function together with the cirque profile height is used to build rules for classification of cirque candidates into cirques or non-cirques. The original classification rules, built by a linear classifier (or discriminant function), are shown as Equation (2): D1 less than 0 means cirque and D1 larger than 0 means non-cirque) with the fitted *c*-value and the height of longitudinal profile, based on the study in the Alps and the High Sudetes based on 55 samples [9].

$$D1 = 400 \times (c\text{-}value) - Height + 500 \tag{2}$$

The original classification rules can be directly applied to our study area for testing the extrapolation applicability of these rules. Alternatively, parameter-refitting can be applied whereby the coefficients in the original rules can be first updated with the *c*-value fitted with the training samples in our study area and then applied to classification. Direct application of the *c*-value is called "original-rule" while parameter refitting is called "coefficient refitted-rule". In addition to these two rules based on linear classifier, non-linear classifier can also be explored for this method. This study further tested the adoption of non-linear classifiers, i.e., a curve-formed classifier, and a machine learning classifier (multi-layer perceptron).

The experiment workflow is shown in (Fig. 2). The hold-out method is applied to the sample set for testing the classification method with coefficient refitted-rule and non-linear classifiers. The sample set was randomly separated, with 70% of cirque and non-cirque samples used for training and the remaining 30% for testing. For comparing classification accuracy between application of the original-rule, the coefficient refitted-rule and the two non-linear classifiers, the original-rule was also evaluated by the training set and test set separately.

Classification indices (i.e., precision, recall/sensitivity, specificity, F1-score, and accuracy) were calculated for evaluating the performance of cirque classification methods.

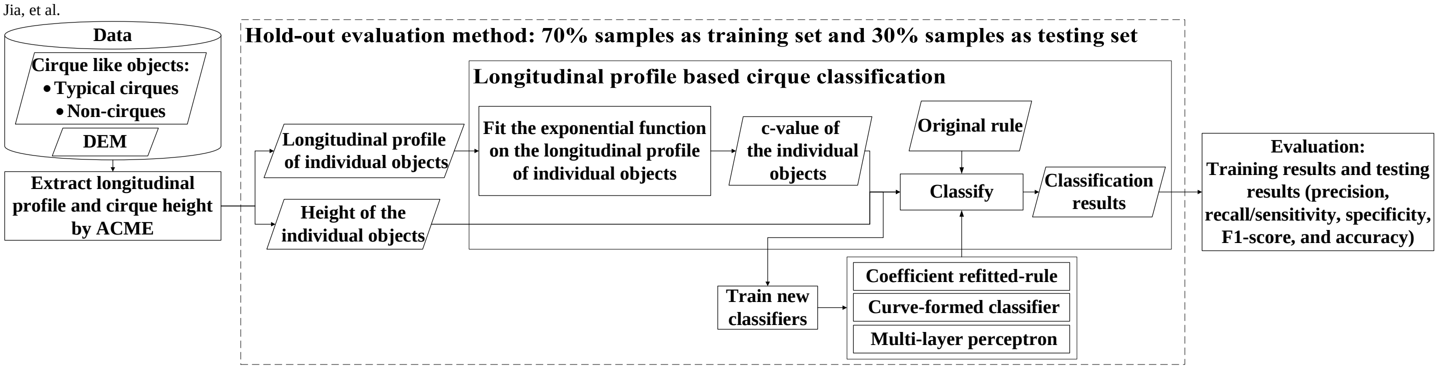

Figure 2. Flow chart for the experiment.

III. Results

Examples of the longitudinal profile of a cirque and a non-cirque corresponding normalized profiles with *c*-value are shown in Fig. 3a and 3b. The concavity of cirque candidates is decreased with *c*-value increasing, with a c-value of zero indicating that the cirque candidates consist of a straight slope. Fig. 3c shows fitted curves of cirques and non-cirques, in which the blue dashed line and red dashed line represent the fitted curve of median *c*-value in cirques and non-cirques, respectively. The median *c*-value of cirques is around -1,5 and the median *c*-value of non-cirques is around -0.2. The actual cirque profile is concave under past glacial erosion, meaning the *c*-value should be less than zero. However, Fig.3c shows three *c*-value of profiles higher than zero, which might be because there are errors between profiles extracted by the median axis and actual profiles of a few cirque candidates.

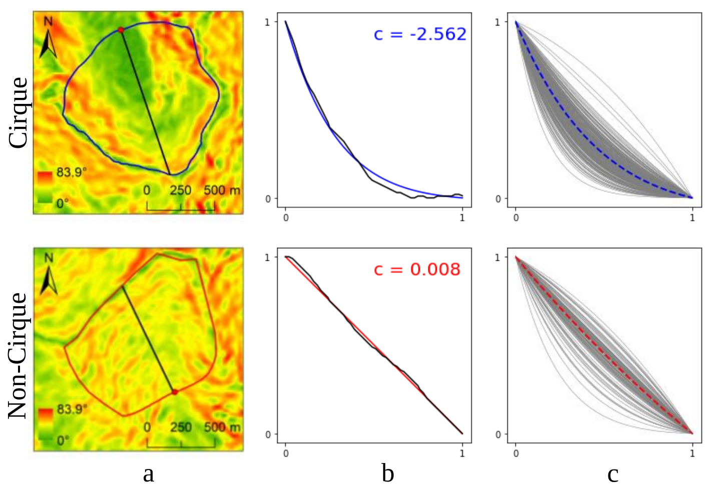

Figure 3. Examples of the longitudinal profiles of cirque and non-cirque based on slope map (a) and corresponding fitted profiles with *c*-value (b). The fitted curves for the longitudinal profiles of cirques and non-cirques (c).

Fig. 4 shows the distribution of height and *c*-value of cirque and non-cirques, and the linear discriminant function refitted by the training samples in the study area. The linear discriminant function of the coefficient-refitted rule is shown in Equation (3). The non-linear curve-formed classifier is shown in Equation (4).

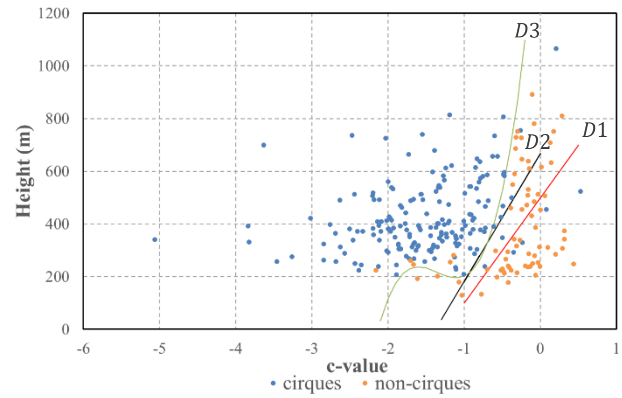

Figure 4. Scatter plot of the *c*-value and cirque height from training set in this study. Red line is original linear discriminant line (the function D1 as Equation (2)). And the coefficient refitted linear discriminant line (the function D2 as Equation (3)) is in black color. Green curve is the non-linear, curve-formed classifier (the function D3 as Equation (4)).

$$D2 = 485.7 \times (c\text{-}value) - Height + 667.7 \tag{3}$$

$$D3 = 666.9 \times (c\text{-}value)^3 + 2707.4 \times (c\text{-}value)^2 + 3540.3 \times (c\text{-}value) - Height + 1701.7 \tag{4}$$

Table I shows classification accuracy of the longitudinal profile cirque classification method using linear and non-linear classifiers under test. The results indicate that classification using the original rule (F1=0.9 for training set, and F1=0.92 for test set) is inferior to all other methods: coefficient-refitted rule (F1=0.93 for training set, and F1=0.96 for test set), curve-formed rule (F1=0.95 for both training and test sets), and multilayer perceptron (F1=0.96 for training set, and F1=0.94 for test set). The original rule shows very high sensitivity but modest specificity (51.4% and 54.8% for training and test sets, respectively) while other classifiers have higher specificity (74.3%-91.6%) and lower sensitivity (93.4%-98.6%). The original rule will produce more false positives than other rules, while other three classifiers will misclassify 4-6% of true cirques as non-cirques.

TABLE I . COMPARISON OF CLASSIFICATION ACCURACY FROM METHODS WITH LINEAR AND NON-LINEAR CLASSIFIERS RESPECTIVELY.

Classification indices	**Linear classifier**				**Non-linear classifier**			
	Original rule		***Refitted rule***		***Curve-formed classifier***		***Multilayer perceptron***	
Precision	83.80%	84.40%	90.50%	92.60%	96.60%	94.80%	95.80%	93.90%
Recall/Sensitivity	97.80%	100.00%	95.60%	98.70%	93.40%	96.10%	96.30%	93.90%
Specificity	51.40%	54.80%	74.30%	80.70%	91.60%	87.10%	88.40%	87.50%
F1-score	0.90	0.92	0.93	0.96	0.95	0.95	0.96	0.94
Accuracy	84.80%	86.90%	89.60%	93.50%	92.90%	93.50%	94.20%	91.80%
	CL	CL	DF	CL	DF	CL	DF	CL

a. DF: Data fitting, CL: Classification

Overall classification performance of the coefficient-refitted rule (Equations 3) and new non-linear classifiers (the curve-formed classifier of Equation (4), and multi-layer perceptron) have improved that from the original rule, with marked improvement of specificity, but with a trade-off of slightly lower sensitivity of predictions.

IV. DISCUSSION

The linear classifier originally used with the longitudinal profile based cirque classification method showed relatively poor performance (besides on the Recall/Sensitivity index) because of low specificity of cirque classification. The overall evaluation of the longitudinal profile classification of cirques using rule-of-thumb shows that all rules under test provide very good classification (F1≥0.9) while the refitting and non-linear classifiers further improve classification (F1>0.93) (Table 1). Note that the curved-formed classifier shown in Fig. 4 is appropriate for differentiating cirque and non-cirques with statistically significant results in this dataset. However, it relied on visual interpretation that is not automated. Comparatively, the multi-layer perceptron classifier is automatic, which is convenient for wide applications.

V. CONCLUSION

In this study, the longitudinal profile based classification method shows improved performance in classifying cirques and non-cirques on the southeastern Tibetan Plateau with a large sample size, when the coefficient-refitted linear classifier and the two non-linear classifiers were adopted respectively. Further refinement of classification methods is likely to produce highly accurate cirque classification. In future work, we will also increase the number of manually mapped cirques and non-cirques in other areas on the southeastern Tibetan Plateau and explore other machine learning methods for further improvement of glacial cirque classification.

VI. ACKNOWLEDGEMENTS

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