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Evaluation of Forest Damaged Area and Severity Caused by Ice-snow Frozen Disasters over Southern China with Remote Sensing

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Abstract: The accurate assessment of forest damage is important basis for the forest post-disaster recovery process and ecosystem management. This study evaluates the spatial distribution of damaged forest and its damaged severity caused by ice-snow disaster that occurred in southern China during January 10 to February 2 in 2008. The moderate-resolution imaging spectroradiometer (MODIS) 13Q1 products are used, which include two vegetation indices data of NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index). Furtherly, after Quality Screening (QS) and Savizky-Golay (S-G) filtering of MODIS 13Q1 data, four evaluation indices are obtained, which are NDVI with QS (QSNDVI), EVI with QS (QSEVI), NDVI with S-G filtering (SGNDVI) and EVI with S-G filtering (SGEVI). The study provides a new way of firstly determining the threshold for each image pixel for damaged forest evaluation, by computing the pre-disaster reference value and change threshold with vegetation index from remote sensing data. Results show obvious improvement with the new way for forest damage evaluation, evaluation result of forest damage is much close to the field survey data with standard error of only 0.95 and 1/3 less than the result that evaluated from other threshold method. Comparatively, the QSNDVI shows better performance than other three indices on evaluating forest damages. The evaluated result with QSNDVI shows that the severe, moderate, mild damaged rates of Southern China forests are 47.33%, 34.15%, 18.52%, respectively. By analyzing the influence of topographic and meteorological factors on forest-vegetation damage, we found that the precipitation on freezing days has greater impact on forest-vegetation damage, which is regarded as the most important factor. This study could be a scientific and reliable reference for evaluating the forest damages from ice-snow frozen disasters.

Keywords: ice-snow disaster; vegetation index; forest; remote sensing; southern China

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1 Introduction

Forests are one of the most important and complex ecosystems on land, and play a significant role for maintaining ecosystem biodiversity, water and energy balance and human needs (Ahammad et al., 2019). But the forest ecosystems have disturbed tremendously by natural disasters, such as ice-storm, over the last several decades, large-scale forest ice-snow disasters have occurred more frequently (King and Bemrose, 2008; Orr et al., 2008). An ice snow freezing disaster can affect thousands of square kilometers of forest areas (Degaetano, 2010), the

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trees or branches may fall down from the forest canopy, leading to short- and long-term ecological balance (Bragg et al., 2003; Blume-Werry et al., 2016; Brugger et al., 2018). Ice-snow disaster has become one of the main natural interferences affecting the structure and function of forest ecosystems (Gleason and Nolin, 2016).

Remote sensing has played the key role in detecting the spatial distribution of forest damage and assessing the severity of forest damage (Chen and Sun, 2010). Although field surveys can provide comprehensive and detailed information of the ice-storm disaster to forest vegetation (Broxton et al., 2015; Busseau et al., 2017), it usually costs lots of manpower, material and financial resources and much time (Olthof et al., 2004). In contrast, remote sensing can provide explicit vegetation changes information before and after ice and snow storm disasters in large-scale region (Millward and Kraft, 2004; Isaacs et al., 2014). Due to the lack of multiple period's images near the ice-snow disaster, some high resolution data, such as Landsat, were restricted for detecting the forest damages accurately and timely. As the high temporal resolution of moderate-resolution imaging spectroradiometer (MODIS) product, it has been used widely (Kim et al., 2006; Walker et al., 2014; Brandt et al., 2016; Tsalyuk et al., 2017).

There was a severe ice and snow storm event that occurred from 10 January to 2 February 2008 over Southern China, which resulted in huge property losses and various natural biome disturbances. According to the official statistics, the ice, snow and sleet caused severe forest losses and destroyed 1.98×10^7 ha of forest, or nearly 13% of China's forests, in the 19 provinces/ municipalities/autonomous-regions of Hunan, Jiangxi, Guangdong, Hubei, Anhui, Guizhou, Henan, Sichuan, Yunnan, Shanxi, Qinghai, Gansu, Zhejiang, Jiangxi, Fujian and Jiangsu, Tibet, Guangxi and Chongqing (Forestry of China Editorial Board, 2008). The total included 6.83×10^6 ha of bamboo, 1.16×10^7 ha of woodland and 1.35×10^5 ha (9.9 billion in number) of saplings (Shao et al., 2011).

Chinese researchers have carried out a number of investigations and analyses on forest damages after this disaster by field survey or remote sensing, including damage to forest stands, damage mechanisms of forest stands and post-disaster restoration and reconstruction (Xu et al., 2008). Wu (2016) computed the normalized difference vegetation index (NDVI) ratio of pre- and post-disaster and regarded the damage threshold as 0.21 with the subjective method to assess the forest vegetation damage in Guangdong Province. Enhanced vegetation index (EVI) data were also used to diagnose the health of forest vegetation (Sun et al., 2012). The unit threshold method were usually used to detect forest vegetation in previous studies, and it cannot differentiate the regional situation differences, which lead to many errors in forest damages estimation after disaster.

In this study, we selected NDVI and EVI to delineate the forest-damaged areas and to assess forest-vegetation damage over southern China in 2008. Current threshold methods are insufficient to accurately extract the critical threshold for evaluating forest damage. Therefore, the objective of this research is to study a new way of computing the threshold for each pixel in images to improve the accuracy of forest damage evaluation, and to explore the suitability of NDVI and EVI in detecting damaged forest-vegetation and to develop a suitable method about extracting the critical threshold. Furtherly, this study will reveal the spatial distribution pattern of damaged forest and its severity caused by ice-snow disaster.

2 Study area and Materials

2.1 Study area

The study area includes Hunan, Jiangxi, Guizhou, Fujian, Zhejiang, Anhui, Hubei and Guangdong provinces, Guangxi Zhuang Autonomous Region and Chongqing Municipality in southern China (Fig. 1). It almost covers disaster area impacted by the extreme ice-snow frozen disaster from middle January to middle February in 2008, which extremely rarely occurred in past 50 years and in some areas even in past 100 years (Shao et al., 2011). This disaster has caused serious damage and great losses to human life and natural resources, especially for the forest cover, and the forest-damaged areas in southern China account for 85% of the total. And the study area also covers almost the hilly mountains area over southern China, whose forest cover rate exceeds 50%, and is one of the three major forest-cover areas in China. There are a large number of evergreen broad-leaved forests and evergreen coniferous forests, such as *Fir tree*, *Masson pine*, *Eucalyptus*.

2.2 Data sources

The MODIS/Terra atmospherically corrected Level 3 16-Day composite vegetation index (MOD13Q1) from

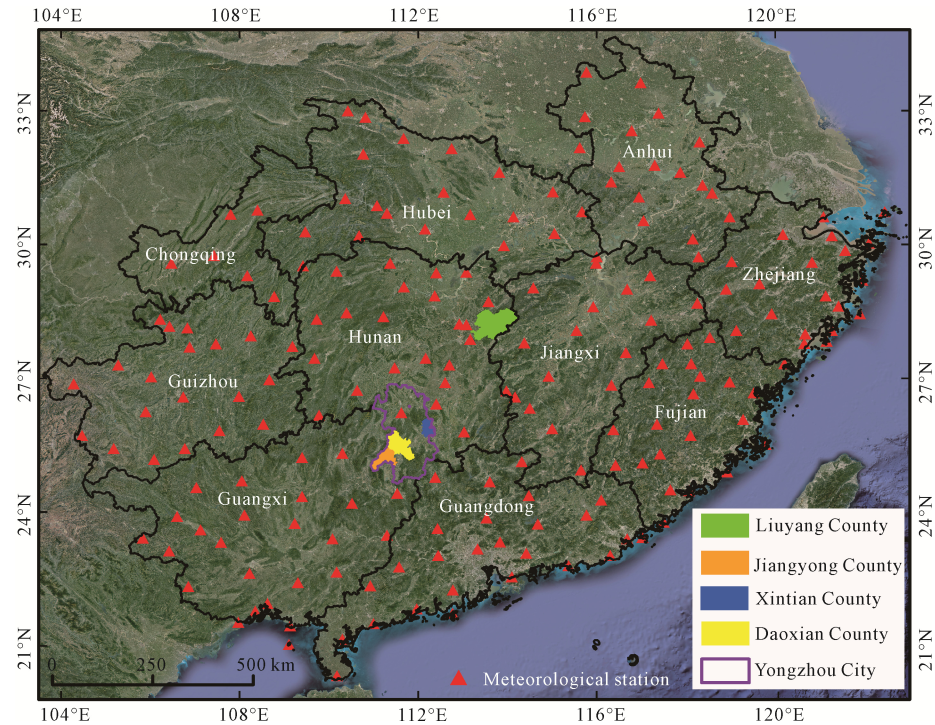

Fig. 1 Location of study area and distribution of meteorological station

2004 to 2008 is used to detect the forest damage from this ice-snow disaster. The MOD13Q1 dataset includes NDVI and EVI, whose temporal resolution is 16 days and spatial resolution is 250 m (Table 1). To avoid the impact from the secondary disaster (e.g., fire disaster and pests) and ensure the accuracy of the extracted result, the MOD13Q1 data for the ice melting period were selected to extract the forest-damaged areas, which include two periods of (Julian Day of Year) DOY049–DOY064 and DOY065–DOY080. Meteorological and digital elevation model (DEM) data were used to mask the damages from other disaster damages. Meteorological data were downloaded from the China Meteorology Ministry (http://data.cma.cn/), and DEM data with 250 m spatial resolution were downloaded from the Google Earth. The land cover in 2005 was obtained from National Earth System Science Data Sharing Infrastructure in China (http://www.geodata.cn/), and it was modified based on the higher-resolution remote sensing images (Landsat 5 TM) in 2008 to acquire the forest cover data in 2008. The damaged sampling data retrieved from the pre-and post-disaster Landsat images and Google Earth high resolution images were used to validate the evaluation result.

Table 1 Data used in this study

Data	Details	Period	Resolution
Weather	Mean temperature, Precipitation (http://data.cma.cn/)	2008-01-10 to 2008-02-02	Daily data
MOD13Q1	EVI data, NDVI data, Quality layer	DOY049–DOY064, 2004 to 2008 DOY065–DOY080, 2004 to 2008	250 m, 16-day
Landsat	Landsat5 TM	2007-12-31, 2008-12-51	30 m
Statistical data	Source from official data and published literature		
Land cover	2008 forest land cover in south China provided by National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn/)		250 m
DEM data	Downloads from Google Earth by professional software		250 m

Notes: MOD13Q1: MODIS/Terra atmospherically corrected Level 3 16-Day composite vegetation index; EVI: Enhanced Vegetation Index; NDVI: Normalized Difference Vegetation Index; DOY: Julian Day of Year; TM: Thematic mapper; DEM: Digital Elevation Model.

3 Methods

3.1 The extraction of ice-snow disaster mask data

In an ice-snow disaster, if the weight of ice-snow on the tree is greater than its limit, the accumulated snow will cause the tree to bend or break, thereby resulting in physiological damage or mechanical damage (Broxton et al., 2015). Therefore, meteorological data are interpolated based on the ANUSPLIN software to extract the mask data of ice-snow disasters, which can show potentially damaged areas. The number of freezing days is calculated according to the standard given by the Chinese National Climate Center (a freezing day is a day with a precipitation amount greater than 0 and an average temperature below 1℃). Chen found that most damaged areas have been frozen for greater than or equal to 3 days (Chen and Sun, 2010). In addition to the number of freezing days, the thickness of ice-snow cover is also an important factor that affects forest damage (Saarinen et al., 2016). Some areas had been frozen for less than 3 days, but there was sufficient precipitation to damage forest vegetation. Hence, the area where the number of freezing days was greater than or equal to 3 or the average daily precipitation was more than 15mm, will be regarded as the potentially damaged area.

3.2 Vegetation index preprocessing

In this study, we use two methods for vegetation index preprocessing. The first approach is to correlate the MODIS quality assessment (QA) with the mathematical formula. We selected valid data for vegetation index products with the availability of QA data (Huete et al., 1999) and calculated the average value of the vegetation index from 2004–2007 for each pixel, which is recorded as $\overline{VI}$. However, we could not completely eliminate all vegetation indices of lower quality based on QA. Due to the similar growth environment in the same period of every year, the value of vegetation index should fluctuate within a certain range (Spruce et al., 2011). If one value deviated seriously from other vegetation index values in the same pixel, the value would be regarded as an outlier. Therefore, the change rate of the vegetation index is selected as the outlier detection factor in this study, which is recorded as R:

$$R = \left| \frac{VI_i - \overline{VI}}{\overline{VI}} \right| \tag{1}$$

where i refers to one of the four years in the study time (i.e., 2004, 2005, 2006 and 2007). The threshold of R for NDVI is set as 0.3, and for EVI is 0.35 for the same period. Based on this method, the NDVI and EVI datasets were separately preprocessed. Consequently, NDVI with Quality Screening (QSNDVI) and EVI with Quality Screening (QSEVI) were obtained in this study.

In the second approach, we use Savitzky-Golay filtering (S-G filtering) to smooth the vegetation index which can reduce the effect of clouds and some abnormal noise to make the data more uniform (Chen et al., 2004). Based on this method, the NDVI and EVI datasets were separately preprocessed. Consequently, NDVI with Savizky-Golay filtering (SGNDVI) and EVI with Savizky-Golay filtering (SGEVI) were also obtained in this study.

3.3 Forest damaged evaluation method

3.3.1 Algorithm of changing threshold for forest damaged by ice-snow disaster

The threshold of forest changes damaged by ice snow disaster varies for each pixel, since the original situation of each pixel is much different. It is important to compute pre-disaster reference values and change threshold for each pixel, based on the time series MODIS products of 2004–2007.

The average value of vegetation index for the same period from 2004 to 2007, which is recorded as $\overline{VI'}$, is used as a pre-disaster reference value. The maximum difference between the pre-disaster vegetation index and pre-disaster reference is selected as the change threshold, which is recorded as $Diff_{\max}$:

$$Diff_{\max} = max(|VI_i' - \overline{VI'}|) \tag{2}$$

where VI_i' is vegetation index value in year i.

3.3.2 Algorithm for evaluating forest damage area

The post-disaster change value of the vegetation index, which is recorded as M, is used as a factor to diagnose whether the vegetation pixel is damaged,

$$M = \overline{VI'} - VI_{2008} \tag{3}$$

where VI_{2008} represents the post-disaster vegetation index for the same period of $\overline{VI'}$. If the M-value was greater than $Diff_{\max}$, the pixel would be considered as forest-damaged area. Both of the two periods (DOY049–DOY064 and DOY065–DOY080) of damaged area would be thought as the forest damaged area caused by ice snow disaster.

3.3.3 Algorithm for evaluating the severity of damaged forest

Since the environment of vegetation growth is similar in the same period of each year, the vegetation index should normally fluctuate in a certain range, and its anomaly can be attributed to the interference from external factors (e.g., meteorological condition). Based on this, Spruce (2011) developed the image threshold method to evaluate pest damage of forest vegetation with computing the variation of vegetation index for each pixel. The equation to compute vegetation index variation is:

$$Assess1 = \frac{\overline{VI'} - VI_{2008}}{\overline{VI'}} \quad (4)$$

Although this method considers that different vegetation has different pre-disaster reference values, it does not consider the change threshold ($Diff_{\max}$) for each pixel. Some vegetation indices changed greatly after the ice-snow disaster, which simply exceeded the normal change range ($Diff_{\max}$); however, they were evaluated as severely affected vegetation, which was obviously unreasonable. Based on this, we improve image threshold method to evaluate the severity of affected forest with the rate of M and $Diff_{\max}$, which is recorded as *Assess2*:

$$Assess2 = \frac{\overline{VI'} - VI_{2008}}{Diff_{\max}} \quad (5)$$

4 Results

4.1 Spatial distribution of forest damaged areas

Table 2 shows the forest-damaged rate for each provincial-level administrative region (PLAR). The experimental results for Anhui, Guizhou, Hunan, Jiangxi and Zhejiang provinces show obvious differences, whereas the forest-damaged rates of other five PLARs are similar. Jiangxi and Anhui provinces were the worst forest-impacted areas based on EVI products (QSEVI and SGEVI). The forest-damaged rates of Jiangxi and Anhui provinces with QSEVI are 41.83% and 36.12%, and that with SGNDVI are 32.43% and 33.95%. However, the worst forest-impacted areas are found in Hunan and Jiangxi provinces, whose official investigation data are consistent with the extracted results of QSNDVI and SGNDVI. Therefore, a preliminary assumption can be established that the extracted results with NDVI are superior to those with EVI.

According to existing researches (Wang et al., 2008; Chen and Sun, 2010; Shi et al., 2012), the forest damage rates in Hunan, Hubei, Anhui, Guangxi, Jiangxi and Guizhou PLARs were 35.30%, 20.30%, 23.55% 13.02%, 30.00% and 17.70%, respectively. With comparison to above reference results, it can be found that the extracted results with EVI are obviously different. Taking Guizhou province as an example, the QSEVI extracted result is 8.76%, which is approximately half of the reference result, and the SGEVI extracted result is 4.91%, which is approximately one-fourth of the reference result. Moreover, the experimental results (25.57% and 21.67%) with EVI data are also distinctly lower than the reference result (35.30%) in Hunan Province. In contrast, using MODIS NDVI products to detect the forest-damaged areas can generate a good result from Table 2. Through the above discussion and analysis, it can be found that the extracted results with NDVI are better than those with EVI.

It is not difficult to find that the forest-damaged areas determined with QSNDVI and QSEVI are larger than those determined with SGNDVI and SGEVI for each PLAR, except for Fujian Province, which is caused mainly by the S-G filtering algorithm. Although the S-G filtering algorithm can eliminate some anomalies from

Table 2 The statistical results of forest-damaged rate with different methods (%)

Provincial-level region	QSEVI	SGEVI	QSNDVI	SGNDVI	Official data
Anhui	36.12	33.95	26.93	22.50	23.55
Chongqing	1.40	0.43	1.78	1.26	
Fujian	6.30	3.81	6.14	6.57	
Guangdong	2.83	2.47	3.54	2.67	
Guangxi	3.55	3.43	10.61	5.00	13.02
Guizhou	8.76	4.91	17.35	13.53	17.70
Hubei	17.35	16.92	16.33	12.67	20.30
Hunan	25.57	21.67	41.03	30.34	35.30
Jiangxi	41.83	32.43	34.89	29.93	30.00
Zhejiang	22.46	16.34	29.77	25.66	
The total damage rate	15.84	12.89	19.62	15.17	
The damaged area (ha)	14.2×10^6	11.6×10^6	17.6×10^6	13.6×10^6	

Notes: QSEVI: enhanced vegetation index with quality screening; SGEVI: enhanced vegetation index with Savizky-Golay filtering; QSNDVI: normalized difference vegetation index with quality screening; SGNDVI: normalized difference vegetation index with Savizky-Golay filtering the time series data of vegetation index, it can also consider some descending vegetation indices affected by ice-snow disaster as anomalies. The advantages of QSNDVI and SGNDVI can be found from the further work, which is required to select an optimal dataset that can detect forest-damaged areas caused by ice-snow disasters.

Fig. 2 shows the spatial difference between forest-damaged areas with QSNDVI and SGNDVI. We selected 2 kinds of sample points to validate the damaged areas. To accurately validate the extracted results, 153 sampling points (point1) and 118 sampling points (point2) are located in type '2' and type '5', respectively. If the accuracy of point1 was higher and the accuracy of point2 was lower, then the extracted result with QSNDVI was more accurate. According to the statistical result, 103 of the sampling points of 'point1' are true with a corrected rate of 67.32%, which means that the extracted result with QSNDVI is better than that with SGNDVI. Furthermore, only 17 sampling points of 'point2' are judged to be correct, with a correct rated of only 14.41%. Consequently, the QSNDVI dataset is more suitable to detect the forest-damaged areas affected by ice-snow disasters in this study, whose extracted result is shown in Fig. 3. It can be found that the forest-damaged areas are mainly distributed in Hunan, Jiangxi, Zhejiang and Guizhou provinces.

4.2 Spatial distribution of forest damage degree

Based on the algorithm of formula 5, evaluating forest damage is performed with QSNDVI. According to the field survey results from the Forestry Bureau in Daoxian County of Yongzhou City, Hunan Province (Ice-snow Disaster Investigation Team, 2008a), evaluated results are divided into three types by adjusting the threshold parameter: severe damage, moderate damage and mild damage. Fig. 4 shows that a large amount of forest vegetation is subjected to severe damage in this ice-snow disaster. To explicitly describe the forest-damaged severity, the evaluated results are recorded for each province in Table 3. It suggests that the severely damaged areas account for a larger proportion, reaching 47.33% in total, and that the percentages of severely damaged areas exceed 29.70% for every province. However, the mildly damaged areas account for a smaller proportion, reaching only 18.52% in total; the mildly damaged areas account for less than 15.00% and close to 10.00% in some provinces.

The pre-disaster image from 31 December 2007 and post-disaster image from 31 December 2008 from Landsat 5 TM (Fig. 5) are contrasted to reflect the evaluated effect of forest-vegetation damage. The severely damaged areas are sketched in Figs. 5a and 5d which show obvious change. Nevertheless, compared with the severely damaged areas, the patches do not show the 'browning' of forest vegetation in the moderately

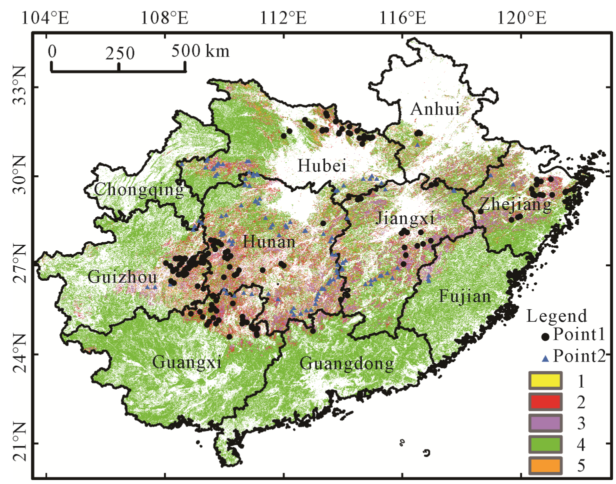

Fig. 2 Comparison of the forest-damaged areas with QSNDVI and SGNDVI data in southern China in 2008. '1': undetected areas; '2': the pixel from QSNDVI data is considered the damaged area, but the pixel from SGNDVI data is considered the undamaged area; '3': damaged area; '4': undamaged area; '5': the pixel from QSNDVI data is considered the undamaged area, but the pixel from SGNDVI data is considered the damaged area; 'point1': sample point for damaged area of type '2'; 'point2': sample point for damaged area of type '5'.

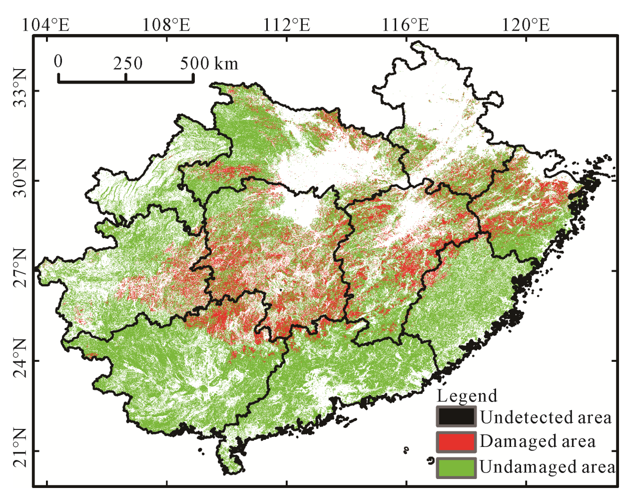

Fig. 3 The spatial distribution of forest-damaged areas in Southern China in 2008

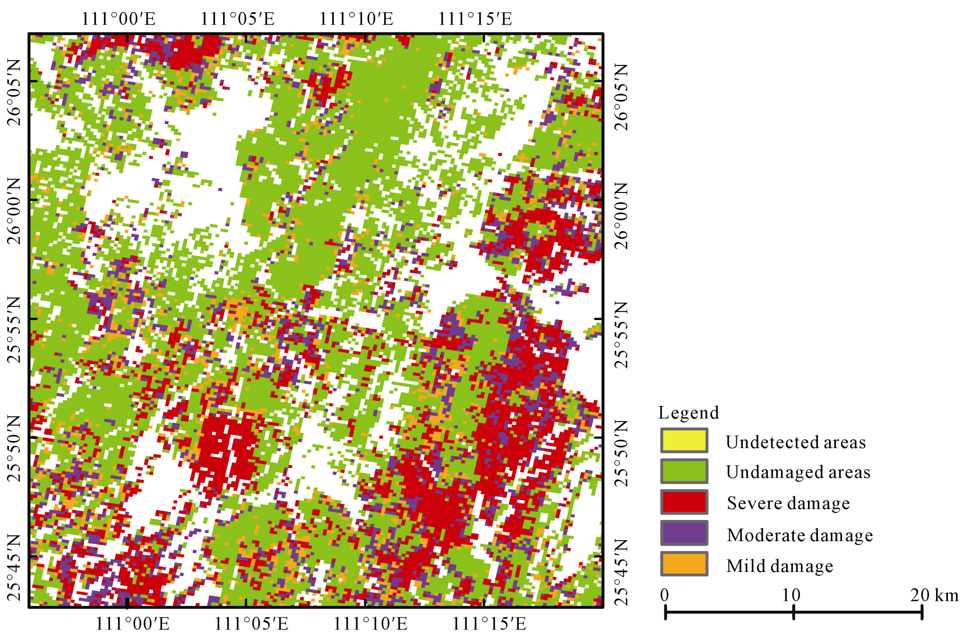

Fig. 4 Assessment result of the forest damage degree taking Daoxian County of Hunan Province, China as an example showed in Fig. 1

Table 3 Area and area percentage of different damage degree in forest in southern China in 2008

Provincial-level region	Severe damage (10^6 ha)	Percent (%)	Moderate damage (10^6 ha)	Percent (%)	Mild damage (10^6 ha)	Percent (%)
Anhui	0.268	30.86	0.371	42.61	0.231	26.53
Chongqing	0.029	48.85	0.018	30.80	0.012	20.35
Fujian	0.241	50.80	0.169	35.68	0.064	13.52
Guangdong	0.245	63.33	0.099	25.68	0.043	10.99
Guangxi	1.044	62.93	0.428	25.81	0.187	11.26
Guizhou	0.786	48.13	0.546	33.42	0.301	18.45
Hubei	0.452	29.73	0.631	41.52	0.437	28.75
Hunan	2.863	52.58	1.651	30.32	0.931	17.10
Jiangxi	1.691	46.58	1.275	35.12	0.665	18.30
Zhejiang	0.716	37.06	0.825	42.69	0.391	20.25
Total	8.335	47.33	6.013	34.15	3.261	18.52

or mildly damaged areas. Generally, the more obvious ‘browning’ of forest vegetation, the more serious its damage. Consequently, the method using the QSNDVI dataset can be used to assess forest damage in this study.

5 Discussion

5.1 Advantage analysis of the improved image threshold method

We have analyzed the drawbacks of the image threshold method by comparing the principle of formula 4 and formula 5. However, the validation with experimental data for the above analysis is still missing. Therefore, the assessment results (image threshold method and improved image threshold method) are contrasted in this study. The counties of Liuyang, Xintian, Daoxian and Jiangyong are located in the core of forest-damaged areas in 2008, and the assessments of forest damage were validated in these counties. The field survey data is recorded in Table 4. And the experimental data is recorded in Table 5 (the classification threshold is set based on the field survey data in Daoxian County).

It can be found that the distinct difference between the field survey data and the evaluated results of two image threshold methods in Xintian County. Fig. 1 shows that Xintian, Daoxian and Jiangyong are belong

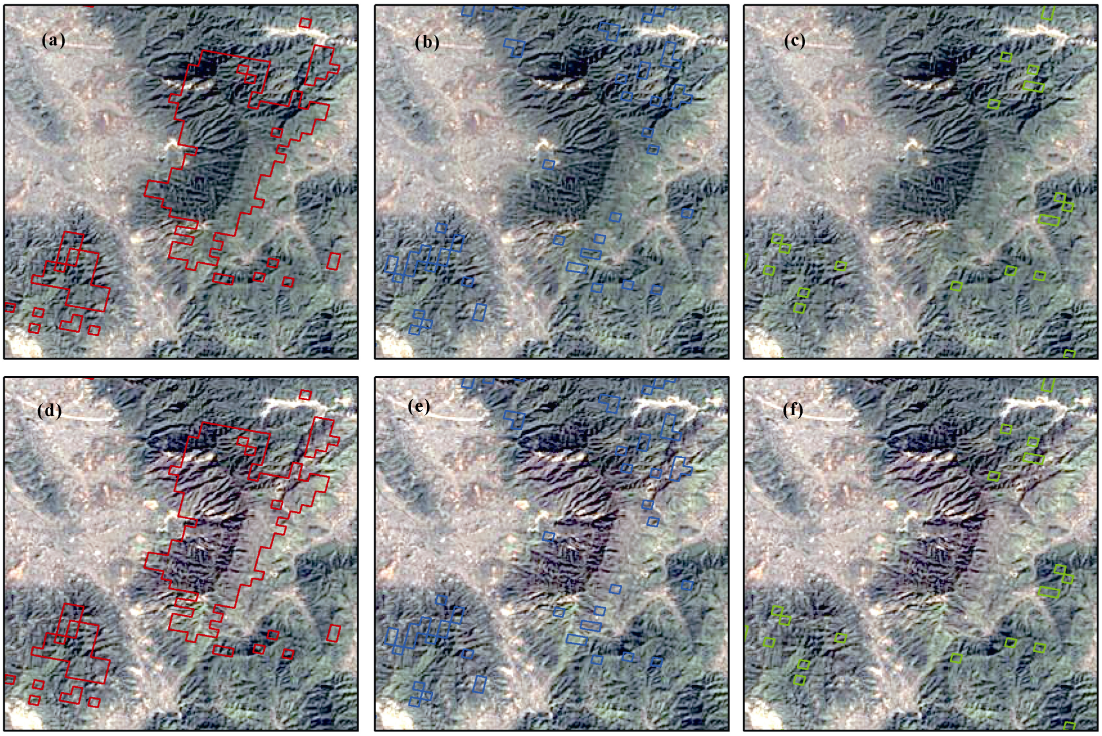

Fig. 5 Comparison of the forest vegetation with the different degrees of damage: (a) pre-disaster image in severe damage (red regions), (b) pre-disaster image in moderate damage (blue regions), (c) pre-disaster image in mild damage (green regions), (d) post-disaster image in severe damage (red regions), (e) post-disaster image in moderate damage (blue regions) and (f) post-disaster image in mild damage (green regions). Pre-disaster image: Landsat 5 TM of Path 121 Row 042 acquired on 31 December 2007; post-disaster image: Landsat 5 TM of Path 121 Row 042 acquired on 31 December 2008.

Table 4 Statistical results of forest damage assessment of ice-snow disaster with field survey method

County	Category	Severe damage	Moderate damage	Mild damage
Daoxian[a]	Area (10^4 ha)	4.06	2.33	1.16
	Percent (%)	53.79	30.81	15.40
Jinagyong[b]	Area (10^4 ha)	2.96	1.72	1.37
	Percent (%)	48.93	28.43	22.64
Xintian[c]	Area (10^4 ha)	0.28	0.22	1.01
	Percent (%)	18.50	14.53	66.97
Liuyang[d]	Area (10^4 ha)	4.00	3.69	2.36
	Percent (%)	39.80	36.72	23.48

Notes: [a]: source is Ice-snow Disaster Investigation Team (2008a); [b]: source is Ice-snow Disaster Investigation Team (2008b); [c]: source is Ice-snow Disaster Investigation Team (2008c); [d]: source is Ice-snow Disaster Investigation Team (2008d)

to Yongzhou City, Hunan Province, the geographical environments of which are very similar. Therefore, the forest damage in the above three counties should be also similar (Levkoev et al., 2017). However, there is an obvious difference between the proportions of the three classes (forest damage) in Xintian and those in Jiangyong and Liuyang. According to the field survey report (Ice-snow Disaster Investigation Team, 2008), the standard of forest-vegetation loss in Xintian has a large gap with that in other three counties, which can easily cause the above difference. On the contrary, the image threshold method can form a unified standard for evaluating forest damage (Wu et al., 2016).

To further explore the advantage of the improved image threshold for assessing forest damage, the experimental results from Jiangyong and Liuyang counties were selected to compute standard error compared to their field survey data. The result shows that the standard error of the image threshold method is 2.96 and that the standard error of the improved image threshold method is only 0.95. Although the image threshold method is better than the improved image threshold method for assessing forest damage in Jiangyong County, the accuracy of the former is much lower than that of the latter. Therefore, the improved image threshold method showed more reliable for forest damage assessment.

Table 5 Statistical results of forest damage assessment with two image threshold methods

Location	Category	Image threshold method			Improved image threshold method		
		Severe	Moderate	Mild	Severe	Moderate	Mild
Daoxian	Area (10^4 ha)	3.85	2.21	1.10	3.85	2.19	1.12
	Percent (%)	53.79	30.81	15.40	53.78	30.61	15.61
Jiangyong	Area (10^4 ha)	3.01	1.94	1.09	3.65	1.65	0.75
	Percent (%)	49.80	32.18	18.02	60.37	27.23	12.40
Xintian	Area (10^4 ha)	0.53	0.43	0.55	0.57	0.54	0.40
	Percent (%)	34.83	28.77	36.40	38.01	35.59	26.40
Liuyang	Area (10^4 ha)	2.08	3.42	4.56	3.88	3.81	2.37
	Percent (%)	20.68	34.00	45.32	38.56	37.85	23.59

5.2 Topographic and meteorological features of damaged forest

Topography is an important factor that affects forest vegetation subjected to an ice-snow disaster (Millward et al., 2010), and previous studies (Fujihara et al., 2017) have suggested that elevation, slope and aspect are three significant factors. The 2008 severe ice and snow storm damage to forest vegetation varied spatially, especially in the complex mountainous regions of southern China. The present study analyzes the features of elevations, aspect and slope data over the study area (Fig. 6). From Fig. 6a, it can be seen that the severity percentage continuously increases in a specific elevation range from 100 to 900 m, with a peak value of 55.58% at 900 m. The severity percentage gradually decreases when the elevation exceeds 900 m. There are a number of economic forests in the hills of southern China that are more fragile than natural forests located in high-elevation regions and are more likely to be affected by a natural disaster (Xiao et al., 2008). In addition, the artificial forest of Chinese fir in northern Guangdong Province is seriously damaged, mainly concentrated in the area of 500–900 m above sea level (He et al., 2010). With increasing altitude, the artificial forest decreases, which reduces the proportion of serious damage to the forest and is consistent with the present study. The pattern of artificial forest is generally single but that of natural forest is complex, which can also affect the resistance of forest vegetation (Xiao et al., 2008).

It also can be found that slope has a significant impact on forest damage from Fig. 6b, which can aggravate forest damage. However, the aspect has less influence on forest damage according to the statistical result shown in Fig. 6c, and the severe proportions are relatively close for each aspect from 45.00% to 50.00%. In other words, elevation and slope have obvious impacts on ice-snow damage to forest vegetation. Therefore,

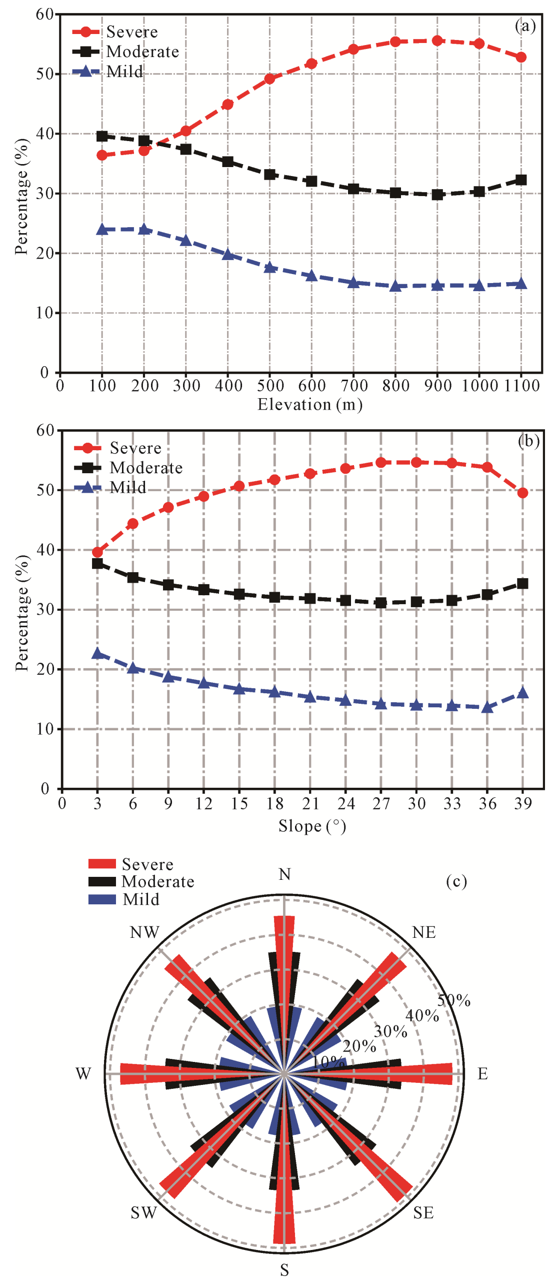

Fig. 6 Topographic statistical results for the three classes (severe, moderate and mild) of damaged areas: (a) elevation, (b) slope and (c) aspect.

effective measures must be taken to prevent such catastrophic events from occurring again for forest-vegetation with a high elevation and a steep slope.

The forest damage caused by ice-snow disasters includes glaze ice accumulating on trees, which can result in the loss of branches and twigs from the forest canopy and can even lead to uprooted and fallen trees due to continuous and disastrous weather (Broxton et al., 2015). Fig. 7 shows the relationship between precipitation and forest damage, and it can be found that the severity proportion rises rapidly with the increase in total precipitation, even exceeding 80.00%. In addition, the ratio between total precipitation and the number of freezing days (average precipitation) is also used to explore the impact of precipitation on forest damage, which is found to be similar to total precipitation, as shown in Fig. 7b. Comparatively, the severe proportion will become stable when elevation and slope reach a certain value from Fig. 6. Compared to the impact of topography factors (elevation, slope and aspect), the precipitation on freezing days made much influence because forest vegetation is more vulnerable to damage when snow accumulates on a tree beyond its weight-bearing range. Consequently, under low-temperature conditions, precipitation is the most important and significant factor for forest damage.

6 Conclusions

Based on the MODIS time series vegetation index product, this study obtained four vegetation indices, computed the pre-disaster reference value and change threshold for each pixel in advance, detected and assessed the forest-damaged areas affected by ice-snow disaster in southern China in 2008, and validated the assessed forest-damaged areas and severity results by sampling, statistical and field survey data. This study found that extracting the change threshold for each pixel in advance can obviously decrease the standard error of forest damage assessment from 2.96 to 0.95 and improve the accuracy of forest damage assessment. Generally, the QSNDVI index is more suitable for delineating the forest-damaged patches caused by ice-snow disasters compared to other three vegetation indices. And the precipitation on freezing days has more impact on forest damages than topography factors. In addition, it is necessary to take effective measures for high-altitude, steep-slope forest vegetation, which can provide scientific basis for disaster prevention and protection of forest resources and ecosystem.

In this study, the pre-disaster reference value and change threshold are critical, which directly impact the accuracy of forest damage assessment. Therefore, we will carry out some researches about accurately and reasonably extracting the pre-disaster reference value and change threshold in future study.

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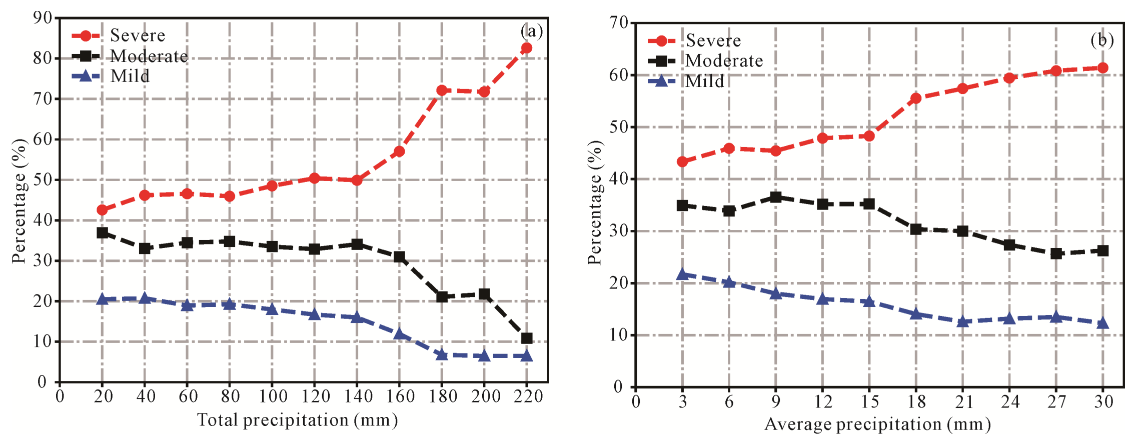

Fig. 7 Meteorological statistical results of the classes (severe, moderate and mild) of damaged areas: (a) total precipitation during the freezing period and (b) average precipitation during the freezing period

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