Improved method of freeze–thaw erosion for the Three-River Source Region in the Qinghai–Tibetan Plateau, China

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ABSTRACT
In order to quantitatively evaluate the intensity of FT erosion, eight typical factors, including annual FT cycle days, precipitation, average diurnal phase-changed water content, rainfall erosivity during the FT period, wind field intensity during the FT period, slope, aspect, and vegetation, were introduced to establish an improved evaluation method of FT erosion in the TRSR, which had better applicability in TRSR with an overall precision of 93%. Results showed that FT erosion was widely distributed in the TRSR, with zones of slight, mild, and moderated erosion being the most widely distributed. During 2000–2015, a slight improvement can be observed in the condition of FT erosion over the whole study region. Vegetation coverage was the dominant factor affecting the intensity of FT erosion in the zones with sparse vegetation or bare land, whereas the climate factors played an important role in high vegetation coverage area. Vegetation coverage played a dominant role in affecting the FT erosion intensity in zones with 0.3 ≤ VC < 0.6, whereas the terrain and climate factors played an important role in areas with sparse vegetation (VC < 0.3) or high vegetation coverage (VC ≥ 0.6). Meanwhile, slope was of great importance in affecting the process of FT erosion in zones with slopes of >18°.

ARTICLE HISTORY
Received 28 December 2016
Accepted 17 August 2017

KEYWORDS
Freeze–thaw erosion; vegetation; climatic factors; Three-River Source Region; global warming

1. Introduction
Freeze–thaw (FT) erosion, defined as a process of gravity-induced migration and accumulation in soil or rocks induced by the volume changes of water, has been considered as a serious environmental threat that leads to changes in agricultural productivity decline, degradation of grassland, land desertification, and decreased biodiversity in high-latitude and high-elevation ecosystems (Chang and Liu 2013). FT erosion is a common phenomenon in the world, accounting for 24% of the world land area and 55% of the total land area of the northern hemisphere (Demidov et al. 1995). Thus, the FT erosion is ranked as the third major erosion type after water and wind soil erosion. The process of the FT erosion is mainly governed by the number of FT cycles, freezing temperature, and the moisture content (Arenson et al. 2004).

To simulate FT cycles, many field experiments such as laboratory simulations and snow removal treatments are applied to perform the freezing or FT treatments (Logsdail et al. 1959; Mostaghimi et al. 1988; Oztas and Fayetorbad 2003; Ferrick and Gatto 2005). Especially, with the exacerbated
global warming, the process of FT erosion has become more sensitive to the climatic factors, such as precipitation and temperature. In recent years, numerous studies have reported the relationships between FT process and soil physical properties, permeability, liquid soil water contents, soil temperatures, soil ice contents, and groundwater level moisture content through laboratory experiments and field studies (Ferrick and Gatto 2005). The field erosion conditions are generally mimicked to study the effects of physicochemical parameters such as soil textures, soil moisture, organic content, and soil particle size (Oztas and Fayetorba 2003). Many results show that the structure of the soil particles configurations is greatly influenced by FT cycles, which finally leads to the changes in the physical and mechanical properties (Othman and Benson 1993). Additionally, the stability of soil aggregates has significantly negative relationship with the decreasing freezing temperature, increasing number of FT cycles, and soil moisture content at the time of freezing (Shi et al. 2012).

Many studies focused on the soil hydrothermal mechanisms, which could provide a theoretical description of this phenomenon based on site observation or field studies (Wang et al. 2007; Wang et al. 2009; Tsutsumi and Fujita 2016). However, little work had been carried out on the large-scale evaluation of FT erosion based on GIS and RS. Moreover, the interrelationship between FT action and erosion driving forces, such as precipitation and wind during the FT cycle, was not considered in the establishment of FT evaluation method in previous studies (Guo et al. 2015). In addition, the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report showed that there was a significant increase of temperature and precipitation in the twenty-first century (Henry 2008). The Three-River Source Region (TRSR), a zone with key importance to the ecological security of China, has undergone dramatic climate changes and a shift in human activities driven by a series of ecological restoration projects during the past decades (Liu et al. 2008; Qian et al. 2010). However, little quantitative information was provided about FT erosion on large scale.

Therefore, we have compiled multi-source data to develop an improved method of FT erosion for TRSR, which is composed of eight factors that derived from the erosion driving forces and environmental background for FT cycles. This study attempts to accurately evaluate and analyze the spatial–temporal change patterns of FT erosion in the TRSR for the past 10 years (2000–2015) and to distinguish the effects of various driving factors on FT erosion.

2. Materials and methods

2.1. Site selection

The TRSR, the headstream of three major rivers (the Yangtze River, Yellow River, and Lancang River), covers an area of 32.36 × 10^5 km^2, accounting for 12.13 of the total area of the Qinghai–Tibetan plateau (31.39°–36.39°N, 98.45°–102.23°E; Figure 1) (Qian et al. 2010). There is a complex mountainous landform and steep terrain in this region with the elevation ranging from 2179 to 6575 m with an average of 4435 m (Shi et al. 2012). From the southeast to the northwest, the climate types shift from humid climate to semi-arid climate, with the precipitation decreasing from 772.8 to 262.2 mm. Meanwhile, the temperature widely ranges from −17.3 °C (in January) to 13.4 °C (in July) (Guo et al. 2016). The average water flow is 1022.3 m³ s⁻¹ out of the region. Soils are not developed well with shallow depth and a high amount of rock fragments. The grassland types for the TRSR change from high-cold steppes to high-cold scrub meadows (Qian et al. 2010).

2.2. Data

(1) Observed meteorological data

There are about 60 meteorological stations available inside or around the study region, and the daily observed data during 2000–2015, such as daily precipitation, daily mean wind velocity, and daily mean soil temperature at 0 cm that refers to the surface soil temperature observed under the
condition of bare land or lower vegetation coverage (VC) with flat ground, can be downloaded for free on the official website of China Meteorological Administration (CMA). Since the distribution of the meteorological stations is uneven in TRTR, the interpolated stations were constructed by the Tropical Rainfall Measuring Mission (TRMM) with Equation (1) (Guo et al. 2015):

$$R_d = 2.048 \times R_{\text{TRMM}}^{0.823}$$

where $R_d$ is the daily precipitation of the meteorological stations, and $R_{\text{TRMM}}$ represents the TRMM3B42-derived daily precipitation.

The dataset of TRMM3B42 was organized at a spatial resolution of $0.25^\circ \times 0.25^\circ$ with a temporal resolution of 3 hours. In order to construct the daily precipitation of the interpolated stations based on the 3-hourly precipitation rate, we first multiplied each 3-hourly precipitation rate by 3 hours to get the total precipitation for each 3-hour period utilizing C# and ArgGIS 10.3. Then, we summed all the 3-hourly total precipitation in defined 24-hour period to get the total daily precipitation. Finally, the daily time-series precipitation was constructed for each interpolated station.

(2) Normalized difference vegetation index (NDVI)

The dataset of SPOT-VEGETATION (SPOT-VGT) in 2000 was acquired from the free website (http://www.free.vgt.vito.be/), at a spatial resolution of 1 km with temporal resolution of 10 days. The NDVI data of moderate resolution imaging spectroradiometer (MODIS) in 2015, organized at 1 km by 1 km with a 16-day interval, was derived from MOD13A2 (H25V5, H26V5), which was a 16-day maximum value composite (MVC).
(3) Digital elevation model

The dataset of digital elevation model was obtained from the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA), available at http://datamirror.csdb.cn/admin/datademMain.jsp, with a spatial resolution of 90 m.

2.3. Methods

(1) Factor standardization

Due to the fact that evaluating factors are measured in different units, standardization should be applied to eliminate the unit difference among variables (Shi et al. 2012). In addition, factors in the evaluating system have different effects in the process of FT erosion. The VC, for example, can reduce the strength of FT cycles, which belongs to the negative factor. On the contrary, the annual FT cycle days, for instance, can aggravate the process of FT erosion, which belongs to the positive factor. Variables of different types can be processed using Equations (2) and (3) to change them into unitless variables (0–1).

\[
I_i = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \quad \text{(Positive)},
\]

\[
I_i = \frac{I_{\text{max}} - I}{I_{\text{max}} - I_{\text{min}}} \quad \text{(Negative)},
\]

where \(I_i\) is the standardized factor of \(I\), \(I_{\text{min}}\) refers to the minimum value of factor \(I\), and \(I_{\text{max}}\) is the maximum value of factor \(I\).

(2) Weight assignment method

Assigning a weight for each factor in the evaluation system is of great importance in the evaluation of FT erosion. Many studies have been conducted to assign weights to evaluation factors, such as entropy method (Guo et al. 2015), artificial neural network (ANN) (Basso et al. 2000), indices weight method (IWM) (Guo et al. 2015), principle component analysis (PCA) (Li et al. 2006), and analytic hierarchy process (AHP) (Park et al. 2004).

However, IWM and AHP weigh the importance of factors depending on experts’ experience, which can lead to subjective disturbance for the final evaluation results. On the contrary, the entropy and PCA often determine the weight for each factor using the image features, which ignores the knowledge of experts (Yi et al. 2014). Here, we combined the AHP, IWM, and PCA methods (Equation (4)) to obtain the weights of indices, so that the objective information quantity of the image and the knowledge of experts could be both considered.

\[
w_{\text{ahp–pca–iwm},i} = \frac{w_{\text{ahp},i}w_{\text{pca},i}w_{\text{iwm},i}}{\sum_{i=1}^{n} w_{\text{ahp},i}w_{\text{pca},i}w_{\text{iwm},i}}, \tag{4}
\]

where \(w_{\text{ahp–pca–iwm},i}\) refers to the weight of factor derived from AHP, PCA, and IWM, \(w_{\text{ahp},i}\) refers to the weight of factor \(i\) derived from AHP, \(w_{\text{pca},i}\) refers to the weight of factor \(i\) derived from PCA, and \(w_{\text{iwm},i}\) refers to the weight of factor \(i\) derived from IWM.

The processes of obtaining the weights of all factors are, respectively, shown in Tables 1 and 2.

(3) Comprehensive evaluation model
For the evaluation models, domestic and abroad scholars have proposed dozens (Li et al. 2006; Guo et al. 2016). However, comprehensive evaluation index model (CEIM) utilizing the weighted linear combination method is the most widely used model in the evaluation of ecosystem or eco-environmental quality. Therefore, the CEIM was applied to calculate the index of soil FT erosion.

\[
ft = \frac{\sum_{i=1}^{n} W_{\text{ahp-pca-iwm},i} I_i}{\sum_{i=1}^{n} W_{\text{ahp-pca-iwm},i}},
\]

where \(ft\) is the FT erosion index, \(W_{\text{ahp-pca-iwm},i}\) refers to the weight of factor \(i\), \(I_i\) refers to the value of evaluation factor \(i\), \(n\) refers to the number of evaluating factors.

(4) Boundary definition of the FT erosion region

The FT erosion region is characterized by a cold climate with strong FT cycles (Zhang et al. 2007; Yan et al. 2013). To date, several efforts have been devoted to determine the extent of the FT erosion zone in the TRSR. And the method of defining the lower bound of the periglacial region as the lower bound of the FT erosion region is widely accepted at home and abroad (Fan and Cai 2003). In this paper, the boundary of the FT erosion region was obtained with the above method (Equation (6)), which excludes desert and ice glacier.

\[
H = \frac{66.3032 - 0.9197X - 0.1438Y + 2.5}{0.005596} - 200,
\]

Table 1: Relative weights of factors of soil FT erosion for AHP.

| Evaluation index | (1) ATCD | (2) Precipitation | (3) ADPWC | (4) REFTP | (5) WFIFTP | (6) Slope | (7) Vegetation | (8) Aspect |
|------------------|---------|------------------|-----------|-----------|-----------|----------|---------------|-----------|
| (1) ATCD         | 1       |                  |           |           |           |          |               |           |
| (2) Precipitation| 1/2     | 1                |           |           |           |          |               |           |
| (3) ADPWC        | 1/2     | 1/4              | 1         |           |           |          |               |           |
| (4) REFTP        | 1/3     | 1/3              | 1/2       | 1         |           |          |               |           |
| (5) WFIFTP       | 1/2     | 1/2              | 2         | 1/3       | 1         |          |               |           |
| (6) Slope        | 3       | 4                | 5         | 3         | 1/2       | 1        |               |           |
| (7) Vegetation   | 2       | 3                | 3         | 2         | 1         | 1/2      | 1             |           |
| (8) Aspect       | 1/3     | 1/2              | 1         | 1         | 1/5       | 1        | 1/3           | 1         |

ATCD, annual FT cycle days; ADPWC, average diurnal phase-changed water content; REFTP, rainfall erosivity during the FT period; WFIFTP, wind field intensity during the FT period. Note: The numbers in the table indicate the relative importance among different factors, for example, 1/2 (h3v2) indicates that precipitation is less important than ATCD.

Table 2: Weights of AHP, PCA, IWM, and the improved AHP.

| Evaluation index | \(W_{\text{ahp}}\) | \(W_{\text{pca}}\) | \(W_{\text{iwm}}\) | \(W_{\text{ahp-pca-iwm}}\) |
|------------------|-----------------|-----------------|-----------------|------------------|
| ATCD             | 0.12            | 0.13            | 0.14            | 0.93             |
| PFTP             | 0.08            | 0.17            | 0.06            | 2.83             |
| ADPWC            | 0.12            | 0.08            | 0.12            | 0.67             |
| REFTP            | 0.06            | 0.18            | 0.1             | 1.80             |
| WFIFTP           | 0.08            | 0.16            | 0.1             | 1.60             |
| Slope            | 0.22            | 0.1             | 0.2             | 0.50             |
| Vegetation       | 0.2             | 0.1             | 0.18            | 0.56             |
| Aspect           | 0.12            | 0.08            | 0.1             | 0.80             |

\(W_{\text{pca}}\), absolute value of the coefficient for each index in the first principal component which accounts for 94% of the total information; \(W_{\text{iwm}}\), weights derived from IWM based on information quantity of the image; ATCD, annual FT cycle days; PRE, precipitation; ADPWC, average diurnal phase-changed water content; REFTP, rainfall erosivity during the FT period; WFIFTP, wind field intensity during the FT period.
where $H$ refers to the altitude of the lower boundary of the FT erosion region (m), $X$ is the latitude (°), $Y$ represents the longitude (°), and all the variables are at a spatial resolution of 1000 m.

3. Evaluation principle and factors

During the past decades, the TRSR has suffered from climate warming, which has been aggravated in the twenty-first century (Guo et al. 2016). As the permafrost region in the mid-latitude, the TRSR is more sensitive to climatic warming than the arctic region (Yang et al. 2004; Shi et al. 2012). Owing to the region’s high altitude and geography, the eco-environment is characterized by long sunshine duration, strong radiation, low temperature, and strong winds (Li and Kang 2006). Then, eight of the most critical indices were chosen to comprehensively evaluate the intensity of FT erosion, which can better reflect the factors that influence the process of FT erosion: annual FT cycle days, precipitation, average diurnal phase-changed water content, rainfall erosivity during the FT period, wind field intensity during the FT period, slope, aspect, and vegetation.

(1) Annual FT cycle days

One FT cycle day is defined that the maximum temperature of one day is greater than 0 °C, whereas the lowest temperature is less than 0 °C (Guo et al. 2015). The strength of FT cycle plays an important role in the process of FT erosion (Guo et al. 2015). The more the fluctuation frequency of the surface temperature at 0 °C, the dramatic the FT cycle effect. Previous studies have shown that the FT erosion intensity would become more severe with the enlarged effect of FT cycle, which could cause greater damage to the rock or soil (Qi et al. 2006). The index of annual FT cycle days refers to the number of days of an FT cycle in a year, which was calculated based on the daily precipitation with the spatial resolution of 1000 m.

\[
PFTP = \sum_{i=1}^{365} P_i, \quad (7)
\]

where \(PFTP\) is the precipitation during the FT period, \(P_i\) refers to the precipitation in one day.

(2) Average diurnal phase-changed water content

Local and international studies have found that the phase-changed water content of the soil has significant relationship with the process of FT cycles (Wang et al. 2012). The volume expands when liquid water turns into solid ice, which can greatly destroy the physical structure of soil or rock. Thus, the destruction or failure of soil and rock would become larger with the increased phase-changed water content (Xie et al. 2015). In addition, the microwave remote sensing can detect the soil FT processes and the accompanying water phase change (Yang et al. 2008). Therefore, the AMSR-E was utilized to obtain the index of average diurnal phase-changed water content with the spatial resolution of 1000 m.

(3) Precipitation

Precipitation is a key factor in affecting the process of FT erosion. The water content of rock or soil would become larger with the increased precipitation. Due to the fact that the volume expands by about 1.1 times when liquid water turns into solid ice during the freezing period, the process can destroy the structure of soil or rock (Fan and Cai 2003). Moreover, during the process of melting, the physical properties of the soil are also greatly influenced by the precipitation, which finally changes the anti-erodibility of soil (Guo et al. 2015). The index was calculated based on the daily precipitation with a spatial resolution of 1000 m.
(4) Rainfall erosivity during the FT period

Precipitation not only increases the water content in soil but also provides the direct driving forces to initiate FT erosion by rain splash and surface runoff during the process of FT erosion (Han et al. 2011). The rainfall erosivity would increase with the enlarged precipitation, which finally leads to the stronger water flow on the soil (Wang et al. 2014). Thus, rainfall erosivity is of great importance in affecting the FT erosion intensity. The index was calculated based on daily precipitation using the Kriging interpolation method with a spatial resolution of 1000 m.

\[
R_k = \frac{1}{N} \sum_{i=1}^{N} \left( \alpha \sum_{j=1}^{m} P_{dijk} \right)
\]

\[
\alpha = 21.239 \beta^{-7.3967}
\]

\[
\beta = 0.6243 + \frac{27.346}{P_{d12}}
\]

(8)

where \(R_k\) is the rainfall erosivity of \(k\) month \((MJ \cdot mm)/(hm^2 \cdot h)\), \(\alpha, \beta\) are the model parameters, \(P_{d12}\) is the annual average value of erosive precipitation \((\geq 12 \text{ mm/day})\) (mm).

(5) Wind field intensity during the FT period

In spring and winter, the number of strong wind days is more than 10 times of the remaining time in TRSR (Shi et al. 2012). High-erosive storm events of combined intensive rain can greatly threaten the degraded soils in semi-arid and arid regions. The transport process of FT erosion materials and the FT rate of rock or soil would be accelerated (Guo et al. 2015). Therefore, wind field intensity during the FT period is another key driving factor in influencing the FT erosion intensity (Wang et al. 2014). This index was calculated based on the daily average wind speed using the Kriging interpolation method with a spatial resolution of 1000 m.

(6) Slope and aspect

Topographic factors play an important role in affecting the quantity and transport distance of the FT erosion materials (Wang et al. 2009). The possibility of the occurrence of sliding, collapse, tumbling and jumping of the rock and soil mass would become larger with the increased slope, which finally accelerates the FT process. Amounts of solar radiation incident change with the aspect, which leads to different soil temperature fluctuations (above or below 0 °C) between day and night for different aspects (Zhang et al. 2007). In this study, slope and aspect were calculated based on the DEM dataset, and then the above two indexes were resampled into grids with a spatial resolution of 1000 m utilizing ArcGIS 10.3.

(7) Vegetation

Vegetation is a key factor in affecting the land surface ecosystem and hydrological process (Fan and Cai 2003). During the process of FT erosion, it not only mitigates the erosion force of rainfall
and increase the soil stability but also reduces the soil temperature difference between day and night, which can greatly reduce the intensity of the FT erosion (Qian et al. 2010). Therefore, high VC can inhibit the process of FT erosion. Here, this index was obtained from the NDVI dataset with the spatial resolution of 1000 m.

4. Results

4.1. Precision validation of the evaluation results

Utilizing the ArcGIS 10.3, the index of FT erosion intensity for TRSR was calculated with the CEIM. Then, the boundary of the FT erosion region was applied to extract the FT erosion intensity for FT erosion region, which finally was graded into five categories with the method of Natural Breaks: slight erosion ($I < 0.32$), mild erosion ($0.32 \leq I < 0.36$), moderate erosion ($0.36 \leq I < 0.38$), intensive erosion ($0.38 \leq I < 0.44$), and severe erosion ($I \geq 0.44$).

In order to validate the evaluation results, 319 sites from regions with different land cover types were chosen (Table 3). The evaluation accuracies of the different FT erosion categories are shown in Table 5. The precision index and the basic error matrices (Equations (9) and (10); Guo et al. 2015) were adopted in order to test the accuracy of the evaluated results.

$$D_{i+} = \sum_{j=1}^{n} D_{ij},$$

$$D_{+j} = \sum_{i=1}^{n} D_{ij},$$

where $n$ refers to the number of categories, $D_{+j}$ refers to the sum of field survey category $j$, $D_{i+}$ refers to the sum of the evaluated category $i$, and $D_{ij}$ refers to the number of the evaluated category $i$ and field survey category $j$ that both occur.

The improved method of FT erosion for TRSR has high efficiency and applicability with the overall precision of 93%. However, there is a significant difference among all the erosion levels (Figure 2). The slight erosion has the best precision (97%), followed by mild erosion (93%) and moderate erosion (92%), whereas the severe erosion showed the worst precision with 83%. These phenomenon lies in the fact that the sampling points in the severe and intensive erosion regions were fewer, which affected the accuracy of the evaluation results.

4.2. Spatial differentiations and changes of freeze–thaw erosion between 2000 and 2015

Figure 3 shows that during 2000–2015, FT erosion was widely distributed in the TRSR. However, there exist great differences in both area and spatial distribution for different erosion levels (Table 4).

As shown in Figure 3(a) and Table 4 for 2000, zones of moderate and mild erosion had the largest area with 99,876 and 95,398 km², which were discontinuously distributed in Zhiduo, Germu, and
Zaduo. Slight erosion zone was mostly concentrated in western Zhiduo, eastern Qumalai, Chengduo, Xinghai, Zeku, and Tongde, with the area of 38,492 km$^2$, accounting for 13.33% of the erosion region. Moreover, the zones of intensive (41,606 km$^2$) and severe (13,437 km$^2$) erosion were mostly concentrated in eastern Zhiduo, southern Germu, eastern Zaduo as well as in southern Jiuzhi and Banma. In addition, No-FT erosion was mainly concentrated in the headstream regions of the Yel-low River and the Yangtze River because of the lower altitude and high annual temperature in these zones. Figure 3(b) shows that in 2015, the slight erosion covered the largest area with 93,798 km$^2$, accounting for 32.48% of the erosion region, which was mostly distributed in Yushu, Chengduo, Nangqian, Gande, Xinghai, and Zeku. Zones of severe and intensive erosion were mostly concentrated in Germu as well as in Zhiduo.

During 2005–2015, the condition of FT erosion over the whole study region has been slightly improved with the increased area of slight erosion in the source region of the Yellow River and Lancang River.

As shown in Table 5 and Figure 4, there existed significant differences in spatial patterns of different levels for these three source regions: the Yangtze River, Yellow River, and Lancang River. In

![Figure 2. Evaluation accuracy of each erosion level.](image-url)
Figure 3. Spatial patterns of soil FT erosion intensity in the TRSR. (a) FT erosion intensity of 2000, (b) FT erosion intensity of 2015.
2000, the source region of the Yellow River had the smallest mean erosion intensity of 0.34 because of the widely distributed mild and slight erosion zones with the area of 24,900 and 23,500 km². The source region of the Lancang River had the largest mean erosion intensity of 0.38, which belonged to the level of intensive erosion. In this sub-region, the moderate erosion zones covered the largest area of 9200 km², followed by mild erosion with 7600 km², whereas the slight erosion had the smallest area of 1900 km². In 2015, the source region of Yangtze River had the largest of erosion intensity of 0.38 that belonged to the level of intensive erosion: the intensive erosion zone was the most widely distributed with an area of 42,000 km², followed by severe erosion with 38,500 km². On the contrary, the source region of Lancang River had the smallest mean erosion intensity of 0.29, where the slight erosion zone was the most widely distributed with the area of 21,100 km².

During 2000–2015, the condition of FT erosion for the source region of the Yellow River had been improved as indicated by the increases in areas of slight erosion and decreases in areas of moderate, intensive, and severe erosion. However, the FT erosion of the source region of the Yangtze River had aggravated, as evidenced by the increased area of intensive and severe erosion. Moreover, the condition of FT erosion for the source region of the Lancang River had also been improved with the largely increased area of slight erosion.

To better monitor changes in FT erosion intensities among the three source regions, the FT erosion intensity index (FTII) (Equation (11)) was applied to analyze the change intensity (CI) of the three source regions during 2000–2015 (Jing et al. 2008),

\[
W_j = 100 \times \sum_{i=1}^{n} R_i \times P_{ij},
\]

where \(W_j\) refers to the FT erosion intensity index of river source region \(j\), \(R_i\) refers to the erosion level of \(i\) in the river source region of \(j\), \(P_{ij}\) refers to the area percentage of erosion level \(i\) in the river source region of \(j\).

As shown in Figure 5, there was a decreasing trend in SEII for the source regions of Yellow River and Lancang River during 2005–2015, with the decreasing magnitudes of 40 and 172, respectively. Meanwhile, the FT erosion intensity change for the source region of Yangtze River showed an increasing trend with an increasing magnitude of 38. Thus, the source region of Lancang River had the dramatic changes in erosion intensity during the study period.

4.3. Change intensity of FT erosion between 2000 and 2015

In order to better analyze the spatial–temporal change patterns of FT erosion for 2000–2015, the CI was calculated with ArcGIS10.3. Considering the standard deviation of erosion CI (0.05) and the natural conditions, the CI was graded into six categories, including intensive decrease (MD, CI <
-0.15), moderate decrease (SD, $-0.15 \leq CI < -0.1$), slight decrease (SD, $-0.1 \leq CI < -0.05$), stable (ST, $-0.05 \leq CI < 0.05$), slight increase (SLI, $0.05 \leq CI < 0.1$), and moderate increase (MI, $0.15 \leq CI < 0.25$).

As shown in Figures 6 and 7, there was a distinct spatial differentiation among different grades of CI during 2000–2015. The stable zone covered the largest area of 163,606 km$^2$, accounting for 46.81% of the total study area and this zone was discontinuously distributed in western Xinghai, Zaduo, Zeku, Qumalai, Gande, Jiuzhi, and Maqin. The slight increase zone had the second largest area of 60,924 km$^2$, which was mostly concentrated in Zhiduo and Germu. Zones of slight and moderate decrease were mainly distributed in Nangqian, Yushu, southern Chengduo, and Banma, with the area of 43,650 and 15,760 km$^2$, respectively. These findings demonstrated that the condition of FT erosion had been slightly improved over the entire TRSR.

5. Discussions

5.1. Relationship between FT erosion intensity and vegetation variables

Vegetation plays an important role in inhibiting the process of FT erosion (Qian et al. 2010). However, the effects of different plant types and VC on the FT erosion intensity vary largely. Here, six typical plant types in TRSR, including coniferous forest, meadow, cultivated land, shrub, grassland, and bare land, were selected to explore the relationships between the vegetation variables and FT...
erosion intensity. As shown in Figure 8, there were significant differences in erosion intensities among different plant types. The mean erosion intensity of cultivated land was 0.43, which belonged to the level of intensive erosion. This phenomena occurred because there was no or lower VC in the cultivated land during the FT erosion period (late winter and early spring) (Guo et al. 2016). Moreover, the unreasonable human activities, such as steep slope reclamation, greatly destroyed the physical structure of soil (Shi et al. 2012). The above reasons finally aggravated the process of FT erosion. On the contrary, the coniferous forest and the meadow showed the strongest ability to prevent soil FT erosion, which had the smallest erosion intensity of 0.33 and 0.34, respectively. This result lied in the factor that zones dominated by coniferous forest and meadow had higher VC, which would be optimal for inhibiting soil erosion (Mostaghimi et al. 1988). Furthermore, the coniferous forest and meadow were mainly distributed in the regions, where the disturbance intensity of human activities was smaller (Liu et al. 2008). For the zone dominated by grasslands, the mean FT erosion intensity was larger of 0.37. In these regions, the increased temperature, precipitation and overgrazing, all exerted substantial influences on VC, soil water content, as well as the physical and chemical structures of the topsoil (Shi et al. 2012). Both natural and anthropogenic factors aggravated the FT erosion process. The fluctuation range and standard deviation of erosion intensity for bare land was smaller because of the low VC. In these regions, intensive and severe erosion were widely distributed. Moreover, the shrubs and grassland had a larger fluctuation range of erosion intensity because of the wide distribution of these plant types.

As shown in Figure 9, (1) in section AB of the curve (VC < 0.3), the relationship between FT erosion intensity and VC was not significant. Zones with sparse vegetation or bare land were almost distributed in the regions with low temperature or steep terrain that exerted a more important influence on the process of FT erosion. (2) In section BC of the curve (0.3 ≤ VC < 0.6), the FT erosion intensity decreased with the increased VC. The phenomenon lied in the fact that the vegetation

Figure 7. Classification of change intensity of FT erosion in the TRSR during 2000–2015.
could not only mitigate the erosion forces of rainfall or wind, but can also increase the soil stability, which in turn reduced the intensity of FT erosion (Fan and Cai 2003). (3) In section CD of the curve (VC ≥ 0.6), there was a positive relationship between FT erosion intensity and VC. The reason was that there existed a significantly positive relationship between VC and climate factors (precipitation and temperature), and with the aggravated global warming, the increased precipitation and rising temperature could not only accelerate the grown of plants, but also exacerbate the process of FT erosion (Wang et al. 2012; Wang et al. 2014; Guo et al. 2015). In addition, high VC was always concentrated in the zones with abundant precipitation (Yang et al. 2004). Precipitation not only increased the water content in soil, but also provided the direct driving forces for FT erosion by rain splash and surface runoff (Yang et al. 2008).

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**Figure 8.** FT erosion intensity for different plant types. The top of each line represents the maximum value of erosion intensity for each plant type, whereas the bottom shows the minimum value. The green line refers to the mean value of erosion intensity, and the bottom of the square represents the standard deviation of erosion intensity.

**Figure 9.** Relationships between mean FT erosion intensity during 2000–2015 and vegetation coverage.
Therefore, we could determine that the VC played a dominant role in affecting the FT erosion intensity in zones with $0.3 \leq \text{VC} < 0.6$, whereas the terrain and climate factors played an more important role in areas with sparse vegetation ($\text{VC} < 0.3$) or high VC ($\text{VC} \geq 0.6$).

5.2. Relationship between FT erosion intensity and slope

Slope was a key factor to influence the spatial patterns of the FT soil erosion intensity (Othman and Benson 1993). Therefore, how to quantitatively evaluate the relationships between slope and erosion intensity was of great importance to prevent the FT soil erosion (Fan et al. 2003; Li et al. 2006). As shown in Figure 10, in the zones with slope $< 18^\circ$, the intensity of FT erosion had no significant relationship with slope. This was because zones with slope $< 18^\circ$ were mostly distributed in the valley region of the three rivers. With the increasing impacts of global warming, corresponding increases in both precipitation and temperature could be observed in these regions, which were conducive to plant growth and vegetation activities (Qian et al. 2010). And these could inhibit the process of FT erosion (Li and Kang 2006). However, zones with slopes of $> 18^\circ$ are mainly concentrated in high-altitude areas with sparse vegetation or bare land. Slope was the dominant factor in the process of FT erosion. Therefore, slope played an important role in zones with slopes of $> 18^\circ$, whereas vegetation and climate factors served as the dominant factors that affected the process of FT cycles in zones with slopes of $< 18^\circ$.

6. Conclusions

Fully considering the eco-environmental characteristics and the influence factors of the FT erosion in TRSR, eight typical factors, including annual FT cycle days, precipitation, average diurnal phase-changed water content, rainfall erosivity during the FT period, wind field intensity during the FT period, slope, aspect, and vegetation, were introduced to establish an improved evaluation method of FT erosion in TRSR. Then, the spatial–temporal change patterns of FT erosion and its driving mechanisms were analyzed during 2000–2105.

(1) The improved method of FT erosion for TRSR had high efficiency and applicability with the overall precision of 93%.
(2) During 2000–2015, FT erosion was widely distributed in the TRSR. Slight, mild erosion, and moderate erosion were the most widely distributed. No-FT erosion was mostly concentrated in the headstream regions of the Yellow River and Yangtze River. The condition of FT erosion over the whole study region has been slightly improved with the increased area of slight erosion in the source region of the Yellow River and Lancang River.
(3) During 2000–2015, the FT erosion of the source region of the Yangtze River was aggravated, whereas that of the source region of Yellow River was improved. Moreover, the FT erosion intensity of the source region of the Lancang River had the most dramatic change during the study period.

(4) The coniferous forest and the meadow showed the strongest ability to prevent soil FT erosion, whereas zones dominated by cultivated land had the severest FT erosion intensity. VC played a dominant role in affecting the FT erosion intensity in zones with $0.3 \leq VC < 0.6$, whereas the terrain and climate factors played a more important role in areas with sparse vegetation ($VC < 0.3$) or high VC ($VC \geq 0.6$).

Meanwhile, slope was of great importance in affecting the process of FT erosion in zones with slopes of $>18^\circ$.

These results can provide scientific bases for the prevention and management of soil FT erosion in the TRSR. However, further studies should be investigated to clarify the mechanisms underlying the FT erosion processes.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was funded by the Open fund of Key Laboratory for Digital Land and Resources of Jiangxi Province, East China University of Technology [grant number DLLJ201709]; Open fund of Key Laboratory for National Geographic Census and Monitoring, National Administration of Surveying, Mapping and Geoinformation [grant number 2016NGCM02]; National Natural Science Foundation of China [grant number 41501425], [grant number 41401111]; and the Natural Science Foundation of Shandong Province [grant number ZR2014DL001], [grant number ZR2015DL005].

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